ECONOMIC, ENVIRONMENTAL AND SOCIAL OPTIMIZATION OF FOREST-BASED BIOMASS SUPPLY CHAINS FOR BIOENERGY AND BIOFUELS

by

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Abstract

Utilization of forest-based biomass for bioenergy and biofuels production could generate additional revenue streams, reduce greenhouse gas (GHG) emissions and generate development opportunities for forest-dependent communities. Barriers such as the capital intensity of conversion technologies, complexity of biomass procurement logistics, and the need to establish sustainable supply chains must be overcome. Mathematical modeling has supported the optimal design of biomass supply chains for bioenergy or biofuels production separately, mostly from an economic perspective. Some studies incorporated environmental and/or social criteria in the optimal supply chain design. However, no study modeled forest-based biomass supply chains for the simultaneous bioenergy and biofuels production, considering economic, environmental and social benefits. The development of such model is the objective of this thesis. First, an optimization model is developed that determines the optimal network design and the optimal yearly flows of raw materials and products that maximize the net present value (NPV) of the supply chain. The model considers the flow of energy among co-located conversion technologies and is applied to a case study in Canada. Second, a life cycle environmental analysis is developed to analyze the environmental impacts of the supply chain alternatives in the case study. Third, the optimization model is reformulated as bi-objective with an environmental objective that maximizes the GHG emission savings associated with the supply chain. These savings are estimated by comparing the emissions of the forest-based biomass supply chain system, versus those of the baseline system where unused biomass is disposed with current methods and energy demands are satisfied with currently available sources. Finally, a multi-objective optimization model is generated that integrates a social objective. The social objective is quantified by a social benefit indicator that assigns different levels of impact of job creation based on the type and location of the jobs. The bi-objective and multi-objective optimization models are applied to the case study and solved using a Pareto-generating solution method. Results indicate a trade-off between the NPV of the supply chain and the other two objectives, and a positive correlation between the generation of high impact jobs in the region, and the overall GHG emission savings.

Preface

The original work presented henceforth was conducted by the author, Claudia Adrileth Cambero Calva, during her PhD program, under the supervision of her academic adviser, Dr. Taraneh Sowlati, at the Industrial Engineering Research Group of the University of British Columbia, Point Grey campus. Dr. Sowlati advised Claudia in the process of defining the topic, scope, objectives and approach of the research project; gathering data and information; developing, validating and applying the models as well as providing editorial guidance for the composition of manuscripts. This thesis presents a background of the research topic, the research objectives, a review of the relevant literature, a description of the case study in Interior British Columbia, several decision support models, results of the application of such models to the case study, as well as the analysis and discussion of the obtained results. For the development of the case study, the author visited the region, interviewed industry managers, and had close collaboration with industry experts who provided detailed data and information and helped validate the model and case study assumptions. Five peer-reviewed publications were generated from the work presented in this dissertation:

- A version of Chapter 2 is published. Cambero, C., Sowlati, T. 2014. Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives – A review of literature. Renewable and Sustainable Energy Reviews, 36: 62-73.
- A version of Chapter 3 is published. Cambero, C., Sowlati, T., Marinescu, M., Roser, D. 2015. Strategic optimization of a forest residues to bioenergy and biofuel supply chain. International Journal of Energy Research, 39: 439-452.
- A version of Chapter 4 is published. Cambero, C., Hans Alexandre, M., Sowlati, T. 2015. Life cycle greenhouse gas analysis of bioenergy generation alternatives using forest and wood residues in remote locations: A case study in British Columbia, Canada. Resources, Conservation and Recycling, 105: 59-72.
- A version of Chapter 5 is published. Cambero, C., Sowlati, T., Pavel, M. 2016. Economic and life cycle environmental optimization of forest-based biorefinery supply chains for

bioenergy and biofuel production. Chemical Engineering Research and Design, 107: 218-235

- A version of Chapter 6 is submitted for publication. Incorporating social benefits in multi-objective optimization of forest-based bioenergy and biofuel supply chains.

In addition, one of the models presented in this dissertation (Chapter 3) served as basis for a sixth publication written in collaboration with a PhD student from the RWTH Aachem University in Germany. In this collaboration, Claudia contributed to verify and validate the model, worked together with the main author of the paper in the analysis of results and manuscript writing, and edited the manuscript that was accepted for publication in a peer-reviewed journal:

- Hombach, L., Cambero, C., Sowlati, T., Walther, G. In Press. Optimal design of supply chains for second generation biofuel incorporating European biofuel regulations. Journal of Cleaner Production.

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Glossary

GHG Greenhouse gas: A gas that traps heat in the atmosphere. This process is the fundamental cause of the greenhouse effect.

Forest-based biomass: In this research, forest-based biomass refers to by-products and waste generated from traditional forestry operations, e.g. bark, sawdust, shavings, small diameter trees and other non-merchantable harvesting residues.

LCA Life cycle assessment: A technique to evaluate the environmental impacts associated with all the stages of a product's life from cradle to grave.

LPG Liquefied petroleum gas: Flammable mixture of hydrocarbon gases used as fuel in heating and transportation applications.

MILP Mixed integer linear programming: Framework to model problems with discrete and continuous decision variables.

MPB Mountain pine beetle (Dendroctonus ponderosae Hopkins): Species of bark beetle native to forests of Western North America. The current outbreak of the MPB has largely affected the Interior British Columbia region, destroying wide areas of lodge pole pine forest.

MOO Multi-objective optimization: Framework to model problems with more than one objective function that are optimized simultaneously.

NPV Net present value: The difference between the present value of cash inflows and the present value of cash outflows over a specific planning horizon.

ORC Organic Rankine cycle: Thermodynamic process that converts heat into work. The heat is supplied externally to a closed loop, which uses an organic substance with a boiling point occurring at a lower temperature than water as working fluid.

SMH Scheduled machine hours: Hours when a machine is programmed to work.

TSA Timber supply area: Administrative area designated by the British Columbia’s Forest Act.

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I would also like to express my gratitude to my thesis committee members Dr. Robert Kozak, Dr. Mihai Pavel and Mrs. Jennifer O'Connor for their very helpful ideas and suggestions during the development of this work that helped me improve the research work presented in this dissertation.

I am grateful to the Forest Feedstock research group at FPInnovations, in particular to Dr. Dominik Röser and Dr. Marian Marinescu for providing relevant data, information, and technical advice for the development of the case study presented in this thesis.

I want to express my gratitude for the financial support provided by the National Council of Science and Technology, Mexico (CONACYT), and by the Natural Science and Engineering Research Council of Canada (NSERC).

I am thankful to all my colleagues at the Industrial Engineering Research Group (IERG) Shaghaygh, Mehdi, Luke, Krishna, Diana, Nazanin, Mahdi and Mahmood for the interesting talks about research and life, and for making the time at the office much more enjoyable.

I am forever grateful to my parents Rosalina and Luis, and to all the members of my big loving family in Mexico, for their love, their support and encouragement throughout all my important endeavors.

And finally, my biggest thank you is to my husband Angel Valerio for believing in me, for inspiring me, and for motivating me to achieve the most challenging and worthwhile goals in my life.

Para Angel y Mateo.

Por ser mi inspiración, motivación y fortaleza.

Chapter 1: Introduction

1.1 Background

Biomass is a low-carbon renewable energy source (Srirangan et al., 2012) that can be used directly in an energy application (heat and electricity) and can be processed or converted into solid, liquid or gaseous fuels for different practical applications (Demirbaş, 2001). Consequently, it is expected to play a major role in the field of sustainable energy production worldwide (Aitken, 2010). Among biomass sources, forest residues such as the portions of tree tops, branches and un-merchantable wood left in the forest after harvesting operations that can be removed from the forest without affecting soil productivity), and wood residues such as sawdust and wood chips and other residual biomass (e.g. agricultural residues) have an advantage compared to green crops such as corn grown as biomass. These residual biomass sources do not affect the food security, offer high greenhouse gas (GHG) savings when replacing fossil fuels, and provide the opportunity to generate valuable products from materials that would otherwise be disposed as waste (Popp et al., 2014; Shabani et al., 2013).

Canada has a developed forestry sector that produces large amounts of forest and wood residues (Canadian Forest Service, 2013). For instance, in 2010, Dymond (2010) estimated that the amount of forest residues in Canada was 20±0.6 million oven-dry tonnes (odt) per year. The utilization of such residues for the production of bioenergy and biofuel products could strengthen the economic competitiveness of the forestry sector, mitigate GHG emissions, and promote employment, particularly in rural areas (FPAC, 2011; Natural Resources Canada, 2015). Despite all these potential benefits, the establishment of new bioenergy and biofuel plants requires large capital investments and proper long-term planning. The economic and technical feasibility of conversion technologies; the availability, quality and cost of biomass; and the demand and price of bioenergy and biofuels must be considered (Shabani et al., 2013; Yue et al., 2014b). The consideration of all these aspects involved in the planning of sustainable forest-based biomass supply chains calls for a comprehensive approach to achieve economic, environmental and social targets. From an economic perspective, the large capital and operating costs of conversion technologies exert pressure on the delivery of high-value, cost-efficient products (Dansereau et al., 2014). From an environmental perspective, global environmental awareness calls for solutions with environmental benefits that replace fossil-based product supply chains (Martinez-Hernandez et al., 2014). From a social perspective, the new projects should be able to create long-term development prospects to the communities that are involved in them (Sims, 2003). All these factors stress the need for the optimal design of a supply chain that maximizes generated value for the industry, the environment and for the society.

Optimization studies in the literature have been developed to support the strategic design and planning of a variety of biomass supply chains for the production of different products (Shabani et al., 2013). Most of these studies aimed to optimize the average annual economic performance of bioenergy or biofuel supply chains separately (Yue et al., 2014b) and used average annual rates of biomass production per region (e.g. An et al., 2011; Ekşioğlu et al., 2009; Elia et al., 2011; Kim et al., 2011b; Leduc et al., 2008; Natarajan et al., 2014; Parker et al., 2010; You et al., 2012). To the best of the author's knowledge, none of the previous supply chain optimization studies modeled the integrated production of bioenergy and biofuels from forest and wood residues with varying availability over the lifetime of the project, which should be considered in the strategic design of a forest-based biomass supply chain network.

Due to the rising public awareness of sustainability issues, a recent branch of optimization studies analyzed bioenergy and/or biofuel supply chains from a wider perspective, integrating environmental and/or social objectives with the economic objective (Čuček et al., 2011; Giarola et al., 2013, 2011; Kanzian et al., 2013; Liu et al., 2014; Pérez-Fortes et al., 2014; Santibañez-Aguilar et al., 2014, 2011; You and Wang, 2011; Zamboni et al., 2009). The majority of these studies focused separately on either the production of bioenergy or biofuels. Their environmental optimization objectives were formulated as the minimization of GHG emissions (Giarola et al., 2013, 2011; Liu et al., 2014), the minimization of environmental footprints (Bernardi et al., 2012; Čuček et al., 2012), or the minimization of overall environmental indicators that were based on Life Cycle Impact Assessment methods such as Impact 2002+ (Pérez-Fortes et al., 2014) or Eco-indicators (Santibañez-Aguilar et al., 2014, 2011). To the extent of the author's knowledge, no study to date has focused on quantifying the net environmental benefits (e.g. GHG emission savings) of introducing a forest-based biomass supply chain that produces bioenergy and biofuels simultaneously. The estimation of such an environmental benefit should include an accurate quantification of the emissions produced by the supply chain, considering that a portion of the generated bioenergy can be used in the operation of biofuel plants. Further, the estimation has to consider the current conditions of energy and fuel provision, and the currently used methods for forest-based biomass disposal in the region of study.

Only a few studies have integrated a social objective in the formulation of models for the optimal design of bioenergy and/or biofuel supply chains. Since bioenergy and biofuel plants utilizing residual biomass are often located in remote areas, their establishment can stimulate community development by providing employment opportunities (Sims, 2003). Thus, job creation has often been the preferred indicator for the social impacts of new bioenergy and biofuel projects (e.g. Ayoub and Yuji, 2012; Santibañez-Aguilar et al., 2014; You et al., 2012; Yue et al., 2014a). However, to the best of the author's knowledge, no study thus far has considered that different types of jobs in different communities might be created and they might offer different levels of benefits. For instance, the social benefit of establishing a new forest-based biomass plant in a community that derives most of its employment income from the forest sector might be higher than that in other (more diversified) communities. Further, the creation of jobs in a sector with large unemployment rates might be preferable than other types of jobs. Thus, an optimization model that aims to quantify the social benefits of new bioenergy and/or biofuel projects should consider both the type and location of the created jobs.

1.2 Research objectives

The main objective of this research is to develop an integrated supply chain optimization model that maximizes the economic, environmental and social benefits of utilizing available forest and wood residues for the production of bioenergy and biofuels. The specific objectives of this research are as follows:

1. To optimize the strategic design of a forest-based biomass supply chain for the production of bioenergy and biofuels from an economic perspective. To achieve this objective, a multi-period mixed-integer programming model is developed that maximizes

the net present value (NPV) of the supply chain over a 20-year planning horizon. The model is applied to a case study in Interior British Columbia, Canada.

2. To investigate the life cycle GHG emission savings associated with the implementation of a forest-based biomass supply chain for the production of selected bioenergy and biofuel products in the case study region.
3. To incorporate environmental considerations into the supply chain optimization model. This objective is achieved by incorporating an environmental objective into the model that quantifies the life cycle GHG emission savings associated with the supply chain. The resulting bi-objective model is applied to the case study.
4. To incorporate social considerations into the supply chain optimization process. To achieve this objective, a social benefit indicator that considers the impact of job creation in different job classes and different locations is developed and introduced as a third objective function to the model. The resulting multi-objective model is applied to the case study.

1.3 Case study

To demonstrate the applicability of the models developed in this work, the models are applied to a case study in the Williams Lake Timber Supply Area (TSA), which is located in Interior British Columbia, Canada. This TSA covers about 4.9 million hectares and is one of the largest TSAs in the province (Ministry of Forests, Lands and Natural Resources Operations, 2012). It has been significantly affected by a mountain pine beetle (MPB) infestation, and almost all harvesting in the area has been focused on beetle-killed lodge pole pine trees. The harvesting has been used mainly to fulfill the demand of local sawmills. Currently, the majority of harvesting residues such as tree tops, branches, leaves and non-merchantable stems, are left in the forest and burned, and a large amount of sawmill waste such as sawdust, shavings, chips and hog fuel, is burned or landfilled.

Different utilization paths for forest and wood residues that are not committed to any other industry in the region are examined in this case study. Four biomass types are considered: forest harvesting residues and non-merchantable MPB-killed logs collected from 1592 aggregated cutting blocks in the forest, as well as wood chips and hog fuel from small local sawmills. The three main mill centers in this TSA are considered as the candidate location for new bioenergy and/or biofuel plants. These are the communities of Anahim Lake, Hanceville and Williams Lake.

Anahim Lake is a remote off-grid community. Its sole sawmill and the entire community (about 360 inhabitants) rely on diesel for electricity generation (BC Hydro, 2014; Province of British Columbia, 2013). Hanceville is a small remote community (about 200 habitants) (BC Curios Ltd, 2013) with limited access to the hydropower grid of the province due to power line capacity restrictions, and its sole sawmill generates 50% of its electricity requirements with an on-site diesel generator. These two communities have no access to the natural gas pipeline of the province, so heating oil is the fuel currently used for industrial heat generation. Williams Lake is the largest community in the TSA (about 18,500 inhabitants) (Statistics Canada, 2015a) which has several wood processing mills (Ministry of Forests, Lands and Natural Resources Operations, 2012). Most of the sawmill residues generated around Williams Lake are used to supply a pellet mill and a power plant currently operating in the area. According to estimations from FPInnovations (Friesen, 2012), Williams Lake has a limited amount of available low cost biomass for the next 10 years, but it is possible that this availability will increase from years 11 to 20. This community is connected to the hydropower grid and the natural gas pipeline of the province.

The bioenergy generation technologies considered in this study were proposed by the Forest Feedstock group at FPInnovations based on the current interest of the communities under study (the replacement of off-grid energy sources in the region with bioenergy was studied in previous techno-economic studies (Marinescu, 2013, 2012)). Other conversion technologies were selected considering the results of the Biopathways Project (FPAC, 2010), which identified fast pyrolysis and pelletizing as two of the most promising technologies among a variety of traditional and emerging (close-to-commercialization) bio-technologies for the utilization of forest and wood residues in British Columbia. In total, 23 combinations of different technologies and sizes are the candidate technologies that can be implemented in the three candidate locations:

- a biomass boiler for the production of heat only (2 MW_{th});
- a biomass boiler coupled with a steam turbine for electricity only (0.5, 2, 3, or 5 MW_{el});
- a biomass boiler coupled with a steam turbine for the co-generation of heat and electricity (0.5, 2, 3, or 5 MW_{el});
- a biomass oil heater with an Organic Rankine cycle (ORC) for the co-generation or electricity only (0.5, 2, 3, or 5 MW_{el});
- a biomass gasifier with an internal combustion engine for the co-generation or electricity only (0.5, 2, 3, or 5 MW_{el});
- a fast pyrolysis plant for the production of bio-oil (200; 400; or 600 odt of input biomass per day);
- a pellet mill (15,000; 30,000; or 45,000 t of pellets per year).

The production of four different products is considered: heat, electricity, bio-oil, and pellets. The generated heat would be used to satisfy local demand, while the generated electricity could be used by the installed biofuel plants, or sold to the grid. The produced pellets and bio-oil are considered as potential export products to be sold to Europe (Rotterdam port).

1.3.1 Assumptions

Although the case study is based on the current conditions of the Williams Lake TSA, some assumptions were necessary for modeling the forest-based biomass supply chain for production of bioenergy and biofuels in the region. In the developed models, the main assumptions are:

- After conventional harvesting, residues (tree tops, branches, and non-merchantable MPB-killed logs) are left as waste in the roadside. These residues can be collected from forest roadside for bioenergy and biofuel production at the minimum stumpage cost.
- Harvesting and road construction in the Williams Lake TSA happen over the following 20 years as per planned by the Ministry of Forests, Lands and Natural Resource Operations.
- The local sawmills remain in operation, and their residues are available for bioenergy and biofuel production over the entire planning horizon.

- The considered bioenergy and biofuel technologies are at a mature commercial development stage.
- Biomass-based electricity in Anahim Lake is sold to the grid at a rate equivalent to the current diesel generation costs. In Hanceville and Williams Lake, biomass-based electricity is sold to the grid at prices equivalent to the current electricity rate in those two communities.
- Pellets and bio-oil are sold to Europe where they are used to substitute coal for electricity generation, and heating oil in industrial applications, respectively. The sales price of bio-oil is equivalent to the price of heating-oil.
- There is an international market for pyrolysis bio-oil for industrial heating applications in Europe, and the infrastructure for truck, train and sea transportation of bio-oil is in place (transport equipment and chemical ports).

Other assumptions related to the economic, environmental and social optimization models are explained in Chapters 3, 4, 5 and 6.

1.4 Organization of the dissertation

In addition to the introduction presented in this Chapter 1, this dissertation includes a literature review chapter, four research chapters, and a chapter on conclusions, strengths, limitations, and future work.

Chapter 2 presents the sustainability considerations in the design and planning of forest-based biomass supply chains, and discusses previous supply chain optimization approaches that incorporated economic, environmental and social objectives. Chapter 3 presents the development of a multi-period optimization model that maximizes the NPV of the forest-based biomass supply chain investment. In this chapter, the model is applied to the case study and the results are presented and analyzed. Chapter 4 explains the method utilized to perform the life cycle GHG assessment of the supply chain alternatives investigated in the case study, and also presents the calculation of the emission values for all the supply chain activities involved. Furthermore, a life cycle analysis of GHG emissions is performed for 16 selected supply chain configurations. The analysis presented in the last part of this chapter is not comprehensive in terms of addressing the vast number of potential supply chain configurations for the case study, but provides modeling insights for the development of the environmental objective function presented in Chapter 5. Chapter 5 presents the formulation of the environmental objective function and its integration into the optimization model. The resulting bi-objective optimization model is applied to the case study incorporating the emission values obtained in Chapter 4 and is solved using a Pareto-generating method. Chapter 6 presents the formulation of the social objective function and its integration into the optimization model. The use of a social benefit factor is proposed to quantify the overall impact of jobs of different types in various locations. The resulting multi-objective optimization model is applied to the case study and is solved using a Pareto-generating method. The estimation of the social benefit factors for the case study is based on the Forest Vulnerability Index of each of the three communities, and the average unemployment rate of various job classes in British Columbia. Finally, Chapter 7 presents the final conclusions, strengths and limitations of the work and some suggestions for future research.

Chapter 2: Literature review

2.1 Synopsis

Optimization approaches have been used in the literature to analyze and improve the performance of forest-based biomass supply chains in terms of their sustainability impacts, mostly from an economic perspective. This chapter presents and discusses the modeling approaches used to optimize economic, environmental and/or social criteria in the design and planning of forest-based biomass supply chains for the production of bioenergy (heat and power) and other bioproducts (e.g. fuels and hydrogen). First, technical, economic, environmental and social aspects relevant to the design of forest-based biomass supply chains are explained. The relevant optimization studies are then classified into economic optimization models, and multi-objective optimization models. Distinctive features and limitations of each group of studies are discussed at the end of this chapter.

2.2 Sustainability considerations in forest-based biomass supply chains

The sustainable use of forest-based biomass resources requires that all the benefits obtained from their current use do not compromise the ability of future generations to benefit from them in a similar manner (Lunnan et al., 2008). For this reason, it is important to consider the technical, economic, environmental and social issues associated with the forest-based biomass supply chains. Figure 2-1 depicts a general structure of the forest-based biomass supply chain that is composed of five basic processes: biomass procurement, storage, transportation, pre-processing, and conversion (Iakovou et al., 2010). Some studies added a sixth process corresponding to the distribution of the energy and bioproducts (e.g. Nagel, 2000; Schmidt et al., 2010a).

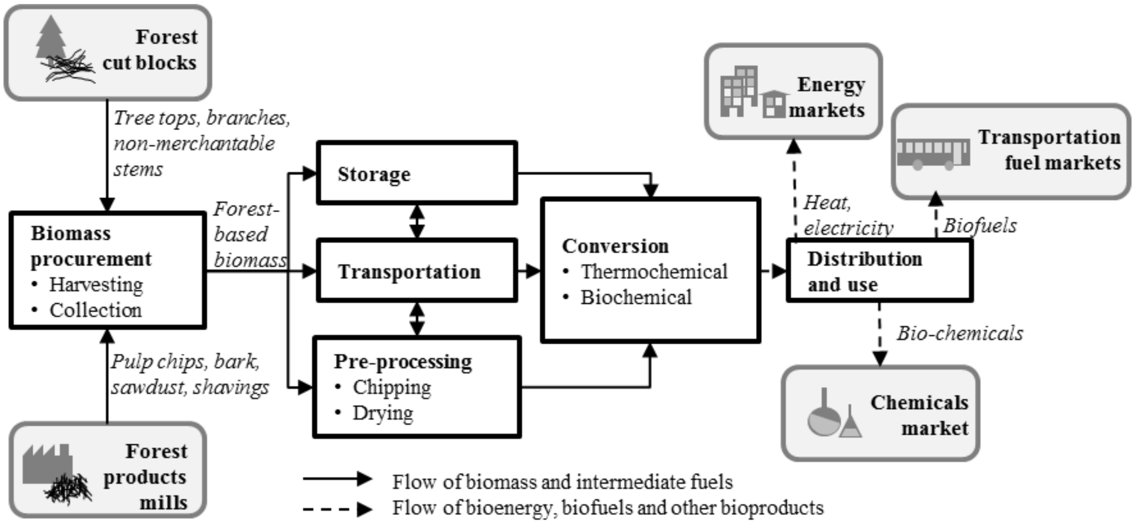

Figure 2-1 General structure of a forest-based biomass supply chain

2.2.1 Technical and economic considerations

The conversion of forest-based biomass into bioenergy, biofuels and bioproducts could generate additional revenue streams for the forest products sector and improve the economic viability of thinning and other forestry management operations (IEA Bioenergy, 2002). For this to be feasible, technical and economic aspects along the entire supply chain should be addressed.

In the design of production systems for bioenergy and bioproducts, some of the most important technical aspects are the type, efficiency and capacity of selected conversion technologies. The type of technology required for biomass conversion is based on the desired product and the available type of forest-based biomass. Biochemical and thermochemical technologies are the most suitable ones for converting lignocellulosic biomass (forest-based biomass included) into energy and chemicals (EPA, 2007a). Biochemical processes such as fermentation are used for the production of liquid or gaseous fuels (Caputo et al., 2005). Thermochemical processes such as combustion, gasification and pyrolysis are used for the production of fuels, heat and electricity (Caputo et al., 2005). The conversion efficiency of a technology determines the amount of product that can be obtained per unit of biomass input. Higher efficient technologies represent lower operating costs, but they typically have higher capital costs than lower efficient technologies (Caputo et al., 2005). The capacity of a conversion technology influences the economic feasibility of producing bioenergy and bioproducts. Since capital costs of conversion technologies are high, achieving economies of scale is important (Meyer et al., 2012). However, operating scales are technically restricted by the amount of available biomass and economically restricted by the cost of delivered biomass to the plant. This stresses the need for a reliable and cost-efficient supply of forest-based biomass.

Forest-based biomass parameters that affect the technical and economic feasibility of using it are its quality attributes, its availability and procurement cost. Biomass quality attributes are energy content, moisture content, particle size, ash and contaminant contents (EPA, 2007a; Lehtikangas, 2001; McKendry, 2002a). These attributes influence the selection of pre-processing operations (e.g. sorting, chipping, drying), the selection of conversion technologies, the conversion yields, and the transportation costs. The amount of biomass that can be sustainably procured determines the scale of the project, and the variation of biomass supply over time drives the need for storage operations to ensure a reliable supply over the life time of the project. Biomass procurement costs include all the costs associated with collecting, storing, pre-processing and transporting biomass from its source to the plant.

Other important factors affecting the economics of the supply chain are the product distribution costs. Heat and electricity are usually produced to satisfy domestic energy needs; however, in the case of biofuels and chemicals, distribution operations have to be planned. For example, in some countries, pipeline distribution is the most economical alternative for fuel distribution, however, chemical and physical properties of certain biofuels impede the use of the existing pipeline infrastructure (Yue et al., 2014b), thus, train, barge or truck transportation has to be arranged.

The combination of all these factors impacts the technical and economic feasibility of a forest-based biomass utilization project. Efficient supply chain designs require decisions on: biomass sources and types; storage, pre-processing and transportation (type, capacity and location); conversion technologies (type, capacity and location); products and markets (type of products, and location of markets); and material flows (of biomass and products) within the supply chain. All these decisions are case-specific, and they must reflect the particularities of each supply chain context.

2.2.2 Environmental considerations

Some of the major environmental issues of forest-based biomass utilization projects are related to their carbon balance and GHG emissions, their particulate matter emissions, and the forest ecosystem health (IEA Bioenergy, 2002).

One of the main drivers of using biomass to produce energy and other products is its potential to reduce the environmental impacts associated with fossil fuels utilization. It has been recognized that the use of fossil fuels (e.g. oil, coal, gas) has accelerated the emission of CO_2 into the atmosphere leading to an increased greenhouse gas effect that causes global warming and climate change (IPCC, 2007). In forest-rich countries, the use of forest-based biomass to offset the use of fossil fuels has the potential to reduce those carbon emissions. Forest-based biomass is considered as a renewable, and low carbon energy (or carbon neutral) source, because the carbon released to the air during combustion is sequestered during the growth of the trees (IPCC, 2007). Some authors argue that biomass carbon neutrality can be achieved in the long term, when the new tree generation has reached a harvestable size (e.g. Vanhala et al., 2013). However, a complete carbon evaluation of forest-based biomass utilization projects should also consider non-biogenic carbon emissions due mainly to the use of fossil fuels for the production, harvesting, collection, handling, pre-processing and transportation of forest-based biomass and distribution of products (Cherubini et al., 2009).

In addition to carbon, other atmospheric pollutants such as non-carbon GHG and particulate matter are generated along the forest-based biomass supply chain. Life cycle approaches are useful to quantify all the emissions to air, water and land, and to estimate potential impacts on climate change, human health, ecosystem quality, and resources depletion (Cherubini et al., 2009).

An important ecological consideration in planning forest-based biomass projects is the role of forest-based biomass in maintaining the health of the forest ecosystem (IEA Bioenergy, 2002). Forest-based biomass (e.g. dead wood and forestry residues) helps to sustain forest soil and site productivity, regulate water flow and maintain biodiversity (IEA Bioenergy, 2002). This biomass fertilizes the forest soil with nutrients and sustains its acidity, thus maintaining forest productivity levels (Hesselink, 2010). Forest-based biomass affects the ability of the soil to hold and transfer water, thus determining water quality, movement and distribution patterns in the forest (Abbas et al., 2011). Forest-based biomass also provides shelter and food to various forest organisms (Abbas et al., 2011). Therefore, its removal might have some negative effects such as reducing forest productivity levels, changing water downstream flows, affecting deadwood-requiring species, and increasing forest access that favors the spread of invasive species (Lattimore et al., 2009). There are also some potential positive effects such as reducing the proliferation of pest species (Lattimore et al., 2009), and reducing the risk of wildfires that disrupt biodiversity patterns (IEA Bioenergy, 2002). In this regard, a large number of research efforts has been devoted to assess the impact of removing forest-based biomass from harvested areas, develop operational guidelines for forest-based biomass removal (Abbas et al., 2011; Lattimore et al., 2009), and develop strategies to mitigate the removal of organic matter from forest areas (Vanclay, 2003).

Many strategies can be applied to improve the environmental performance of bioenergy and bioproducts production from forest-based biomass. For example, the design of conversion facilities that integrate emission control equipment, water treatment processes, waste management and recycling could reduce the emission of pollutants to air, water and land. The use of highly efficient technologies along the supply chain reduces the amount of fossil fuel required for biomass collection, handling and transportation. The location of conversion plants close to large sources of biomass (e.g. forest-products mills) and to markets reduces the amount of fossil fuel required to transport biomass and products (Lattimore et al., 2009). Understanding the environmental impacts of different supply chain choices is key to ensure that the environmental benefits of using forest-based biomass are maximized.

2.2.3 Social considerations

The establishment of new forest-based biomass utilization projects might have multiple social impacts in forest-rich regions. These social impacts might include changes in people's way of life, culture, community, political systems, environment, health, well-being, personal rights, property rights, and even fears and aspirations (Vanclay, 2003). However, many of these effects cannot be consistently quantified. Social effects that are commonly used in optimization of forest-based biomass supply chains and can be quantified are job and income creation.

The quantity and quality of created jobs depend on the design of the forest-based biomass supply chain. The overall number of created direct, indirect and induced jobs depends on the size of the project. Overall, larger projects generate more jobs. However, there are some trade-offs that have to be analyzed. The number of created jobs per unit of forest-based biomass used tends to decrease as economies of scale are achieved due to the use of more efficient logistics and production systems (IEA Bioenergy, 2002).

Along with job creation, the development of new forest-based biomass projects generates income and development opportunities for rural communities (McKay, 2006) that could be translated into improved well-being for the population. Studies evaluating the potential social impact of these projects should analyze how the income will be allocated. For example, job creation is particularly beneficial in rural areas and within job classes with higher levels of unemployment (Thornley et al., 2008).

2.3 Optimization of forest-based biomass supply chains

Mathematical programming is a useful tool to maximize or minimize a quantitative objective considering scarce resources. An optimization problem is typically comprised of an objective function (linear or non-linear equation) expressed as a mathematical function of decision variables and other parameters that will be maximized or minimized according to the necessity of the problem, and a set of constrains (linear or non-linear inequalities or equations). In general, when the objective function and constrains are linear, the optimization formulation is a linear programming model (LP). When all the decision variables in a model are integer values, the model becomes an integer programming model (IP). When the model has continuous and integer variables, it is a mixed integer programming model (MIP).

Mathematical programming models are particularly useful when different decisions at different supply chain stages are combined (Shabani et al., 2013). The development of solution algorithms and advances in computational hardware and software (Bixby, 2002) permit the inclusion of a large number of parameters, decision variables and constraints in the mathematical programming models simultaneously, and provide optimal solutions in relation to a defined objective function. However, to ensure the tractability of the model, and to keep computational solution times within practical margins, practitioners have to strive for simplicity in models formulation (Berry, 2013).

In the literature, a number of optimization studies focused on the design, planning and management of biomass supply chains that included forest-based biomass resources. The majority of them (34 out of 43) pursued a single economic objective function. Recently, research efforts (9 studies) were made to optimize multiple objectives related to economic performance, environmental impact, and social impacts. Figure 2-2 shows the classification of optimization studies of biomass supply chains including forest-based biomass.

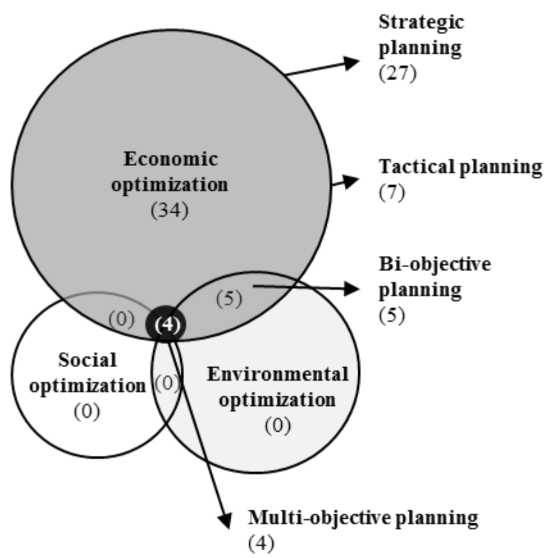

Figure 2-2 Classification of biomass supply chain optimization studies that included forest-based biomass. The number of studies in each category is indicated in parenthesis.

2.3.1 Economic optimization

Economic optimization models have been developed to deal with a wide range of decisions at strategic and tactical planning levels of biomass supply chains. Table 2-1 shows the classification of studies and their major decisions. A large number of the problems were formulated as MIP models, while the most common objective was to minimize the total supply chain cost, and to a lesser extent, to maximize profit.

