On the design and analysis of forest biomass to biofuel and bioenergy supply chains

by

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

The Faculty of Graduate and Postdoctoral Studies

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

April 2015

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Abstract

The efficient management of a diverse portfolio of resources is vital for sustainable economic growth in the bioenergy and biofuel sector. Considerable complexities and inherent uncertainties in supply and demand, and ever evolving technology for the utilization of biomass necessitate careful design and management of supply chains. Supply chain modelling is commonly implemented to develop “decision support tools” required in the planning of highly integrated, multi-faceted value-adding processes. This thesis demonstrates an object-oriented approach to simulate the supply chain of forest biomass to biofuel and bioenergy in three case studies in British Columbia, Canada. Three main sources of complexity, namely uncertainties, interdependencies, and resource constraints, are considered in system parameterization and model development. After verification and validation, the models are used as a representation of the system to conduct model-based analysis. The supply chain of forest biomass for large-scale power generation is considered in the first case study. Different harvesting systems are considered that are employed based on the limitations on the annual harvest volume, characteristics of the stand, and intended products. Reliability of feedstock supply over the project’s lifespan, and the delivered costs were subject of the analysis. Demand fulfilment at the power plant and the cost of raw materials depend on the realized harvest volume, dictated by the practice of primary wood processing facilities. The delivered cost to the plant shows an ascending trend during the planning horizon, further complicating the investment. The second case study concentrates on the wood pellets production and distribution supply chains; modifications in an existing system are evaluated through simulation, and assessment of integrating torrefaction into the chain is carried out. Torrefaction technology promises an opportunity to reduce the distribution cost of wood pellets in the presented case study, contingent on the market readiness and fluctuating prices. Combined heat and power generation is considered in the third case study where modifications to an existing supply chain are evaluated. Realization of the vast bioenergy and biofuel potentials in BC requires coordinated planning across the forest biomass supply chains, and simulation modeling provides valuable decision support tools to facilitate future investments.

Preface

This dissertation presents the original work carried out by the author, Mahdi Mobini, during his PhD program. Defining the research scope and the objectives of the project, as well as the selection of the methodology were supervised by the research advisor, Dr. Taraneh Sowlati, and committee members Dr. Kevin Lyons and Dr. Shahab Sokhansanj. The author made several site visits and had numerous communications with industrial experts in order to gather the required data and information to perform this research. Model development and the analysis were carried out by the author. The simulation modules for torrefaction process, presented in Chapter 4, were developed in collaboration with Dr. Joern Meyers, Dr. Frederik Trippe, from Karlsruhe Institute of Technology. The experimental data on the quality of feedstock used in Chapter 5 were obtained from Mr. Ehsan Oveisi from Biomass and Bioenergy Research Group at UBC.

Manuscripts based on the models and case studies presented in Chapters 3, 4 and 5 were generated by the author. The complete publication list is shown below.

Chapter 3: Mobini, M., Sowlati, T. & Sokhansanj, S. 2011, "Forest biomass supply logistics for a power plant using the discrete-event simulation approach", *Applied Energy*, vol. 88, no. 4, pp. 1241-1250.

Mobini, M., Sowlati, T. & Roser, D. 2014. Analysis of forest biomass supply chains: applications of simulation modeling [Homepage of NSERC Strategic Research Network on Value Chain Optimization (VCO)], [Online]. Available: http://www.reseauvco.ca/fileadmin/vco/documents/Webinairs/Mobini_VCO_Transfer_Project_Nov_18_2014.pdf.

Chapter 4: Mobini, M., Sowlati, T. & Sokhansanj, S. 2013, "A simulation model for the design and analysis of wood pellet supply chains", *Applied Energy*, vol. 111, pp. 1239-1249.

Mobini, M., Meyer, J., Trippe, F., Sowlati, T., Fröhling, M. & Schultmann, F. 2014, "Assessing the integration of torrefaction into wood pellet production", Journal of Cleaner Production, vol. 78, no. 1, pp. 216-225.

Chapter 5: Mobini, M., Sowlati, T., Oveisi, E. & Sokhansanj, S., Supply chain simulation of combined heat and power generation from urban waste biomass, in preparation.

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List of Abbreviations

AAC	Annual allowable cut
ACC	Annual capital cost
ABS	Agent based simulation
AC	Ash content
APS	Advanced planning and scheduling
BC	British Columbia
BD	Bulk density
CHP	Combined heat and power
dt	Dry tonne
EMC	Equilibrium moisture content
GHG	Greenhouse Gas
GIS	Geographical information system
HV	Heating value
MC	Moisture content
MPB	Mountain pine beetle
OOS	Object oriented simulation
PMH	Productive machine hour
PSC	Pellet supply chain
PDF	Probability distribution function
PS	Particle size
ROP	Re-order point
SHH	Scheduled machine hour
TBF	Time between failure
TCC	Total capital cost
TSA	Timber supply area
TTR	Time to repair

List of Symbols

Symbol	Description	Unit
ACC	Annual capital cost	$
AC	Ash content of wood per dry tonne	%
dW_{in}	Dry mass of infeed material	dt
E	Electricity price	$ kWh^{-1}
EMC	Equilibrium moisture content	%
G_b	Basic specific gravity of wood (oven dry mass per green volume)	dt m^{-3}
G_{MC}	Specific gravity of the specie (dry mass of wood per m^3 at moisture content MC)	dt m^{-3}
H	Relative humidity	%
HV	Higher heating value of fuel	kWh dt^{-1}
HD	Dryer heat demand	kWh t^{-1}
HD_g	Gasifier heat demand	GJ h^{-1}
i	Annual interest rate	%
lh	Evaporation enthalpy	kJ kg^{-1} K^{-1}
MC	Moisture content	%
MC_{Fuel}	Moisture content of fuel	%
MC_t	Target moisture content	%
N	Service life of the plant	year
P	Equipment power	kW
Q_{supply}	Supplied thermal energy	KJ
Q_{demand}	Thermal energy demand of the torrefaction reactor	KJ
Q_{excess}	Excess heat of the torrefaction process	KJ
R_{Heat}	Required heat	kWh
SF	Simultaneity factor	%
T	Temperature	°C