The majority of studies presented in Table 2-1 focused either on the production of bioenergy or biofuels, separately. Strategic studies considered a single planning period (e.g. one year) and relied on average annual biomass production (cultivation, harvesting and/or collection) rates and costs per supply area (An et al., 2011; Ekşioğlu et al., 2009; Elia et al., 2011; Kim et al., 2011b; Leduc et al., 2008; Natarajan et al., 2014; Parker et al., 2010; You et al., 2012). In the strategic optimization of biomass supply chains dealing with forest-biomass resources, since the location and amounts of forest residues change over the long term, based on conventional forest harvesting plans, it is necessary to consider these expected changes. Only Feng et al. (2010) considered the impact of expected long-term variations of biomass supply on the strategic design of a forest-based biomass supply chain for the production of bioenergy and traditional forest products. In their model, the forecasted variability of biomass supply impacted the flow of biomass and products over the planning horizon, but it did not affect strategic investment decisions such as the installation period for conversion plants, since the installation of all plants was allowed only at time zero. Other studies (Huang et al., 2010; Leduc et al., 2010a; Natarajan et al., 2014; You et al., 2012) considered the impact of long-term demand variation on determining the installation period for new biorefineries, but these studies also considered a constant annual supply and a constant cost of biomass over the entire life time of the project. Some of the studies in Table 2-1 incorporated uncertainty through the design of stochastic optimization models, and considered uncertainty in parameters such as biomass supply availability, price and demand for products and conversion yields (Kim et al. (2011b) and Chen and Fan (2012)). However, these studies also modeled the supply chain system in a single time-step. There are still opportunities to develop optimization models for the strategic design of forest-based biomass supply chains that produce bioenergy and biofuels simultaneously. These models should accommodate multiple planning periods to account for the impact of expected long-term variation of parameters such as forest-based biomass availability and cost, as well as the demand and cost of products, on strategic decisions such as technology installation period.

Table 2-1 Major decisions addressed in biomass supply chain optimization papers that included forest-based biomass resources

Major decisions			References
Strategic	Feedstock	Biomass source	Freppaz et al. (2004), Frombo et al. (2009a)
		Biomass type and source	Keirstead et al. (2012), Natarajan et al. (2014), Upadhyay et al. (2012)
	Conversion facilities	Plant location and feedstock sources	*Multiple plants:* Chen and Fan (2012 *Single plant:* Elia et al. (2011), Huang et al. (2010), Rentizelas and Tatsiopoulos (2010)
		Plant location	*Multiple plants:* Kim et al. (2011a, 2011b) *Single plant:* Kaylen et al. (2000), Leduc et al. (2010a, 2010b)
		Plant location and size	*Multiple plants:* Ekşioğlu et al. (2009), Natarajan et al. (2014), Schmidt et al. (2010a, 2010b), Yagi and Nakata (2011)
		Plant location, technology type and size	*Multiple plants:* An et al. (2011), Feng et al. (2010), Frombo et al. (2009b), Parker et al. (2010), Tittmann et al. (2010)
		Technology type and size	Börjesson and Ahlgren (2010), Chinese and Meneghetti (2005), Difs et al. (2010), Frombo et al. (2009a), Keirstead et al. (2012), Nagel, (2000), Wetterlund and Söderström, (2010)
	Products	Type and volume of products to produce	Freppaz et al. (2004), Kaylen et al. (2000)
	Markets	Customers/markets to serve	Chinese and Meneghetti, (2005)
	Flow of materials	Flows of biomass and products	Ekşioğlu et al. (2009), Freppaz et al. (2004), Keirstead et al. (2012), Kong et al. (2012), Tittmann et al. (2010)
Tactical	Biomass logistics	Location of storage and pre-processing terminals	Rauch and Gronalt, (2010)
		Flows of biomass through storage and pre-processing terminals	Akhtari et al. (2013), Gunnarsson et al. (2004), Kanzian et al. (2009)
	Production planning and scheduling	Biomass procurement planning and scheduling	Ghaffariyan et al. (2013), Palander and Väätäinen (2012), Shabani and Sowlati (2013)
		Production planning	Shabani and Sowlati (2013)

2.3.2 Economic, environmental and social optimization

The integration of economic, social and environmental objectives in the optimization of biomass supply chains for the production of bioenergy and bioproducts has been addressed in a few studies using multi-objective optimization (MOO) approaches. MOO is a sub-discipline within operations research for considering multiple, non-commensurate and conflicting objectives (Bogetoft and Pruzan, 1997). In MOO problems, there may not be a single solution that optimizes all objectives, instead a set may exist (sometimes an infinite set) of “Pareto optimal solutions” (Deb, 2005). Pareto optimal is a solution where one of the objectives cannot be improved without sacrificing another one.

In 1999, Azapagic (1999) proposed an approach for incorporating LCA into MOO for system optimization . This approach has been used in some applications, mostly in process systems engineering (Grossmann and Guillén-Gosálbez, 2010). The combined use of LCA and MOO to support decisions in biomass supply chains is a relatively new research area. To the best of the author’s knowledge, only nine supply chain MOO studies in the literature were related to the use of forest-based biomass which are the works of Čuček et al. (2012), Kanzian et al. (2013), Pérez-Fortes et al. (2014), Santibañez-Aguilar et al. (2014, 2011), You et al. (2012), You and Wang, (2011), and Yue et al. (2014a, 2013). Within this group, only Čuček et al. (2012), Santibañez-Aguilar et al. (2014); You et al. (2012), and Yue et al. (2014a) integrated social objectives into the multi-objective optimization. Table 2-2 describes the main characteristics of these MOO models in terms of their optimization model, the analyzed criteria and the decisions.

Table 2-2 Multi-objective optimization studies in the design of biomass supply chains that included forest-based biomass resources

Reference	Case	Model	Objectives			Decisions						
						Strategic					Tactical	
			Economic	Environmental	Social	F	T	C	L	P	IOT	SPT
Kanzian et al. (2013)	Bioenergy from forest-based biomass	MIP	Max. profit	Min. CO_2 emissions	---						x	x
Pérez-Fortes et al. (2014)		MIP	Max. NPV	Min. overall impact (Impact 2002+)	---							x
You and Wang (2011)	Biofuels from multiple feedstocks	MIP	Min. annualized total cost	Min. GHG emissions	---	x	x	x	x	x	x	
Santibañez-Aguilar et al. (2011)		LP	Max. annualized profit	Min. overall impact (Eco-indicator 99)	---	x	x			x		
Santibañez-Aguilar et al. (2014)		MILP	Max. annualized profit	Min. overall impact (Eco-indicator 99)	Max. jobs	x	x	x	x	x		
You et al. (2012)		MIP	Min. annualized total cost	Min. GHG emissions	Max. accrued Jobs	x	x	x	x	x	x	
Yue et al. (2013)		MINLP	Min. unit cost per functional unit	Min. GHG emissions per functional unit	---	x	x	x	x	x	x	x
Yue et al. (2014a)	Bioenergy from multiple feedstocks	MILP	Min. levelized cost	Min. GHG emissions per unit of energy	Max. accrued Jobs	x	x	x	x			x
Čuček et al. (2012)	Energy, food and boards from multiple feedstocks	MINLP	Max. profit	Min. non-renewable energy use, water use and pollution	Min. land use changes (relevant for energy crops)	x	x	x	x	x		

NOTE: Abbreviations are as follow: LP: linear programming; MIP: mixed integer programming; MINLP: mixed integer non-linear programming; F: feedstock decisions; T: technology type; C: plant size; L: plant location; P: products; IOT: inventory size, production operations and transportation equipment selection; S: storage, pre-treatment and transportation decisions.

In the estimation of the environmental objective, the majority of previous studies aimed to minimize the environmental impact of meeting a specific demand for bioenergy or biofuels. This environmental impact quantification cannot be used to estimate accurately the net environmental benefits of introducing a new biomass supply chain, since the estimation of the net environmental benefits should compare the proposed system with the current state of the system. Two of the previous studies (Čuček et al., 2012; Pérez-Fortes et al., 2014) considered the unburdening effect of substituting existing products. However, none of the previous studies estimated the environmental benefits of the proposed supply chain compared to the current state of the system, including existing energy and fuel sources and existing biomass disposal methods. In addition, since previous studies that integrated an environmental objective focused either on the generation of bioenergy or biofuels, none of these studies modeled the energy flows among bioenergy and biofuel plants installed at the same site (e.g. bioenergy technologies supplying energy to co-located biofuel technologies) which impacts the economic and environmental performance of the supply chain.

In previous optimization studies, job creation has been the preferred indicator to account for social impacts of new bioenergy and biofuel supply chains (Ayoub and Yuji, 2012; Santibañez-Aguilar et al., 2014; You et al., 2012; Yue et al., 2014a), mostly using multipliers for the computation of total job creation (e.g. Yue et al. (2014a) used multipliers from the IMPLAN profession model and JEDI model). While the quantification of job creation based on multipliers provides some high level information, it is not the most appropriate approach to analyze social benefits of new projects at a community level. This is because job creation might have different levels of impact in different areas, being particularly beneficial in rural areas with high levels of unemployment or depopulation trends (Thornley et al., 2008). This situation was recently considered in a general sustainable facility location model proposed by Mota et al. (2015) where the impact of job creation across different regions was considered. In their approach, the authors considered differences among plant locations (e.g. regional unemployment rate, population density and income distribution); however, they did not address other elements such as the type of created jobs (skill requirements) that might pose restrictions to the operational feasibility of some specific conversion plants (BioTalent Canada, 2013).

Among the studies presented in Table 2-2, the most commonly used solution approach was the ε-constraint method (Haimes et al., 1971) that produced a set of Pareto optimal solutions (Pareto set) showing the potential trade-offs and compromises among them. In this method, the bi-objective optimization model is reformulated as a single objective sub problem, keeping one of the objectives arbitrarily and constraining the other one within user-specified ε values (Haimes et al., 1971). The main drawbacks of this method are that (1) it only guarantees the generation of weakly Pareto-optimal solutions (a solution is weakly Pareto-optimal if there is no alternative feasible solution where all the objectives can be improved simultaneously, but at least one of the objectives can be improved without affecting another one; and a solution is strictly Pareto-optimal if none of the objectives can be improved without sacrificing another one) and (2) the feasibility of the sub problems depends on the chosen ε values. To avoid these pitfalls, Mavrotas, (2009) proposed an augmented ε-constraint method (AUGMECON) that avoids the generation of weakly Pareto optimal solutions through the utilization of lexicographic optimization to identify the Pareto set boundaries, and the use of slack variables in the constrained objectives for all intermediate Pareto optimal points that are penalized in the objective function. The generated set of Pareto optimal solutions allow the decision maker (planner) to select the solution that best suits his/her preferences. This might not be an easy task, especially when there are many decision makers involved; however, multi criteria decision methods such as Analytical Hierarchy Process (AHP), ELECTRE and PROMETHEE can be useful to select among the generated Pareto optimal solutions (Scott et al., 2012).

2.4 Discussion and conclusion

Optimization methods have been used to support the design and planning of biomass supply chains for the production of bioenergy and other bioproducts considering different sustainability criteria. These methods are useful in determining the optimal configuration of supply chains when multiple alternatives exist. In the literature, the majority of studies aimed to minimize the cost or maximizing the profit of the supply chain for the production of bioenergy or biofuels, separately. These types of optimization studies are useful but not sufficient to support the sustainable decision making in the design and planning of biomass supply chains. A recent branch of the literature has proposed multi-objective optimization models that integrate economic, environmental and social objectives. Within this group of studies, the minimization of the life cycle GHG emissions has been the most frequently used environmental objective, and the maximization of the number of created jobs has been the only social objective, which was quantified with the use of generic multipliers.

In the literature related to multi-objective optimization of biomass systems, there is a need to develop models that capture the particularities of forest-based biomass supply chains. Changes in the availability of forest-based biomass (amount and location) over the long-term planning horizon, and their impact on capital investment decisions have not been considered in previous optimization studies. Also, to the best of the author's knowledge, none of the previous multi-objective studies modeled the energy flows among co-located bioenergy and biofuel technologies that might affect the quantification of the environmental, economic and social impacts of the whole system, and consequently the optimal design of the supply chain. In addition, since the current models focused only on minimizing emissions and maximizing jobs associated with the supply chain, there is an opportunity for new comprehensive approaches that estimate the environmental and social benefits of the supply chain more accurately. To achieve this, it is required to compare the emissions of the proposed supply chain against the baseline emissions, and to consider the impact of different type of jobs created in different locations.

Chapter 3: Single-objective optimization model

3.1 Synopsis

In this chapter, a supply chain optimization model for the integrated production of bioenergy and biofuels from forest and wood residues is developed and applied to the case study introduced in Chapter 1. The model is formulated as a multi-period mixed integer linear programming model (MILP) that considers the variability per period in (a) available biomass quantities and cost per supply source, (b) demand and price values of biofuel and bioenergy products and (c) transportation and operating costs. The model determines (1) the location, type and size of the technologies to install and the period to install them, (2) the mix of bioenergy and biofuel products to generate, (3) the type and amount of forest and wood residues to acquire and the sourcing points, (4) the amount of forest and wood residues to transport from sources to facilities, (5) the amount of each product to transport from facilities to markets, and (6) the amount of energy to purchase from currently used energy sources for the operation of the installed conversion plants. The objective function of the model is to maximize the NPV of the supply chain over a 20-year planning horizon with yearly time steps. All technical and economic data used in the development of the case study are presented in this Chapter, and the performance of the optimal supply chain is analyzed. Moreover, a sensitivity analysis is performed to evaluate the impact of variations in parameters on the economic design and performance of the optimal solution.

3.2 The forest-based biomass supply chain model

The forest-based biomass supply chain optimization model proposed in this work (Figure 3-1) considers different types of biomass f that can be procured from a variety of supply sources i (e.g. forest cut blocks, forest product mills). In each candidate location j, there are l candidate technologies that can be installed for the generation of bioenergy type o to be used locally (e.g. supplied to biofuel conversion plants, local forest product mills, or other external entities such as the electricity grid) or for the production of biofuel product n to be sold to market m. When economically beneficial, heat and/or electricity from currently used energy sources can be supplied to complement the energy needs of the conversion plant l.

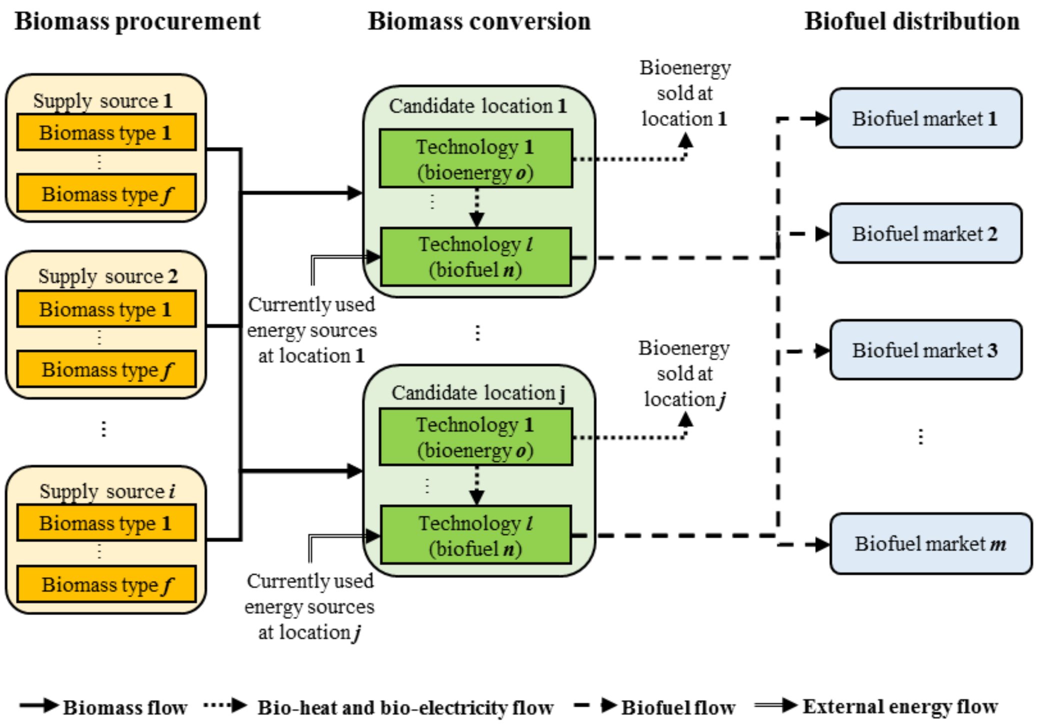

Figure 3-1 Supply chain of forest residues to bioenergy and biofuel

Forest residues include harvesting residues such as tree tops and branches, and some small diameter logs and low quality non-merchantable logs (not suitable for either lumber or pulp production). Wood residues encompass wood chips, sawdust, shavings, bark and hog fuel produced in forest product mills. At each candidate location, biomass can be converted to heat, electricity, and biofuels such as bio-oil and ethanol in different plants (McKendry, 2002a). The selection of conversion processes and technologies is determined by the type and quantity of available biomass, and the desired form of energy (McKendry, 2002b). Heat and electricity are assumed to be used or sold at the location where they were generated, and biofuels are distributed to their final markets.

3.3 Single-objective optimization model

The multi-period MILP model developed in this chapter aims to maximize the NPV of the supply chain of forest and wood residues to bioenergy and biofuels. Table 3-1 presents the list of sets and indices, Table 3-2 the list of decision variables, Table 3-3 the technical and economic parameters used in the model.

Table 3-1 List of sets and indices

Sets	Definition
F	Set of biomass types; index $f \in F$
I	Set of biomass supply sources; index $i \in I$
J	Set of candidate locations for bioenergy and biofuel plants; index $j \in J$
L	Set of candidate conversion technologies; index $l \in L$
M	Set of candidate markets for biofuels; index $m \in M$
N	Set of biofuels that are transported to a market; index $n \in N$
O	Set of bioenergy types that are used or sold at the plant location; index $o \in O$
T	Time periods; index $t \in T$

Table 3-2 List of decision variables

Decision variables	Definition
$B_{f,i,j,t}$	Amount of biomass type f to be procured from supply source i and transported to location j in period t (odt)
$E_{o,j,t}^{Conv}$	Amount of energy (equivalent to bioenergy type o) to be supplied from currently used sources, for the operation of all conversion plants installed at location j in period t (MWh)
$P_{n,j,l,t}^{Bf}$	Amount of biofuel type n to be produced at location j with technology l in period t (units of product)
$P_{o,j,l,t}^{Be}$	Amount of bioenergy type o to be generated at location j with technology l in period t (MWh)
$Q_{j,l,t}$	Binary: 1, if technology l should be installed or operating at location j in period t; 0, otherwise
$S_{n,j,m,t}^{Bf}$	Amount of biofuel type n to be transported from location j to be sold at market m in period t (units of product)
$S_{o,j,t}^{Be,Ext}$	Amount of bioenergy type o to be sold to an external customer at location j in period t (MWh)
$S_{o,j,t}^{Be,Conv}$	Amount of bioenergy type o to be used internally at location j (by other conversion technologies) in period t (MWh)
$U_{f,j,l,t}$	Amount of biomass type f to be used in conversion technology l at location j in period t (odt)

Table 3-3 List of technical and economic parameters of the model

Parameters	Definition
Technical Parameters	
$\beta_{f,i,t}$	Available biomass type f at supply source i in period t (odt [a])
$\delta_{o,f,l}^{Be}$	Yield of bioenergy type o generated from one unit of biomass type f using technology l (units of output/odt of biomass input)
$\delta_{n,f,l}^{Bf}$	Yield of biofuel type n produced from one unit of biomass type f using technology l (units of product output/odt of biomass input)

Parameters	Definition
$\eta_{o,j,t}^{BeMax,Ext}$	Maximum external demand for bioenergy type *o* at location *j* in period *t* (MWh of bioenergy)
$\eta_{o,j,t}^{BeMin,Ext}$	Minimum external demand for bioenergy type *o* at location *j* in period *t* (MWh of bioenergy)
$\eta_{n,m,t}^{BfMax}$	Maximum demand for biofuel type *n* at market *m* in period *t* (units of product)
$\eta_{n,m,t}^{BfMin}$	Minimum demand for biofuel type *n* at market *m* in period *t* (units of product)
$\gamma_{l,n}^{Bf}$	Maximum capacity of conversion technology *l* to produce biofuel type *n* (units of product output/year)
$\gamma_{l,o}^{Be}$	Maximum capacity of conversion technology *l* to generate bioenergy type *o* (MWh/year)
$\phi_{o,f,l}^{Conv}$	Energy demand (in terms of bioenergy type *o*) required to convert one unit of biomass type *f* using technology *l* (MWh/odt)
Economic Parameters	
α	Depreciation rate
$\lambda_{f,i,t}^{Bm}$	Cost of purchasing, pre-processing and/or collecting one unit of biomass type *f* in supply source *i* in period *t* ($/odt)
$\lambda_{j,l,t}^{Fix}$	Fixed cost of technology *l* in location *j* in period *t* ($)
$\lambda_{j,l,t}^{Var}$	Variable cost of converting one unit of biomass using technology *l* in location *j* in period *t* (biomass dependent) ($/odt)
$\lambda_{f,i,j,t}^{Tra,Bm}$	Cost of transporting one unit of biomass type *f* from supply source *i* to location *j* in period *t* ($/odt)
$\lambda_{n,j,m,t}^{Tra,Bf}$	Cost of transporting one unit of biofuel type *n* from location *j* to market *m* in period *t* ($/unit of product)
$\lambda_{o,j,t}^{Energy}$	Cost of supplying the energy equivalent to one unit of bioenergy type *o* from currently used sources at location *j* in period *t* ($/MWh)
$\rho_{o,j,t}^{Be}$	Price of bioenergy type *o* at location *j* in period *t* ($/MWh)
$\rho_{n,m,t}^{Bf}$	Price of biofuel type *n* at market *m* in period *t* ($/unit of product)

3.3.1 Model constraints

Equation 1 restricts the amount of each biomass type *f* that can be procured from each source *i* in each period *t*:

$$\sum_{j\in J} B_{f,i,j,t} \leq \beta_{f,i,t} \quad \forall\, f \in F, i \in I, t \in T \tag{1}$$

To prevent the deterioration of biomass and the loss of dry-matter, no biomass storage is considered in the model. The sum of biomass from all sources is fully utilized by all technologies in all periods (Equation 2).

$$\sum_{i \in I} B_{f,i,j,t} = \sum_{l \in L} U_{f,j,l,t} \qquad \forall\, f \in F, j \in J, t \in T \tag{2}$$

Equations 3 and 4 relate the amount of products generated by each technology *l* to the respective production yields. Note that the production yields are influenced by the technology type, and also by the biomass type (e.g. different types of biomass have different ash, moisture and energy content that affect their yield of conversion through different conversion paths).

$$P^{Bf}_{n,j,l,t} = \sum_{f \in F} \left(\delta^{Bf}_{n,f,l} \times U_{f,j,l,t} \right) \qquad \forall\ \ n \in N, j \in J, l \in L, t \in T \tag{3}$$

$$P^{Be}_{o,j,l,t} = \sum_{f \in I} \left(\delta^{Be}_{o,f,l} \times U_{f,j,l,t} \right) \qquad \forall\ \ o \in O, j \in J, l \in L, t \in T \tag{4}$$

Generation of bioenergy type *o* or production of biofuel type *n* in a conversion technology *l* at a location *j* can only occur when that technology at that location is operating in period *t* (denoted by the binary variable $Q_{j,l,t}$). The amount of biomass that can be sent to and used by the conversion technology in each period *t* is limited by its maximum output capacity (Equations 5 and 6).

$$P^{Bf}_{n,j,l,t} \le \gamma^{Bf}_{l,n} \times Q_{j,l,t} \qquad \forall\ n \in N, j \in J, l \in L, t \in T \tag{5}$$

$$P^{Be}_{o,j,l,t} \le \gamma^{Be}_{l,o} \times Q_{j,l,t} \qquad \forall\ o \in O, j \in J, l \in L, t \in T \tag{6}$$

In each period *t*, the total amount of biofuel type *n* that is distributed to markets, and the total amount of bioenergy type *o* that is sold or used at a location *j* cannot exceed the production levels (Equations 7 and 8).

$$\sum_{m \in M} S^{Bf}_{n,j,m,t} \le \sum_{l \in L} P^{Bf}_{n,j,l,t} \qquad \forall\, j \in J, n \in N, t \in T \tag{7}$$

$$S^{Be,Ext}_{o,j,t} + S^{Be,Conv}_{o,j,t} \le \sum_{l \in L} P^{Be}_{o,j,l,t} \qquad \forall\, o \in O, j \in J, t \in T \tag{8}$$

Equations 9 and 10 set the demand boundaries for bioenergy and biofuels.

$$\eta^{BfMin}_{n,m,t} \le \sum_{j \in J} S^{Bf}_{n,j,m,t} \le \eta^{BfMax}_{n,m,t} \qquad \forall\, n \in N,\ m \in M, t \in T \tag{9}$$

$$\eta^{BeMin}_{o,j,t} \le S^{Be,Ext}_{o,j,t} \le \eta^{BeMax}_{o,j,t} \qquad \forall\, o \in O,\ j \in J, t \in T \tag{10}$$

Equation 11 indicates that the energy requirements of all conversion technologies at location *j* can be met by a mix of generated bioenergy and energy from currently used sources.

$$\sum_{f\in F}\sum_{l\in L}\left(\phi_{o,f,l}^{Conv}\times U_{f,j,l,t}\right)=S_{o,j,t}^{Be,Conv}+E_{o,j,t}^{Conv}\qquad\forall\, o\in O,\ j\in J,\ t\in T \tag{11}$$

Equation 12 ensures that once a conversion technology *l* is installed at location *j*, it will continue in operation during subsequent periods within the planning horizon.

$$Q_{j,l,t}\geq Q_{j,l,t-1}\qquad\forall\, l\ \in L,\ j\in J,\ t\in T \tag{12}$$

Equations 13 and 14 force the model to select, at each location, just one technology type and size for each type of bioenergy or biofuel product. Note that in Equations 13 and 14 the index l^o refers to the subset of technologies *l* that can produce bioenergy type *o*, and l^n refers to the subset of technologies *l* that can produce biofuel product *n*. These constraints can be omitted in cases when the number of technologies installed and in operation in the supply chain is bounded by limited biomass availability or demand for products.

$$\sum_{l^o\in L}Q_{j,l,t}\leq 1\quad\forall\quad o\in O, j\in J, t\in T \tag{13}$$

$$\sum_{l^n\in L}Q_{j,l,t}\leq 1\quad\forall\quad n\in N, j\in J, t\in T \tag{14}$$

In addition, non-negativity constraints and binary constraints are part of the model (Equations 15 and 16).

$$B_{f,i,j,t}, E_{o,j,t}^{Conv}, P_{n,j,l,t}^{Bf}, P_{o,j,l,t}^{Be}, S_{n,j,m,t}^{Bf}, S_{o,j,t}^{Be,Ext}, S_{o,j,t}^{Be,Conv}, U_{f,j,l,t}\geq 0$$
$$\forall\, f\in F, i\in I, j\in J, l\in L, n\in N, m\in M, t\in T \tag{15}$$

$$Q_{j,l,t}\in\{0,1\}\qquad\forall\ l\ \in L, j\in J, t\in T \tag{16}$$

3.3.2 Economic objective function

The economic objective of the model is to **maximize the NPV** calculated in Equation 17:

$$NPV=\sum_t\frac{1}{(1+\alpha)^{t-1}}\left(Total\ revenue_t-Total\ cost_t\right) \tag{17}$$

The total revenue in period *t* is determined by the selling price per unit of each biofuel or bioenergy product multiplied by the amount sold to a market *m* or the grid in period *t* (Equation 18):

$$Total\ revenue_t = \sum_{n\in N}\sum_{j\in J}\sum_{m\in M}\left(\rho^{Bf}_{n,m,t} \times S^{Bf}_{n,j,m,t}\right) + \sum_{o\in O}\sum_{j\in J}\left(\rho^{Be}_{o,j,t} \times S^{Be,Ext}_{o,j,t}\right)\ \ \forall\, t \in T \tag{18}$$

The total cost, in each period, includes the purchase cost of biomass, the transportation cost of biomass, fixed costs associated with each technology (annualized capital investment, salaries and maintenance costs), variable costs (biomass dependent costs such as wages and operational costs), and the transportation cost of products to markets during period *t* (Equation 19).

$$Total\ cost_t = \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\left(\lambda^{Bm}_{f,i,t} \times B_{f,i,j,t}\right) + \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\left(\lambda^{Tra,Bm}_{f,i,j,t} \times B_{f,i,j,t}\right) + \sum_{n\in N}\sum_{m\in M}\sum_{j\in J}\left(\lambda^{Tra,Bf}_{n,j,m,t} \times S^{Bf}_{n,j,m,t}\right) + \sum_{l\in L}\sum_{j\in J}\left(\lambda^{Fix}_{j,l,t} \times Q_{j,l,t}\right) + \sum_{f\in F}\sum_{j\in J}\sum_{l\in L}\left(\lambda^{Var}_{j,l,t} \times U_{f,j,l,t}\right) + \sum_{o\in O}\sum_{j\in J}\left(\lambda^{Energy}_{o,j,t} \times E^{Conv}_{o,j,t}\right)\ \ \forall\, t \in T \tag{19}$$

Note that in Equation 19 the energy cost of biofuel production $\left(\lambda^{Energy}_{o,j,t}\right)$ is disaggregated from the variable costs $\left(\lambda^{Var}_{j,l,t}\right)$ because the energy cost applies only to the portion of energy that is supplied from currently used energy sources $\left(E^{Conv}_{o,j,t}\right)$.

3.4 Case study technical and economic data

All cost figures in this case study are adjusted for currency exchange and inflation rate to 2013 $CAD (Canadian currency), and a 5% discount rate is used in the model for depreciable assets.

3.4.1 Availability, cost and quality attributes of biomass

Biomass types, availability and cost, quality attributes and associated bio-oil yields are described in Table 3-4.

Table 3-4 Biomass types, availability and cost, quality attributes and associated bio-oil yield

Type	Availability and cost	Ash content (%)	Initial moisture content (% wet basis)	Higher heating value (GJ/odt)	Bulk density (kg/m^3)	Bio-oil yield (m^3/odt)
Wood residues						
Sawmill chips	Anahim Lake: 16,150 odt/year at $25/odt Hanceville: 6000 odt/year at $25/odt Williams Lake: 1422 odt/year at 25/odt	0.52[a]	33.2 [a]	17.7[a]	206.7 [a]	0.66[e]
Sawmill hog fuel	Anahim Lake: 9920 odt/year at $10/odt Hanceville: 3685 odt/year at $10/odt Williams Lake: 1073 odt/year at $10/odt	4.75[a]	44.9 [a]	17.8[a]	142.9 [a]	0.49[e]
Forest residues						
Non-merchantable MPB-killed logs	Residues from 1592 aggregated cutting blocks (supplied by Forest Feedstock group at FPInnovations). Pre-processing cost of forest residues is assumed to be $20.1/odt throughout the Williams Lake TSA (biomass collection & chipping costs).	1.00[b]	29.8[d]	19.0[d]	174.1[d]	0.64[e]
Logging residues (tops, branches, etc.).		1.92[c]	29.8[d]	19.0[d]	174.1[d]	0.61[e]

[a] derived from reference (Kehbila, 2010), [b] (Badger, 2002), [c] sample W6 in reference (Lehtikangas, 2001), [d] average from case 3 in (Naimi et al., 2009), [e] derived from reference (Rogers and Brammer, 2012) with basis on ash content.

The average annual amounts of sawmill residues in Anahim Lake and Hanceville are based on the annual amount of chips reported in (Marinescu, 2013, 2012) using sawmill product yields of 56.9% lumber, 26.7% chips and 16.4% hog fuel (Milota et al. 2005). The average annual amounts of sawmill residues in Williams Lake were obtained from (Akhtari, 2012).

In British Columbia, more than 90% of the harvesting consists of full tree processing at the roadside (Waito and Johnson, 2010). With this method, the harvesting residues can be collected from aggregated piles at the roadside, loaded into a grinding unit and conveyed into a truck for transportation to the conversion plants. Based on the 20 year harvesting block data of the TSA, the amount of forest residues that can be economically available for bioenergy or biofuels at each of these communities is expected to change over the next 20 years. Figure 3-2 shows the estimated annual amounts of harvesting residues that can be procured at a delivered cost of up to $60/odt (based on data from FPInnovations). Note that the harvesting block data are available in 5-year periods and the average annual availability of each aggregated cutting block is obtained by dividing the total 5-year amount by five. In our analysis, additional harvesting residues are available at each location for delivered costs greater than $60/odt.