Symbol	Description	Unit
TCC	Total capital cost	$
$t_{boiling}$	Boiling temperature	°C
t_{in}	Temperature of the infeed	°C
$t_{torrefaction}$	Torrefaction temperature	°C
W	Processed mass	t
$W_{eva.}$	Mass of water	t
W_{in}	Infeed material mass	t
W_{Fuel}	Required mass of fuel	t
y	Yield in a given stand group	m^3 ha^{-1}
δ	Equipment productivity adjustment factor	%
γ	Efficiency of biomass burner	%
Δt	Period of time	h
η	Efficiency of torrefaction gas burner and heat exchange	%
θ	Heat capacity of water	kJ kg^{-1} K^{-1}
θ'	Heat capacity of steam	kJ kg^{-1} K^{-1}
$\bar{v}_i$	Average volume per tree in a given stand group *i*	m^3
ϱ	Heat capacity of ash	kJ kg^{-1} K^{-1}
σ	Heat capacity of biomass	kJ kg^{-1} K^{-1}
φ	Torrefaction heat demand	kJ kg^{-1}
∂	Fraction of input energy contained in torrefaction gas	%

Acknowledgements

First and foremost I would like to express my gratitude to Dr. Taraneh Sowlati, my supervisor, for the support and guidance throughout my PhD program. Also, I would like to thank the supervisory committee members, Dr. Kevin Lyons and Dr. Shahab Sokhansanj, for their constructive feedback and comments. I wish to extend my appreciation to Mr. Robert Tarčon and Dr. Dominik Roser for invaluable collaboration, and to my colleagues in the UBC Industrial Engineering Research Group for the productive discussions.

This research is mainly funded by the UBC Four Year Doctoral Fellowship and in part through collaborative research and development between UBC, Natural Sciences and Engineering Research Council of Canada, and Wood Pellet Association of Canada.

Words fail to describe my gratitude to my parents, Shahrzad Sadeghian and Ali Mobini Dehkordi, and my siblings Zahra, Hadi, and Zeinab. Without their support and encouragement it would have never been possible for me to achieve my goals.

To my beloved family for their unconditioned and unceasing love and dedication.

Chapter 1. Introduction

1.1 Background

Fossil fuels account for approximately 80% of all energy consumed globally (REN21 2014), yet their finite availability, insecure distribution network, volatile pricing and negative environmental impacts have created a major renaissance in the renewable energy movement. Biomass, hydro power, wind, solar, and geothermal are all major renewable energy resources, among them, biomass has received attention for its carbon-neutral nature, for being locally available, and for the relatively easier storage and conversion to energy (Richardson 2002). The use of biomass for energy production (i.e. bioenergy) has increased in many countries in order to mitigate global warming, create jobs, and secure energy supply (Junginger et al. 2014). It is forecasted that our reliance on bioenergy will continue to grow globally and bioenergy will become a major proportion of the energy supply considering the size of potentially available resources, market demands, and technological trends (Berndes et al. 2003, Liu et al. 2014).

Canada is a natural-resource rich country with an abundance of forest and grassland biomass that retains a promising prospects for an increased generation of bioenergy. Currently, biomass derived from a mix of “forest biomass”, landfill methane gas, biogas, municipal solid wastes, and agricultural residues accounts for 8% of the total renewable energy supply in Canada (Nyboer et al. 2011). Forest biomass is defined as the accumulated, above- and below-ground mass of the wood, bark, and leaves of woody shrub and tree species (Young 1980). The province of British Columbia (BC) has the largest forest biomass harvest operations in Canada with an annual volume of 77.3 million m^3 (BC MFLNRO 2011). Forest biomass, in different forms such as residues from harvesting activities and milling by-products and wastes, is used as a renewable source of energy in the BC which has more than 1600 MW of bioenergy (heat and/or power) generation capacity and 3.2 M t of wood pellet production capacity (Bradley 2010, Cocchi et al. 2011). Ralevic and Layzell (2006) estimated that, in addition to the existing capacity, theoretically 21% of the annual fossil fuel consumption in BC could be replaced by utilizing biomass from sustainable forestry operations. There has been an increased interest in using harvesting residues left in the forest area (commonly considered as waste and burned at a proper time) for bioenergy production (BIOCAP 2008, Campbell et al. 2008, Verkerk 2008). It is estimated that up to 32.3 million dry tonnes (dt) of sustainably supplied forest biomass could be used for bioenergy and biofuel production in BC (Campbell et al. 2008, Bradley 2010, Dymond et al. 2010, Lloyd et al. 2014).

All these estimates suggest that there is a significant potential for additional forest biomass-based bioenergy and biofuel projects in BC, however, there are several barriers to realization of this potential. Bioenergy and biofuel projects are capital intensive, therefore investment grants play a critical role in economic feasibility of bioenergy projects in order to make them competitive with conventional fuels. Successful implementation of bioenergy projects also requires sound technical and managerial knowledge of the installation and operation of the conversion technology and the logistics systems to keep operational costs manageable (Awudu and Zhang 2012). Furthermore, bioenergy projects are inherently tied to local contingencies. The composition of input biomass impacts the design, planning, and performance of the supply chain, and thus the economics of the project (Baxter et al. 2011, Liu et al. 2014). Consequently, one of the key barriers to economic viability of bioenergy projects is the cost of pre-processing and delivering biomass to the conversion facility (Liu et al. 2014, Wolfsmayr and Rauch 2014). In bioenergy projects, efficient management of a vast portfolio of the resources, including raw materials, personnel, and equipment is required to maximize the return on capital investment, which necessitates careful design and management of the supply chains.

The major driving force in the implementation of bioenergy projects is the mitigation of Greenhouse Gas (GHG) emissions and other negative environmental impacts of the fossil fuels. Therefore, it is essential that the environmental benefits of using biomass prevail over the environmental impacts, associated with the production, collection and supply of biomass (Allen et al. 1998). The importance of considering the environmental and economic aspects of the bioenergy, in addition to the complexity of local level contingencies create the need for devising advanced decision support tools to ensure the project’s success.

1.2 Problem description

Different processes and activities are carried out in order to transform the raw materials, i.e. forest biomass, to the final products and deliver them to customers. The set of these processes and activities constitute the forest products supply chains, which are composed of various interrelated and interdependent organizations producing different products and serving different markets.