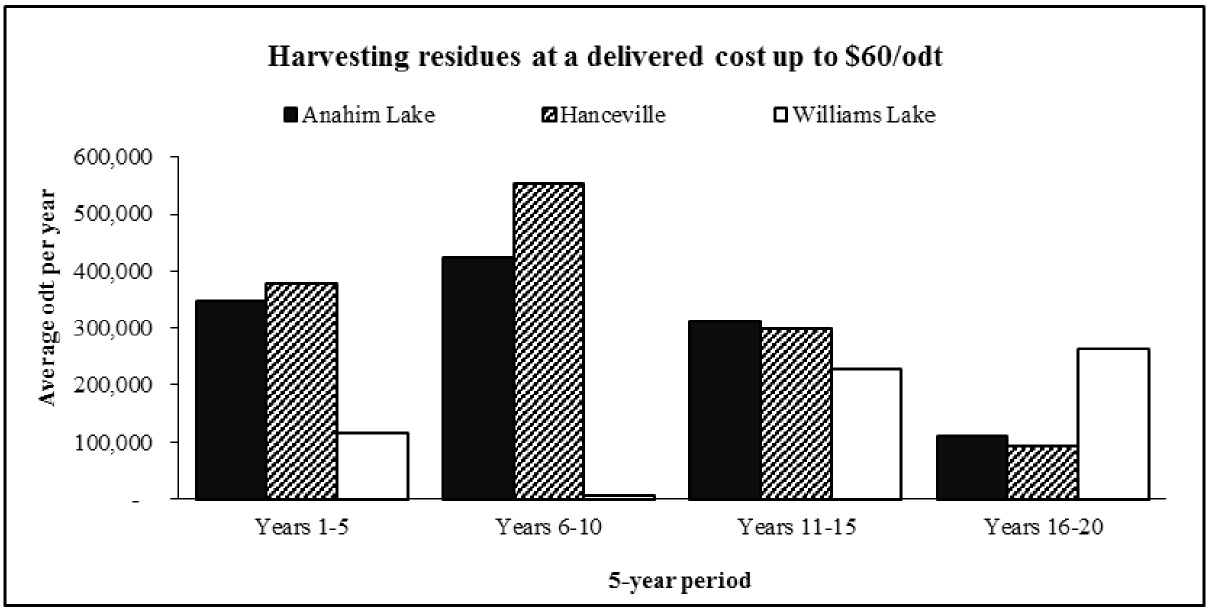

Figure 3-2 Harvesting residues (including chips from MPB stems and hog fuel) at a delivered cost up to $60/odt for each location.

3.4.2 Transportation distances and costs of biomass

Harvesting residues are chipped at the roadside and transported to the plant. Delivered costs of harvesting residues from each aggregated cutting block across the Williams Lake TSA (each aggregated cutting block includes blocks of identical harvest year within a 10km radius) to each potential location were supplied by the Forest Feedstock group at FPInnovations (their biomass availability and cost estimations were done using FPInterface, a forest operations model developed by FPInnovations (FPInnovations, 2013) based on data layers acquired from the Ministry of Forests, Lands and Natural Resource Operations which include vegetation polygons, road network and a harvest raster (Friesen, 2012)). Transportation of sawmill residues is done using a tri-axle walking floor trailer with a weight capacity of 28 t. Transportation of sawmill residues among locations is assumed to cost $126.5/h, with average transportation speeds of 86 km/h (empty) and 77 km/h (loaded) (a highway connects the three communities) (Akhtari, 2012). The transportation distances are 232 km and 320 km from Anahim Lake to Hanceville and Williams Lake, respectively, and 97 km from Hanceville to Williams Lake.

3.4.3 Cost and characteristics of biomass conversion technologies

Table 3-5 presents the biomass requirements, nominal conversion efficiencies and associated fixed and variable costs for bioenergy generating technologies. Note that the electrical and thermal efficiencies of the ORC systems and the gasification systems are assumed to be fixed, regardless of the amount of heat that is recovered from the system. However, when steam turbine systems are designed for electricity only, their electrical efficiency is maximized by extracting the largest practical amount of energy from the steam. When these systems are designed for cogeneration of electricity and heat, the steam is exhausted from the turbine with enough energy to be used for industrial thermal processes, thus reducing their electrical efficiency (EPA, 2007b). In this study, the heat portion that is not used by the sawmill is considered as waste.

Table 3-5 Characteristics of bioenergy generating technologies

Technology	Size	Input biomass requirements [a]	Efficiency [b]		Fixed cost per year ($) [c]	Variable cost ($/odt of biomass)[d]
			Thermal	Electrical		
Biomass stoker boiler (heat-only)	2 MW_{th}	All biomass types in Table 3-4	71.3%	0.0%	419,253	47.3
Biomass boiler + steam turbine (cogeneration)	0.5 MW_{el}	All biomass types in Table 3-4	21.7%	14.5%	208,284	101.4
	2 MW_{el}		20.2%	16.2%	761,336	38.0
	3 MW_{el}		14.1%	16.9%	1,077,145	30.2
	5 MW_{el}		12.9%	18.3%	1,651,232	23.4
Biomass boiler + steam turbine (electricity only)	0.5 MW_{el}	All biomass types in Table 3-4	0.0%	18.7%	208,284	130.8
	2 MW_{el}		0.0%	18.7%	761,336	43.9
	3 MW_{el}		0.0%	18.7%	1,077,145	33.4
	5 MW_{el}		0.0%	18.7%	1,651,232	23.9

Technology	Size	Input biomass requirements [a]	Efficiency [b]		Fixed cost per year ($) [c]	Variable cost ($/odt of biomass)[d]
			Thermal	Electrical		
Biomass oil heater + ORC (cogeneration or electricity only)	0.5 MW_{el}	All biomass types in Table 3-4	48.5%	11.1%	429,584	89.0
	2 MW_{el}		52.1%	12.0%	1,028,817	31.9
	3 MW_{el}		54.1%	11.5%	1,602,296	25.8
	5 MW_{el}		55.5%	11.8%	2,623,063	21.1
Biomass gasifier + internal combustion engine (cogeneration or electricity only)	0.5 MW_{el}	Low ash, clean biomass (sawmill chips & chipped non-merchantable MPB logs). Moisture content < 15% (wet basis)	10.3%	12.6%	176,366	164.7
	2 MW_{el}		9.0%	19.2%	651,509	82.3
	3 MW_{el}		9.0%	18.7%	925,640	61.1
	5 MW_{el}		8.7%	21.2%	1,899,377	48.7

[a] Based on (Bridgwater et al., 2002; EPA, 2007b; Kehbila, 2010; McKendry, 2002c).
[b] Net conversion efficiency: ratio (%) of energy output divided by energy in input biomass (Marinescu, 2013, 2012).
[c] Considers annualized capital costs (for a project life time of 20 years), and other fixed annual costs (e.g. maintenance, labour). Based on (Marinescu, 2013, 2012).
[d] Based on (Marinescu, 2013, 2012).

To estimate the conversion yield (coefficient $\delta^{Be}_{o,f,l}$) for combustion and gasification technologies of Table 3-5, it is considered that biomass moisture content affects its recoverable energy since the process of water evaporation uses some of the heat released by the biomass combustion (Boundy et al., 2011). The net biomass energy content is estimated using the constant 2.45 GJ/t of water at 25 ºC as the latent heat of vaporization of water (Boundy et al., 2011). It is also considered that every 10% increase in biomass moisture content reduces the burning efficiency of the combustion chamber by 2% (EPA, 2007b), affecting the electrical and thermal efficiency of the entire system proportionally.

For combustion technologies, all four types of biomass considered in this study can be used. For gasification technologies a consistent supply of biomass with a low ash content and a low moisture content (less than 15%) has to be used to achieve an efficient process (Bridgwater et al., 2002). Therefore, only wood chips and chipped non-merchantable MPB logs are considered as potential feedstock for gasification plants, and a portion of the generated heat has to be used to dry the feedstock and achieve the specified moisture content. For combustion technologies, it is assumed that the comminuted biomass is entered into the system as received.

Table 3-6 presents the characteristics and costs of biofuel production technologies. Similar to gasification technologies, in pelletizing technologies only low ash, clean biomass can be used, and it has to be dried to less than 10% moisture content.

Table 3-6 Characteristics and costs of pyrolysis and pelleting technologies

Technology	Size	Input biomass requirements	Product yield	Fixed cost ($/year)[a]	Variable costs ($/odt of biomass)[a]
Pyrolysis	200 odt/day	All biomass types in Table 3-4	Feedstock dependant (see Table 3-4)	1,881,814	24.7
	400 odt/day			3,494,664	19.0
	600 odt/day			4,940,125	17.6
Pelletizing	15,000 t/year	Low ash, clean biomass (sawmill chips & chipped non-merchantable MPB logs). Moisture content < 10% (wet basis)	0.91 t pellets [b]	327,330	14.6
	30,000 t/year		0.91 t pellets [b]	714,682	30.4
	45,000 t/year		0.91 t pellets [b]	861,628	24.6

[a] Cost of pelletizing technologies are based on (Badger, 2002; Campbell, 2007; Sultana et al., 2010) and costs of pyrolysis technologies are based on (Badger, 2002; Rogers and Brammer, 2012). Variable costs do not include heat or electricity-related costs.

[b] (Peng et al., 2010).

In Table 3-5 and Table 3-6, fixed cost parameters include annualized capital and maintenance costs of preparation yards, storage facilities, preprocessing (drying, hammer milling) and conversion technologies; variable costs include annual operating and labour costs related to each technology type and size.

3.4.4 Transportation distance and cost of products

It is assumed that the heat generated will meet local demand, electricity will be sold to the grid, and pyrolysis bio-oil and pellets (regarded as biofuels in this study) will be transported to markets or ports. The market for pyrolysis bio-oil and pellets is the pellet export facility located in the port of North Vancouver (rail distance 505 km from Williams Lake). The transportation of pyrolysis bio-oil is done using semi-trailer tanks with 5 axles and a volume capacity of 27,276 l. Transportation of bio-oil and pellets has two stages: first, by tank or truck to Williams Lake, then by rail to the port of North Vancouver. The cost of transporting a full truck load of bio-oil is assumed to be \$2.02/km (Logistics Solution Builders, 2005). The truck transportation of pellets is assumed to be outsourced to the same trucking company transporting the biomass. Rail transportation from Williams Lake to the port of North Vancouver costs \$29/t (Murray, 2010). The assumed density of bio-oil is 1200 kg/m^3.

3.4.5 Demand and price of products

The demand for heat and electricity in each location is estimated using previous technical reports and literature, and is assumed stable over the planning horizon. The demand for pellets and bio-oil is based on the total economically available forest residues in the region. The price of heat and electricity is based on current energy prices in each community (i.e. Anahim Lake is not connected to the Hydro grid, and produces electricity from diesel at a price of \$0.285/kWh), the price of bio-oil is derived from the current cost of household heating oil in the region (1l of bio-oil contains 54% of the energy content of heating oil), and the price of pellets is based on the current price of pellets for export at the port of North Vancouver (Table 3-7). Although the developed model can consider variability in prices and demand, in this case study they are considered fixed over the planning horizon.

Table 3-7 Product demand and price parameters (parameters assumed the same for all periods)

Product	Demand (min-max) at location/market				Units
	Anahim Lake	Hanceville	Williams Lake	Port of export	
Heat	0 – 19,710[a]	-	12,322 - 12,322[c]	-	MWh
Electricity	3,942 - 39,420[a]	3,942 - 39,420[b]	-	-	MWh
Bio-oil	-	-	0 - 81,377	0 - 81,377	m^3
Pellets	-	-	-	0 - 135,000	t
Product	**Current price of equivalent product at location/market**				**Units**
	Anahim Lake	**Units**	**Williams Lake**	**Port of export**	
Heat	83	83	10	-	\$/MWh
Electricity	285	95	95	-	\$/MWh
Bio-oil	-	-	640	-	\$/m^3
Pellets	-	-	-	143	\$/t

[a] (Marinescu, 2013), [b] (Marinescu, 2012), [c] (Akhtari, 2012)

3.5 Results and discussion

The MILP model was solved using the AIMMS 3.11^{TM} software that integrates modeling language, a graphical user interface and numerical solvers (Paragon decision technology, 2014). The model for this case study has 141,221 constraints, and 396,121 decision variables of which 1,380 were integers. With an Intel 2.67 GHz processor, an optimal solution was found in 79 seconds.

3.5.1 Optimal solution

Table 3-8 shows the optimum conversion technology types and capacities at each location determined by the model. The installation of a 5 MW biomass boiler connected to a steam turbine is selected as the best alternative for cogeneration of heat and electricity in Anahim Lake. However, for the on-grid locations, bio-electricity does not compete with the electricity prices of the province (Hanceville and Williams Lake). The (economically) optimal solution also indicates that the production of bio-oil in Hanceville (assuming a high demand for bio-oil) as well as the small scale production of pellets in Williams Lake would generate additional profit. The location and capacity of pyrolysis and pellet plants are driven by the biomass availability (mostly chipped MPB-killed timber around Hanceville) and the closeness to the rail system (that passes through the community of Williams Lake). Note that currently there is a large pellet plant operating in Williams Lake, and based on the data analyzed in this case study, the model suggests that the increased production of pellets in the community could be cost-efficient.

Table 3-8 Optimal selection of technologies for each location, base case scenario

Location	Technology	Product	Capacity
Anahim Lake	Biomass boiler + steam turbine	Heat and electricity	5 MW (electrical)
Hanceville	Biomass boiler + steam turbine	Electricity	0.5 MW (electrical)
	Pyrolysis plant	Bio-oil	400 odt/day
Williams Lake	Biomass stoker boiler	Heat	2 MW (thermal)
	Pellet plant	Pellets	15,000t/year

The NPV of the optimal solution for the 20-year planning horizon would be $552,543,949. The average annual revenue of the supply chain considering all the selected technologies is $67,315,323 and the average annual cost is $25,232,960. In this solution, the average annual amount of products is 81,377 m^3 of bio-oil and 15,000 t of pellets in the port of export, 39,420 MWh of electricity and 19,710 MWh of heat in Anahim Lake, 1002 MWh of electricity in Hanceville and 12,322 MWh of heat in Williams Lake. The amount of heat and electricity produced in Hanceville and Williams Lake is just enough to cover the minimum demand of the existing customers (e.g. the sawmill and the grid) and all energy needs of the pyrolysis and the installed pellet plants are covered by existing energy sources in each location. Since the demand and price of products are assumed to be fixed over the planning period, revenue remains fixed. Overall, bio-oil, pellets, electricity and heat sales account for about 77%, 3%, 17% and 3% of the revenue, respectively.

In the three locations, 100% of available sawmill chips and hog fuel is used. Forest residues and chipped MPB-killed timber are used as a complement to fulfill the feedstock demand of the installed plants. Overall, the average annual composition of the biomass mix is 12% sawmill chips, 7% sawmill hog fuel, 37% harvesting residues, and 44% chipped MPB-killed timber. Due to fluctuations in availability of harvest residues over time (changes occur in each 5-year period), the total cost components (sum of all selected plants) fluctuate over the planning horizon (Figure 3-3). The largest fluctuations happen at the beginning of year 16 since biomass purchase and transportation costs increase by 19% as a result of the significant decrease in biomass supply around the communities of Anahim Lake and Hanceville.

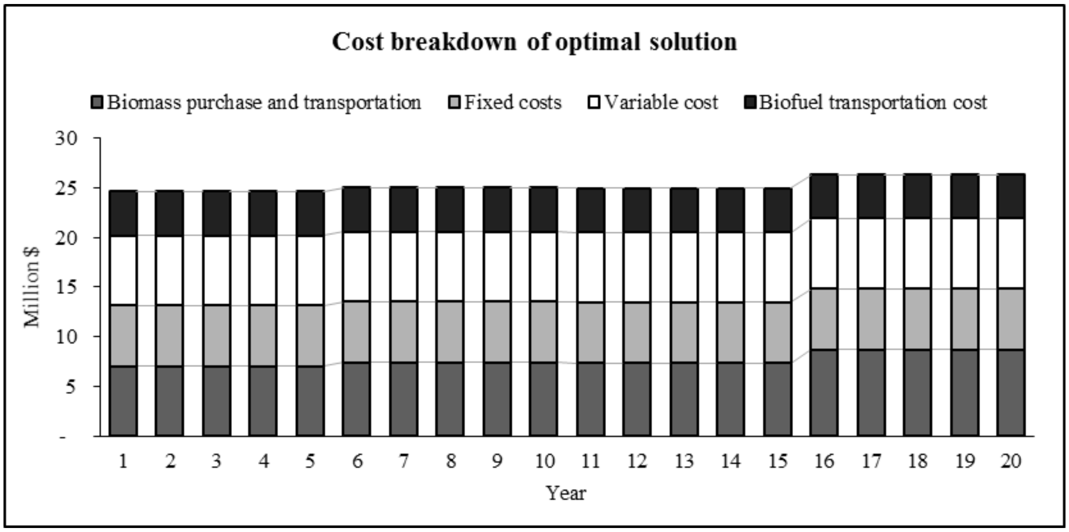

Figure 3-3 Breakdown of cost components over the planning horizon

3.5.2 Sensitivity analysis

To evaluate the effect of potential variations in model parameters on the supply chain profit, a sensitivity analysis is performed. The parameters evaluated are those related to biomass cost and availability, as well as product demand and price.

The sensitivity of the model to biomass cost is analyzed separately for forest harvesting residues and for sawmill residues. The purchasing cost of forest harvesting residues is increased from \$0/odt to \$20/odt, and the cost of sawmill residues (both hog fuel and wood chips) is increased from \$0/odt for both residues to \$20/odt for hog fuel and \$50/odt for wood chips. Product prices are varied one at a time. Electricity costs are increased from \$0.095/kWh to \$0.285/kWh independently for each location to evaluate the effect of changes in the price of electricity in each community. Similarly, heat costs in Anahim Lake are increased from \$0.083/kWh to \$0.285/kWh. In Williams Lake, biomass based heating is only compared to the current cost of natural gas heating (the base case scenario). The price of pellets is changed from \$135/t to \$150/t to capture the price variability of such product, and the bio-oil price is varied by ±20%. Similarly, the maximum demand for products is evaluated individually for each type of product deemed relevant. The demand for bio-oil and pellets is changed by ±20%, also the demand for heat in Anahim Lake is changed by ±20%. Finally, the biomass availability for all sources is changed by ±20% from the base case scenario. Figure 3-4 summarizes the results of the sensitivity analysis.

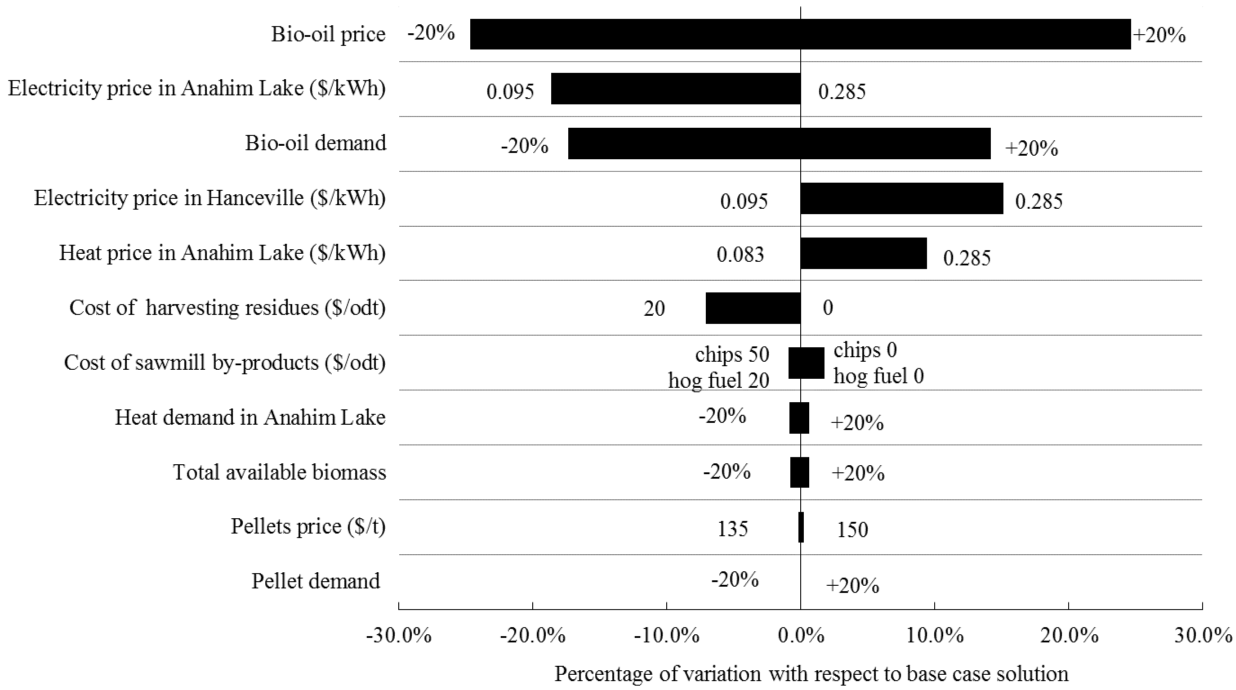

Figure 3-4 Sensitivity of optimal solution to selected parameters

Table 3-9 shows those changes in the parameters that affected the technology selection.

Table 3-9 Impact of changes in parameters on technology selection

Conversion technology & size	Base case	Changes to parameters			
		Bio-oil demand (+20%)	**Electricity price, Hanceville (from $0.095 to $0.285/kWh)**	**Forest residues price (+ $20/odt)**	**Pellet price ($135/t)**
Anahim Lake Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1	period 1	period 1	period 1	period 1
Hanceville					
Biomass boiler + steam turbine electricity only, 0.5 MW	period 1	period 1		period 1	period 1
Biomass boiler + steam turbine electricity only, 5 MW			period 1		

Conversion technology & size	Base case	Changes to parameters			
		Bio-oil demand (+20%)	Electricity price, Hanceville (from $0.095 to $0.285/kWh)	Forest residues price (+ $20/odt)	Pellet price ($135/t)
Pyrolysis plant, 400 odt/day	period 1			period 1	period 1
Pyrolysis plant, 600 odt/day		period 1			
Williams Lake					
Biomass stoker boiler, 2 MW	period 1	period 1	period 1	period 1	period 1
Pyrolysis plant, 400 odt/day			period 1		
Pellet plant, 15,000 t/year	period 1	period 1	period 11		period 11

The impact of variation in some parameters on the total NPV is high (Figure 3-4), and changes the decision on technology selection (Table 3-9). When the bio-oil price is decreased or increased by 20%, the same technologies are chosen with a loss or gain in profit around 25%. When the electricity price in Anahim Lake is reduced to $0.095/kWh, the same technologies are selected with a loss in profit of 19%. When the electricity price in Hanceville is increased to the rate of diesel generation in the region ($0.285/kWh), the installation of a larger electricity plant is recommended (5MW), with a gain in profit of 15%. When the bio-oil demand is decreased by 20%, the same technologies are recommended, and the loss of profit is around 17%. Contrarily, when the bio-oil demand is increased by 20%, the installation of a 600 odt/day pyrolysis plant in Hanceville is preferred over the 400 odt/day option. Other significant parameters are the price of heat in Anahim Lake (with no changes in technology selection), and the cost of forest harvesting residues (which may affect the availability of biomass for pellet production in Williams Lake) as shown in Figure 3-4.

3.6 Summary and conclusions

In this chapter, a single-objective optimization model that supports the strategic design and planning of a forest and wood residues supply chain for the production of bioenergy and biofuels was developed. The model was formulated as a mixed integer linear programming (MILP) that selects the optimal conversion technologies to install in each location over a long-term planning horizon, and recommends the amount of biomass to procure from each supply source, as well as the amount of products to generate and distribute during each time period (of one year). The model was applied to the case study described in Section 1.3, and was solved using the AIMMS software package. The optimal solution generated by the model suggested that a net present value of $552,543,949 could be generated from the production of bio-oil, pellets, heat and electricity using available forest and wood residues. Through a sensitivity analysis, it was shown that the parameters with the higher impact on the NPV of the optimal supply chain were the bio-oil price and demand, and the price of electricity.

In the optimal solution, a fast pyrolysis plant in the community of Hanceville represented the most profitable technology, accounting for 77% of the overall revenue. This solution was consistent with the results of the Biopathways Project (FPAC, 2010) in which the installation of fast pyrolysis plants in the region was suggested as the most profitable alternative. It is worth noting that biomass fast pyrolysis technologies and their products are not commercial yet (in this study, the bio-oil price was derived based on the price of heating oil, and a high demand for bio-oil was assumed). However, currently, there are pilot demonstration plants (e.g. Union Fenosa in Spain, Dynamotive in Canada and Wellman in the UK) and companies are promoting the commercialization of bio-oil across the world (e.g. Dynamotive, Ensyn Technologies) (Oasmaa et al. 2009; Vamvuka, 2011). This may foster the development of a bio-oil market that could be leveraged by the communities in the Williams Lake TSA. The optimal solution also suggested that the combustion of forest-based biomass in biomass boilers connected to steam turbines could reduce electricity costs in comparison with diesel-based generation in the remote communities of Anahim Lake and Hanceville.

The multi-period nature of the developed model was used to capture fluctuations in harvesting residue availability and cost in the Williams Lake TSA, which influenced the installation period of pellet plants. In this study, product demand and price were considered steady over the planning horizon, however, the sensitivity analysis showed that uncertainty in those parameters affects the long-term strategic design of the supply chain. Thus, decision makers should consider market assessments to further support the design of the supply chain.

The above-described model was developed for the economic optimization of the supply chain design by maximizing its NPV over a defined planning horizon. This model required the characterization of the supply chain in terms of their revenue and cost-generating activities. To incorporate the environmental criteria in the decision making process, it is first necessary to understand the life cycle environmental emissions of all stages of the forest-based biomass supply chains, and then, to incorporate those emissions into the optimization model, as will be shown in the next two chapters.

Chapter 4: Life cycle GHG assessment

4.1 Synopsis

The main goal of this chapter is to evaluate and compare the GHG emissions performance of different forest-based biomass supply chain alternatives for the production of bioenergy and biofuels in the case study region introduced in Section 1.3. The evaluation is based on the LCA methodology described in (ISO, 2006). The SimaPro v7.0 (Product Ecology Consultants, 2012) software was used to support the compilation of a life cycle inventory (LCI) and the computation of the LCIA (LCIA) of each unit process. The LCIA values will be used as input for the environmental objective that will be developed in Chapter 5. Due to the vast amount of supply chain configuration alternatives considered in the case study (e.g. different biomass types and sources, as well as multiple conversion technologies and products), it is not possible to analyze or present the overall GHG emissions performance of each one of the several potential supply chain configurations. Instead, in this chapter, an analysis is developed for 16 selected supply chain configurations. The results of this analysis will be used to provide modeling insights to incorporate environmental considerations in the multi-objective decision support model developed in this dissertation.

4.2 Goal and scope

The goal of the life cycle GHG assessment presented herein is to quantify the net life cycle GHG emissions associated with the installation of the bioenergy and biofuel technologies presented in Section 1.3 in the communities of Anahim Lake, Hanceville and Williams Lake. Since the results of this analysis will be incorporated into the optimization of a supply chain with multiple products in different final applications, it is not possible to define a single functional unit. Thus, to facilitate a fair assessment of the life cycle GHG emissions performance of different supply chain alternatives, it is necessary to establish a common basis for comparison. In this study, the basis for comparison is the total amount of GHG emissions of the base case scenario, i.e. the current system that provides the same products and services to the community (e.g. equivalent amounts of electricity and heat in the considered markets). Figure 4-1 shows the life cycle unit processes associated with the base case scenario of this case study, where forest and wood residues are produced as by-products of current harvesting and milling operations and are simply disposed of, while hydro-electricity and fossil fuels are the currently used energy sources.

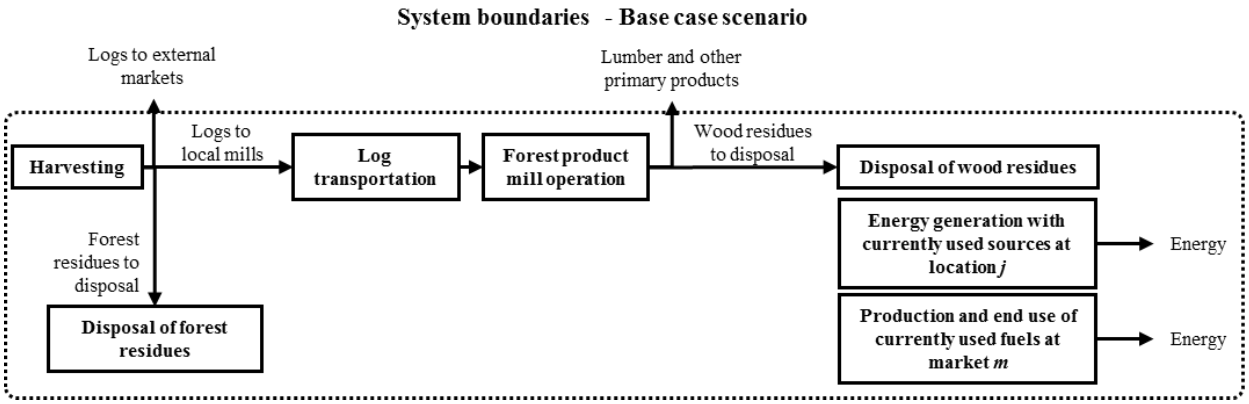

Figure 4-1 System boundaries for base case scenario

For the estimation of the emissions associated with the introduction of a forest-based biomass supply chain, the system boundary of the base case scenario is extended. The extended system boundary includes all stages of procuring forest residues and non-merchantable MPB logs to the conversion plants, as well as the distribution of the generated products. Figure 4-2 shows the life cycle unit processes associated with a forest-based biomass supply chain scenario. Boxes with light shading in Figure 4-2 correspond to added unit processes (do not exist in the base case scenario depicted in Figure 4-1). Boxes with darker shading in Figure 4-2 correspond to unit processes that exist in the base case scenario but their flows in each location might be modified as a result of the implementation of a forest-based biomass supply chain. Energy and materials used for facility construction and decommission, as well as for the manufacturing of each piece of equipment are not within the scope of this study as recommended in (Briggs, 2010), because while they might be significant for environmental impacts such as mineral extraction and ecotoxicity, they typically do not account for more than 0 to 5% of the total GHG emissions (with global warming potential impact) (refer for example to (Ghafghazi et al., 2011)) which is the focus of this study.

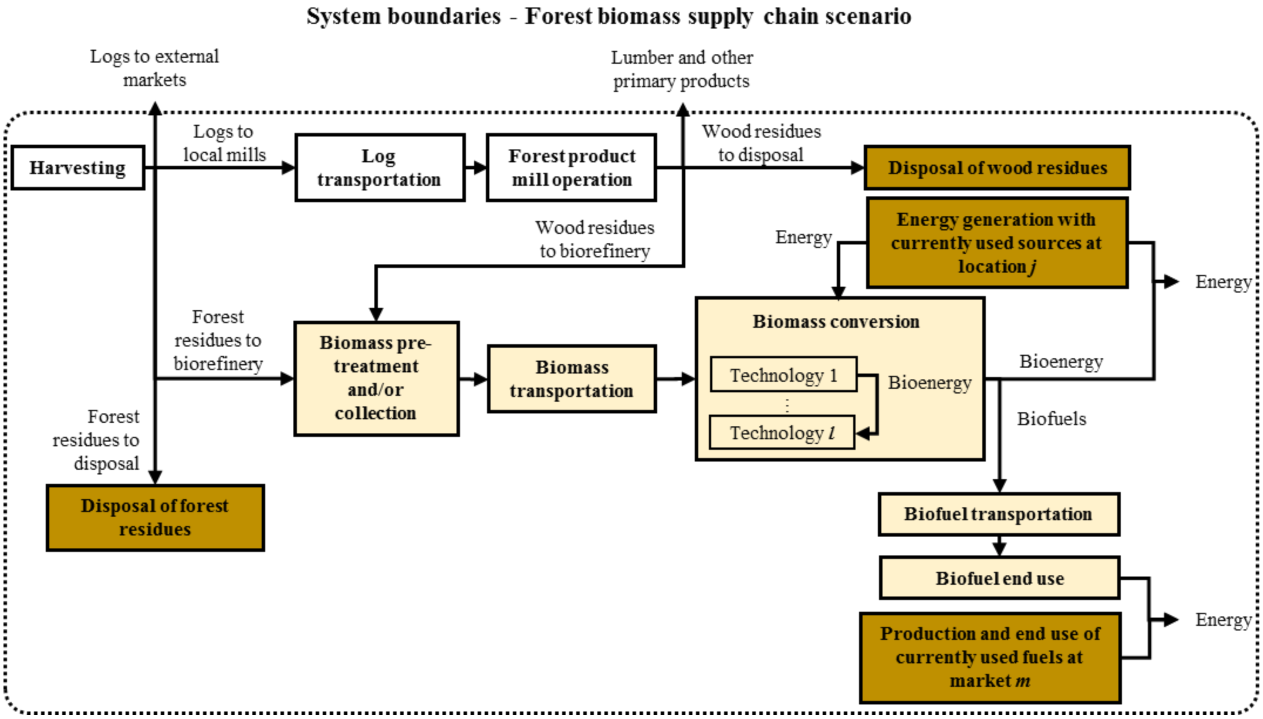

Figure 4-2 System boundaries for forest-based biomass supply chain scenario

4.3 Life cycle inventory (LCI)

In a "cradle-to-grave" life cycle inventory of GHG emissions, all the GHG emissions generated during the production, use and disposal of products need to be accounted for. In biomass systems, non-biogenic carbon emissions are generated in activities along the supply chain due to the use of fossil fuels and other materials (e.g. lubricants) required for the operation of equipment and machinery. In addition, biogenic carbon emissions are generated during biomass burning which correspond to the total amount of carbon that was sequestered during tree growth. Typically, these biogenic emissions are considered to be carbon-neutral (Cherubini et al., 2009). However, when biomass is landfilled, a large amount of the biogenic carbon embedded in the biomass is not released into the atmosphere and remains stored in the landfill (Pawelzik et al., 2013). In this study, since both burning and landfilling activities are included within the compared scenarios, the total amount of GHG emissions (from biogenic and non-biogenic sources) is accounted for all unit processes to assure that equitable comparisons between the scenarios are performed.

Different data sources were used to compile the life cycle inventories of the base case scenario presented in Figure 4-1 and the forest biomass supply chain scenario depicted in Figure 4-2, and to estimate the GHG emissions associated with supplementary unit processes such as fossil fuel and lubricants production and use. Whenever available, site specific information was used, otherwise data from relevant published reports were obtained. Specific gases with GHG effects for which data are compiled in this study include CO_2, CO, CH_4, N_2O, and hydro fluorocarbons (HFC-134a), and were categorized as either biogenic or non-biogenic, where the latter category might contain trace amounts of biogenic emissions since some of the employed databases (e.g. GHGenius) do not report segregated fossil and biogenic emissions.

4.4 Life cycle impact assessment (LCIA)

All material inputs, energy consumption and emission data for the unit processes depicted in Figure 4-1 and Figure 4-2, and for the unit processes related with the production and use of fossil fuels and lubricants were entered into the SimaPro v7.0 software (Product Ecology Consultants 2012). This software was used to compute the amounts of CO_2 equivalent GHG emissions of each unit process based on the IMPACT 2002+ v2.1 methodology (Jolliet et al., 2003). The results were then modified to account for biogenic emissions as well. All GHG emissions of each unit process are shown in Tables 4-1, 4-2, and 4-3 for unit processes in the base case scenario, in the forest-based biomass supply chain scenario and for supporting unit processes (fuels and lubricants), respectively. For biomass-related unit processes with biogenic emissions, the percentage of emissions that is biogenic is shown within brackets. Table 4-1, Table 4-2 and Table 4-3 also present the assumptions and references used to compile the emissions inventory.

Table 4-1 GHG emissions generated per unit process, base case scenario

Unit Process	GHG emissions	Assumptions and references
Harvesting	34.6 kg CO_2-eq/odt of harvested logs	Average diesel consumption of 3.5 l/m^3 of harvested logs, including pre-harvesting, logging, camping, road construction and silvicultural operations (Sambo, 2002) and lubricant use 0.02% of the amount of diesel consumed (Johnson et al., 2012).
Log transportation	0.2 kg CO_2-eq/odt of logs transported over 1 km in trucks	Fuel consumption of 0.68 l/km considering a 2-way trip in a semi-trailer with 3 axles with a weight-restricted capacity of 28t.
Forest product mill operation	6.3 kg CO_2-eq/odt of produced sawmill by-products	All material and energy inputs from (Milota et al., 2005). Heat and electricity-related emissions are not included.
Disposal of	88.9 and 72.6 kg CO_2-eq/odt of	NETL Life Cycle Inventory library (NETL, 2013). Assumed

Unit Process	GHG emissions	Assumptions and references
wood residues	sawmill chips landfilled (58.9% and 72.0% biogenic) in Hanceville and Williams Lake, respectively	average transportation distance to landfill is 100 km from Hanceville and 10 km from Williams Lake.
	92.7 and 73 kg CO_2-eq/odt of sawmill hog fuel landfilled in Hanceville and Williams Lake, respectively (56.4% and 71.8% biogenic)	NETL Life Cycle Inventory library (NETL 2013). Assumed average transportation distance to landfill is 100 km from Hanceville and 10 km from Williams Lake.
	1532.7 kg CO_2-eq/odt of biomass burned in beehive burner in Anahim Lake (100% biogenic)	EPA A42 report (EPA, 2015)
Disposal of forest residues	1,630.0 kg CO_2-eq/odt of forest residues burned (99.9% biogenic)	NETL Life Cycle Inventory library (NETL 2013)
	1,660.0 kg CO_2-eq/odt of MPB-killed logs burned (99.9% biogenic)	NETL Life Cycle Inventory library (NETL 2013)
Energy generation with currently used sources at each location	879 kg CO_2-eq per MWh of electricity generated from diesel on-site (cradle-to-grave)	GHGenius (S&T Consultants Inc, 2014)
	51.7 kg CO_2-eq per MWh of electricity supplied by the British Columbia electricity mix (cradle-to-grave)	Electricity mix in British Columbia is 94.3% hydro, 5.7% natural gas and 0.1% other sources (e.g. fuel oil) with efficiencies of 100%, 45% and 34%, respectively (Product Ecology Consultants, 2012; St. Lawrence, 2008). GHG emissions of electricity generation in British Columbia were extracted from GHGenius considering a grid distribution efficiency of 92% (S&T Consultants Inc, 2014).
	317 CO_2-eq per MWh of heat generated from fuel oil (cradle-to-grave)	GHGenius (S&T Consultants Inc, 2014)
Production and end use of currently used fuels at biofuel markets	1050 kg CO_2-eq per MWh of electricity generated from coal and distributed to end user in Europe (cradle-to-grave)	System process “Electricity coal power plant in NL S” extracted from the ETH-ESU 96 library in Simapro (Product Ecology Consultants, 2012)
	72.5 kg CO_2-eq per GJ of heat generated from natural gas in British Columbia (cradle-to-grave)	GHGenius (S&T Consultants Inc, 2014).
	88 kg CO_2-eq per GJ of heat generated from fuel oil in British Columbia (cradle-to-grave)	GHGenius (S&T Consultants Inc, 2014).
	98 kg CO_2-eq per GJ of heat generated from fuel oil in Europe (cradle-to-grave)	System process “Residual oil Europe in boiler 1 MW S” extracted from the ETH-ESU 96 library in Simapro (Product Ecology Consultants, 2012)

Table 4-2 GHG emissions generated per additional/modified unit process, forest-based biomass supply chain scenario

Unit Process	GHG emissions	Assumptions and references
Biomass pre-treatment and/or collection	12.10 kg CO_2-eq per odt of harvesting residues and/or MPB -killed logs pre-treated (chipped) and collected at forest	Average diesel consumption of 3.83 l/odt of biomass load and lubricant use of 0.06 l/odt (Johnson et al., 2012).
Biomass transportation	0.32 kg CO_2-eq per odt of chipped harvesting residues and/or chipped MPB-killed logs transported for 1 km by truck; 0.28 kg CO_2-eq per odt of sawmill chips transported for 1 km by truck; 0.50 kg CO_2-eq per odt of hog fuel transported for 1 km by truck	Fuel consumption of 0.68 l/km considering a 2-way trip in a semi-trailer with 3 axles and walking floor with a volume-restricted capacity of 110 m^3 (Friesen, 2012). Bulk density and moisture content of biomass types are reported in Table 3.4.
Biofuel end use	86.0 kg CO_2-eq per GJ of pellets or bio-oil (100% biogenic)	Assumed the same as biomass combustion (EPA A42 report in (EPA, 2015))
Biomass conversion	86.0 kg CO_2-eq per GJ of input biomass combusted (100% biogenic)	EPA A42 report (EPA, 2015)
	85.6 kg CO_2-eq per GJ of input biomass gasified (100% biogenic)	EPA A42 report (EPA, 2015) and Pa et al. (2011)
	15.18 kg CO_2-eq per odt of biomass pelletized (non-heat or electricity emissions)	Approximately 5.32 l of diesel (with an energy density of 38.7 MJ/l) is used during biomass pre-treatment and pellet production (Scenario 2 in (Mani, 2005)).
	0.05 kg CO_2-eq per odt of biomass converted through fast pyrolysis (non-heat or electricity emissions)	Approximately 0.56 MJ of heating fuel is combusted during the start-up and operation of the fast pyrolysis reactor (Fan et al., 2011).
Biofuel transportation	0.15 kg CO_2-eq per tkm of load transported by truck	Fuel consumption of 0.68 l/km considering a 2-way trip in a semi-trailer with 3 axles and walking floor with a weight-restricted capacity of 28 t (Friesen, 2012). Bio-oil density of 1.22 kg/l (Bridgwater et al., 2002; Rogers and Brammer, 2012).
	0.02 kg CO_2-eq per tkm of load transported in rail	Diesel consumption is about 0.219 MJ/tkm (approximately 5.66 x 10^{-3} l/tkm) for rail transportation in Canada (S&T Consultants Inc, 2014).
	0.01 kg CO_2-eq per t km of load transported by ocean	Diesel consumption is about 0.151 MJ/tkm (approximately 3.89 x 10^{-3} l/tkm) for ocean transportation in Canada considering a weight class of 30,000 t (S&T Consultants Inc, 2014).

Table 4-3 GHG emissions generated per supporting unit process, lubricants and fuels

Unit Process	GHG emissions	Assumptions and references
Diesel combustion	2.46 kg CO_2-eq/l of diesel combusted in heavy duty engines	GHGenius (S&T Consultants Inc, 2014)
Diesel supply	0.68 kg CO_2-eq/l of supplied diesel (well to tank)	GHGenius (S&T Consultants Inc, 2014)
Gasoline combustion	1.95 kg CO_2-eq l of gasoline combusted in heavy duty engines	GHGenius (S&T Consultants Inc, 2014)
Gasoline supply	0.63 kg CO_2-eq/l of supplied gasoline (well to tank)	GHGenius (S&T Consultants Inc, 2014)
LPG (Propane) combustion	1.14 kg CO_2-eq/l of LPG combusted in heavy duty engines	GHGenius (S&T Consultants Inc, 2014)
LPG (Propane) supply	0.14 kg CO_2-eq/l of supplied LPG (well to tank)	GHGenius (S&T Consultants Inc, 2014)
Lubricant oil production	0.85 kg CO_2-eq/l of produced lubricant oil	System process “Lubricating oil, at plant/RER S” extracted from the Ecoinvent library in Simapro (Product Ecology Consultants, 2012)

4.5 Life cycle GHG analysis of selected supply chain alternatives

In this section, 16 potential supply chain configurations are analyzed with the goal to evaluate the GHG emission performance of alternative bioenergy systems for the production of electricity and heat in the two most remote communities of the case study (Anahim Lake and Hanceville) presented in Section 1.3. First, the 16 alternative configurations are described, and then the analysis and comparison among those alternatives are presented.

4.5.1 Technologies and plant sizes

The installation of a total of 8 bioenergy conversion technologies is analyzed and compared for each of the two communities (2 plant sizes × 4 technologies) (Figure 4-3). The plant sizes considered for the bioenergy systems are: a) small plants (0.5 or 2 MW) to replace diesel generation at the local sawmills (note that a 0.5 MW plant and a 2 MW bioenergy plant would suffice to replace diesel generation at the sawmill in Hanceville and Anahim Lake based on the sawmill size, respectively), and b) larger plants (5 MW) to supply electricity to local sawmills and the communities. The technologies that are analyzed include: 1) biomass boilers coupled with steam turbine systems for the generation of electricity-only (ST*), 2) biomass boilers coupled with steam turbine systems for cogeneration of electricity and heat (ST), 3) oil heating boilers coupled with Organic Rankine cycles for cogeneration of electricity and heat (ORC), and

4) biomass gasifiers with internal combustion engines for cogeneration of electricity and heat (Gas).

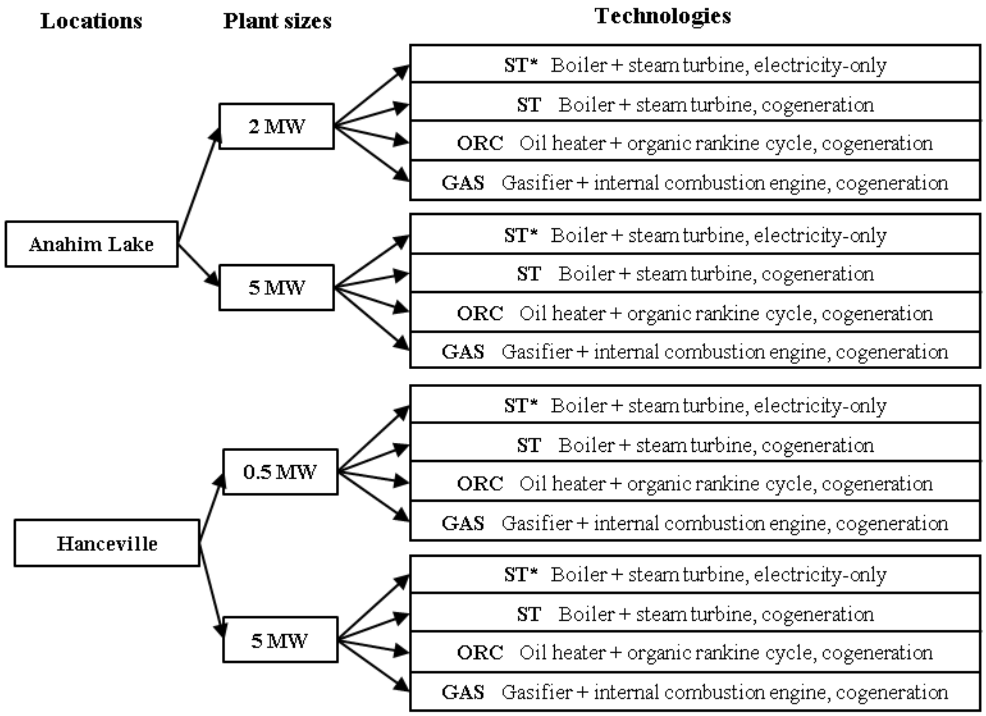

Figure 4-3 Technologies and plant sizes analyzed

4.5.2 Biomass mix of each plant alternative

For each bioenergy system alternative, the amount and type of biomass used for bioenergy depends on the technology conversion efficiency (electrical and thermal), the plant size, and the amount of available biomass of each type, as well as its moisture and energy contents. Conversion efficiencies of the selected technologies and plant sizes were described in Section 3.4.3.

Previous LCA studies that considered different types of biomass (Jäppinen et al., 2014; Petersen Raymer, 2006; Puettmann and Lippke, 2012) assumed that the entire biomass demand of a conversion technology could be met by one specific type of biomass (e.g. harvesting residues versus small-diameter trees in (Jäppinen et al., 2014)). However, in a realistic case, the biomass available at a lower cost would be used first, and then, if necessary, more expensive sources would be used to complement the biomass demand. For this analysis, the composition of the biomass mix for each bioenergy system alternative is estimated by selecting the mix of biomass with the lowest cost per net GJ of biomass procured to the plant.

Average transportation distances required to bring enough material to the bioenergy plants vary among plant alternatives based on their specific biomass demand (e.g. for gasification technologies only low-ash material is required), and varies between locations based on the forest density and the harvesting plans of the region for the next 20 years. For example, to get an annual supply of forest residues and non-merchantable MPB logs of 20,000 odt, average transportation distances of 9.9 km for Anahim Lake and 18.3 km for Hanceville are required during the following 20 years. If only non-merchantable MPB logs are collected from the residues piles in the forest roadside, these distances increase to 14.3 km and 31.3 km, respectively.

The biomass mix that minimizes the overall biomass costs including price, collection, comminution, and transportation costs is estimated based on biomass characteristics and procurement costs presented in Table 3-4, and the technological considerations in Table 3-5. The composition and the average procurement cost of the biomass mix of each alternative are presented in Figure 4-4 for a) Anahim Lake and b) Hanceville.

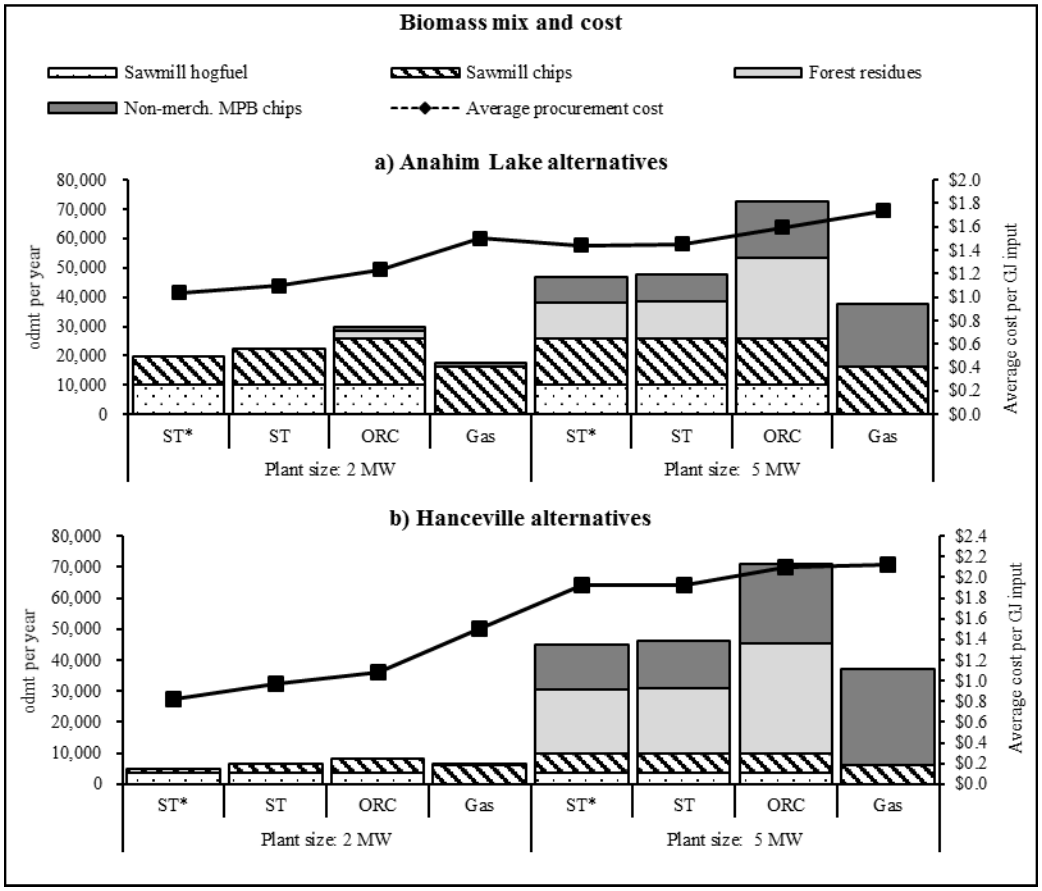

Figure 4-4 Annual biomass demand and average biomass procurement cost for all bioenergy system alternatives in (a) Anahim Lake and (b) Hanceville

Sawmill hog fuel is the most economical biomass type ($0.60/GJ) and is entirely consumed by all combustion alternatives (ST*, ST and ORC), as shown in Fig. 4-4. Sawmill chips at a cost of $1.48/GJ, are the second selected biomass type for combustion alternatives, and the base feedstock for the gasification alternatives (Gas). Despite the higher energy content and lower moisture content of forest residues and non-merchantable MPB logs over sawmill residues, their collection, chipping and transportation costs make their procurement expensive, and thus they are only added to complement the biomass demand of the plants in both locations. The average biomass procurement cost for the 0.5 MW plant alternatives in Hanceville is up to 21% lower than that for the 2 MW alternatives in Anahim Lake, since a larger share of the biomass mix is composed of hog fuel. For 5 MW plant alternatives, the average procurement cost for alternatives in Hanceville are 38% to 50% higher than that for alternatives in Anahim Lake since

Hanceville has a lower availability of sawmill chips and hog fuel and larger transportation distances for biomass procurement than Anahim Lake.

4.5.3 Input and output flows of each bioenergy system

The relevant input and output flows of each bioenergy system are estimated based on the biomass mix requirements and the output of each bioenergy plant alternative.

Table **4-4** shows the values for system alternatives in Anahim Lake and Table 4-5 shows the values for system alternatives in Hanceville.

Table 4-4 Reference, input and waste flows of baseline and bioenergy system alternatives in Anahim Lake

Description	Baseline	2 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Reference flows									
Logs to external markets (odt)	10,493	10,493	10,493	10,493	10,493	10,493	10,493	10,493	10,493
Lumber (odt)	34,417	34,417	34,417	34,417	34,417	34,417	34,417	34,417	34,417
Electricity (MWh)	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420
Heat (GJ)	70,956	70,956	70,956	70,956	70,956	70,956	70,956	70,956	70,956
Input flows									
Logs to local sawmill (odt)	60,487	60,487	60,487	60,487	60,487	60,487	60,487	60,487	60,487
Electricity from diesel generator (MWh)	39,420	23,652	23,652	23,652	23,652	-	-	-	-
Electricity from British Columbia’s grid (MWh)	-	-	-	-	-	-	-	-	-
Heat from fuel oil combustion (GJ)	70,956	70,956	175	-	44,433	70,956	-	-	12,882
Sawmill chips to bioenergy (odt)	-	9,676	12,643	16,150	16,150	16,150	16,150	16,150	16,150
Sawmill hog fuel to bioenergy (odt)	-	9,920	9,920	9,920	-	9,920	9,920	9,920	-
Residues to bioenergy (odt)	-	-	-	2,295	-	12,044	12,609	27,178	-
Non-merchantable MPB logs to bioenergy (odt)	-	-	-	1,621	1,207	8,509	8,909	19,202	21,664

Description	Baseline	2 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Waste flows									
Sawmill chips to beehive (odt)	16,150	6,474	3,507	-	-	-	-	-	-
Sawmill hog fuel to beehive (odt)	9,920	-	-	-	9,920	-	-	-	9,920
Sawmill chips to landfill (odt)	-	-	-	-	-	-	-	-	-
Sawmill hog fuel to landfill (odt)	-	-	-	-	-	-	-	-	-
Residues to roadside burning (odt)	30,663	30,663	30,663	28,369	30,663	18,620	18,054	3,485	30,663
Non-merchantable MPB logs to roadside burning (odt)	21,664	21,664	21,664	20,043	20,457	13,155	12,755	2,462	-

Table 4-5 Reference, input and waste flows of baseline and bioenergy system alternatives in Hanceville

Description	Baseline	0.5 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Reference flows									
Logs to external markets (odt)	79,480	79,480	79,480	79,480	79,480	79,480	79,480	79,480	79,480
Lumber (odt)	12,787	12,787	12,787	12,787	12,787	12,787	12,787	12,787	12,787
Electricity (MWh)	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420	39,420
Heat (GJ)	41,209	41,209	41,209	41,209	41,209	41,209	41,209	41,209	41,209
Input flows									
Logs to local sawmill (odt)	22,472	22,472	22,472	22,472	22,472	22,472	22,472	22,472	22,472
Electricity from diesel generator (MWh)	3,942	-	-	-	-	-	-	-	-
Electricity from British Columbia’s grid (MWh)	35,478	35,478	35,478	35,478	35,478	-	-	-	-
Heat from fuel oil combustion (GJ)	41,209	41,209	19,971	-	29,641	41,209	-	-	-
Sawmill chips to bioenergy (odt)	-	1,258	2,651	4,550	6,000	6,000	6,000	6,000	6,000
Sawmill hog fuel to bioenergy (odt)	-	3,685	3,685	3,685	-	3,685	3,685	3,685	-

Description	Baseline	0.5 MW				5 MW			
		ST*	ST	ORC	Gas	ST*	ST	ORC	Gas
Residues to bioenergy (odt)	-	-	-	-	-	20,741	21,307	35,875	-
Non-merchantable MPB logs to bioenergy (odt)	-	-	-	-	681	14,654	15,053	25,346	31,117
Waste flows									
Sawmill chips to beehive (odt)	-	-	-	-	-	-	-	-	-
Sawmill hog fuel to beehive (odt)	-	-	-	-	-	-	-	-	-
Sawmill chips to landfill (odt)	6,000	-	-	-	-	-	-	-	-
Sawmill hog fuel to landfill (odt)	3,685	-	-	-	3,685	-	-	-	3,685
Residues to roadside burning (odt)	44,043	44,043	44,043	44,043	44,043	23,302	22,736	8,168	44,043
Non-merchantable MPB logs to roadside burning (odt)	31,117	31,117	31,117	31,117	30,436	16,463	16,063	5,771	-

4.5.4 Results and discussion

The net GHG emissions of each bioenergy system alternative were estimated based on the GHG emissions per unit process described in Section 4.4, and calculated and analyzed using a spreadsheet software.

4.5.4.1 Net GHG emissions

The net GHG emissions for the baseline system are 178,631 t of CO_2 equivalent emissions in Anahim Lake, and 143,429 t of CO_2 equivalent emissions in Hanceville. The main difference in emissions is due to the energy mix difference in these two communities. In Anahim Lake, 100% of the electricity is provided by diesel generators, while in Hanceville only 10% is provided by diesel generators, and the rest is from the grid of the province, which is mostly based on hydroelectric generation.

In Anahim Lake, all the analyzed bioenergy alternatives generate less net GHG emissions than the baseline system (Figure 4-5a). In Ahanim Lake, the net GHG emission reduction ranges from 13,964 to 40,909 t of CO_2 equivalent emissions depending on the selected bioenergy system alternative.

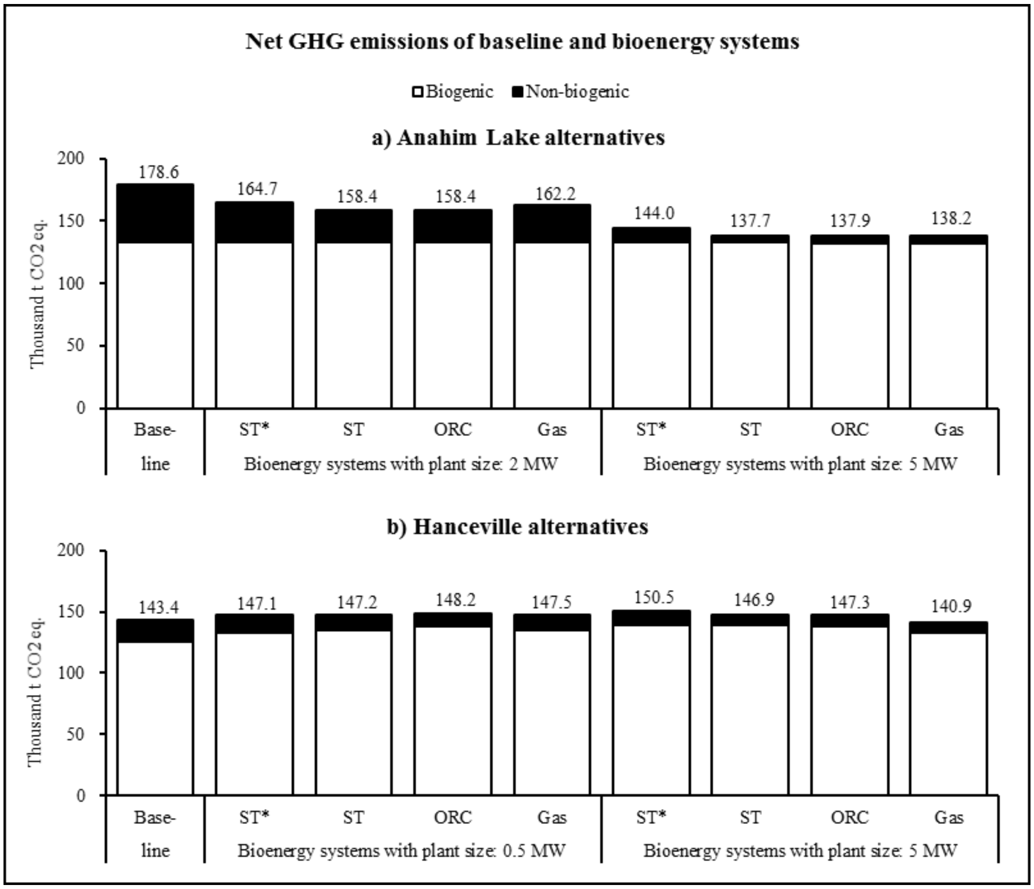

Figure 4-5 Net GHG emissions of baseline and bioenergy system alternatives in (a) Anahim Lake and (b) Hanceville

Figure 4-5a shows that the most significant differences among alternatives in Anahim Lake are due to non-biogenic emissions. The total amount of biogenic emissions does not differ significantly among alternatives because it is assumed that all biogenic carbon is released regardless if biomass is combusted/gasified for bioenergy generation or if it is burned in the forest or beehive burner. There are negligible differences among the total biogenic emissions of the alternatives due to the formation of different substances during combustion under the different combustion (or burning) process conditions considered in the data sources. As shown in

Figure 4-5a, the installation of a 2 MW bioenergy system could produce between 13.9 and 20.2 thousand less t of CO_2 equivalent emissions than the baseline system, and a 5 MW system could generate between 34.7 and 40.9 thousand less t of CO_2 equivalent emissions than the baseline system. For both plant sizes, the technology alternative with the lowest net GHG emissions is the ST system, which has one of the highest electrical efficiencies of all analyzed technologies and is able to fulfil the entire heat demand of the Anahim Lake sawmill. Although the Gas system has a higher electrical efficiency, due to its low thermal efficiency, it is not able to fulfil the entire heat demand regardless of the plant size, thus more GHG emissions are generated as a result of a higher utilization of heating oil.

In Hanceville (Figure 4-5b), the baseline system generates less net GHG emissions than most bioenergy systems. Figure 4-5b shows the differences among alternatives in terms of both non-biogenic and biogenic emissions. While all bioenergy systems have less non-biogenic GHG emissions (due to the replacement of current energy sources with bioenergy) than the baseline system, they also generate more biogenic emissions. The increased biogenic emissions in bioenergy systems are due to the release (during combustion) of the biogenic carbon embedded in sawmill residues that is stored in landfills in the baseline system (when biomass is combusted all the carbon is released, and when it is landfilled, a large portion of the carbon is captured in the soil). The increase of biogenic emissions offsets and surpasses the reduction of non-biogenic emissions in all 0.5 MW bioenergy systems and in the ST*, ST and ORC 5 MW bioenergy systems. The 5 MW Gas system is the only alternative that generates net GHG emission reduction (2.5 thousand less t of CO_2 equivalent emissions than the baseline system), because it has a higher electrical efficiency than the other alternatives and does not utilize sawmill hog fuel (thus, sawmill hog fuel in this alternative is still landfilled).

4.5.4.2 Biogenic GHG emissions breakdown

Figure 4-6 shows the breakdown of biogenic GHG emissions of the baseline and all bioenergy alternatives based on their source: disposal of unused forest residues, disposal of unused sawmill residues, conversion of biomass into bioenergy and other biogenic emissions in other processes along the supply chain.

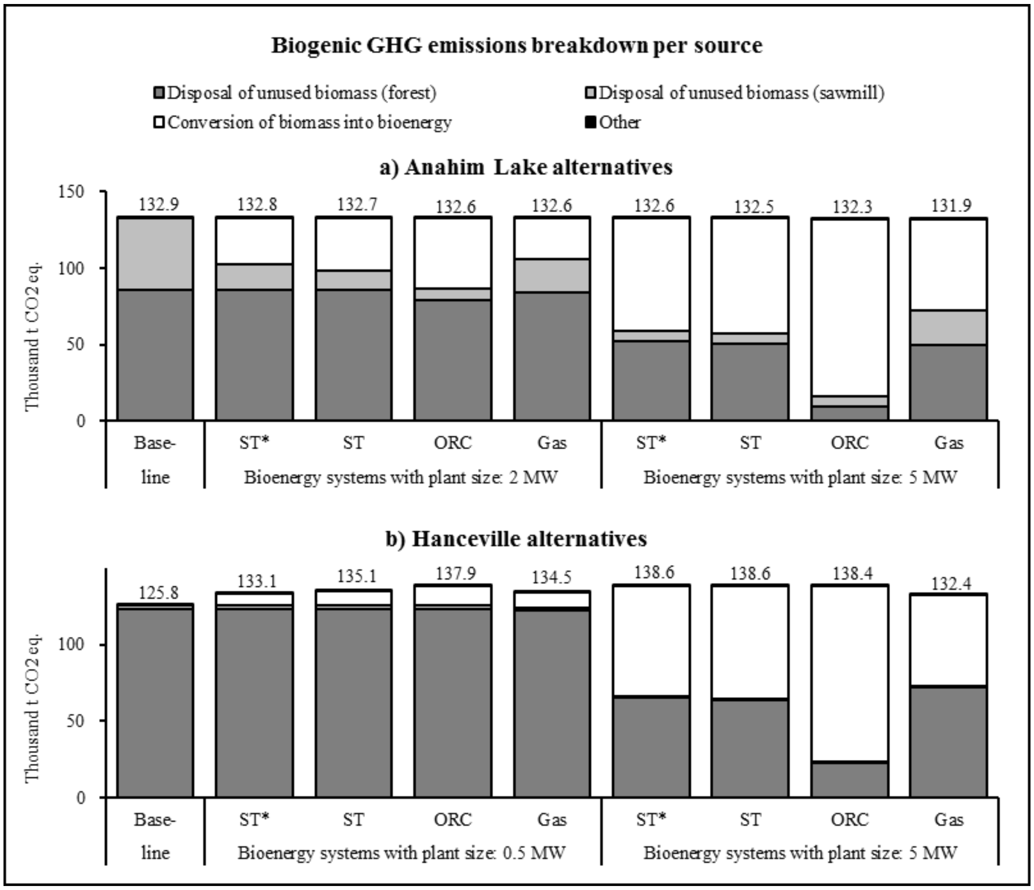

Figure 4-6 Biogenic GHG emission savings per source of emissions for baseline and bioenergy system alternatives in (a) Anahim Lake and (b) Hanceville

In Anahim Lake (Figure 4-6a), 85,930 t of CO_2 equivalent emissions are due to the burning of unused forest residues in the forest cut blocks, and 46,889 t of CO_2 equivalent emissions are due to the burning of unused sawmill residues in beehive burners. In the bioenergy systems with 2 MW bioenergy plants, the largest amount of biogenic emissions (above 79,499 t of CO_2 equivalent emissions in all systems) is due to the large amount of forest residues that remains unused and is burned in the forest. This is followed by the emissions generated during biomass combustion for bioenergy generation (above 26,460 t of CO_2 equivalent emissions in all systems). For all 5 MW systems, most biogenic emissions are generated at the bioenergy plants (above 59,731 t of CO_2 equivalent emissions in all systems).

In Hanceville, Figure 4-6b shows that in the baseline system, almost all biogenic emissions (123,424 t of CO_2 equivalent emissions) are attributed to the burning of unused forest residues, and the biogenic emissions due to landfilling are negligible (2,301 t of CO_2 equivalent emissions). In all 0.5 MW bioenergy systems, since the biomass mixes are mostly composed of sawmill residues, biogenic emissions due to the burning of residues at the forest do not change compared to the baseline system, but additional biogenic emissions are generated during the conversion of biomass into bioenergy (above 7,559 t of CO_2 equivalent emissions in all 0.5 MW bioenergy systems). For 5 MW bioenergy systems, biomass conversion is responsible for more than 72,620 t of CO_2 equivalent biogenic GHG emissions.

4.5.4.3 Non-biogenic GHG emission breakdown

Figure 4-7 illustrates the breakdown of non-biogenic GHG emissions of the baseline and all bioenergy alternatives based on their source: biomass production (harvesting, log transportation, sawmill operation), biomass supply to bioenergy plants (collection & chipping, biomass transportation), disposal of unused biomass (burning at roadside, landfilling) and provision of heat and electricity from current sources (heat from fuel oil and electricity from diesel or the British Columbia grid). Note that non-biogenic emissions related to the disposal of unused biomass are due to the transportation of a crew to the forest to burn roadside forest residues and to the transportation of sawmill wastes to the landfill.