Forest products supply chains have features that differentiate them from many other industries. The supply chains have a divergent structure; multiple products originate from the source material. The large number of actors across the chain is a major source of complexity; each stage of the supply chain requires decision making that not only affects its immediate outcome, but also influences downstream practices, therefore, integrated design and coordinated decision making across the supply chain is needed to reduce the overall costs, and improve the robustness and competitiveness of the supply chains (D'Amours et al. 2008, Sharma et al. 2013).

Other sources of complexity in the supply chains root in dynamics of the system in terms of spatial distribution, temporal availability and accessibility of resources, and heterogeneous physical properties of biomass. The local availability and accessibility of forest biomass contributes to complexity of the supply chain (Ruiz et al. 2013), where harvest sites are usually geographically dispersed and have slow and uncertain regeneration rates complicating the supply chain design and management. The quality of raw material is another complicating factor given that different tree crops can have varying physical properties and the physical properties of biomass in general can create logistical challenges (Demirbas 2001, Richardson 2002). For example, low bulk density of harvesting residues increases transport volume and cost, its low heating value and high moisture content raises processing costs, and its inhomogeneous shape affects the standardization of equipment and logistical operations. The effects of inherent complexities on supply chains are widely emphasized in the literature (De Meyer et al. 2014, Mafakheri and Nasiri 2014).

Access to reliable supply of feedstock is essential in bioenergy and biofuel applications. The procurement costs of raw materials and market demand for primary wood products influence the security of raw materials supply for bioenergy projects that tides the supply chains to other wood processing chains (Richardson 2002). This underlines the utmost importance of coordinated planning across the forest biomass supply chains to realize the forest-based bioenergy potentials.

In order to incorporate the different factors affecting the success of bioenergy projects, while considering the aforementioned complexities, reliable decision support tools are required. Mathematical modelling provides valuable insights in the design, planning, and analysis of the supply chains; hence, different modelling approaches are used in different stages of the projects with various purpose and objectives.

Optimization modelling is used to find the best alternative(s) from a pre-specified feasible solution space for the decision variables, whereas, simulation modelling of the supply chain is implemented to provide a representation of a given state of the system (not necessarily the optimum) to understand and analyze the response of the supply chain under different conditions. Stochastic optimization and simulation modelling approaches are used in supporting decisions related to design and planning of supply chains considering uncertainties in different aspects of the supply chains. Agent-based and object-oriented models are developed to support integrated planning of several autonomous organizations (with dynamic interactions and interconnections) over the planning horizon that is usually long-term. To cope with the challenges and disadvantages of simulation and optimization models, development of hybrid models has gained attention. A review of different modelling approaches used in previous studies in greater detail is provided in Chapter 2. The object-oriented simulation underpins the work presented in this thesis, where three simulation models are developed to support decision making in biofuel and bioenergy supply chains.

1.3 Research objectives

The overall goal of this thesis is to evaluate the supply chain of forest biomass for biofuel and bioenergy production considering the uncertainties, interdependencies, and resource constraints along the chain. The focus in this thesis is on three case studies with the following specific objectives:

a) Evaluate the availability and stability of feedstock supply and its associated costs for electricity generation in a large-scale power plant (Case Study 1).

b) Analyze an existing wood pellet production and distribution supply chain, investigate the effects of changing the supply chain configurations on the final cost of wood pellets, and assess the integration of torrefaction into the wood pellet supply chain (Case Study 2).
c) Analyze supply chain of biomass utilized for combined heat and power (CHP) generation, and evaluate the effect of changes in the sources/types of raw materials and pre-processing stages on the final cost (Case Study 3).

Stochastic simulation modelling was chosen as the method for achieving the objectives. The simulation models are developed based on the information and data obtained from the industrial experts and the literature specific to each case study. After verification and validation, the models are used as a representation of the actual system to conduct model-based analysis. Three simulation *models,* comprised of several simulation *modules,* are developed and used to support decision making regarding the design and planning of forest biomass supply chains. Discrete-event and discrete-rate approaches are combined in an object-oriented simulation environment, ExtendSim (Imagine That 2011), to develop the supply chain models. This combination enabled the development of models capable of incorporating dynamic features of the systems, respective to the scope of the study.

The first case is on the direct combustion of forest biomass at a power plant. The widespread mountain pine beetle (MPB) infestation has substantial implications for forest products industry in BC (Brown et al. 2010). To take advantage of the leftover harvesting residues and the increasing availability of underutilized volume in Quesnel Timber Supply Area (TSA) in Quesnel, BC, the development of a 300 MWh power plant was suggested (Kumar et al. 2005). To address the questions related to the stability of the supply over the lifespan of the power plant, and to estimate the delivered cost of feedstock a simulation model is developed. The choice of comminution equipment and the location of processing (and/or pre-processing) in the forest biomass supply chain are among the most important decisions in designing a supply system for fuelwood (Richardson 2002). Three applicable harvesting systems are considered in the case study based on the literature specific to the area (MacDonald 2006). The object-oriented simulation is selected as the appropriate modelling methodology to incorporate the uncertainties of equipment failure, the effects of weather conditions on equipment performance, interdependencies between processes, and other miscellaneous criteria.

The second case study examines the production and distribution of wood pellets from forest biomass as a solid biofuel. Pelletization (densification) of biomass increases the energy density and produces a homogeneous shape that facilitates its transportation and consumption as fuel. Simulation modelling of the entire supply chain, from sources of biomass to the end users is performed. The model is used as a tactical-level decision support tool for evaluating changes in the mixture of raw materials and drying fuel. It is also used as a strategic-level decision support tool to assess the integration of torrefaction into the wood pellet production and distribution supply chain.

The third case study assesses the gasification of woody biomass in a CHP plant. The supply chain includes a set of suppliers that provide different types of biomass, including green wood chips, harvesting residues, hog fuel, and trim ends. The biomass is transported to a collection yard where pre-processing operations including size reduction, screening, and mixing are carried out. The feedstock is then transported to the plant based on the inventory level at the plant. The difference between this supply chain and that of the large-scale power plant are the addition of the collection yard and storage at the CHP plant (which insert urban traffic restrictions), and the division of the upstream supply of raw material into two tiers each managed separately. The simulation model, developed based on the case study, is used at the tactical and operational levels, to estimate the delivered cost of different types of biomass with different preprocessing stages.