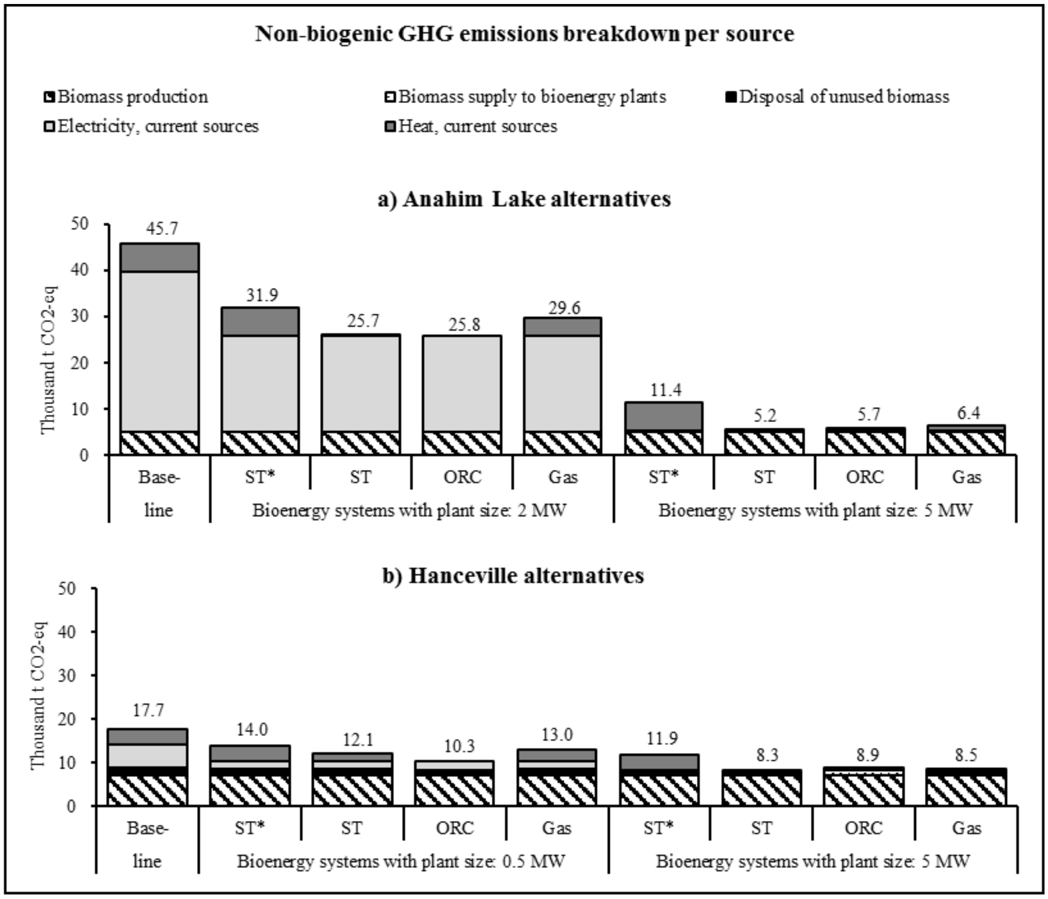

Figure 4-7 Non-biogenic GHG emissions per source of emissions for baseline and bioenergy system alternatives in (a) Anahim Lake and (b) Hanceville

Since the flows of harvested logs and logs procured to local sawmills are identical for all considered systems in each community (refer to Table 4-4 and 4-5), biomass production emissions remain unchanged across all alternatives. In Anahim Lake (Figure 4-7a), biomass production emissions (4,900 t CO_2-eq) are the major contributor to non-biogenic emissions in systems where bioenergy substitutes most fossil electricity and heat (5 MW ST, ORC and Gas systems). For other systems, existing energy systems contribute to the largest proportion of emissions. For example, diesel generation of electricity is the major contributor to the non-biogenic GHG emissions of the baseline system and the two 2 MW bioenergy alternatives, while heat generation from heating oil is the main contributor to the non-biogenic GHG emissions from the 5 MW ST*. Non-biogenic emissions related to supplying forest residues to the bioenergy plants are significant only for 5 MW systems (from 314 to 749 t of CO_2 equivalent emissions for the ST* and the ORC systems respectively) because biomass demand in 2 MW systems is fulfilled using sawmill residues available onsite.

In Hanceville alternatives (Figure 4-7b), biomass production accounts for a larger proportion of the non-biogenic GHG emissions than in Anahim Lake alternatives for two reasons: (1) the amount of biomass production emissions in Hanceville alternatives (7,087 t CO_2-eq) is larger than those in the Anahim Lake alternatives, because more harvested logs are included in the analysis (to fulfil the biomass demand of the bioenergy system with larger demand for non-merchantable MPB logs (the 5 MW Gas system) given that the production of chips in Hanceville is smaller than in Anahim Lake); (2) the amount of non-biogenic emissions from current energy sources in Hanceville is smaller than those in Anahim Lake, due to differences in the reference energy systems. Similar to Anahim Lake, in Hanceville non-biogenic emissions related to supplying forest residues to the bioenergy plants are significant only for 5 MW systems (from 687 to 1,303 t of CO_2 equivalent emissions for the ST* and the ORC systems, respectively).

At a 0.5 MW scale, the ORC system generates the lowest amount of non-biogenic GHG emissions because it has the highest thermal efficiency, and is the only technology that satisfies the complete heat demand of the sawmill. In all the other bioenergy alternatives, a fraction of the heat demand has to be supplied by heating oil. For a larger scale plant (5 MW), the ST system is the bioenergy alternative with the lowest amount of non-biogenic GHG emissions. Although the Gas system has a higher electrical efficiency and is able to satisfy the heat demand in Hanceville, additional non-biogenic GHG emissions are generated using the ST system because of the transportation of unused sawmill hog fuel (not suitable for gasification) to the landfill, as well as the additional transportation and collection operations associated with the procurement of non-merchantable MPB logs to supplement the biomass demand.

In comparison with the alternative systems in Anahim Lake, the disposal of unused biomass produces larger non-biogenic emissions in alternative systems in Hanceville (particularly for the baseline system and the 0.5 MW system alternatives). These non-biogenic emissions are due to the transportation of unused chips and hog fuel to a landfill (in Anahim Lake, unused chips and hog fuel are burnt in a beehive burner, thus no transportation is needed). In Hanceville, disposal of unused biomass (mostly landfilling) contributes between 1,374 to 1,494 t of CO_2 equivalent emissions for 0.5 MW bioenergy alternatives, and between 537 and 687 t of CO_2 equivalent emissions for 5 MW bioenergy alternatives (Figure 4-7b).

4.6 Summary and conclusions

This chapter presented the estimation of the life cycle GHG emissions associated with each alternative unit process in the forest-based biomass supply chain in the Williams Lake TSA case study (introduced in Section 1.3 of this dissertation). These estimated values will serve in the next chapter for the estimation of environmental coefficients that will be used in the environmental optimization of the forest-based biomass supply chain design.

In addition, this chapter presented an analysis for 16 alternative supply chain configurations for electricity and heat generation in the remote communities of Anahim Lake and Hanceville. The results of this study showed that the selection of the system with the lowest net GHG emissions depends on whether the unused forest and wood residues are burned or landfilled, as well as the type of energy source used in the current system. When compared to the baseline system in Anahim Lake, a net GHG emission reduction between 13,964 and 40,909 t of CO_2 equivalent emissions was achieved by using available forest and wood residues for the generation of heat and electricity, because currently the residues are burned and fossil fuels are used to generate energy in the community. Under these conditions, in Anahim Lake, the alternative with the lowest GHG emissions was a 5 MW biomass boiler coupled with a steam turbine to cogenerate electricity and heat. However, in Hanceville, where sawmill wood residue is landfilled and the reference electricity mix is mostly based on hydro generation, the net GHG emission reduction that was achieved by the introduction of a bioenergy system were significantly lower than that in Anahim Lake (2,535 t of CO_2 equivalent emissions in the 5 MW gasification system alternative) or null (for all other alternatives).

The development of this analysis provided some modeling insights for the development of the environmental objective function of the multi-objective model pursued in this dissertation. First, the estimation of the GHG emission benefit has to consider the baseline case as reference for comparison in order to ensure a fair comparison among alternative supply chain configurations.

And second, since biomass landfilling is considered as the alternative fate of unused forest and wood residues, biomass carbon neutrality cannot be assumed in the analysis since the carbon balance is radically different for landfilled products. Biomass carbon neutrality assumptions imply that landfilling processes generate net negative GHG emissions. These modeling insights will be considered in the bi-objective optimization model presented in next chapter.

Chapter 5: Bi-objective optimization model

5.1 Synopsis

In Chapter 3, a single-objective optimization model was developed for the economic optimization of a forest-based biomass supply chain for the production of bioenergy and biofuels. In this chapter, the model is extended into a bi-objective optimization model that incorporates an environmental objective function. The environmental objective function developed in this chapter aims at maximizing the GHG emission savings associated with the introduced supply chain, considering the current scenario (the current disposal of residues and the currently used energy sources) as the base case for comparison. The bi-objective optimization model is applied to the case study (the Williams Lake TSA) to analyze the trade-offs between the economic and the environmental performances of the case study supply chain. The GHG emission values per unit process estimated in Section 4.4 are used in this chapter to estimate the coefficients of the environmental objective function. The bi-objective MILP optimization model is solved using a Pareto-generating method (augmented ε-constraint or AUGMECON) to generate a set of Pareto-optimal solutions that enable the analysis of the compromises that have to be made between the economic and the environmental performances of the supply chain during the decision making process.

5.2 Bi-objective optimization model

The multi-period MILP model developed in Chapter 3 is used as the base model and an environmental objective function is added to it. The resulting model is a bi-objective MILP. Equations 1 to 16 in Chapter 3 delineate the feasible solution space for both objectives: the economic objective function introduced in Equations 17 to 19 in Chapter 3, and the environmental objective function described in this chapter. Table 5-1 presents the parameters used to formulate the environmental objective function.

Table 5-1 List of environmental parameters of the model

Parameters	Definition
$e_{i,f}^{Bm}$	GHG emissions of producing, pre-processing and/or collecting one unit of biomass type *f* in supply source *i* (kg CO_2-eq/odt of biomass)
e_{l}^{Conv}	GHG emissions (non-heat or electricity related) of converting one unit of biomass in technology *l* (kg CO_2-eq/odt of biomass)
$e_{f,i,j}^{Tra,Bm}$	GHG emissions of transporting one unit of biomass type *f* from supply source *i* to location *j* (kg CO_2-eq/odt of biomass)
$e_{n,j,m}^{Tra,Bf}$	GHG emissions of transporting one unit of biofuel type *n* from location *j* to market *m* (kg CO_2-eq/unit of biofuel)
$e_{n}^{Use,Bf}$	GHG emissions associated with the end use of one unit of biofuel type *n* (kg CO_2-eq/unit of biofuel)
$e_{f,i}^{Disp}$	GHG emissions of disposing one unit of biomass type *f* with current practices in supply source *i* (kg CO_2-eq/odt of biomass)
$e_{o,j}^{Energy}$	Life cycle GHG emissions of supplying the energy equivalent to one unit of bioenergy type *o* from currently used sources at location *j* (kg CO_2-eq/MWh)
$e_{n,m}^{Fuel}$	Life cycle GHG emissions of supplying the fuel equivalent to one unit of biofuel type *n* from currently used sources at market *m* (kg CO_2-eq/unit of biofuel)

5.2.1 Environmental objective function

The environmental objective function is to maximize the total GHG emission savings associated with the introduction of a forest-based biomass supply chain for the production of bioenergy and biofuels. In a thorough GHG emission savings estimation, it is necessary to compare the current emissions of the base case scenario against the emissions of a forest-based biomass supply chain scenario using a life cycle approach (from the production of raw materials (biomass) to the end use of the products). In Chapter 4, Figure 4-1 presented the life cycle unit processes associated with the base case scenario, and Figure 4-2 presented the life cycle unit processes associated with the implementation of a forest-based biomass supply chain for the production of bioenergy and biofuels scenario. In Table 5-2, the difference between the emissions of unit processes in both scenarios is shown, and the mathematical notation of differences is presented.

Table 5-2 Comparison of GHG emissions in base case and forest-based biomass supply chain scenarios

Unit process	Description of emissions in base case scenario	Description of emissions in forest-based biomass supply chain scenario	Mathematical notation of emission savings (Base case emissions – forest-based biomass supply chain emissions)
Harvesting	All forest harvesting emissions	All forest harvesting emissions	-
Log Transportation	All emissions associated with transporting logs from forest to local mills	All emissions associated with transporting logs from forest to local mills	-
Forest Product Mill operation	All emissions associated with the operation of local mills	All emissions associated with the operation of local mills	-
Biomass pre-treatment and/or collection	None	All emissions associated with pre-treatment (e.g. chipping) and collection of forest and wood residues procured to conversion plants	$-\sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{i,f}^{Bm}\times B_{f,i,j,t}\right)$
Biomass transportation	None	All emissions associated with transporting forest and wood residues to conversion plants	$-\sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{f,i,j}^{Tra,Bm}\times B_{f,i,j,t}\right)$
Biomass conversion	None	All heat/electricity and non-heat/electricity related emissions associated with converting biomass into bioenergy and/or biofuels (heat/electricity-related emissions only consider the portion of energy that is satisfied with currently used energy sources)	$-\sum_{f\in F}\sum_{j\in J}\sum_{l\in L}\sum_{t\in T}\left(e_{l}^{Conv}\times U_{f,j,l,t}\right)-\sum_{o\in O}\sum_{j\in J}\sum_{t\in T}\left(e_{o,j}^{Energy}\times E_{o,j,t}^{Conv}\right)$
Biofuel transportation	None	All emissions associated with transporting all biofuels from conversion plants to final markets	$-\sum_{n\in N}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\left(e_{n,j,m}^{Tra,Bf}\times S_{n,j,m,t}^{Bf}\right)$
Biofuel end use	None	All emissions associated with the final use of biofuels at markets	$-\sum_{n\in N}\sum_{j\in J}\sum_{m\in M}\sum_{t\in T}\left(e_{n}^{Use,Bf}\times S_{n,j,m,t}^{Bf}\right)$
Disposal of forest and wood residues	All emissions from current disposal of unused forest and wood residues	All emissions from current disposal of unused forest and wood residues minus the portion of emissions related to the residues procured to conversion plants	$\sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{f,i}^{Disp}\times B_{f,i,j,t}\right)$
Energy generation with currently used sources at location *j*	All emissions from current generation of electricity and heat at candidate locations	All emissions from current generation of electricity and heat at candidate locations minus emissions related to the portion of electricity and heat that is satisfied by bioenergy	$\sum_{o\in O}\sum_{j\in J}\sum_{t\in T}\left(e_{o,j}^{Energy}\times S_{o,j,t}^{Be,Ext}\right)$

Unit process	Description of emissions in base case scenario	Description of emissions in forest-based biomass supply chain scenario	Mathematical notation of emission savings (Base case emissions – forest-based biomass supply chain emissions)
		generated in conversion plants at candidate locations.	
Production and end use of currently used fuels at market *m*	All emissions from production and end use of currently used fuels at all markets	All emissions from production and end use of currently used fuels at all markets minus emissions related to the portion of fuel satisfied by produced biofuels	$\sum_{n\in N}\sum_{m\in M}\sum_{j\in J}\sum_{t\in T}\left(e_{n,m}^{Fuel}\times S_{n,j,m,t}^{Bf}\right)$

Based on the comparison in Table 5-2, the environmental objective function can be expressed as the sum of the emissions avoided by replacing current energy and fuels and the emissions avoided by diverting forest and wood residues from their current disposal minus the emissions generated by forest-based biomass supply chain-related activities. These activities include production/pre-treatment/collection and transportation of biomass, transportation and end use of biofuels, and conversion of biomass into bioenergy and/or biofuels (Equations 20-22). Thus, the environmental objective function of the model is to **maximize the GHG emission savings** calculated in Equation 20:

$$\begin{aligned} &GHG\ emission\ savings \\ &\qquad = Avoided\ GHG\ emissions \\ &\qquad - \ Forest\ biomass\ supply\ chain\ GHG\ emissions \end{aligned} \tag{20}$$

Where,

$$\begin{gathered} Avoided\ GHG\ emissions = \\ \sum_{o\in O}\sum_{j\in J}\sum_{t\in T}\left(e_{o,j}^{Energy}\times S_{o,j,t}^{Be,Ext}\right)\ + + \sum_{n\in N}\sum_{m\in M}\sum_{j\in J}\sum_{t\in T}\left(e_{n,m}^{Fuel}\times S_{n,j,m,t}^{Bf}\right) + \\ \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{i,f}^{Disp}\times B_{f.i.j.t}\right) \end{gathered} \tag{21}$$

and,

$$\begin{gathered} Forest\ biomass\ supply\ chain\ GHG\ emissions = \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{i,f}^{Bm}\times\right. \\ \left.B_{f.i.j.t}\right) + \sum_{f\in F}\sum_{i\in I}\sum_{j\in J}\sum_{t\in T}\left(e_{f,i,j}^{Tra,Bm}\times B_{f,i,j,t}\right) + \end{gathered} \tag{22}$$

$$\sum_{n \in N} \sum_{j \in J} \sum_{m \in M} \sum_{t \in T} \left(e_{n,j,m}^{Tra,Bf} \times S_{n,j,m,t}^{Bf}\right) + \sum_{f \in F} \sum_{j \in J} \sum_{l \in L} \sum_{t \in T} \left(e_{l}^{Conv} \times U_{f,j,l,t}\right) + \sum_{o \in O} \sum_{j \in J} \sum_{t \in T} \left(e_{o,j}^{Energy} \times E_{o,j,t}^{Conv}\right)$$

Note that in Equation 22, the model separates the emissions associated with biomass conversion into energy $\left(e_{o,j}^{Energy}\right)$ (e.g. heat and/or electricity) and non-energy-related emissions (e_{l}^{Conv}). Non-energy-related emissions are proportional to the amount of biomass converted through each process, while energy–related emissions depend on the amount of energy from currently used sources, which depend on the amount of bioenergy produced onsite (decision variables in the model). The separation of energy was not done by previous studies, mostly because the majority of previous bi-objective (or multi-objective) optimization studies addressing economic and environmental objectives considered either bioenergy or biofuel supply chains separately (e.g. Bernardi et al., 2012; Giarola et al., 2013). In the only multi-objective supply chain optimization study that considered both bioenergy and biofuel products (Čuček et al., 2012), the scope of the analysis did not include the potential energy flows between co-located plants. In this thesis, these energy flows are accounted for a more accurate estimation of GHG emission savings of the forest-based biomass supply chain.

5.3 Case study environmental data

The GHG values of the unit processes presented in Table 4-1 and Table 4-2 are the basis to estimate all the environmental coefficients of the model (refer to environmental coefficients in Table 5-1) using a spreadsheet software according to the assumptions described below. Environmental coefficient values in this chapter are estimated under the assumption of carbon neutrality for biomass combustion because they are equivalent to the emissions captured during tree growth. To ensure consistency in the analysis, under this assumption, biomass landfilling has net negative GHG emissions since a large portion of the carbon contained in the biomass is captured in the soil.

5.3.1 Emissions of biomass pre-treatment and/or collection

The GHG emissions of producing biomass depend on the type of biomass and its source. GHG emissions of chipped harvesting residues and non-merchantable MPB-killed timber from supply sources ($e_{i,f}^{Bm}$) are shown in Table 4-2 (related to the amount of diesel and lubricants used to operate the collection and chipping machinery).

5.3.2 Emissions of biomass and biofuel transportation

The GHG emissions of transporting each type of biomass f from supply source i to the plant location j ($e_{f,i,j}^{Tra,Bm}$) are based on the transportation distance from location i to location j as well as on the bulk density and moisture content of the transported biomass due to volume restrictions of the trucks.

For the transportation of biofuels, the GHG emission coefficient ($e_{n,j,m}^{Tra,Bf}$) considers the distance between the conversion plants and the final markets. It is assumed that the final use of both biofuel types is in Europe (Rotterdam). Thus, the transportation of both products requires three different transportation modes: truck transportation from Anahim Lake or Hanceville to Williams Lake (320 km or 97 km, respectively), rail transportation from Williams Lake to the port of North Vancouver (505 km), and ocean transportation from North Vancouver to the port of Rotterdam (16,500 km). It is assumed that pyrolysis transportation is done by tanks and tank containers, and that chemical ports exist both in North Vancouver and Rotterdam ports (based on pyrolysis transportation requirements in (Karhunen et al., 2014)).

5.3.3 Emissions of biomass conversion

The GHG emissions of biomass conversion (e_l^{Conv}) depend on the type of conversion process: combustion, gasification, pelletizing or fast pyrolysis. For all combustion technologies, GHG emissions were taken from the EPA A42 report (EPA, 2015). The same values are used as the basis for gasification technologies for which the values of NO_X and NMVOC are modified based on (Pa et al., 2011). In addition to these emissions, gasification technologies require biomass to be dried in order to achieve a moisture content below 15%. The amount of heat (coefficient

$\phi_{o,f,l}^{Conv}$ where o= heat, and $l \in$ set of gasification technologies) required for drying depends on the initial moisture content of the biomass as shown in Table 3-4, and the input biomass quality requirements of conversion technologies in Table 3-5 (refer to Section 3.4).

The non-electricity and non-heat related GHG emissions associated with the pyrolysis process (coefficient e_l^{Conv} for $l \in$ set of pyrolysis technologies) are due to the use of heating fuel for the start-up and operation of the fast pyrolysis reactor. Heat and electricity demand ($\phi_{o,f,l}^{Conv}$) of the process are based on a requirement of about 200 kWh of electricity per odt of biomass converted in the pyrolysis reactor (Rogers and Brammer, 2012), and 18.5 kWh of electricity for each odt of biomass conditioned to achieve a particle size less than 2mm and a moisture content less than 10% (estimation based on the electricity consumption of drying and hammer milling equipment reported in (Campbell, 2007)). Note that in this study, it is assumed that the heat required to dry the biomass and to maintain the process is generated through the combustion of the pyrolysis by-products char and gas as in (Fan et al., 2011; Rogers and Brammer, 2012).

Similarly, the non-electricity and non-heat related GHG emissions of pellet production (coefficient e_l^{Conv} for $l \in$ set of pelletizing technologies) are associated with the use of diesel during biomass pre-treatment and pellet production. The annual electricity demand is based on the requirement of 119.53 kWh of electricity to convert each odt of woody biomass into pellets (Scenario 2 in (Mani, 2005)), which considers biomass pre-treatment and pellet production). The heat demand for biomass drying to an acceptable moisture content of 10% is calculated based on the initial moisture content of biomass shown in Table 3-4 (Section 3.4).

5.3.4 Emissions of current biomass disposal methods

The GHG emissions of disposing each type of biomass f vary depending on the biomass source (a forest cut block or sawmill). In forest cut blocks, the current practice in the region is the open burning of forest residues. Since the sawmill in Anahim Lake is located in a non-populated area, chips and hog fuel are burnt in an authorized wood residue burner (Ministry of Environment, 2015). In Hanceville and Williams Lake, sawmill residues must be transported to a landfill to avoid local air pollution. Note that due to the long-term carbon storage effect of landfills (a large portion of the carbon contained in wood is not released back to the atmosphere), the GHG emissions of landfilling in this study (coefficient $e_{f,i}^{Disp}$ where *f* refers to sawmill chips and hog fuel, and *i* refers to the sawmills in Hanceville and Williams Lake) are negative to reflect the net negative carbon balance from landfilling (even after considering the non-biogenic emissions resulted from transporting biomass to the landfill). Landfilling GHG emissions values in Table 4-1 (section 4.4) assume that 98.2% of the carbon in landfilled biomass remains stored within the landfill and only 1.8% is released to the atmosphere: for each t of carbon in landfilled biomass (1.639 t of CO_2 equivalent emissions), only 37.6 kg of CO_2 equivalent emissions are released as CH_4 and 14.8 kg of CO_2 equivalent emissions are released as CO_2, leading to a net GHG capture of 1.587 t of CO_2 equivalent emissions. Thus, considering the non-biogenic GHG emissions related to the transportation of biomass to the landfills, the net emissions of landfilling used in this chapter are: -1,550.2 and -1,566.4 kg CO_2-eq per odt of sawmill chips produced at Hanceville and Williams Lake and disposed at landfill, respectively; and -1,546.3 and -1,566.1 kg CO_2-eq per odt of sawmill hog fuel produced at Hanceville and Williams Lake and disposed at landfill, respectively.

5.3.5 Emissions of currently used energy and fuels

The life cycle GHG emissions of supplying energy from currently used sources at each location ($e_{o,j}^{Energy}$) are based on the current energy use profiles of each community (described in Section 1.3 in Chapter 1). For the GHG emissions of supplying fuels from current sources at each biofuel market ($e_{n,m}^{Fuel}$), it is assumed that bio-oil would substitute heating oil in industrial heating applications, and pellets would substitute coal in electricity production. The combustion of 1 l of bio-oil (with an energy content of 17 GJ/t and density of 1.22 kg/l) in a boiler with an efficiency of 80% produces 0.017 GJ of heat, and the combustion of 1 t of pellets (with an energy content of 18.3 GJ/t) in a coal plant with an efficiency of 35% can substitute 1.79 MWh of electricity generated in the same plant.

5.4 Solution method for bi-objective optimization model

The bi-objective optimization model is given by Equations 1-22. Since the goal of this chapter is to generate a set of Pareto-optimal solutions showing the trade-offs between the environmental and economic objectives, the AUGMECON method (Mavrotas, 2009) was implemented as follows:

1. The boundaries for the ε values of each of the two objective functions were estimated through lexicographic optimization:
    a. Lexicographic optimal solution for the economic objective function:
        i. Equation 17 was maximized. The resulting optimal NPV value was recorded.
        ii. Equation 20 was maximized by constraining the NPV to the value recorded in the previous step.
    b. Lexicographic optimal solution for the environmental objective function:
        i. Equation 20 was maximized. The resulting optimal GHG emission savings value was recorded.
        ii. Equation 17 was maximized by constraining the GHG emission savings to the value recorded in the previous step.
    c. The boundaries of each objective function were obtained from their minimum (lower bound) and maximum values (higher bound) in the lexicographic optimal solutions, and the range was estimated as follows:

        Range = higher bound – lower bound
2. Using the AUGMECON method (Mavrotas, 2009), the model was run 50 times to generate a set of efficient Pareto-optimal solutions. First, the economic objective function (NPV) was maximized 25 times (g=25) by constraining the environmental objective function (GHG emission savings) as depicted in Figure 5-1 (adapted from Mavrotas, 2009). The environmental objective function (GHG emission savings) was then maximized 25 times (g=25) by constraining the economic objective function (NPV). To do so, the objective functions depicted in Figure 5-1 (highlighted) were inverted accordingly.

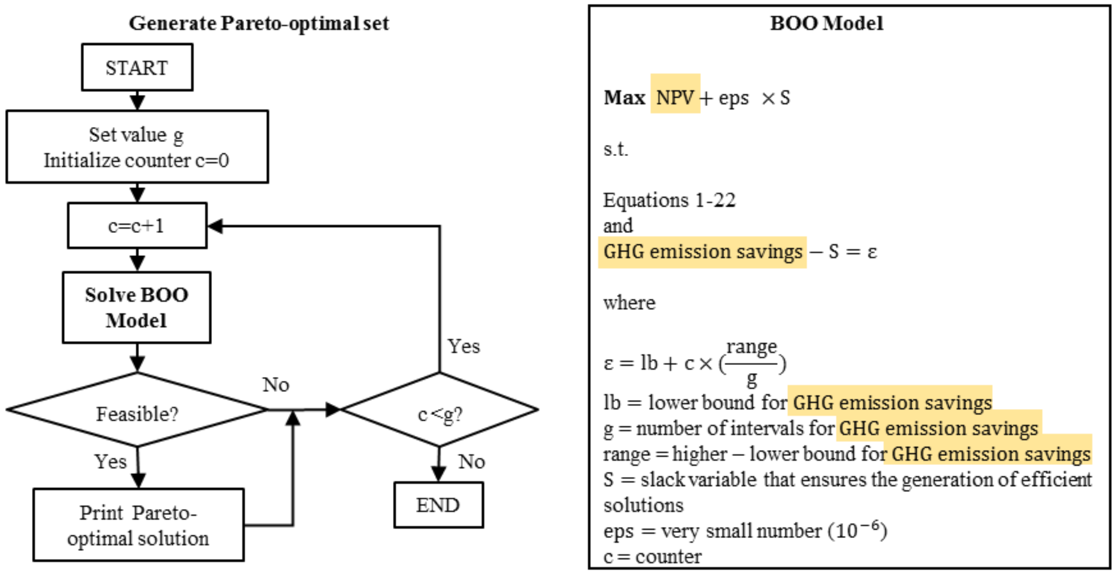

Figure 5-1 AUGMECON method implemented for two objective functions: NPV and GHG emission savings

5.5 Results and discussion

In each individual run, the resulted mixed integer linear programming (MILP) model had 141,229 constraints, 396,129 continuous variables and 1,380 binary variables. A set of Pareto-optimal points was generated in a total solving time of about 286 minutes using the AIMMS 3.11^{TM} software (Paragon decision technology, 2014) and an MIP solver CPLEX 12.1 on a computer with an Intel 2.67-GHz processor.

Pareto-optimal solutions generated through the AUGMECON method show the trade-off between the economic and environmental objectives of the forest-based biomass supply chain model (Figure 5-2). The shape of the curve in Figure 5-2 shows the expected compromises between the economic and the environmentally optimal designs of the supply chain. Over a 20-year planning horizon, the supply chain with the optimal economic performance (Solution A in Figure 5-2) generates an NPV of 553 M$ with overall savings of 2.67 Mt of CO_2 equivalent GHG emissions. Conversely, the supply chain with the optimal environmental performance (Solution C in Figure 5-2) generates more than twice the GHG emission savings (6.76 Mt of CO_2 equivalent emissions), but generates only about three quarters of the economic optimization optimal solution NPV (404 M$). The shape of the Pareto curve shows a negative slope, and a change in slope around the point identified as Solution B. When moving from A to B, there is a gradual NPV decrease, while the GHG emission savings increase. However, from B to C, there is a steep decrease in NPV for a relatively small increase in GHG emission savings. This steep decrease in economic performance is due to changes (e.g. selection of different technologies and sizes) in the design of the supply chain network that generates only slighter additional GHG emission savings.

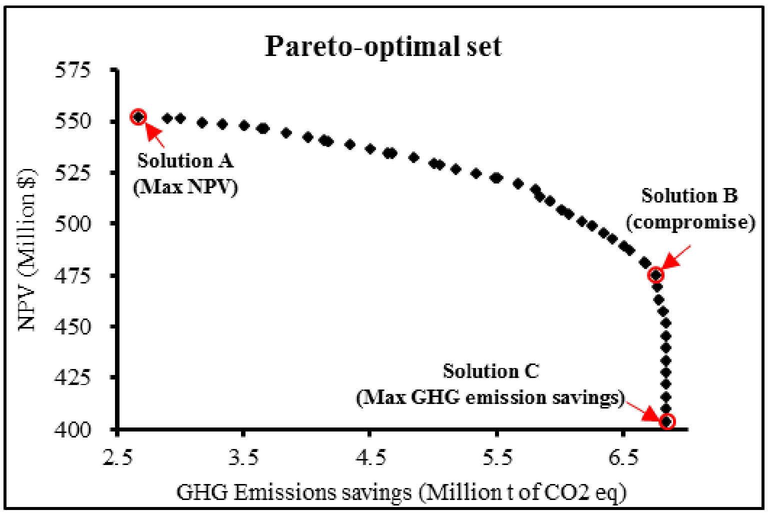

Figure 5-2 Pareto-optimal set

For each of the three representative Pareto-optimal solutions (Solutions A, B and C in Figure 5-2), Table 5-3 shows the selected technologies and installation periods, the average annual amount of products, and the average annual composition of the biomass mix.

Details of the economically optimal solution (Solution A) were explored in Chapter 3. The compromise solution (Solution B) generates 153% more GHG emission savings than the economically optimal one with a 16% drop in the NPV. This solution prescribed a larger production capacity of pellets that could be used to replace fossil fuels in export markets (e.g. Europe) generating significant GHG emission savings even after transportation-related emissions are weighed in the GHG emissions balance. This result is consistent with LCA literature where pellets exported from Canada perform better in terms of GHG emissions than fossil energy fuels in Europe (e.g. Sikkema et al. 2010). The technology selection for bioenergy production in Solution B shows the relevance of modeling the energy flows. Since the production of pellets and bio-oil requires large amounts of heat and electricity, the installation of heat and electricity co-generation systems is preferred over the electricity-only options in Hanceville and the heat-only option in Williams Lake to cover the energy needs of the selected pellet and bio-oil plants with a cleaner energy source. In addition, with an increased demand for biomass and a smaller utilization of sawmill residues in Hanceville and Williams Lake (since the model suggests that it is environmentally better to landfill sawmill residues in these communities instead of procuring them for conversion into bioenergy and biofuels), the proportion of harvesting residues in the biomass mixes increased as well.

The maximization of the environmental benefit (Solution C) involves the installation of a 5 MW ORC plant in Anahim Lake, and a location change for pyrolysis production (production in Williams Lake starts at period 1). Compared to Solution B, Solution C represents a minor increase in GHG emission savings (1%) resulting from a higher efficiency of the selected technologies (e.g. a 5 MW biomass boiler + steam turbine in Hanceville) and reduced transportation distance of pyrolysis bio-oil (its production in Williams Lake since period 1 eliminates the truck transportation between Hanceville and Williams Lake from periods 1 to 15), but a significant NPV decrease (17%) mainly due to the increased capital cost of the selected technologies.