1.4 Structure of the thesis

Chapter 2 presents a literature review of the studies focused on forest biomass supply chains with emphasis on simulation models. Chapter 3 presents the development and application of a simulation model for evaluation of cost and availability of forest residues from beetle infested forest area in Quesnel, BC for bioenergy production. The wood pellet production and distribution supply chain is the focus of Chapter 4. The supply chain of CHP generation from woody biomass is the subject of Chapter 5. Finally, conclusions, strengths, limitations, and directions for future research are presented in Chapter 6.

Chapter 2. Literature review

2.1 Introduction

Careful design and management of biomass supply chains are essential for realization of the bioenergy potentials. Effective implementation of supply chain management, leading to efficient decision making throughout the project's planning horizon, can contribute to the sustainability of the bio-industry by minimizing the environmental impacts, minimizing costs, maximizing the value, and maximizing the benefits to the society (Gold and Seuring 2011). Hence, different approaches are employed to model biomass supply chains and develop decision support tools. Each approach has its advantages and disadvantages and is opted respective to the decision problem under study.

Deterministic supply chain models that describe the supply chain using simple mathematical formula in a single-period or multi-period basis are commonly used in early stages of investment evaluation and general assessments of the potential supply chain configurations. These models are relatively fast to develop and easy to understand and are used for conducting initial feasibility analysis, and when more elaborated in techno-economic bioenergy assessment studies (for recent applications see (Akhtari et al. 2014)). Dynamic features of the system, such as temporal and geographical dependencies of the parameters of the system, are not fully represented in these models. Average expected values of the input parameters of the system are used; although sensitivity analyses are conducted to evaluate the effects of changes in different parameters on the outputs of the models, the effects of concurrent changes and other complexities are barely reflected. Therefore, deterministic models fail to capture the dynamics of the real system and the extent of complexity required in describing the supply chain.

Mathematical optimization models are commonly developed to enhance strategic and tactical planning of the supply chains by providing the optimum solution for a set of objective functions, subject to a set of constraints. The majority of their applications in the forest biomass supply chains are concerned with integrated tactical and strategic-level planning (Kim et al. 2011, Shabani et al. 2013, Mafakheri and Nasiri 2014), while operational decisions are usually addressed separately for different stages of the supply chain. Selection of the conversion technology and finding the optimum location and capacity of the conversion plants are strategic-level decisions that are bioenergy-related questions commonly addressed using optimization models. Also, optimization models have been used to assess when and where to process forest residues, how to transport stored residues in order to satisfy the demand at heating plants, whether or not additional harvest areas and sawmills need to be contracted and many other strategic and tactical supply chain decision problems (for a recent review see (Shabani et al. 2013, Sharma et al. 2013, De Meyer et al. 2014, Mafakheri and Nasiri 2014)).

The main challenges in development and application of supply chain optimization models include incorporating the uncertainties, developing the relationships explaining the interdependencies between different components of the system, and keeping the computational costs at a reasonable level. Deterministic optimization models aiming for integrated supply chain planning are therefore built based on simplifications of the system so that the underling mathematics can be solved (Klibi et al. 2010, Campuzano and Mula 2011). Moreover, the interdependencies between different processes/stages are usually simplified in this type of models; thus, in some cases models do not represent the complexities that might significantly alter the final decisions.

More recently, stochastic optimization models have been used to incorporate the uncertainties in the planning of forest biomass supply chains. Scenario-based optimization, robust optimization and other methods are used to deal with the uncertainty in raw material supply, demand, price, conversion yield, and carbon tax and emission reduction policies, e.g. see (Kim et al. 2011, Kazemzadeh and Hu 2013, Azadeh et al. 2014, Shabani 2014, Tong et al. 2014). Stochastic optimization methods rely on finding feasible solutions for all or a selected number of possible scenarios under certain conditions (Klibi et al. 2010, Sharma et al. 2013). These approaches are well-fitted for long- and medium-term decision problems, however, when the planning periods are broken down into several time steps, e.g., weekly or daily, the complexity of the solution procedure and computational costs unmanageably rise and limit the applications.

Simulation modeling of the supply chains is performed when the interdependency between actors becomes intractably complex and the underlying relationships between variables become non-linear, or when there is too much uncertainty to parameterize. A supply chain can be too large and complex to be mathematically formulated, but most supply chain entities can be coded as a simulation object and can be parameterized based on a set of inputs and outputs (Buckley and An 2005). Tactical and operational planning of the forest biomass supply chains is often the focus of simulation studies since the supply chain structure is highly multifaceted and describing the interactions within and between system components is difficult, if not impossible, using other types of models. Incorporating uncertainties in the simulation models is more straightforward than in optimization models, provided that the required data are available. Supply chain simulation can offer valuable information about the most important variables in the supply chain and the interdependencies between the actors; hence, it can be used to experiment with new policies and decision rules across a wide array of conditions (Campuzano and Mula 2011). While static and optimization models have proven useful in supporting the supply chain decision problems, simulation models offer a greater flexibility and comprehensiveness, which lends itself to the objectives of this research.

The evaluation of biomass supply chains pose consideration of various dynamic and uncertain factors, such as supply, demand, costs, prices, operations productivity, weather condition, etc. Monte-Carlo, discrete event, and continuous (system dynamics) simulation approaches are the most prevalent adopted approaches and the applications include, but not limited to, predicting the performance of harvesting machines under different conditions (Eliasson 1999, Bergstrom et al. 2007, Ersson et al. 2013), planning the harvesting operations (McDonagh et al. 2004, Wang et al. 2005, Hogg et al. 2010), assessing different biomass transportation systems (Ravula et al. 2008, Acuna et al. 2012b), analysing sawmill operations (Baesler et al. 2004, Grigolato et al. 2011), devising inventory planning systems (Vinterbäck 2004), estimating the logistics costs of bioenergy feedstock and other types of forest biomass with different configurations of the harvesting systems (De Mol et al. 1997, Mahmoudi et al. 2009, Zamora-Cristales et al. 2013).

Agent-Based Simulation (ABS) and Object Oriented Simulation (OOS) approaches are more advanced modeling approaches that have attracted increasing attention due to their capability in describing complex systems and for their ability to cope with the extensive amount of required data manipulation (by using structured databases) and computational costs of the models. These approaches are commonly employed in decision making problems where integrated planning of several components of the supply chain (with dynamic interactions and interconnections) in a usually long-term planning horizon is envisioned (Kleijnen 2005, Allen 2011). Different supply chain management paradigms, e.g., centralized versus decentralized decision making, information and resource sharing, collaboration and/or competition of autonomous entities, and various inventory policies are studied by means of these types of models (Macal and North 2010). Also, development of hybrid simulation and optimization models of supply chains are conducted using the ABS and OOS models commonly for coordinated strategic, tactical and operational planning of the supply chains (Manzini et al. 2005).

A general review of the recent literature on the simulation models used in the forest biomass supply chains is presented in the remainder of this chapter. Thinning and harvesting operations, logistics of forest harvesting residues, and mill operations, are the main areas of application that are usually modelled by Monte-Carlo, system dynamics and discrete-event approaches. Applications of ABS and OOS in the biomass supply chains are more focused on the long-term supply chain planning which are also reviewed in the followings.

2.2 Simulation of forest biomass supply chains

In developing accurate and informative decision support tools, there are a number of key processes along the biomass supply chain that have often been subject of simulation modeling. One such process is the thinning of younger stands (pre-commercial and commercial), which in managed forests is conducted to control and tend the growth of the trees with regards to the intended end-products and harvesting cycles. In order to make the thinning residues an economically attractive source of biomass high efficiency and productivity of operations are needed (Hakkila 2005). Time studies and simulation modeling were conducted to evaluate the performance of different equipment and test the thinning operation plans and policies. Table 2-1 lists a few recent simulation studies concerning thinning operations with brief explanations on the scope of modeling and the major findings.

Table 2-1. Selected recent simulation studies focused on forest thinning operations.

Reference	Brief explanation and major findings
Talbot et al. (2005)	Simulated two methods for in-field chipping and extraction of biomass during thinning operations. In the first method, a mobile chip-harvester travels on the strip roads, and when the capacity of the bin is reached it returns to the landing and loads the bin-trucks. In the second system, the chip harvester is coupled with a bin forwarder that transports the chips to the landing. The selection of the best alternative was dependent on the chipper productivity, bin size, and in-field extraction distances.
Bergstrom et al. (2007)	Simulated the performance of accumulating felling heads in thinning operations. Estimated that up to 44% increase in productivity was achievable compared to a single tree felling system.
Sängstuvall et al. (2012)	Developed simulation models to assess the performance of forest thinning machines. Costs were estimated based on existing conditions and projected advancements in the machines.

Among the most important decisions in the biomass supply chains is the choice of equipment and the suitable harvesting systems, which have been supported by means of simulation modeling approaches. In fact, simulation has proven to be a useful tool in analyzing logging operations and comparing alternative harvesting systems (Talbot et al. 2003). Selection between alternative systems under various circumstances and scheduling the operations are decisions problems commonly addressed in simulation studies. An important source of uncertainty in the biomass supply chains is related to the effects of terrain conditions on the performance of the equipment that were incorporated in the simulation studies in the literature, providing a realistic perspective of the actual system. Transportation management is another area of applications for simulation modeling in the forest biomass supply chains. Seeking improvement opportunities in the existing systems by changing the trucks' assortments and loading/unloading procedures, finding the number of required trucks to minimize the waiting times, and comparing different transportation modes are conducted through simulation modeling. Table 2-2 provides a brief review of selected recent studies concerning the performance of harvesting systems and transportation of logs.

Table 2-2. Selected simulation studies focused on forest harvest operations and biomass transportation.

Reference	Brief explanation and major findings
Asikainen (2001)	Simulation models were developed for comparing the alternatives in logging and barge transportation of timber from forest islands. The waiting times of the equipment caused by the interactions between them were found as a decisive factor. The results indicated that for short distance transportation (< 30 km) using a small barge was sufficient since the harvesting and forwarding could be continued without interruptions. When long transportation distances (>150 km) were involved, increasing the number of barges would be necessary to keep the balance between harvesting and barging operations.
McDonagh et al. (2004)	Developed a simulation model to evaluate the productivity of different harvesting systems under various terrain conditions. Four common harvesting systems in southeast US were included in this model. Based on the changes in stand and terrain parameters (slope and average extraction distance), the performance of each harvesting system was estimated and the best alternative was suggested.
Wang et al. (2005)	A simulation model developed and used to evaluate the cut-to-length harvesting method using different sets of equipment.
Väätäinen et al. (2005)	Used simulation modelling to evaluate the possible improvements for the queuing the trucks at the unloading stations in a power plant. It was estimated that increasing the unloading rate from 146 m^3 h^{-1} to 200 m^3 h^{-1} reduced the average waiting time from 65.5 minutes to 19.5 minutes. Also, controlling the arrival schedule of the trucks proved to be an effective approach to reduce the waiting times. The study suggested that increasing the unloading capacity along with efficient truck scheduling could reduce the waiting time to 6.5 minutes.
Hogg et al. (2010)	Simulation modelling was performed in order to analyze different harvesting systems in South Africa. Time studies were conducted on a multi-stem mechanized harvesting system, which included felling operation followed by skidding, delimbing and debarking at the roadside, cross cutting and loading to the trucks. The model was built based on the existing system and the results of the time study and was used to develop two hypothetical scenarios. The first alternative included the same set of equipment as the existing system with changes in the parameters of the model related to the scheduling procedures (daily shifts, scheduled maintenance times, etc.), and the second alternative included a new set of equipment.

Planning for post-harvest extraction of leftover residues for bioenergy applications is another area for which simulation modeling is performed. Selection of comminution (size reduction) device and the location of comminution along the supply chain are among the most important decisions in designing the system (Richardson 2002). Simulation modeling was conducted to estimate the cost of feedstock delivered to the energy plants with different configurations of the supply chains. Issues regarding storage and handling of forest biomass are considered in the simulation studies. Also, the input energy consumed during the logistical operations was estimated as the environmental footprints. Due to low bulk density of harvest residues transportation of the material is costly and simulation modeling was conducted to analyze the different transportation modes. A brief list of studies concerned with the decision problems in the pre-processing and transportation of harvesting residues is provided in Table 2-3.

Table 2-3. Simulation studies on the harvesting residue supply chains.