Table 5-3 Supply chain network design of representative Pareto-optimal solutions

Technologies	Solution A (Max NPV)	Solution B (Compromise)	Solution C (Max GHG emission savings)
Anahim Lake			
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1	period 1	
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1
Pellet plant, 45,000 t/year		period 1	period 1
Hanceville			
Biomass boiler + steam turbine (electricity only), 0.5 MW	period 1		
Biomass boiler + steam turbine (heat and electricity), 2 MW		period 1	
Biomass boiler + steam turbine (heat and electricity), 5 MW			period 1

Technologies	Solution A (Max NPV)	Solution B (Compromise)	Solution C (Max GHG emission savings)
Pellet plant, 45,000 t/year		period 1	period 1
Pyrolysis plant, 400 odt/day	period 1	period 1	period 1
Williams Lake			
Biomass boiler (heat only), 2 MW	period 1		
Biomass oil heater + ORC (heat and electricity), 2 MW		period 1	period 1
Pellet plant, 15,000 t/year	period 1		
Pellet plant, 45,000 t/year		period 1	period 1
Pyrolysis plant, 400 odt/day		period 16	period 1
Average annual amount of products	32,032 MWh thermal, 40,422 MWh electrical, 15,000 t of pellets, 81,377 m^3 of bio-oil	32,032 MWh thermal, 42,436 MWh electrical, 135,000 t of pellets, 81,377 m^3 of bio-oil	32,032 MWh thermal, 69,863 MWh electrical, 135,000 t of pellets, 81,377 m^3 of bio-oil
Average annual biomass mix[a]	Sawmill chips (12%), Sawmill hog fuel[b] (7%), Harvesting residues[c] (37%), MPB chips[d] (44%)	Sawmill chips (5%), Sawmill hog fuel[b] (3%), Harvesting residues[c] (40%), MPB chips[d] (53%)	Sawmill chips (4%), Sawmill hog fuel[b] (4%), Harvesting residues[c] (51%), MPB chips[d] (43%)
NPV	553 M$	475 M$	404 M$
GHG emission savings	2.67 M t CO_2-eq	6.76 M t CO_2-eq	6.84 M t CO_2-eq

[a] Percentage based on dry weight.
[b] Includes sawdust.
[c] Chipped harvesting residues (tops and branches).
[d] Chipped MPB-killed timber.

The average annual profit and GHG emission savings are provided in Figure 5-3a and Figure 5-3b. The components of the average annual revenue, costs, avoided GHG emissions, and generated supply chain GHG emissions are provided in Figure 5-3c to Figure 5-3f.

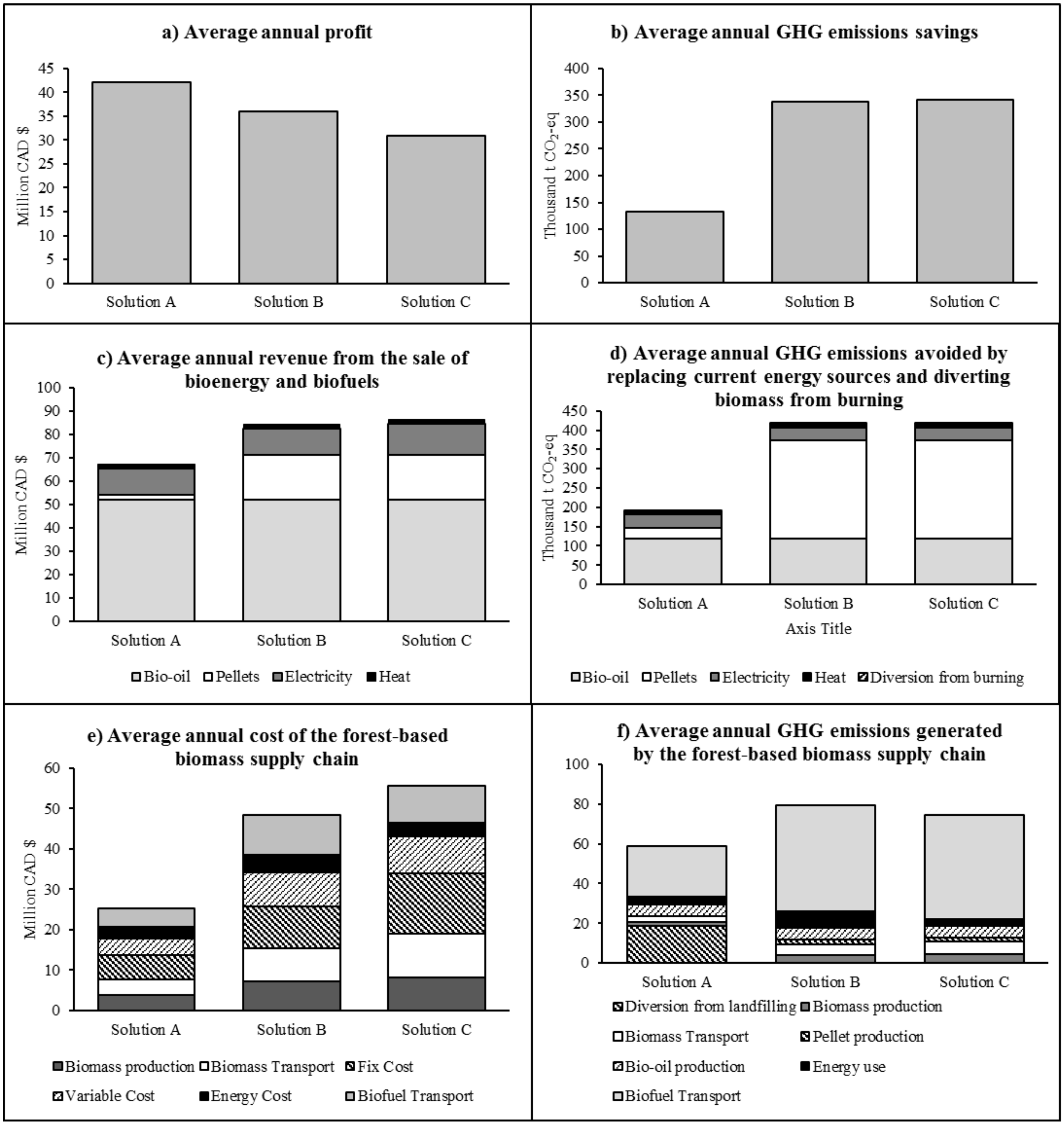

Figure 5-3 Revenue, cost and GHG emissions breakdown of representative solutions

As shown in Figure 5-3c, bio-oil sales constitute the largest revenue share for the three solutions (77% in Solution A, 60% in Solution B, and 60% in Solution C). In contrast, pellets account for the largest share of GHG emission savings in Solutions B and C (Figure 5-3d). This is due to the assumption that bio-oil is used to substitute heating oil in industrial heat applications, while pellets are assumed to substitute coal in power plants. Different end-use utilization assumptions would yield different GHG emission saving profiles. While the market for Canadian wood pellets is well-established in Europe and pellets are widely used there for co-firing with coal (IEA Bioenergy Task 40, 2007), the market for bio-oil is rather incipient. Bio-oil can substitute fossil fuels in many applications including heat and electricity production. It can also be used as feedstock for the production of transportation fuels, synthetic gas and other chemicals such as food flavorings, specialties, resins, and fertilizers (Bridgwater, 2003), but its utilization for heat generation is its most attainable application for the case study (Czernik and Bridgwater, 2004). This is because the use of bio-oil for electricity production requires substantial engine modifications, while other applications, such as bio-oil upgrading to transportation fuels are feasible but still not economical (Czernik and Bridgwater, 2004; Mohan et al., 2006; Vamvuka, 2011).

Figure 5-3e shows that the major cost component for all three solutions is the large capital investment required to install the selected conversion technologies (24%, 21% and 27% in Solutions A, B, and C, respectively). In Solutions A and B, the next major cost component is the biofuel transportation cost required to bring pellets and bio-oil to Europe (18% and 20%, respectively), while for Solution C, it is the biomass transportation cost required to satisfy all the feedstock demand of conversion plants (20%) (Figure 5-3e). Between Solutions B and C, minor changes can be distinguished in the biomass production and variable costs. However, significant differences exist in terms of fixed costs due to the installation of more expensive technologies in Solution C, and increased biomass transportation costs due to the operation of the pyrolysis plant in Solution C from period 1 in Williams Lake (note that feedstock availability around Williams Lake from period 1 to 15 is considerably lower than after period 16). Also, significant differences exist between Solutions B and C due to the smaller amount of energy supplied from currently used sources in solution C (a larger portion of energy demand of the pellet and pyrolysis plants in Anahim Lake and Hanceville is satisfied by the installed technologies in Solution C). Although Solutions B and C have a larger energy requirement than Solution A to fulfill the demands of the installed pellets and pyrolysis plants, the energy costs remain at a comparable level due to the utilization of bioenergy generated onsite. Figure 5-3f shows that the main contributor to GHG emissions is biofuel transportation in all cases (43%, 67% and 70% in

Solutions A, B and C, respectively). Between Solutions B and C, only minor differences can be noticed concerning the average annual GHG emissions generated due to energy use (42% lower in Solution C). Note that biomass disposal activities can contribute to the amount of avoided GHG emissions (e.g. when forest residues are used in conversion plants instead of being burned in the forest, there is no need to transport a crew to the forest to burn them, thus avoiding GHG emissions) or to the total GHG emissions (e.g. when sawmill residues are procured to the conversion plants instead of being landfilled, net GHG emissions are generated). Figure 5-3d shows that there are no significant avoided GHG emissions when diverting forest residues from burning in the forest. In contrast, Figure 5-3f shows that a large portion of the GHG emissions in Solution A (32%) is due to the diversion of sawmill chips and hog fuel in Hanceville from their current disposal in landfills to their use as energy feedstock.

5.6 Summary and conclusions

This chapter presented the formulation of the environmental objective function for the forest-based biomass supply chain design problem described in Chapter 3. The novelty of the resulting bi-objective optimization model lies on 1) the explicit modeling of energy flows among bioenergy and biofuel plants that is required in order to accurately estimate the material flows and the emissions across the supply chain, and 2) the formulation of an environmental objective function that compares the forest-based biomass supply chain emissions against the base case system. The model was applied to the case study described in Section 1.3, and was solved using the AUGMECON method that was coded in the AIMMS software package. The model generated a set of Pareto-optimal solutions, each one of them recommending a forest-based biomass supply chain design consisting of biomass types and sources, conversion technology types and sizes, products and markets. The generation of a Pareto set allows decision makers to select the most acceptable solution based on their preferences, while understanding the compromises associated with their choice.

Results indicated that the conversion of biomass into heat and electricity, and into pellets and bio-oil for exportation to Europe (to substitute coal in electricity generation and residual oil in industrial heating), could generate a positive NPV and significant GHG emission savings compared to the base case system. This was based on the assumption that in the base case system, biomass is disposed as waste, and fossil fuel and hydro electricity are used to satisfy energy requirements. The analysis of the Pareto-optimal solutions showed a clear trade-off between the environmental and economic optimal designs of the supply chain. The environmentally optimal solution recommended the large scale production of pellets, while the economically optimal solution did not recommend the production of pellets at a large scale since the generated revenue would not offset the high capital investments and the cost of transporting the products to Europe. All Pareto-optimal solutions recommended the conversion of biomass into electricity to replace diesel oil in the off-grid communities of the case study.

In the next chapter, the model will be extended to consider a social objective as well.

Chapter 6: Multi-objective optimization model

6.1 Synopsis

In this chapter, the bi-objective optimization model developed in Chapter 5 is converted into a multi-objective optimization model. This is achieved with the introduction of a third objective that maximizes a social benefit indicator associated with the implementation of a forest-based biomass supply chain in a region. The social benefit indicator developed in this chapter is a weighted sum that quantifies the new jobs created along the supply chain based on their type and location. The multi-objective optimization model is applied to the case study addressed in Chapters 1, 3, 4 and 5. For the case study, the social benefit weights are based on the Forest Vulnerability Index of the three candidate locations, and the average unemployment rate of three aggregated job classes in British Columbia. The multi-objective optimization model is solved using the AUGMECON method to generate a set of three-dimensional Pareto-optimal solutions. The job breakdown by job class and location is presented for each one of the single-objective optimal solutions and the Pareto-optimal set is analyzed to identify the trade-offs and compromises among the three objective functions.

6.2 Multi-objective optimization model

The bi-objective optimization model presented in Chapter 5 is used as the basis for the multi-objective optimization model that includes an economic, an environmental and a social benefit objective function. The extended model is a multi-objective MILP. Some modifications are made to the set of model constraints to ensure that the multi-objective optimization model is bounded for the three objectives. Additional technical parameters introduced to the model and the social benefit weights used in the social benefit objective function are presented in Table 6-1.

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Table 6-1 List of additional and social benefit parameters of the model

Parameters	Definition
Additional set	
V	Set of job classes; index $v \in V$
Additional parameters	
$\varphi_{f,l}$	Binary parameter: 1, if biomass type *f* can be converted in technology *l;* 0, otherwise.
μ	Sufficiently large number (e.g. 1×10^9)
θ_n^{Bf}	Minimum capacity utilization rate for technologies producing biofuel type *n*
θ_o^{Be}	Minimum capacity utilization rate for technologies generating bioenergy type o
Social parameters	
$w_{v,f,i}^{Bm}$	Number of hours of work within job class *v* to produce, pre-process and/or collect one unit of biomass type *f* in supply source *i* (hours/odt of biomass)
$w_{v,f,i,j}^{Tra,Bm}$	Number of hours of work within job class *v* to transport one unit of biomass type *f* from external supply source *i* to plant location *j* (hours/odt of biomass)
$w_{v,n,j,m}^{Tra,Bf}$	Number of hours of work within job class *v* to transport one unit of biofuel type *n* from plant location *j* to market *m* (hours/unit of biofuel)
$w_{v,l}^{Conv,Salary}$	Number of hours of work (salaried work) within job class *v* to operate technology *l* (hours/year)
$w_{v,l}^{Conv,Hourly}$	Number of hours of work (hourly wage work) within job class *v* to operate technology *l* (hours/odt of biomass)
$w_{v,l}^{Constr}$	Number of hours of work within job class *v* to install technology *l* (hours)
$\chi_{v,j}$	Social benefit weights associated with creation of a job within class *v* in plant location *j*.

6.2.1 Modified model constraints

Changes to the set of model constraints that were presented in Section 3.3.1 are as follows:

Inequalities in Equations 7 and 8 are modified into equalities in Equations 7b and 8b to link the production of biofuel and bioenergy to their demand.

$$\sum_{m\in M} S_{n,j,m,t}^{Bf} = \sum_{l\in L} P_{n,j,l,t}^{Bf} \quad \forall\, j \in J, n \in N, t \in T \tag{7b}$$

$$S_{o,j,t}^{Be,Ext} + S_{o,j,t}^{Be,Conv} = \sum_{l\in L} P_{o,j,l,t}^{Be} \quad \forall\, o \in O, j \in J, t \in T \tag{8b}$$

This modification avoids the production of bioenergy and biofuels when there is no demand for them (without this modification to Equations 7 and 8, the maximization of a social objective function that involves job creation would maximize the amount of products produced regardless of how much of that product can actually be sold). However, for technologies with by-products, the equality in Equations 7b and 8b is necessary only for the primary product (e.g. electricity in combined heat and power systems). For by-products (e.g. heat in combined heat and power systems), the constraint in Equations 7b and 8b can be relaxed to inequalities (as in Equations 7 and 8) in order to avoid forcing the model to sell all the generated amounts of by-products.

Equation 23 is added to the model to ensure that biomass requirements of each technology are met.

$$U_{f,j,l,t} \leq \mu \times \varphi_{f,l} \qquad \forall\, f \in F, j \in J, t \in T \qquad \textbf{(23)}$$

Equations 24 and 25 are added to avoid the installation of idle plants. They ensure that the production of biofuel is greater than the minimum capacity utilization rate in all periods.

$$P_{n,j,l,t}^{Bf} \geq \gamma_{l,n}^{Bf} \times Q_{j,l,t} \times \theta_{n}^{Bf} \qquad \forall\; n \in N, j \in J, l \in L, t \in T \qquad \textbf{(24)}$$

$$P_{n,j,l,t}^{Bf} \geq \gamma_{l,o}^{Be} \times Q_{j,l,t} \times \theta_{o}^{Be} \qquad \forall\; o \in O, j \in J, l \in L, t \in T \qquad \textbf{(25)}$$

Thus, the feasible solution space for the multi-objective optimization model is delineated by Equations 1-6, 7b, 8b, 9-16, and 23-25.

6.2.2 Social benefit objective function

The social objective function of the model is to **maximize the social benefit** associated with the implementation of a forest-based biomass supply chain for the production of bioenergy and biofuels. This social benefit objective function is calculated in Equation 26:

$$Social\ benefit = \sum_{v \in V} \sum_{j \in J} \left(\left(Hours_{v,j}^{Bm} + Hours_{v,j}^{Conv,Salary} + Hours_{v,j}^{Conv,Hourly} + Hours_{v,j}^{Constr} \right) \times \chi_{v,j} \right) \qquad \textbf{(26)}$$

Where,

$$Hours_{v,j}^{Bm} = \sum_{f \in F} \sum_{i \in I} \sum_{t \in T} \left(w_{v,f,i}^{Bm} \times B_{f,i,j,t} \right) \qquad \forall\, v \in V,\; j \in J \qquad \textbf{(27)}$$

$$Hours_{v,j}^{Conv,Hourly} = \sum_{f \in F} \sum_{l \in L} \sum_{t \in T} \left(w_{v,l}^{Conv,Hourly} \times U_{f,j,l,t} \right) \qquad \forall v \in V, j \in J \qquad \textbf{(28)}$$

$$Hours_{v,j}^{Conv,Salary} = \sum_{l \in L} \sum_{t \in T} \left(w_{v,l}^{Conv,Salary} \times Q_{j,l,t} \right) \qquad \forall\; v \in V, j \in J \qquad \textbf{(29)}$$

$$Hours_{v,j}^{Constr} = \sum_{l \in L} \left(w_{v,l}^{Constr} \times \sum_{t \in T} \left(Q_{j,l,t} - Q_{j,l,t-1} \right) \right) \qquad \forall v \in V, j \in J \qquad \textbf{(30)}$$

Equation 26 estimates the social benefit objective function as a weighted sum of the newly created jobs (in terms of total hours of work) throughout the lifetime of the project and accounts for activities related to forest-based biomass production, and the construction and operation of conversion plants. In Equation 26, the weights $(\chi_{v,j})$ account for the difference in the social impact of different types of jobs (*v*) created in different locations (*j*). Thus, the complete set of weights $(\chi_{v,j})$ is given by a matrix of the size number of elements in set *V*× number of elements in set *J*. The maximization of the social benefit objective function (Equation 26) favors the creation of jobs in certain location, and for specific sets of job skills (job types).

The total hours of work required for biomass production (e.g. collection and chipping) are estimated in Equation 27. Equations 28 and 29 estimate the total hours of work required for the operation of the installed technologies, and Equation 30 estimates the amount of hours of work required for the construction of the conversion plants (that includes the installation of the technologies).

Equations 27 and 28 relate the hours of work required per unit of biomass procured/converted with continuous variables $B_{f,i,j,t}$ and $U_{f,j,l,t}$. Equations 29 and 30 relate the hours of work required to construct/operate each plant with binary variable $Q_{j,l,t}$, which indicates if technology *l* is in operation ($Q_{j,l,t}$ =1) or not ($Q_{j,l,t}$ =0) at location *j* in period *t*. Based on Equation 30, the amount of hours of work related to the installation/construction of technology *l* in location *j* is larger than zero only for the period of time when the technology is installed $\left(Q_{j,l,t} - Q_{j,l,t-1}\right) = 1$.

In order to accurately estimate the total hours of work and the social benefit associated with the introduction of the forest-based biomass supply chain, it is important to account for transportation-related jobs as well. Equation 31 estimates the hours of work associated with the transportation of biomass from the production sources to the conversion plants and Equation 32 estimates the hours of work associated with the transportation of biofuels from conversion plants to markets. Note that transportation-related hours of work are estimated (Equations 31 and 32), but are not considered within the social objective function to be maximized, as their maximization would imply the selection of the farthest biomass sources or markets over more accessible biomass sources or markets which is neither realistic nor desirable.

$$Jobs_{v,j}^{Tra,Bm} = \sum_{f \in F} \sum_{i \in I} \sum_{t \in T} \left(w_{v,f,i,j}^{Tra,Bm} \times B_{f,i,j,t} \right) \qquad \forall\, v \in V, j \in J \tag{31}$$

$$Jobs_{v,j}^{Tra,Bf} = \sum_{n \in N} \sum_{m \in M} \sum_{t \in T} \left(w_{v,n,j,m}^{Tra,Bf} \times S_{n,j,m,t}^{Bf} \right) \quad \forall\, v \in V, j \in J \tag{32}$$

The total hours of work estimated in Equations 27 to 32 consider newly created jobs only. Therefore, hours of work associated with the harvesting of logs, or the operation of forest product mills that exist currently are not considered in the computation of jobs created (measured in hours of work). The total social benefit generated by the forest-based biomass supply chain (including transportation-related social benefits) is estimated by Equation 33. This total social benefit (Equation 33) is estimated for analysis purposes, but it is not used as an objective function to be optimized in the model.

$$\begin{gathered} Total\ social\ benefit = \\ \sum_{v \in V} \sum_{j \in J} \left(\left(Jobs_{v,j}^{Bm} + Jobs_{v,j}^{Conv,Salary} + Jobs_{v,j}^{Conv,Hourly} + Jobs_{v,j}^{Constr} + \right. \right. \\ \left. \left. Jobs_{v,j}^{Tra,Bm} + Jobs_{v,j}^{Tra,Bf} \right) \times \chi_{v,j} \right) \end{gathered} \tag{33}$$

6.3 Case study social data

6.3.1 Social benefit weights

In this case study, the values of the social benefit weights are estimated based on the average unemployment rate of each job class and the Forest Vulnerability Index of each location. Social benefit weights are estimated as follows:

$$\chi_{v,j} = Average\ unemployment\ rate_v \times Forest\ Vulnerability\ Index_j$$

6.3.1.1 Average unemployment rate per job class

During the economic downturn in 2009, the unemployment rate in the forest industry of British Columbia reached an average of 13% (LMI Insight and R.A. Malatest & Associates Ltd, 2013). Four years after the economic downturn (in 2013), the unemployment rate decreased to below 5% across the province, suggesting that a portion of the displaced workers were successful to transfer their skills to other industries, particularly those workers in the wood product manufacturing sector (LMI Insight and R.A. Malatest & Associates Ltd, 2013). In contrast, workers with a set of skills particular to the forest industry such as forestry and logging workers faced higher levels of unemployment (LMI Insight and R.A. Malatest & Associates Ltd, 2013). For example, in 2013, the unemployment rate for millwrights and primary production managers was 2.5%, while the unemployment rate for logging machinery operators was 26.4% (LMI Insight and R.A. Malatest & Associates Ltd., 2013).

Based on the data presented in the sections 4.3.3 and 4.3.4 of (LMI Insight and R.A. Malatest & Associates Ltd, 2013), in 2013, there was a negative correlation between the average earnings and the average level of unemployment of different types of jobs in the British Columbia forestry sector (correlation coefficient r = -0.61). In this case study, such an observation served as the basis to classify the job types according to their earnings in three classes: class 1, class 2 and class 3, and to estimate the average unemployment rate for each class. Table 6-2 shows the average unemployment rate of each job class considered in this study, and describes the occupations grouped within each job class.

Table 6-2 Average unemployment rate per job class

Class	Average unemployment rate	Description
Class 1	2.78%	Occupations with average earnings above $85,000/year (e.g. primary production and construction managers)
Class 2	3.63%	Occupations with average earnings between $65,000 and $85,000/year (e.g. forestry, logging & forest products supervisors, tugboat captains, and forest product marketers)

Class 3	12.50%	Occupations with average earnings under $65,000/year (e.g. silviculture & forestry workers, logging machinery operators, heavy equipment operators, and truck drivers)

6.3.1.2 Forest Vulnerability Index per location

The Forest Vulnerability Index is estimated by the government of British Columbia to evaluate how vulnerable a region is to changes in forest product markets (Horne, 2009). This index is estimated based on the Forest Dependency Index of the community (the proportion of employment income in a community that is derived from the forest sector (Korber et al., 1998)), and its Diversity Index (a measure of economic diversification for a community that ranges from 0 if the community is entirely dependent on one sector, to 100 if the community is equally dependent on each of the defined sectors) (Horne, 2009). To estimate the Forest Vulnerability Index, the community's Forest Dependency Index is multiplied by (100 – its Diversity Index). The larger this product is, the more vulnerable a community is assumed to be. The final step for the calculation of the Forest Vulnerability Index is the normalization of all the products of communities (or areas) in British Columbia so that 100 is given to the most vulnerable community and 0 to the least vulnerable one. Table 6-3 presents the Forest Vulnerability Index for the three locations included in this case study as estimated by the government of British Columbia (Ministry of Forests, Lands and Natural Resources Operations, 2012).

Table 6-3 Forest Vulnerability Index per location

(Ministry of Forests, Lands and Natural Resources Operations, 2012).

Location	Index	Description
Anahim Lake	39	Forest Vulnerability Index of the Chilcotin Forest District
Hanceville	39	Forest Vulnerability Index of the Chilcotin Forest District
Williams Lake	51	Forest Vulnerability Index of the Central Cariboo Forest District.

6.3.2 Hours of work for biomass pre-treatment and/or collection

For biomass chipping and collection, the production rate of the hydraulic loader is tied to the production capacity of the grinder, and one worker is required for the entire operation. Based on an average productivity of 23.6 odt/SMH for loading and comminution (Johnson et al., 2012), a total of 0.04 hours of work is required to comminute and load 1 odt of harvesting residues and non-merchantable logs. This activity falls into job class 3.

Since chips and hog fuel are generated as by-products during the conventional production of lumber, no extra hours of work are required to produce them, and no additional chipping activities are considered necessary for their conversion into bioenergy and/or biofuels.

6.3.3 Hours of work for biomass and biofuel transportation

Since the scope of the social objective function of this case study covers the Williams Lake TSA, only the hours of work related to truck transportation from plant locations to Williams Lake are accounted. Hours of work associated with rail transportation of biofuels from Williams Lake to North Vancouver, and ocean transportation from North Vancouver to Rotterdam are not included.

To estimate the amount of hours required to transport one odt of each type of biomass and one unit of each type of biofuel product (m^3 of bio-oil and t of pellets) by truck, a full load transportation is assumed with a volume capacity of 110 m^3, a weight capacity of 28 t, and a waiting time of one hour per trip for loading and unloading (Friesen, personal communication 2013). Since biomass is bulky and contains water, the amount (in odt) of each type of biomass that is transported per trip is calculated based on the bulk density and moisture content of the load (Table 3-4 in Section 3.4.1). The amount of bio-oil (in m^3) that can be transported per trip is calculated based on a bio-oil density of 1.22 kg/l. Truck transportation duration depends on the distance and type of road. In this study, average speeds of 42.5 km/h (empty) and 38.5 km/h (loaded) for transportation of biomass between forest blocks and the sawmills are assumed; and speeds of 86 km/h (empty) and 77 km/h (loaded) for transportation of biomass between sawmills and biofuels between plant locations to Williams Lake are assumed (Akhtari, 2012).

6.3.4 Hours of work for biomass conversion

In all conversion plants, feedstock (chipped biomass) is received and stored in bins, covered buildings, on cement pads or in piles on the ground (based on (Murray, 2010)). Front end loader operators are required for feedstock handling and transferring the feedstock to the next step (pre-treatment or conversion). In addition, hours of work required for plant operation vary based on the type of technology and its size.

Table 6-4 shows the work-related assumptions for combustion and gasification plants. The total amount of full time jobs required to operate each type of plant is approximated based on the values presented by Thornley et al. (2008). The full time jobs are converted into hours of work and categorized into three classes based on the labour requirement description in (EPA, 2007b). The labour requirement description in (EPA, 2007b) is for steam systems and is assumed to be similar for gasification and stoker technologies of equivalent capacities.

Table 6-4 Hours of work required for the operation of combustion and gasification plants (per year)

Technology	Hours per job class					
	Hourly-wage work			Salaried work		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Biomass stoker boiler (2MW)	-	-	2,080	-	-	-
Biomass boiler+steam turbine (cogeneration or electricity only), 0.5 MW	-	7,200	2,080	-	-	-
Biomass boiler+steam turbine (cogeneration or electricity only), 2 MW	-	16,480	4,160	-	2,080	-
Biomass boiler+steam turbine (cogeneration or electricity only), 3 MW	-	16,480	4,160	-	2,080	-
Biomass boiler+steam turbine (cogeneration or electricity only), 5 MW	-	16,480	4,160	-	2,080	-
Biomass boiler+steam turbine electricity only, 0.5 MW	-	7,200	2,080	-	-	-
Biomass boiler+steam turbine electricity only, 2 MW	-	16,480	4,160	-	2,080	-
Biomass boiler+steam turbine electricity only, 3 MW	-	16,480	4,160	-	2,080	-
Biomass boiler+steam turbine electricity only, 5 MW	-	16,480	4,160	-	2,080	-
Biomass oil heater + ORC (0.5 MW)	-	-	2,080	-	-	-
Biomass oil heater + ORC (2 MW)	-	2,080	2,080	-	2,080	-
Biomass oil heater + ORC (3 MW)	-	6,240	4,160	-	2,080	-
Biomass oil heater + ORC (5 MW)	-	16,480	4,160	-	2,080	-
Biomass gasifier + ICE (0.5MW)	-	-	2,080	-	-	-
Biomass gasifier + ICE (2MW)	-	2,080	2,080	-	2,080	-
Biomass gasifier + ICE (3MW)	-	6,240	4,160	-	2,080	-
Biomass gasifier + ICE (5MW)	-	16,480	4,160	-	2,080	-

The description of work requirements of a pellet plant with a capacity of 6 t/h (approximately 45,000 t/year assuming an 85% utilization rate) was obtained from (Sultana et al., 2010). Wage and salary values are based on (Murray, 2010) and adjusted for inflation to be categorized within a job class. For smaller plants (30,000 t/year and 15,000 t/year, equivalent to a 4 t/h and 2 t/h pellet plant, respectively) work requirements are adjusted from (Campbell, 2007). Work requirements for pyrolysis plants are estimated based on (Rogers and Brammer, 2012). Due to the lack of detailed description of roles, particular roles for salaried work in pyrolysis plants are assumed similar to those in pellet plants, and are classified based on (Sultana et al., 2010) and (Murray, 2010). All work requirements for pellets and pyrolysis plants used in this study are presented in Table 6-5.

Table 6-5 Hours of work required for the operation of pellet and pyrolysis plants (per year)

		Hours per year in each plant					
		Pellet plants			**Pyrolysis plants**		
Job description	**Class**	**45,000 t/year**	**30,000 t/year**	**15,000 t/year**	**600 odt/day**	**400 odt/day**	**200 odt/day**
Hourly-wage work							
Supervisor / control room operator	2	7,200	7,200	2,080	7,200	7,200	7,200
Maintenance worker	2	2,080	2,080	0	2,080	2,080	2,080
Machinery operator / plant attendant	3	21,600	14,400	2,080	7,200	7,200	7,200
Front end loader operator	3	0	4,160	2,080	0	0	0
Salaried work							
General manager	1	2,080	2,080	1,040	2,080	2,080	1,040
Financial manager	2	2,080	2,080	0	2,080	2,080	1,040
Marketer	2	2,080	2,080	0	2,080	2,080	0
Delivery coordinator / materials operator	2	2,080	2,080	1,040	2,080	2,080	0
Secretary	3	2,080	2,080	0	2,080	2,080	2,080

In Equation 28, the total amount of hours of hourly-wage work depends on the amount of biomass that is handled at each plant. Thus, the amount of work hours of hourly-wage work required to handle each odt of biomass (parameter $w_{v,l}^{Conv,Hourly}$) is estimated by dividing the annual hourly-wage labor requirements reported in Table 6-4 and Table 6-5 (which are based on the assumption of full capacity utilization of plants) by the maximum annual biomass capacity of each plant.

6.3.5 Hours of work for plant design and construction

Hours of direct work required for plant design and construction are estimated based on the methodology and capital investment disaggregation factors presented in (Thornley et al., 2014). Employment generated at the facility during the design and construction phases are estimated based on the capital investment costs of each plant (covering plant purchase and equipment installation, engineering, supervision, construction, legal expenses, etc.). Using the capital investment disaggregation factors for biorefineries reported in (Thornley et al., 2014), the total expenditure for each employment category during plant design and construction is estimated (assuming the same disaggregation factors for all technologies). The expenditure per employment category is combined with the average earnings per industry type (Statistics Canada, 2015b) to estimate the total amount of employees involved in each employment category in person years and then converted into total hours of work using a factor of 2080 hours per year. Table 6-6 presents the estimated labor requirements for the construction of all plant alternatives.

Table 6-6 Total hours of work required for the construction of plants

Plant alternative	Hours per labor class		
	Class 1	Class 2	Class 3
Biomass stoker boiler (2MW)	-	26,082	39,415
Biomass boiler+steam turbine (cogeneration or electricity only), 0.5 MW	-	12,957	19,581
Biomass boiler+steam turbine (cogeneration or electricity only), 2 MW	-	47,363	71,575
Biomass boiler+steam turbine (cogeneration or electricity only), 3 MW	-	67,010	101,265
Biomass boiler+steam turbine (cogeneration or electricity only), 5 MW	-	102,724	155,236
Biomass boiler+steam turbine electricity only, 0.5 MW	-	12,957	19,581
Biomass boiler+steam turbine electricity only, 2 MW	-	47,363	71,575
Biomass boiler+steam turbine electricity only, 3 MW	-	67,010	101,265
Biomass boiler+steam turbine electricity only, 5 MW	-	102,724	155,236
Biomass oil heater + ORC (0.5 MW)	-	26,725	40,386
Biomass oil heater + ORC (2 MW)	-	64,003	96,722

Plant alternative	Hours per labor class		
	Class 1	Class 2	Class 3
Biomass oil heater + ORC (3 MW)	-	99,679	150,636
Biomass oil heater + ORC (5 MW)	-	163,182	246,601
Biomass gasifier + ICE (0.5MW)	-	10,972	16,581
Biomass gasifier + ICE (2MW)	-	40,531	61,250
Biomass gasifier + ICE (3MW)	-	57,584	87,022
Biomass gasifier + ICE (5MW)	-	118,161	178,565
Pyrolysis plant (200 odt/day)	-	8,195	118,168
Pyrolysis plant (400 odt/day)	-	146,497	221,387
Pyrolysis plant (600 odt/day)	-	214,687	324,435
Pellet plant (15,000 t/year)	-	6,616	9,998
Pellet plant (30,000 t/year)	-	16,223	24,516
Pellet plant (45,000 t/year)	-	23,091	34,895

6.4 Solution method for multi-objective optimization model

The multi-objective optimization model is given by Equations 1-6, 7b, 8b, 9-30. In order to generate a set of Pareto-optimal solutions that consider the three objective functions, the AUGMECON method (Mavrotas, 2009) was implemented as follows:

1. The boundaries for the ε values of each of the three objective functions were estimated through lexicographic optimization. The method to perform a lexicographic optimization for two objectives was presented in Section 5.4. In this chapter the same method was used, and extended for a third objective. To estimate the lexicographic optimal solution of each of the three objective functions, after the two first objective functions were optimized and recorded, the last objective was optimized by constraining the other two objectives to the values recorded in previous optimization runs.
2. A set of efficient Pareto-optimal solutions was generated following the method described in Figure 6-1 (adapted from Mavrotas, 2009). In order to get a representative Pareto-set, the algorithm described in Figure 6-1 was run three times, each time with a different primary objective function for the MOO model. Twenty-five intervals for each objective

function were tested (25×25×3 = 1875 model runs) generating a total of 523 different efficient Pareto-optimal solutions.

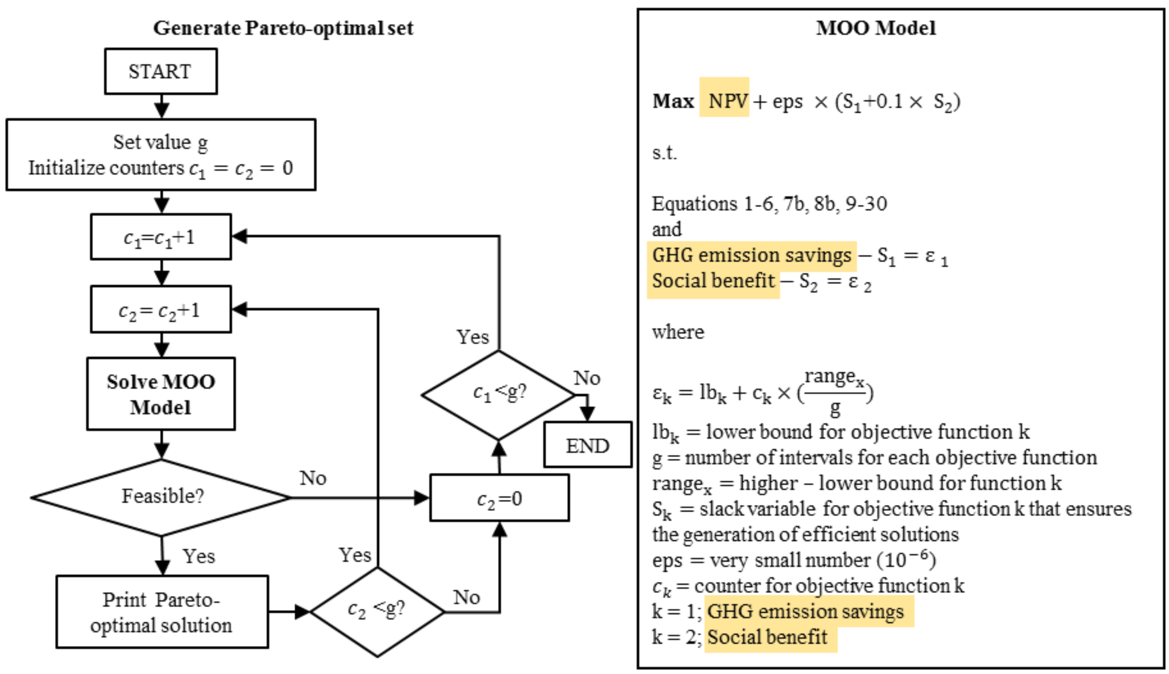

Figure 6-1 AUGMECON method implemented for three objective functions: NPV, GHG emission savings and social benefit

6.5 Results and discussion

6.5.1 Optimal solutions for single objectives

Results of the lexicographic optimization for the three objectives (maximize NPV, maximize GHG emission savings and maximize social benefit) are shown in Table 6-7. To assess the impact of maximizing the social benefit vs. maximizing the total number of created jobs, the model was run a fourth time (with lexicographic optimization) using Equation 26 as the social objective function, but using a setting of one for all social benefit factors ($\chi_{v,j}$=1).

Table 6-7 Supply chain network design of optimal solutions for single objectives

Technologies	Maximum NPV	Maximum GHG emission savings	Maximum social benefit	Maximum total job creation
Anahim Lake				
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1			
Biomass oil heater + ORC (heat and electricity), 5 MW		period 1	period 1	period 1
Pellet plant, 45,000 t/year		period 1	period 1	period 1
Hanceville				
Biomass boiler + steam turbine (electricity only), 0.5 MW	period 1			
Biomass boiler + steam turbine (heat and electricity), 5 MW		period 1		
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1	period 1
Pellet plant, 45,000 t/year		period 1	period 1	period 1
Pyrolysis plant, 200 odt/day				period 1
Pyrolysis plant, 400 odt/day	period 1			
Williams Lake				
Biomass boiler (heat only), 2 MW	period 1			
Biomass oil heater + ORC (heat and electricity), 2 MW		period 1		
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1	
Biomass boiler + steam turbine (heat and electricity), 2 MW				period 1
Pellet plant, 15,000 t/year	period 1			
Pellet plant, 45,000 t/year		period 1	period 1	period 1
Pyrolysis plant, 200 odt/day				period 1
Pyrolysis plant, 400 odt/day		period 1	period 1	
NPV	550 M$	424 M$	330 M$	379 M$
GHG emission savings	2.67 M t CO_2-eq	6.84 M t CO_2-eq	6.79 M t CO_2-eq	6.5 M t CO_2-eq
Social benefit (created jobs)	13 M points (82 jobs)	36 M points (203 jobs)	43 M points (238 jobs)	41 M points (239 jobs)

When the NPV is maximized, the multi-objective model proposes the same design for the supply chain network as obtained in Chapter 3 (also Solution A in Chapter 5). However, when the GHG emission savings are maximized, the optimal solution differs from that found in Chapter 5, pyrolysis production occurs only in Williams Lake. The differences in the supply chain structure and the maximum NPV and GHG emission savings between the solution found in this chapter and the one reported in previous chapters (Chapter 3 and Chapter 5) are due to the changes in constraints presented in Section 6.2.1. The constraints presented in Section 6.2.1 however, are necessary when maximizing job-related objective functions to prevent the installation of idle plants and overproduction of bioenergy and biofuel products.

When the social benefit is maximized, the model recommends a network similar to the maximum GHG emission savings solution, except that a larger plant size is selected for the cogeneration of heat and electricity in Williams Lake (5 MW instead of 2 MW). The optimal solution changes when the objective function changes from maximizing the social benefit to maximizing the total number of jobs. When maximizing the total job creation objective, the production of pyrolysis bio-oil is separated into two smaller plants (in Hanceville and in Williams Lake) instead of having a single larger plant in Williams Lake. The separated production of bio-oil implies a larger number of workers required to operate both plants, thus achieving a marginally larger total number of created jobs, but with a total social benefit reduced by 4%.

To assess the sustainability trade-offs among the economic, environmental and social criteria, Figure 6-2 shows the normalized sustainability indicators for the solutions with the maximum NPV, maximum GHG emission savings and maximum social benefit. A clear trade-off between the economic objective and the other two sustainability objectives can be distinguished. The maximization of the GHG emission savings or the social benefit associated with the forest-based biomass supply chain reduces the NPV by 23% and 40%, respectively, compared to the solution where the NPV is maximized. Figure 6-2 also shows that even when there are differences between the NPV and the social benefit of the environmentally and the socially optimal solutions, they perform similarly in terms of their associated GHG emission savings.

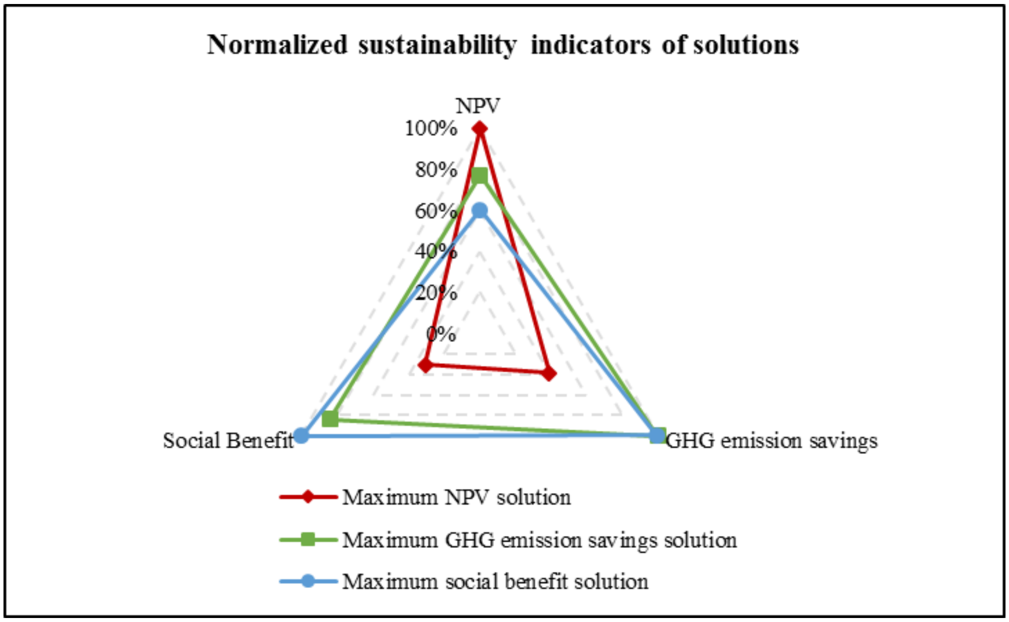

Figure 6-2 Normalized sustainability indicators of solutions with maximum NPV, maximum GHG emission savings, and maximum social benefit

Since the social benefit objective function has no units attached, the associated number of created jobs (in a 20-year basis) is reported for each solution. Figure 6-3 shows the distribution of created jobs by class and by location. Figure 6-3a indicates that the majority of jobs generated in the three solutions fall within job class 3 (e.g. truck drivers, maintenance workers, machinery operators, front end loader operators). When the NPV of the supply chain is maximized, more jobs are created in the community of Hanceville, and when the other two objectives are maximized, the majority of jobs are created around Williams Lake which is a community highly dependent on the forestry industry (Forest-Vulnerability Index of 51).

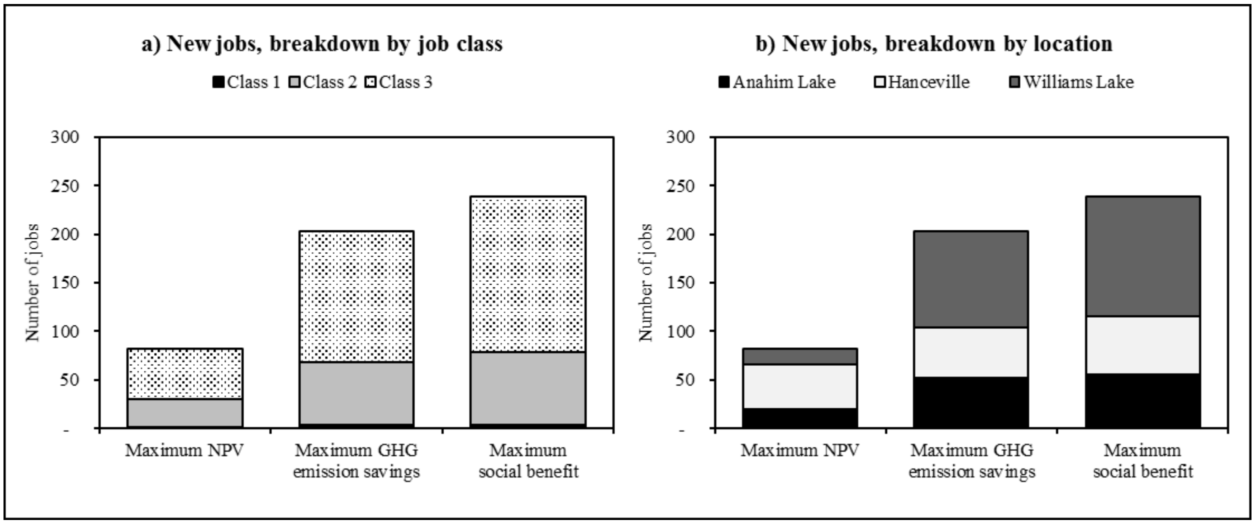

Figure 6-3 Breakdown of new jobs by class and location (total number of jobs)

6.5.2 Pareto-optimal solutions for multiple objectives

The performance of each one of the 523 Pareto-optimal solutions is measured based on their economic (NPV), environmental (GHG emission savings) and social (social benefit) indicators. To facilitate the graphical visualization and sustainability trade-off analysis of the entire Pareto set, Figure 6-4 shows three different views of the same three-dimensional scatter plot. In each view, the x and y axes represent two of the analyzed indicators, and varying levels for the third indicator are represented through the use of different markers. In each view, the maximum values for NPV, GHG emission savings and social benefits are indicated in red, and the three selected compromise solutions are indicated in blue.

Compromise solution 1 is the only solution for which all performance values are above 83% of the maximum values. Compromise solutions 2 and 3 have at least two of the indicators above 90% of their maximum values, and have the highest possible value for the third indicator. Note that there are no solutions where the NPV and social benefits are both above 90% of their maximum values, highlighting the large trade-off between these two objectives.

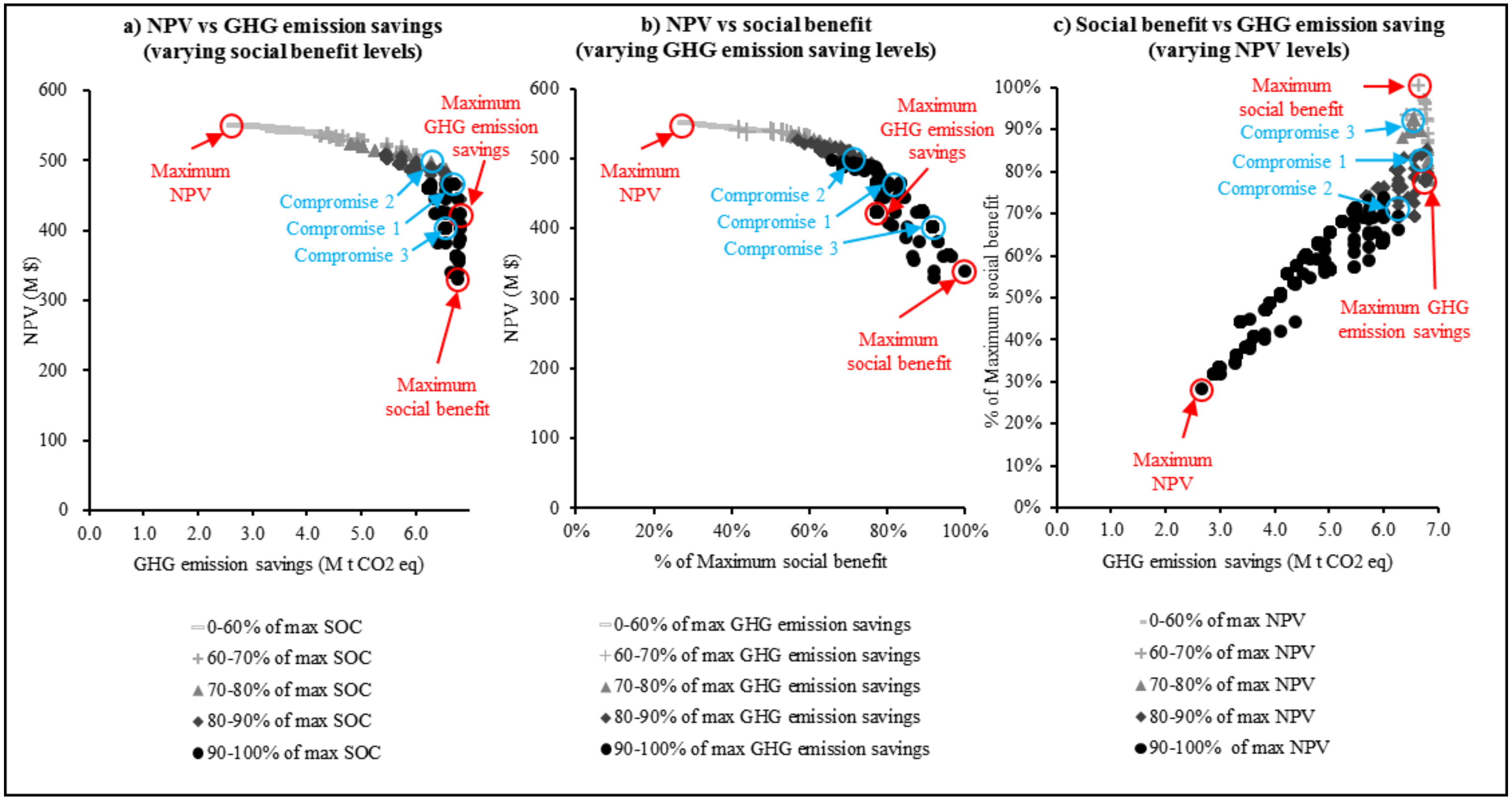

Figure 6-4 Views of the Pareto-optimal solutions comparing (a) NPV vs GHG emission savings, (b) social benefit vs NPV, and (c) social benefit vs GHG emission savings of the Pareto-optimal set

One of the main observations that can be made from the analysis of the shape of the Pareto-optimal set is that Figure 6-4a and Figure 6-4b have similar trends showing clear trade-offs between the NPV of the forest-based biomass supply chain and each one of the other two objectives. An increase in GHG emission savings and jobs with higher impact increases the supply chain costs, thus reduces its overall profit. In contrast, Figure 6-4c shows a positive relationship between the social and environmental objectives, because, in most cases, an improvement in GHG emission savings represents an improvement in the overall social benefit.

In Figure 6-4a, the utmost layer of points between solutions with maximum NPV and maximum GHG emission savings represents the efficient frontier of feasible solutions when only these two objectives are considered. This layer resembles the results of the bi-objective optimization model in Chapter 5. It is observed that by moving right from the economically optimal solution on the curve, significant increases in GHG emission savings can be achieved by sacrificing comparatively small amounts of profit until reaching a point (around 6.5 M t of CO_2 equivalents) from which only slight environmental improvements can be made but with large economic sacrifices.

Similarly, in Figure 6-4b, the utmost layer of points between solutions with maximum NPV and maximum social benefit represents an efficient frontier of feasible solutions when only the NPV and the social benefit objectives are considered in the analysis. It is also evident that as we move away from the economically optimal solution, a larger production of bioenergy and pellets results in an increased social benefit for the communities in the Williams Lake TSA. By sacrificing less than 50 M $ of the maximum NPV, the supply chain can almost triplicate its beneficial social impacts (measured in this study by means of the social benefit indicator).

In Figure 6-4c, when considering only the social benefit and the GHG emission savings (the rightmost layer connecting solutions with maximum social benefit and maximum GHG emission savings), the GHG emission savings vary little when the social benefit is increased above 80%. When weighing as well the NPV objective, the width of the point cloud in Figure 6-4c shows that different levels of social benefit can be obtained for a constant level of GHG emission savings, and vice versa.

To further investigate the trade-offs among the three objectives, the three compromise solutions indicated in Figure 6-4 are analyzed in terms of their structure and indicators (Table 6-8).

Table 6-8 Supply chain network design of compromise Pareto-optimal solutions

Technologies	Compromise solution 1	Compromise solution 2	Compromise solution 3
Anahim Lake			
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1	period 1	
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1
Pellet plant, 45,000 t/year	period 1	period 6	period 1
Hanceville			
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1	period 1	period 1
Pellet plant, 45,000 t/year	period 1	period 1	period 1
Williams Lake			
Biomass boiler (heat only), 2 MW		period 1	
Biomass oil heater + ORC (heat and electricity), 5 MW			period 1
Biomass boiler + steam turbine (heat and electricity), 5 MW	period 1		
Pellet plant, 15,000 t/year		period 1	
Pellet plant, 45,000 t/year	period 1		period 1
Pyrolysis plant, 400 odt/day	period 1	period 1	period 1
Results			
NPV (% of maximum value)	465 M$ (85%)	493 M$ (90%)	401 M$ (73%)
GHG emission savings (% of maximum value)	6.71 M t CO_2-eq (98%)	6.29 M t CO_2-eq (92%)	6.56 M t CO_2-eq (96%)
Social benefit (% of maximum value) (total number of jobs)	39 M points (83%) (217 jobs)	33 M points (72%) (186 jobs)	43 M points (92%) (236 jobs)

The three compromise solutions involve the installation of 5 MW plants for cogeneration of heat and power and 45,000 t/year pellet plants in Anahim Lake and Hanceville, as well as the installation of a 400 odt/day pyrolysis plant in Williams Lake. The main differences among the compromise solutions are related to the production scale of bioenergy (electricity and heat) and pellets in Williams Lake: Compromise solutions 1 and 3 recommend the installation of 5 MW combined heat and power plants and 45,000 t/year pellet plants which impacts their NPV negatively, but affects their GHG emission savings and social benefits positively. The main difference between these two compromise solutions is the type of bioenergy plant installed. Compromise solution 2 generates higher levels of NPV and GHG emissions with the installation of smaller bioenergy and pellet plants in Williams Lake, but with a considerably lower social benefit.

6.6 Summary and conclusions

In this chapter a multi-objective MILP model was developed that maximizes the economic, environmental and social benefits associated with the implementation of a forest-based biomass supply chain for the production of bioenergy and biofuels. To quantify the social benefits of the supply chain, a social benefit objective function was proposed that considers different impact levels of job creation based on its type (or class) and location. The developed model was applied to the case study explored in previous chapters of this dissertation. In the case study, the social benefit objective function was estimated based on the Forest Vulnerability Index of each candidate location, and the unemployment rate associated with each job class. A set of Pareto-optimal solutions considering the three objectives was generated using the AUGMECON method. The analysis of the Pareto-optimal solutions exhibited trade-offs between the economic performance of the supply chain and its potential to generate both environmental and social benefits. This analysis also showed a positive association between the level of GHG emission savings and the social benefit associated with the implementation of a forest-based biomass supply chain in the region. Minor structural differences were distinguished between the solution with the maximum GHG emission savings and the solution with the maximum social benefit (larger generation of electricity in the community of Williams Lake).

Chapter 7: Conclusion, strengths, limitations, and future research

7.1 Conclusions

Unused forest-based biomass (e.g. forest and wood residues) could be utilized for the production of bioenergy and biofuel to generate additional revenue streams for the forestry industry, while mitigating GHG emissions and creating development opportunities in forest-rich communities. In the planning of forest-based biomass supply chains for the production of bioenergy and biofuels, decision support models that incorporate different sustainability indicators could support informed decision making. This requires the utilization of multi-objective modeling approaches to provide decision makers with detailed information regarding the potential compromises among the economic, environmental and social impacts associated with the proposed supply chains.

The overall goal of this dissertation was to develop a supply chain optimization model to maximize the economic, environmental and social benefits of utilizing available forest and wood residues for the production of bioenergy and biofuels. This objective was achieved through the progressive construction of a multi-objective optimization model, and the application of the model to a case study. The case study aimed to investigate the potential production of electricity, heat, bio-oil and pellets using currently unused harvesting and sawmill residues in the Williams Lake TSA located in Interior British Columbia.

Chapter 2 presented sustainability factors in the design and planning of forest-based biomass supply chains, and reviewed biomass supply chain optimization studies that included forest-based biomass and considered economic, environmental and/or social objective functions. The review of literature showed that the integration of different sustainability objective functions in optimization models for the design of forest-based biomass supply chains was scarce. In addition, it was discussed that although many sustainability indicators had been proposed, only a few of them were quantified. The most frequently quantified indicators were related to the supply chain cost, GHG emissions and job creation. The review also revealed the need for a supply chain optimization model with the following characteristics: (1) able to consider multiple forest-based biomass types, technologies, and products; (2) able to model the energy flows among co-located technologies; and (3) able to accurately estimate the economic, environmental and social benefits of the supply chain.

In Chapter 3, a single-objective optimization model was developed to recommend the optimal design of a forest-based biomass supply chain to maximize the NPV of the investment. The proposed model was different from previous studies since it modeled the production of bioenergy and biofuels simultaneously; it modeled the flow of energy among co-located technologies; and it had a multi-period formulation that considers the variability of parameters such as the amount and location of available biomass that can affect strategic investment decisions. The model was applied to the case study. The purpose of the case study was to investigate the potential production of electricity, heat, bio-oil and pellets using currently unused harvesting and sawmill residues in the region. The optimal solution indicated that it was possible to generate a positive NPV from the production and sales of bio-oil, pellets, heat, and electricity over the following 20 years, considering a 5% discount rate. This means that the internal rate of return (IRR) of the project is larger than 5%. However, the typical hurdle rate (the minimum rate that a company expect to earn) used by firms for investments ranges from 7% to 30% or more (Meier and Tarhan, 2007; Wright et al., 2013), being in the higher end for high risk projects such as supply chain case described in this study.

In the optimal solution of the economic optimization of the case study, pyrolysis bio-oil was the most profitable product (assuming a sales price equivalent to that of fuel-oil and a large demand). It is worth noting that the market for bio-oil is still incipient and the sensitivity analysis showed that the optimal solution is highly sensitive to the demand and price of the products. However, the market for biofuels, in general, is forecasted to rise in the medium term, despite the significant reduction in oil price in 2014, as their substitution for fossil fuels remains largely mandate-driven (IEA, 2016). International support for biofuel development is expected to continue and with this, the efforts to develop a market for bio-oil for different applications (including transportation fuels) is likely to continue.

For this analysis, cost and price figures were based on 2013 values, while the global energy market has changed. Since 2014, there has been a significant reduction in the price of crude oil.

Chapter 4 presented the development of a life cycle GHG emissions assessment for the supply chain alternatives of the case study, and presented the analysis of 16 alternative supply chain configurations for electricity and heat generation in the remote communities of Anahim Lake and Hanceville. This analysis showed that the environmental comparison among different supply chain alternatives required the consideration of the emissions of the baseline case as reference for comparison. These baseline emissions should include the emissions from currently used energy sources and the emissions from disposing the forest-based biomass currently unused. From the analysis, it was concluded that the formulation of an environmental objective function for a forest-based biomass supply chain optimization model had to consider that biomass carbon neutrality is not guaranteed when unused forest-based biomass is landfilled.

Chapter 5 presented the development of the environmental objective function that was added to the model. The novelty of the proposed environmental objective function lied on the quantification and maximization of the GHG emissions savings associated with the introduction of a forest-based biomass supply chain. These GHG emission savings were estimated by comparing the emissions of the forest-based biomass supply chain system, versus the emissions of a baseline case system where forest-based biomass continues to be disposed of with currently used methods (e.g. burning and landfilling) and energy demands continue to be satisfied from currently used sources (e.g. fossil and renewable sources). The resulting bi-objective optimization model was applied to the case study and a set of Pareto-optimal solutions was generated. The Pareto set showed a trade-off between the economic performance of the supply chain and its potential to save GHG emissions. For example, in terms of pellet production, the larger the production, the larger the potential to save GHG emissions (due to the substitution of coal and heating oil in Europe), and the lower the profit (due to the high capital and product transportation costs). However, replacing the use of diesel generators with forest-based bioenergy was both economically and environmentally advisable in the two off-grid communities of the case study (Anahim Lake and Hanceville).

Finally, in Chapter 6, a social objective function was developed and added to the model. The proposed social objective function aimed at maximizing the social benefit associated with the implementation of a forest-based biomass supply chain, considering that different types of jobs in different locations generate varying levels of social benefit. While the economic and the environmental objective functions developed in Chapters 3 and 5 were bounded by the supply chain costs or the supply chain GHG emissions, the social objective function introduced in Chapter 6 required modifications to the set of constraints of the model. The modified constraints and the added constraints avoided the installation of idle plants and the overproduction of bioenergy and biofuel. The resulting multi-objective optimization model was applied to the case study and a set of Pareto-optimal solutions considering the three objectives was generated. In the case study, the estimation of the social benefit associated with the created jobs was based on the average unemployment levels for different forestry jobs in the province and the Forest Vulnerability Index of the communities of the case study. The analysis of the generated Pareto-optimal solutions exhibited a trade-off between the social and the economic performance of the supply chain and a positive association between the level of GHG emission savings and the social benefit of the forest-based biomass supply chain.

Overall, the results of the case study showed that the replacement of current fossil energy sources with bioenergy and the large-scale production of bio-oil and pellets for exportation could have the potential to generate a NPV of up to 550 M $, GHG emission savings up to 6.8 M t of CO_2 equivalents, and up to 230 highly impacting jobs in the region during the next 20 years. The magnitude of each one of these benefits would depend on the compromises achieved among these three sustainability criteria. Without a multi-objective decision support tool such as the one presented in this work, the consideration and quantification of compromises among the economic, environmental and social benefits of the forest-based supply chain would not be possible for decision makers. The application of the developed model could facilitate the dialogue among investors and other stakeholders (e.g. community and government) to support them in the design, planning and implementation of new forest-based biomass projects.

7.2 Strengths

From a modeling perspective, the main strength of this research is that it proposed a novel multi-objective optimization model that aims at quantifying and maximizing the economic, environmental and social benefits associated with the implementation of a supply chain for the production of a variety of bioenergy and biofuel products from different types of forest and wood residues. Previously, the majority of biomass supply chain studies focused on the utilization of energy crops or agricultural residues, relying on fixed annual biomass production rates and costs per supply area. In this regard, the developed model addressed challenges particular to the supply of forest-based biomass such as the existence of numerous biomass sources distributed over vast regions, and where available biomass quantities change over the long-term planning horizon. In addition, the majority of previous studies focused on the production of either bioenergy or biofuel products separately, and the developed model allows the production of various bioenergy and biofuel products in multi-product technologies, and allows the use of produced bioenergy as input for co-located conversion technologies.

Another strength of this research lies on the characteristics of the proposed environmental and social objective functions. The environmental objective function was formulated as a comparison of the GHG emissions generated by the proposed supply chain with the emissions of the current system. This could not be done in multi-objective optimization models published before because in their estimation of total GHG emissions, only a few studies considered the GHG emissions avoided from the replacement of fossil fuels, and no study considered the alternative fate or disposal of the unused biomass before. In terms of the social objective, this is the first study proposing the consideration of a social benefit indicator instead of a job creation indicator as the social objective function of the biomass supply chain optimization.

Overall, the developed model can be applied to a variety of regions to investigate the production of multiple bioenergy and biofuel products from forest-based biomass. It can be used to recommend sustainable design of forest-based biomass supply chains, and can be used to analyze the potential compromises among the three different objective functions.

From an application perspective, this work included an in-depth investigation of the production of bioenergy and biofuels in the Williams Lake TSA. This investigation required the compilation and analysis of a large amount of real data and information related to the economic, environmental and social aspects of the supply chain alternatives. The economic, environmental and social data generated in this study could be useful in other relevant studies. Previously, techno-economic feasibility assessments had been developed for the introduction of different bioenergy technologies in the investigated communities, however, the potential installation of pyrolysis and pellet plants in the region had not been investigated before. The life cycle GHG emission values estimated in Section 4.4 were a contribution to the literature. They can be used as building blocks for other projects studied in the region. The analysis presented in Section 4.5 was the first study that evaluated the life cycle GHG emissions of small bioenergy systems (under 5 MW) generating heat and electricity in remote off-grid forest-rich communities. In addition, this research proposed and estimated a social benefit indicator to compare the potential social impact of new forest-biomass projects in British Columbia based on regionally developed indicators.

7.3 Limitations

A limitation of this research is that it focused on the use of biomass for energy purposes only (heat, electricity and biofuels), due to the relevance of the bioenergy sector in meeting growing energy demands and in mitigating global GHG emissions. Consideration of other products such as chemicals and biomaterials would require modifications to the supply chain stages included in the model. For example, the development of life cycle GHG assessments tailored to other products may suggest additional unit processes that should be added to the model.

In the model developed in this research, production yields of all conversion technologies at discrete sizes were assumed to be known a priori; thus, they were input parameters exogenous to the model. Thus, other conversion technologies generating multiple products may be considered in the model, provided that production yield for each product is assumed fixed. These production yields may be estimated through process optimization.

The application of the developed model required large amounts of data, and the relevance of the results and the conclusions generated for the considered technology alternatives depended on how representative the data were of the analyzed alternatives. There was limited information regarding the differences in emissions from various wood burning boiler systems. The values reported in the case study relied on the emission factors provided by the EPA AP-42 standard (EPA, 2015) that do not differentiate among plant size or boiler technology. Since the focus of the environmental analysis of this study was on GHG emissions, and since GHG emissions associated with biomass combustion were assumed carbon neutral in the multi-objective model, this assumption did not affect the comparison results. Published information regarding the hours of work required for the operation and construction of different combustion and gasification plants was also limited. Specific work requirements for the technologies considered in this study were approximated from the best reports available (Thornley et al., 2008; EPA, 2007b).