Reference	Brief explanation and major findings
Gallis (1996)	The effects of changes in storage duration of biomass, interest rate, and employed equipment for supplying forest biomass were studied. The storage duration was found as an important factor affecting the final cost. Through scenario based analyses, authors concluded that reducing the storage duration significantly reduced the final cost of delivered biomass.
De Mol et al. (1997)	Used simulation to estimate the cost and input energy of biofuel collection and supply for a power plant in The Netherlands. The logistics system considered in the study included pre-treatment (size reduction and/or drying), transportation, storage, and handling operations.
Asikainen (1998)	Chipping and trucking of harvesting residues were studied. Simulation models were developed to compare mobile chipping (with three different truck configurations) and stationary chipping performed at a terminal storage. In the mobile chipping system, on site chipping was modelled either as chipping directly into a truck or chipping onto the ground and loading by wheel loaders. The simulations suggested that using a separate loader in order to decouple chipping and trucking operations provided the minimum cost. The results also showed that considering the waiting times due to the interactions of the machines were important in estimating the costs; if the interactions between the chipping and trucking were not considered the results would vary by 20%.

Reference	Brief explanation and major findings
Hall et al. (2001)	Developed a deterministic simulation model to estimate the logistics costs of different forest residue delivery systems to a biomass power plant in New Zealand. Seven configurations of the delivery system were modelled and compared. The sensitivity analysis showed significant effects of moisture content and bulk density on the delivered cost of biomass.
Mahmoudi et al. (2009)	Logistics of forest biomass for bioenergy production was modelled in the interior BC. The case study was a potential 300 MW power plant near the city of Quesnel, BC suggested by Kumar et al. (2005). The model provided estimates of quantity, unit cost, supply time, moisture content and carbon emissions of the logistics system. Delays in the processes caused by the weather conditions, and fluctuations in the moisture content of biomass over time were incorporated, and stochastic processing times were considered. They concluded that the biomass availability would be a serious issue in the feasibility of the project when the harvesting residues were considered as the only source of raw material. Also, it was estimated that the delivered cost of feedstock can be reduced by about 10% if the operations were completely shut down during the spring break-up (April and March) and in the fall freeze up (September and October), because, the highest amount of rain precipitation was during these four months.
Asikainen (2010)	A simulation model on the stump crushing and truck transportation of the wood chips is developed. It was used to find the optimum number of trucks relative to the distance from the harvest area. The comparison of obtained results from the simulation model and the static spreadsheet model showed that consideration of the stochastic elements, such as machine productivity, truck travel times, and equipment interactions can significantly affect the obtained results and the drawn conclusions.
Karttunen et al. (2012)	Barge transportation of forest harvesting residues was simulated. The results indicated chipping at the roadside and barge transportation to the utilization location was a cost-efficient option when travel distances were 100-150 km.
Zhang et al. (2012)	Developed a simulation model of the supply chain of biomass to biorefineries. The model includes harvesting, pre-processing, and storage activities and estimates costs, energy input, and CO_2 emissions. It was used for strategic planning of the supply chain by finding the optimum location and capacity of biorefinery plants in a given region. Given the nature of the decision problem, this model does not account for the equipment failure and weather related delays, deterministic parameters are used e.g., for the truck loads, travel speeds, equipment availability, and biomass specifications.

Reference	Brief explanation and major findings
Zamora-Cristales et al. (2013)	Developed a discrete-event simulation model to analyze the cost of using a mobile chipping system for preprocessing of harvesting residues for bioenergy production. The model was used to compare four transportation alternatives in a case study. The alternatives included using two single trailer trucks, three single trailer trucks, two double trailer trucks, and three double trailer trucks. The results showed that using two double trailers trucks was the most cost-effective option. The sources of uncertainties considered in this study were traveling, processing, and unloading times of the mobile chipper in addition to the travel times, and loading and unloading times of the trucks. However, the variations in the moisture content and bulk density of the biomass were not considered.
Spinelli et al. (2014)	Used simulation modelling to compare two different approaches in logistics of forest harvesting residues: chipping at the roadside and chipping at the landing. The model was developed and validated based on the results of time studies. It was concluded that in the given case study chipping at the roadside and employing two chip vans would provide the best configuration.
Eriksson (2014)	Developed discrete-event simulation models to evaluate the logistics issues of extraction and consumption of stump wood as a source of bioenergy in Sweden. Different configurations of the supply chain were compared in terms of the delivered cost. The lowest cost was estimated when on-site stump crushing and self-loading trucks are employed. The importance of minimizing the equipment idle times and efficient inventory control were evident in the simulation results.

Simulation modelling has been implemented to conduct experiments in the sawmilling industry as a major part of the forest products industry; flow of biomass inside the plants is modeled and decisions such as equipment replacement, plant layout design, analyzing flow of materials, and production scheduling and inventory control are the most commonly addressed aspects of the systems. A list of sample studies in this area is given in Table 2-4.

Table 2-4. Simulation studies focused on milling operations.

Reference	Brief explanation and major findings
Randhawa et al. (1994)	Developed an OOS environment that allows rapid prototyping of sawmill operations with various configurations of the equipment and facility layout.

Reference	Brief explanation and major findings
Reeb (2003)	Used a simulation model to assess the impact of adding a new lumber grader equipment to the processing line of a planer mill and estimated 34% increase in the generated profit as the result.
Baesler et al. (2004)	Developed a sawmill simulation model that was used to identify the bottleneck by analyzing different configurations. Opportunities for improvement were assessed using the simulation model and results showed that up to 25% increase in the productivity of the plant was possible.
Vinterbäck (2004)	Demand forecasting in wood pellet industry was conducted by a simulation model. Historical weather data were used to estimate the daily pellet consumption of the small-scale customers. The results of the simulation model were used in an 'order-point inventory model' (Bierman et al. 1991) to support the distribution and inventory planning.
Thoews et al. (2008)	A simulation modelling approach was used to evaluate improvement opportunities in a sawmill.
Grigolato et al. (2011)	Used simulation to evaluate the effects of variability in log diameter and different facility layouts in a sawmill. Instalment of a new cut-saw machine and controlling the distribution of log diameter were suggested as improvement opportunities with up to 56% expected increase in the productivity of the plant.