The candidate combustion and gasification technologies included in the case study were based on suggestions from previous technical reports performed in the region (Marinescu, 2013, 2012). In those technical reports, the sizes of the technologies were based on the expressed interests of stakeholders (management of local sawmills) and the energy demand profile of the communities. In contrast, the sizes for pelletizing and pyrolysis technologies, and the demand for pellets and pyrolysis bio-oil were approximated based on the total economically available amount of biomass in the region. Since bio-oil sales accounted for the largest portion of the revenue, it is important to develop market assessments for pyrolysis bio-oil in the future. Results from such market assessments should be used to determine the bio-oil demand and the size of the pyrolysis plants included in the analysis.

The developed model could consider changes in biomass supply and cost, as well as product demand and price on a year-to-year basis. However, in the case study, spatial and temporal related data for harvesting residues (including MPB-killed timber) relied on 5-year forecasts of available biomass in aggregated cutting blocks around the Williams Lake TSA (from FPInterface). In addition, product demand and price were considered steady over the planning horizon. The sensitivity analysis in Chapter 3 showed that changes in these parameters (product demand and price and biomass availability and cost) affected the performance long-term strategic design of the supply chain (especially for the installation of pellet plants). The availability of finer spatial and temporal biomass data, and market analysis data for the region could provide finer results for the case study.

The proposed multi-objective optimization model was deterministic, and it did not consider the impact of uncertainty. The data used in the model included several assumptions such as average biomass moisture content, bulk density, energy content and conversion yields. Variability in these parameters could contribute to a higher cost of the forest-based biomass supply chain, and to larger requirements of biomass which might imply an increase in GHG emissions as well. Considering variability in such data could improve the reliability of the obtained results, this would require the incorporation of uncertainty to the model.

Another limitation of the model is that other relevant environmental and social sustainability impacts associated with forest-based biomass supply chains such as particulate matter emissions were not included. However, the modeling approach presented in this study could be used to consider other environmental data, provided that emissions data are available.

7.4 Future research

Future development of the model could include the incorporation of other types of biomass and products. This would require a careful analysis of the supply chain and the life cycle of those biomass types and products in order to ensure that all relevant stages are addressed by the model. Additionally, the model could be extended to consider centralized and decentralized conversion processes. In decentralized conversion processes, biomass is converted into intermediate products (e.g. chips, briquettes, biocrude) that are then transported to final conversion plants, while in centralized conversion processes biomass is converted into final products at the same location. The differences between these two types of processes generate different sustainability impacts that should be analyzed in future work, especially when the model is applied to large geographical regions.

Another area for further research is to enhance the applicability of the case study results is the development of a detailed supply and demand assessment in the region. This assessment should be done to identify the types and sizes of the conversion technologies to be included in the analysis. A market forecast study should also be conducted to generate different scenarios of demand and price for bioenergy, biofuels and other bioproducts produced in the Williams Lake TSA over the planning horizon. Moreover, a survey should be done among currently operating bioenergy and biofuel plants in North America to obtain more precise data on capital and operative costs, energy consumption rates, labor requirements and conversion yields of biomass conversion technologies.

In addition to the sustainability criteria considered in this work, further work should consider the incorporation of other quantifiable sustainability indicators into the multi-objective optimization to facilitate the discussion regarding the sustainability trade-offs of forest-based biomass supply chains. Data regarding other environmental impacts of energy supply chains such as the generation of particulate matters and fossil fuel depletion could be incorporated into the analysis and used for a more complete evaluation of the environmental impacts of new forest-based biomass projects.

Finally, future analysis could involve the incorporation of uncertainty in the decision making process. This could be done through: (1) sensitivity or scenario analyses that evaluate changes to the generated Pareto-optimal set due to different external conditions such as different biofuel demands and prices, and different biomass availability and price forecasts, and assuming different end-uses for the generated products (e.g. bio-oil for transportation); (2) incorporation of uncertainty in the modeling through stochastic or robust optimization approaches; or (3) development of simulation models that assess the implementability of the generated solutions of interest considering uncertainty of different technical parameters (e.g. biomass moisture content, production yields, transportation, etc.).

Bibliography

Abbas, D., Current, D., Phillips, M., Rossman, R., Hoganson, H., Brooks, K.N. 2011. Guidelines for harvesting forest biomass for energy: a synthesis of environmental considerations. *Biomass & Bioenergy*. **35**(11): 4538–4546.

Aitken, D.W. 2010. Transitioning to a renewable energy future. International Solar Energy Society, ISES. White Paper.

Akhtari, S. 2012. Economic assessment and optimization of forest biomass supply chain for heat generation in a district heating system (Masters thesis). University of British Columbia.

Akhtari, S., Sowlati, T., Day, K. 2013. Optimal flow of regional forest biomass to a district heating system. *International Journal of Energy Research*. **38**(7): 954–964.

An, H., Wilhelm, W.E., Searcy, S.W. 2011. A mathematical model to design a lignocellulosic biofuel supply chain system with a case study based on a region in Central Texas. *Bioresource Technology*. **102**(17): 7860–7870.

Ayoub, N., Yuji, N. 2012. Demand-driven optimization approach for biomass utilization networks. *Computers & Chemical Engineering*. **36**: 129–139.

Azapagic, A. 1999. Life cycle assessment and its application to process selection, design and optimisation. *Chemical Engineering Journal*. **73**(1): 1–21.

Badger, P. 2002. Processing cost analysis for biomass feedstock. Oak Ridge National Laboratory.

BC Curios Ltd. 2013. British Columbia travel and discovery: Hanceville. Retrieved from http://www.ourbc.com/travel_bc/bc_cities/cariboo_chilcotin/hanceville.htm. Date of access: Feb. 18, 2013.

BC Hydro. 2014. Quick facts. Retrieved from http://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/accountability-reports/financial-reports/annual-reports/quick-facts-for-year-ended-march-31-2013.pdf. Date of access: Jun. 24, 2014.

Bernardi, A., Giarola, S., Bezzo, F. 2012. Optimizing the economics and the carbon and water footprints of bioethanol supply chains. *Biofuels, Bioproducts & Biorefining*. **6**(6): 656–672.

Berry, D.M. 2013. The essential similarity and differences between mathematical modeling and programming. *Science of Computer Programming*. **78**(9): 1208–1211.

BioTalent Canada. 2013. Sequencing the data: people - driving Canada's bio-economy. Labour market information report 2013.

Bixby, R.E. 2002. Solving real-world linear programs: a decade and more of progress. *Operations Research*. **50**(1): 3–15.

Bogetoft, P., Pruzan, P. 1997. Planning with multiple criteria: investigation, communication, choice, 1st ed. Elsevier Science Publishers B.V., North Holland, Amsterdam, New York, Oxford, Tokyo.

Börjesson, M., Ahlgren, E.O. 2010. Biomass gasification in cost-optimized district heating systems—A regional modelling analysis. *Energy Policy*. **38**(1): 168–180.

Boundy, B., Diegel, S.W., Wright, L., Davis, S. 2011. Biomass energy data book, 4th ed. Oak Ridge National Laboratory.

Bridgwater, A.V. 2003. Renewable fuels and chemicals by thermal processing of biomass. *Chemical Engineering Journal*. **91**(2-3): 87–102.

Bridgwater, A.V., Toft, A.J., Brammer, J.G. 2002. A techno-economic comparison of power production by biomass fast pyrolysis with gasification and combustion. *Renewable & Sustainable Energy Reviews*. **6**(3): 181–246.

Briggs, D. 2010. Research guidelines for life cycle inventories. (Phase I final report). Consortium for Research on Renewable Industrial Materials (CORRIM).

Campbell, K. 2007. A feasibility study guide for an agricultural biomass pellet company. Agricultural Utilization Research Institute, St. Paul, Minnesota.

Canadian Forest Service. 2013. Biomass, bioenergy and bioproducts. Retrieved from http://cfs.nrcan.gc.ca/pages/65. Date of access: Feb. 13, 2013.

Caputo, A.C., Palumbo, M., Pelagagge, P.M., Scacchia, F. 2005. Economics of biomass energy utilization in combustion and gasification plants: effects of logistic variables. *Biomass & Bioenergy*. **28**(1): 35–51.

Chen, C., Fan, Y. 2012. Bioethanol supply chain system planning under supply and demand uncertainties. *Transportation Research Part E*. **48**: 150-164.

Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-Gallasch, S. 2009. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: key issues, ranges and recommendations. *Resources, Conservation & Recycling*. **53**(8): 434–447.

Chinese, D., Meneghetti, A. 2005. Optimisation models for decision support in the development of biomass-based industrial district-heating networks in Italy. *Applied Energy*. **82**(3): 228–254.

Čuček, L., Klemeš, J.J., Varbanov, P.S., Kravanja, Z. 2011. Life cycle assessment and multi-criteria optimization of regional biomass and bioenergy supply chains. *Chemical Engineering Transactions*. **25**: 575–580.

Čuček, L., Varbanov, P.S., Klemeš, J.J., Kravanja, Z. 2012. Total footprints-based multi-criteria optimisation of regional biomass energy supply chains. *Energy*. **44**(1): 135–145.

Czernik, S., Bridgwater, A.V. 2004. Overview of applications of biomass fast pyrolysis oil. *Energy & Fuels*. **18**(2): 590–598.

Dansereau, L.P., El-Halwagi, M., Mansoornejad, B., Stuart, P. 2014. Framework for margins-based planning: forest biorefinery case study. *Computers & Chemical Engineering*. **63**: 34–50.

Deb, K. 2005. Multi-objective optimization, in: Burke, E.k., Kendal, G. (Eds.), Search methodologies: introductory tutorials in optimization and decision support techniques. Springer, US., pp. 273-316.

Demirbaş, A. 2001. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Conversion & Management*. **42**(11): 1357–1378.

Difs, K., Wetterlund, E., Trygg, L., Söderström, M. 2010. Biomass gasification opportunities in a district heating system. *Biomass & Bioenergy*. **34**(5): 637–651.

Dymond, C.C., Titus, B.D., Stinson, G., Kurz, W.A. 2010. Future quantities and spatial distribution of harvesting residue and dead wood from natural disturbances in Canada. *Forest Ecology & Management*. **260**(2): 181-192.

Ekşioğlu, S.D., Acharya, A., Leightley, L.E., Arora, S. 2009. Analyzing the design and management of biomass-to-biorefinery supply chain. *Computers & Industrial Engineering*. **57**(4): 1342–1352.

Elia, J.A., Baliban, R.C., Xiao, X., Floudas, C.A. 2011. Optimal energy supply network determination and life cycle analysis for hybrid coal, biomass, and natural gas to liquid (CBGTL) plants using carbon-based hydrogen production. *Computers & Chemical Engineering*. **35**(8): 1399–1430.

EPA. 2007a. Biomass conversion: emerging technologies, feedstocks, and products. U.S. Environmental Protection Agency.

EPA. 2007b. Biomass combined heat and power - catalog of technologies. U.S. Environmental Protection Agency - Combined Heat and Power Partnership.

EPA. 2015. Emissions Factors & AP 42, Compilation of air pollutant emission factors. Retrieved from http://www3.epa.gov/ttnchie1/ap42/. Date of access: Jan. 16, 2016.

Fan, J., Kalnes, T.N., Alward, M., Klinger, J., Sadehvandi, A., Shonnard, D.R. 2011. Life cycle assessment of electricity generation using fast pyrolysis bio-oil. *Renewable Energy*. **36**(2): 632–641.

Feng, Y., D'Amours, S., LeBel, L., Nourelfath, M. 2010. Integrated bio-refinery and forest products supply chain network design using mathematical programming approach (No. 50). CIRRELT. Universite de Montreal, Universite Laval Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation - CIRRELT, Montreal and Laval, Que.

FPAC. 2011. The new face of the Canadian forest industry. The emerging bio-revolution: the Bio-pathways Project (No. 2). Forest Products Association of Canada.

FPAC. 2010. Transforming Canada's forest products industry: summary of findings from the future Bio-pathways Project (No. 1). Forest Products Association of Canada.

FPInnovations. 2013. FPInterface. Retrieved from http://fpsuite.ca/l_en/fpinterface.html. Date of access Jan. 15 2013.

Freppaz, D., Minciardi, R., Robba, M., Rovatti, M., Sacile, R., Taramasso, A. 2004. Optimizing forest biomass exploitation for energy supply at a regional level. *Biomass & Bioenergy*. **26**(1): 15–25.

Friesen, C. 2012. Estimating Williams Lake TSA Biomass Supply Using FPInterface. FPInnovations, Vancouver.

Frombo, F., Minciardi, R., Robba, M., Rosso, F., Sacile, R. 2009a. Planning woody biomass logistics for energy production: a strategic decision model. *Biomass & Bioenergy*. **33**(3): 372–383.

Frombo, F., Minciardi, R., Robba, M., Sacile, R. 2009b. A decision support system for planning biomass-based energy production. *Energy*. **34**(3): 362–369.

Ghaffariyan, M.R., Acuna, M., Brown, M. 2013. Analysing the effect of five operational factors on forest residue supply chain costs: a case study in Western Australia. *Biomass & Bioenergy*. **59**: 486–493.

Ghafghazi, S., Sowlati, T., Sokhansanj, S., Bi, X., Melin, S. 2011. Life cycle assessment of base–load heat sources for district heating system options. *The International Journal of Life Cycle Assessment*. **16**(3): 212–223.

Giarola, S., Bezzo, F., Shah, N. 2013. A risk management approach to the economic and environmental strategic design of ethanol supply chains. *Biomass & Bioenergy*. **58**: 31–51.

Giarola, S., Zamboni, A., Bezzo, F. 2011. Spatially explicit multi-objective optimisation for design and planning of hybrid first and second generation biorefineries. *Computers & Chemical Engineering*. **35**(9): 1782–1797.

Grossmann, I.E., Guillén-Gosálbez, G. 2010. Scope for the application of mathematical programming techniques in the synthesis and planning of sustainable processes. *Computers & Chemical Engineering*. **34**(9): 1365–1376.

Gunnarsson, H., Ronnqvist, M., Lundgren, J.T. 2004. Supply chain modelling of forest fuel. *European Journal of Operational Research*. **158**(1): 103–123.

Haimes, Y.Y., Lasdon, L.S., Wismer, D.A. 1971. On a bicriterion formulation of the problems of integrated system identification and system optimization. *IEEE Transactions on Systems, Man & Cybernetics.* **SMC-1**(3): 296–297.

Hesselink, T.P. 2010. Increasing pressures to use forest biomass: a conservation viewpoint. The *Forestry Chronicle*. **86**: 28–35.

Horne, G. 2009. 2006 Economic dependency tables for forest districts. Ministry of Management Services, BC Stats, Victoria.

Huang, Y., Chen, C.-W., Fan, Y. 2010. Multistage optimization of the supply chains of biofuels. *Transportation Research Part E: Logistics and Transportation Review.* **46**(6): 820–830.

Iakovou, E., Karagiannidis, A., Vlachos, D., Toka, A., Malamakis, A. 2010. Waste biomass-to-energy supply chain management: a critical synthesis. *Waste Managemen*t. 30(10): 1860–1870.

IEA. 2016. Biofuels can provide up to 27% of world transportation fuel by 2050. Retrieved from https://www.iea.org/topics/renewables/subtopics/bioenergy/. Date of access: May 15th, 2016.

IEA Bioenergy. 2002. Sustainable production of woody biomass for energy: A position paper prepared by IEA Bioenergy- Executive committee.

IEA Bioenergy Task 40. 2007. Global wood pellets markets and industry: policy drivers, market status and raw material potential.

IPCC. 2007. Fourth assessment report. Climate change 2007: synthesis report. Intergovernmental Panel on Climate Change, Geneve.

ISO. 2006. Environmental management – Life cycle assessment – Principles and framework. International Organization for Standardization (International Standard No. ISO 14040).

Jäppinen, E., Korpinen, O.-J., Laitila, J., Ranta, T. 2014. Greenhouse gas emissions of forest bioenergy supply and utilization in Finland. *Renewable & Sustainable Energy Reviews*. **29**: 369–382.

Johnson, L., Lippke, B., Oneil, E. 2012. Modeling biomass collection and woods processing life-cycle analysis. *Forest Products Journal*. **62**(4): 258–272.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., Rosenbaum, R. 2003. IMPACT 2002+: A new life cycle impact assessment methodology. *The International Journal of Life Cycle Assessment*. **8**(6): 324–330.

Kanzian, C., Holzleitner, F., Stampfer, K., Ashton, S. 2009. Regional energy wood logistics - Optimizing local fuel supply. *Silvia Fennica*. **43**(1): 113–128.

Kanzian, C., Kühmaier, M., Zazgornik, J., Stampfer, K. 2013. Design of forest energy supply networks using multi-objective optimization. *Biomass & Bioenergy*. **58**: 294–302.

Karhunen, A., Laihanen, M., Ranta, T. 2014. Requirements for transportation of fast pyrolysis bio-oil in Finland. *International Journal of Sustainable Energy*. 1–11.

Kaylen, M., Dyne, D.L.V., Choi, Y.-S., Blase, M. 2000. Economic feasibility of producing ethanol from lignocellulosic feedstocks. *Bioresource Technology*. **72**(1): 19–32.

Kehbila, A.T. 2010. Evaluation of primary wood processing residues for energy in British Columbia (Masters thesis). University of British Columbia.

Keirstead, J., Samsatli, N., Pantaleo, A.M., Shah, N. 2012. Evaluating biomass energy strategies for a UK eco-town with an MILP optimization model. *Biomass & Bioenergy*. **39**: 306–316.

Kim, J., Realff, M.J., Lee, J.H. 2011a. Optimal design and global sensitivity analysis of biomass supply chain networks for biofuels under uncertainty. *Computers & Chemical Engineering*. **35**(9): 1738–1751.

Kim, J., Realff, M.J., Lee, J.H., Whittaker, C., Furtner, L. 2011b. Design of biomass processing network for biofuel production using an MILP model. *Biomass & Bioenergy*. **35**(2): 853–871.

Kong, J., Rönnqvist, M., Frisk, M. 2012. Modeling an integrated market for sawlogs, pulpwood, and forest bioenergy. *Canadian Journal of Forest Research*. **42**(2): 315–332.

Korber, D., Beckley, T., Luckert, M., White, W. 1998. Cultural, geographical, and sectoral refinements to measures of forest industry dependence. *Canadian Journal of Forest Research*. **28**(9): 1380–1387.

Lattimore, B., Smith, C.T., Titus, B.D., Stupak, I., Egnell, G. 2009. Environmental factors in woodfuel production: opportunities, risks, and criteria and indicators for sustainable practices. *Biomass & Bioenergy*. **33**(10): 1321–1342.

Leduc, S., Lundgren, J., Franklin, O., Dotzauer, E. 2010a. Location of a biomass based methanol production plant: a dynamic problem in northern Sweden. *Applied Energy*. **87**(1): 68–75.

Leduc, S., Schwab, D., Dotzauer, E., Schmidt, E., Obersteiner, M. 2008. Optimal location of wood gasification plants for methanol production with heat recovery. *International Journal of Energy Research*. **32**(12): 1080–1091.

Leduc, S., Starfelt, F., Dotzauer, E., Kindermann, G., McCallum, I., Obersteiner, M., Lundgren, J. 2010b. Optimal location of lignocellulosic ethanol refineries with polygeneration in Sweden. *Energy*. **35**(6): 2709–2716.

Lehtikangas, P. 2001. Quality properties of pelletised sawdust, logging residues and bark. *Biomass & Bioenergy*. **20**(5): 351–360.

Liu, Z., Qiu, T., Chen, B. 2014. A study of the LCA based biofuel supply chain multi-objective optimization model with multi-conversion paths in China. Applied Energy. **126**: 221–234.

LMI Insight and R.A. Malatest & Associates Ltd. 2013. British Columbia forest sector: labour market and training needs assessment. Prepared for BC Coastal Forest Industry, Labour Market Information Working Group.

Logistics Solution Builders. 2005. Operating costs of trucks in Canada. Prepared for Transport Canada. Transport Canada.

Lunnan, A., Vilkriste, L., Wihelmsen, G., Mizaraite, D., Asikainen, A., Röser, D. 2008. Policy and economic aspects of forest energy utilisation, in: Röser, D., Asikainen, A., Raulund-Rasmussen, K., Stupak, I. (Eds.). *Sustainable use of forest-based biomass for energy: a synthesis with focus on the Baltic and Nordic region*. Springer, Dordrecht, The Netherlands. pp. 197–234.

Mani, S. 2005. A systems analysis of biomass densification process (Doctoral thesis). University of British Columbia.

Marinescu, M. 2013. Technical and economic analysis of bioenergy technologies at a sawmill in Anahim Lake, BC. FPInnovations.

Marinescu, M. 2012. Technical and economic analysis of bioenergy technologies at a sawmill in Hanceville, BC. FPInnovations.

Martinez-Hernandez, E., Campbell, G.M., Sadhukhan, J. 2014. Economic and environmental impact marginal analysis of biorefinery products for policy targets. *Journal of Cleaner Production*. **74**: 74–85.

Mavrotas, G. 2009. Effective implementation of the ε-constraint method in multi-objective mathematical programming problems. *Applied Mathematics & Computation*. **213**(2): 455-465.

McKay, H. 2006. Environmental, economic, social and political drivers for increasing use of woodfuel as a renewable resource in Britain. *Biomass & Bioenergy*. **30**(4): 308–315.

McKendry, P. 2002a. Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*. **83**(1): 37–46.

McKendry, P. 2002b. Energy production from biomass (part 2): conversion technologies. *Bioresource Technology*. **83**(1): 47–54.

McKendry, P. 2002c. Energy production from biomass (part 3): gasification technologies. *Bioresource Technology*. **83**(1): 55–63.

Meier, I., Tarhan, V. 2007. Corporate investment decision practices and the hurdle rate premium puzzle. Working Paper, HEC Montreal and Northwestern University.

Meyer, J.C., Hobson, P.A., Schultmann, F. 2012. The potential for centralised second generation hydrocarbons and ethanol production in the Australian sugar industry, in: *Proceedings of the Australian Society of Sugar Cane Technologists*.

Milota, M.R., West, C.D., Hartley, I.D. 2005. Gate-to-gate life-cycle inventory of softwood lumber production. *Wood and Fiber Science*. **37**(CORRIM special issue): 47–57.

Ministry of Environment. 2015. Wood residue burner and incinerator regulation. Retrieved from http://www.bclaws.ca/Recon/document/ID/freeside/51_519_95. Date of access: Nov. 24, 2015.

Ministry of Forests, Lands and Natural Resources Operations. 2012. Mid term timber supply: Williams Lake Timber Supply Area.

Mohan, D., Pittman, C.U., Steele, P.H. 2006. Pyrolysis of wood/biomass for bio-oil: a critical review. *Energy & Fuels.* **20**(3): 848–889.

Mota, B., Gomes, M.I., Carvalho, A., Barbosa-Povoa, A.P. 2015. Towards supply chain sustainability: economic, environmental and social design and planning. *Journal of Cleaner Production.* **105**: 14-27.

Murray, G. 2010. Lillooet Biomass Energy Corporation business plan for a wood pellet plant. Gordon Murray Corporate Finance Ltd.

Nagel, J. 2000. Determination of an economic energy supply structure based on biomass using a mixed-integer linear optimization model. *Ecological Engineering*. **16**(Supplement 1), 91–102.

Naimi, L., Oveisi, E., Sokhansanj, S., Sowlati, T., Law, A., Bi, X., Lim, J., Melin, S., Igathinathane, C., Skea, D., Day, K., MacDonald, J., Sauder, T., Womac, A. 2009. The performance (quality) of size reduction of woody biomass, in: *2009 ASABE Annual International Meeting*. ASABE paper number 097457, Reno, Nevada.

Natarajan, K., Leduc, S., Pelkonen, P., Tomppo, E., Dotzauer, E. 2014. Optimal locations for second generation Fischer Tropsch biodiesel production in Finland. *Renewable Energy*. **62**: 319–330.

Natural Resources Canada. 2015. Forest bioeconomy, bioenergy and bioproducts. Retrieved from http://www.nrcan.gc.ca/forests/industry/bioproducts/13315. Date of access: Oct. 27, 2015.

NETL. 2013. NETL Life Cycle Inventory Data - Unit Process. US Department of Energy. Retrieved from http://www.netl.doe.gov/research/energy-analysis/life-cycle-analysis. Date of access: Sep. 29, 2015.

Oasmaa, A., Solantausta, Y., Arpiainen, V., Kuoppala, E., Sipila, K. 2009. Fast pyrolysis bio-oils from wood and agricultural residues. *Energy & Fuels*. **24**(2): 1380-1388.

Pa, A., Bi, X.T., Sokhansanj, S. 2011. A life cycle evaluation of wood pellet gasification for district heating in British Columbia. *Bioresource Technology*. **102**(10): 6167–6177.

Palander, T., Väätäinen, J. 2012. Impacts of interenterprise collaboration and backhauling on wood procurement in Finland. *Scandinavian Journal of Forest Research*. **20**(2): 177–183.

Paragon decision technology. 2014. AIMMS - The modelling system. Retrieved from http://www.aimms.com. Date of access: Jun. 20, 2014.

Parker, N., Tittmann, P., Hart, Q., Nelson, R., Skog, K., Schmidt, A., Gray, E., Jenkins, B. 2010. Development of a biorefinery optimized biofuel supply curve for the Western United States. *Biomass & Bioenergy*. **34**(11): 1597–1607.

Pawelzik, P., Carus, M., Hotchkiss, J., Narayan, R., Selke, S., Wellisch, M., Weiss, M., Wicke, B., Patel, M.K. 2013. Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. *Resources, Conservation and Recycling*. **73**: 211–228.

Peng, J.H., Bi, H.T., Sokhansanj, S., Lim, J.C., Melin, S. 2010. An economical and market analysis of Canadian wood pellets. *International Journal of Green Energy*. **7**(2): 128–142.

Pérez-Fortes, M., Laínez-Aguirre, J.M., Bojarski, A.D., Puigjaner, L. 2014. Optimization of pre-treatment selection for the use of woody waste in co-combustion plants. *Chemical Engineering Research & Design*. **92**(8): 1539–1562.

Petersen Raymer, A.K. 2006. A comparison of avoided greenhouse gas emissions when using different kinds of wood energy. *Biomass & Bioenergy*. **30**(7): 605–617.

Popp, J., Lakner, Z., Harangi-Rákos, M., Fári, M. 2014. The effect of bioenergy expansion: Food, energy, and environment. *Renewable & Sustainable Energy Reviews*. **32**: 559–578.

Product Ecology Consultants. 2012. SimaPro Software. Retrieved from http://www.pre.nl/content/databases. Date of access: Jul. 7, 2012.

Province of British Columbia. 2013. Tourism BC: Anahim Lake. Retrieved from http://www.hellobc.com/anahim-lake.aspx. Date of access: Feb. 18, 2013.

Puettmann, M.E., Lippke, B. 2012. Woody biomass substitution for thermal energy at softwood lumber mills in the US in land Northwest. *Forest Products Journal*. **62**(4): 273–279.

Rauch, P., Gronalt, M. 2010. The Terminal Location Problem in the Forest Fuels Supply Network. *International Journal of Forest Engineering*. **21**(2): 32–40.

Rentizelas, A.A., Tatsiopoulos, I.P. 2010. Locating a bioenergy facility using a hybrid optimization method. *International Journal of Production Economics*. **123**(1): 196–209.

Rogers, J.G., Brammer, J.G. 2012. Estimation of the production cost of fast pyrolysis bio-oil. *Biomass & Bioenergy*. **36**: 208–217.

Sambo, S.M. 2002. *Fuel consumption for ground-based harvesting systems in Western Canada. Advantage*. FERIC.

Santibañez-Aguilar, J.E., González-Campos, J.B., Ponce-Ortega, J.M., Serna-González, M., El-Halwagi, M.M. 2014. Optimal planning and site selection for distributed multiproduct biorefineries involving economic, environmental and social objectives. *Journal of Cleaner Production*. **65**: 270–294.

Santibañez-Aguilar, J.E., González-Campos, J.B., Ponce-Ortega, J., Serna-González, M., El-Halwagi, M. 2011. Optimal planning of a biomass conversion system considering economic and environmental aspects. *Industrial & Engineering Chemistry Research*. **50**(14): 8558–8570.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E. 2010a. Potential of biomass-fired combined heat and power plants considering the spatial distribution of biomass supply and heat demand. *International Journal of Energy Research*. **34**(11): 970–985.

Schmidt, J., Leduc, S., Dotzauer, E., Kindermann, G., Schmid, E. 2010b. Cost-effective CO2 emission reduction through heat, power and biofuel production from woody biomass: a spatially explicit comparison of conversion technologies. *Applied Energy*. **87**(7): 2128–2141.

Scott, J.A., Ho, W., Dey, P.K. 2012. A review of multi-criteria decision-making methods for bioenergy systems. *Energy*. **42**(1): 146–156.

Shabani, N., Akhtari, S., Sowlati, T. 2013. Value chain optimization of forest-based biomass for bioenergy production: a review. *Renewable & Sustainable Energy Reviews*. **23**: 299–311.

Shabani, N., Sowlati, T. 2013. A mixed integer non-linear programming model for tactical value chain optimization of a wood biomass power plant. *Applied Energy*. **104**: 353–361.

Sikkema, R., Junginger, M., Piochler, W., Hayes, S., Faaij, A. 2010. The international logistics of wood pellets for heating and power production in Europe: costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. *Biofuels, Bioproducts & Biorefining*. **4**(2): 132-153.

Sims, R.E.H. 2003. Bioenergy to mitigate for climate change and meet the needs of society, the economy and the environment. *Mitigation & Adaptation Strategies for Global Change*. **8**(4): 349–370.

Srirangan, K., Akawi, L., Moo-Young, M., Chou, C.P. 2012. Towards sustainable production of clean energy carriers from biomass resources. *Applied Energy*. **100**: 172–186.

Statistics Canada. 2015a. Census agglomeration of Williams Lake, British Columbia. Focus on Geography Series, 2011 Census. Retrieved from http://www12.statcan.gc.ca/census-recensement/2011/as-sa/fogs-spg/Facts-cma-eng.cfm?LANG=Eng&GK=CMA&GC=950. Date of access: Apr. 16, 2015.

Statistics Canada. 2015b. Earnings, average weekly, by industry (all industries). Retrieved from http://www.statcan.gc.ca/tables-tableaux/sum-som/l01/cst01/labr73a-eng.htm. Date of access: Jul. 31, 2015.

Sultana, A., Kumar, A., Harfield, D. 2010. Development of agri-pellet production cost and optimum size. *Bioresource Technology*. **101**(14): 5609–5621.

S&T Consultants Inc. 2014. GHGenius: A model for lifecycle assessment of transportation fuels. Retrieved from http://www.ghgenius.ca/. Date of access: Jul. 7, 2014.

Thornley, P., Chong, K., Bridgwater, T. 2014. European biorefineries: Implications for land, trade and employment. *Environmental Science & Policy*. **37**: 255–265.

Thornley, P., Rogers, J., Huang, Y. 2008. Quantification of employment from biomass power plants. *Renewable Energy*. **33**(8): 1922–1927.

Tittmann, P.W., Parker, N.C., Hart, Q.J., Jenkins, B.M. 2010. A spatially explicit techno-economic model of bioenergy and biofuels production in California. *Journal of Transport Geography*. **18**(6): 715–728.

Upadhyay, T.P., Shahi, C., Leitch, M., Pulkki, R. 2012. Economic feasibility of biomass gasification for power generation in three selected communities of Northwestern Ontario, Canada. *Energy Policy*. **44**: 235–244.

Vamvuka, D. 2011. Bio-oil, solid and gaseous biofuels from biomass pyrolysis processes - An overview. *International Journal of Energy Research*. **35**(10): 835–862.

Vanclay, F. 2003. International principles for social impact assessment. *Impact Assessment and Project Appraisal*. **21**(1): 5–12.

Vanhala, P., Repo, A., Liski, J. 2013. Forest bioenergy at the cost of carbon sequestration? *Current Opinion in Environmental Sustainability*. **5**(1): 41–46.

Waito, B., Johnson, L. 2010. *A national scan of regulations & practices relevant to biomass harvesting.* Prepared for World-Wide Fund (WWF) Canada, and the Forest Products Association of Canada (FPAC).

Wetterlund, E., Söderström, M. 2010. Biomass gasification in district heating systems – The effect of economic energy policies. *Applied Energy*. **87**(9): 2914–2922.

Wright, D. G., Dey, P.K., Brammer, J. G. 2013. A fuzzy levelised energy cost method for renewable energy technology assessment. *Energy Policy*. **62**: 315-323.

Yagi, K., Nakata, T. 2011. Economic analysis on small-scale forest-based biomass gasification considering geographical resources distribution and technical characteristics. *Biomass & Bioenergy*. **35**(7): 2883–2892.

You, F., Tao, L., Graziano, D.J., Snyder, S.W. 2012. Optimal design of sustainable cellulosic biofuel supply chains: Multiobjective optimization coupled with life cycle assessment and input–output analysis. *AIChE Journa*l. **58**(4): 1157–1180.

You, F., Wang, B. 2011. Life cycle optimization of biomass-to-liquid supply chains with distributed–centralized processing networks. *Industrial & Engineering Chemistry Research*. **50**(17): 10102–10127.

Yue, D., Kim, M.A., You, F. 2013. Design of sustainable product systems and supply chains with life cycle optimization based on functional unit: general modeling framework, mixed-integer nonlinear programming algorithms and case study on hydrocarbon biofuels. *ACS Sustainable Chemistry & Engineering*. **1**(8): 1003–1014.

Yue, D., Slivinsky, M., Sumpter, J., You, F. 2014a. Sustainable design and operation of cellulosic bioelectricity supply chain networks with life cycle economic, environmental, and social optimization. *Industrial & Engineering Chemistry Research*. **53**(10): 4008–4029.

Yue, D., You, F., Snyder, S.W. 2014b. Biomass-to-bioenergy and biofuel supply chain optimization: overview, key issues and challenges. *Computers & Chemical Engineering*. **66**: 36–56.

Zamboni, A., Bezzo, F., Shah, N. 2009. Spatially explicit static model for the strategic design of future bioethanol production systems. 2. Multi-objective environmental optimization. *Energy & Fuels*. **23**(10): 5134–5143.