2.3 Agent-based and object-oriented simulation modelling in the forest products industry

Agent-Based Simulation (ABS) and Object Oriented Simulation (OOS) modelling have gained extra attention in supply chain planning due to their ability to consider multiple, interdependent entities which act over differing temporal and spatial scales. "ABS" and "OOS" are used interchangeably in the supply chain modelling context and refer to models where several "*agent*" or "*entities*" represent individual components of a supply chain. Distributed decision making can then be interrogated at multiple levels across the chain while the interactions between the components are captured. Whereas earlier applications of this approach are called OOS, e.g., (Randhawa et al. 1994, Gallis 1996, Chu 1997), more recent publications use the term ABS. The ABS modelling is conducted in an object-oriented programming environment in which "*agents*" are developed, thus the two methods are closely related. To emphasize that the simulation models developed in this thesis represent the supply chains as a composition of "*supply chain objects*" (such as harvesting equipment and vehicles) and decision making "*entities*" (such as inventory planning and transportation scheduling entities) the term OOS is used in the following chapters to refer to the type of simulation approach adapted in this thesis. For cited literature in the following paragraphs the specific term used by the authors are used.

Moyaux et al. (2004) presented an ABS model developed based on the Quebec forest products industry. The model was used to evaluate the incentives for collaboration between different decision making agents in the supply chain. Three levels of collaboration between companies were considered: no collaboration, partial collaboration, and full collaboration. The results showed that not only each individual company benefited from the collaboration with other companies, but also the whole supply chain costs were reduced when information sharing and collaboration between companies existed at the full level. Frayret et al. (2008) proposed a generic structure of ABS modelling for the lumber production supply chains. The agent-based structure was coupled with constraint programming and other operations research tools to form an Advanced Planning and Scheduling (APS) system. An application of the proposed framework was demonstrated in the scheduling of drying and finishing activities for hundred different types of products in two drying and one finishing line.

A strategic-level ABS model, called CAMBIUM, was developed by Schwab (2008) to evaluate the economic effects of natural disturbances and demand fluctuations on the forest products industry in BC. The model incorporates the interactions and competition between different 'economic agents' to capture the changes in the structure of the industry from a province-wide strategic (long-term) point of view. The model was used to assess the effects of the US market downturn and the mountain pine beetle (MPB) infestation on the forest products industry in BC. Simulation results indicated that, as a result of the demand fluctuation and the infestation, an imbalance in the demand and supply of roundwood is expected which would exacerbate between 2030 and 2060. Vahid (2011) extended the CAMBIUM model and integrated it with a facility location optimization model. The hybrid model was used to evaluate the establishment of a new sort yard based on the expected changes in the profitability of forest products supply chains in the coastal region of BC. It was also used to evaluate the performance of the supply chains with respect to different harvest policies.

Kostadinov et al. (2014) developed an ABS model focused on the simulation of markets for roundwood and fuelwood in Switzerland. The model was composed of different agents such as wood producing agents (forests), sawmills, and customers for roundwood and fuelwood that interact through negotiation protocols. The model was used to assess two scenarios of scarce and excess supply and the performance of the supply chain under different demand levels.

Implementation of the OOS and ABS models paves the way for development of hybrid simulation and optimization models. This approach has received much attention in the literature of supply chain modeling due to the offered capability to overcome the disadvantages of stand-alone optimization/simulation models. Iterative implementation of simulation and optimization has been widely used as the methodology to overcome the computational costs of optimization models and simultaneously incorporating the uncertainties in the simulation models by creating a feedback loop between simulation and optimization. Also, other approaches for combining simulation and optimization approaches are suggested in the literature that are reviewed in great details in (Amaran et al. 2014, Figueira and Almada-Lobo 2014). Applications of hybrid simulation and optimization modeling approach in the Canadian forest products supply chain are reviewed by Shashi and Pulkki (2013). The authors concluded that implementing a 'simulation-based optimization' approach can provide a suitable decision support tool for integrated planning of the forest products supply chains.

2.4 Conclusions

The necessity of using advanced decision support tools in the supply chain management of the forest products industry is emphasized in the literature. Different modelling approaches are amenable to different types of analysis and for differing degrees of complexity. Applicability of static and deterministic models in supply chain planning is limited, therefore, mathematical optimization and simulation approaches are commonly used for operational, tactical, and strategic planning of the supply chains. The choice between simulation and optimization is primarily made according to the specific purpose of conducting the analysis.

Simulation of the supply chain provides a decision maker with a relatively realistic representation of the real-world systems, therefore in many studies it is employed in tackling the decision problems revolving around the design of new supply chains based on the expected performance of its components. Simulation of the supply chain is also conducted to evaluate different methods and policies, and conduct what-if analyses and scenario based analyses for developing and validating improvement opportunities, and estimating system responses without interrupting the actual supply chains. The scope of reviewed simulation models varies from a single piece of equipment to full logistical systems with alternative harvesting and distribution systems. Fewer studies have endeavoured to model the whole supply chains, and integrated planning of several supply chains. Modelling the whole supply chain based on actual systems requires extensive data gathering. Moreover, incorporation of the many components of the systems makes the structure of the models more complex. Nonetheless, providing an integrated perspective of the supply chain in simulation models is clearly necessary to provide a more holistic representation of the interactions and interdependencies between the different phases of the chain.

The uncertainties in the equipment performance have been modeled, though less attention has been devoted to the uncertainties in the quality of biomass. Instead, deterministic parameters have been used for the composition of biomass in most of the reviewed simulation models. Gathering the required data on the quality of biomass across the supply chains is a costly and time consuming task and incorporating the quality measures in the supply chain models makes the model development and analysis more complex. Nevertheless, incorporating the quality of biomass in a simulation is a step forward and will be performed in this research effort based on the available information in the literature and obtained data from the industry.

Another challenge in the simulation of biomass supply chains is in modelling the flow of biomass between and within the different stages of the chain. Most often, and quite efficiently, equipment capacities (e.g., skidders load volume), truck loads, biomass piles, and cutblocks are defined as simulation entities in discrete-event simulation models. However, this method cannot be used when the continuous flow of biomass is to be modelled, such as inside the biomass processing facilities. Discrete-rate simulation, which is a combination of continuous and discrete-event simulation approaches (Damiron and Nastasi 2008, Krahl 2009), will be used to incorporate a more realistic picture of processes and activities inside facilities. Also, using this approach allows consideration of the effects of the quality of biomass on the performance of the equipment by defining the processing rates as a ‘controlled variable’ dependant on the stochastic quality parameters, which will be discussed in the following chapters.

Chapter 3. Evaluation of the forest biomass supply chain for large-scale power generation

3.1 Introduction

Among the most important factors that need to be assessed in the feasibility of a bioenergy project are the long-term stability of feedstock (i.e., availability and reliability of raw materials supply), final cost of generated energy, and environmental impacts of utilizing biomass. The economics of the forest-to-energy projects have been extensively considered in the literature. The associated costs of supplying biomass for energy production were examined in the U.K. (Allen et al. 1998), in the U.S.A. (Gallagher et al. 2003), in Western Europe (Hamelinck et al. 2005), in Italy (Caputo et al. 2005), in Japan (Yoshioka et al. 2006), and in Western Canada (Kumar et al. 2005, MacDonald 2006, Stennes and McBeath 2006, Kumar et al. 2008, MacDonald 2009, Niquidet et al. 2012), and in many other studies. The essential logistical factors discussed in these studies were region-dependent and were mostly related to the different suppliers of biomass available in different locations, composition of biomass, annual yields of the harvesting areas, etc. Integrating GIS systems with the supply chain models enables to capture the spatial distribution of harvest areas and supply chain entities and provide suitable decision support tool for designing the supply chains.

As discussed in the previous chapters, there are numerous dynamic features (e.g., spatial and temporal variability in biomass properties, personnel and equipment availability and performance, supply and demand, etc.) that need to be considered in the design and planning of a forest biomass supply chain. Incorporating these complexities, which are simplified in deterministic supply chain models, is the main driver for development of stochastic simulation models.

The main objectives in this chapter are to assess the supply of forest biomass for a proposed bioenergy power plant, and estimate the delivered cost of raw material to the plant. These two factors, i.e., reliability of raw material supply and its cost, are decisive in the feasibility of bioenergy projects and are assessed in the given case study. In order to provide a representation of the required supply chain, simulation modeling is carried out. Essential data and information from the industrial experts and the available literature are gathered and the model is verified through rigorous debugging procedures and validated through comparison with the literature and experts' opinion. Model-based analyses are then performed to address the abovementioned objectives. Specifically, this chapter will present simulation of the supply of forest biomass from Quesnel Timber Supply Area (TSA) to a potential power plant located near the city of Quesnel, BC.

3.2 Case study

Quesnel TSA covers approximately 1.6 million ha and is one of the most affected areas by the mountain pine beetle (MPB) outbreak in BC (BC MFLNRO 2009). The annual allowable cut (AAC) was significantly increased by the authorities to allow creating the most value from the infested trees before they decay or burn (AAC is the volume of log permitted to be harvested during a year in a TSA to ensure the sustainability and productivity of the forests in long-term). The development of a power plant with a net capacity of 300 MW located near the city of Quesnel, BC was proposed in (Kumar et al. 2005) to generate bioenergy from underutilized available biomass.

This plant would require approximately 1.35 M dt of biomass per year that is to be supplied from the infested areas in the Quesnel TSA. MacDonald (2006) developed a GIS-based model to estimate the availability and delivered cost of feedstock to this plant. This study proposed three harvesting systems applicable to each cutblock based on the proportion of sawlog that could be extracted. The expected productivity of the harvesting equipment in the interior BC as well as data obtain from other jurisdictions were used to estimate the cost of the delivered feedstock to the bioenergy plant using each system. Mahmoudi et al. (2009) simulated the flow of biomass from the Quesnel TSA to this power plant over a one-year planning horizon considering the harvesting residues as the only source of raw material to achieve the minimum cost. They concluded that the amount of biomass provided through the conventional harvesting system would cover only 30% of the power plant's demand. Therefore, raw material availability would be a serious issue in the feasibility of the project if only relying on sawlog extraction as the primary product and fuelwood as the by-product. This would necessitate the implementation of customized harvesting systems to assure the supply of required feedstock for the suggested power plant and maximize the value generation from the infested areas.

To further explore the stability of raw material supply and its costs under different conditions, a simulation model is developed in this thesis that allows considering three harvesting systems (proposed by MacDonald (2006) specifically for the Quesnel TSA). The model is used to estimate the availability of potential fuelwood as standing timber volume and harvesting residues. To capture the dynamics of the system in terms of the available feedstock for bioenergy production in each year a shelf-life model based on (Eng et al. 2005) is used to simulate the effects of a continued mountain pine beetle infestation in this area.

3.2.1 Forest biomass availability

To estimate the amount of available, harvestable, and merchantable biomass in the area over time several factors must be taken into account that relate to the actual availability of standing timber, the harvestable volume considering the local constraints, and characteristics of the forest. The data on actual land base, forest inventory, and the existing road network for the Quesnel TSA were obtained from (FPInnovations 2009). The dataset includes forest cover attributes (ownership and harvesting constraints) and biogeoclimatic zones, and Land Units for 445,156 forest cover polygons in the Quesnel TSA. For each polygon area (ha), yield (m^3 ha^{-1}), average age of the stand, and percentage of pine species in the initial volume (as of 2006) are given and it is assumed that the 20-years planning horizon (service life of the plant) starts in 2006.

The harvest operations in this study are limited to the polygons with more than 30% pine in the composition of the species, with a minimum age of 60 years, with at least 70 m^3 ha^{-1} yield, and with less than 8 h cycle travel time from the city of Quesnel. The study area is therefore limited to 18 land units west of the Fraser River except for those that are farther than 8 hours away, listed in Table 3-1. Each land unit is further clustered into categories based on the percentage of pine in the total volume, the average age of the stand, and the existing road network, into a total 184 stand groups. Based on the road network in the Quesnel TSA, the area is divided into three categories of dense, partial, and sparse classes which are used in estimations of road construction and maintenance, and administration costs.

Table 3-1. Name, number of forest cover polygons, and area of the considered land units.

Land Units Name	No. of polygons	Harvestable area (ha)
Euchiniko	8170	30708
Pelican	10964	41777
Whittier	4995	15065
Pantage	11337	38673
Chine	8281	32908
Marmot	9107	27065
Snaking	11879	40897
Baezaeko	11979	46553
Coglistiko	8541	37212
Kluskus	9554	34731
Baker	13838	46923
Tibbles	12796	39235
Narcosli	4911	19082
Toil	3179	16688
Wentworth	9876	37973
Clisbako	9546	34807
Ramsey	9699	37757
Twan	3430	11274

The merchantable volume in the form of sawlog and ‘potential fuelwood’ (i.e. standing timber that is not suitable for sawlog but still merchantable for alternative products) in each cutblock depend on many factors including the characteristics of the standing timber and suitability of the harvesting systems (MacDonald 2006). The merchantable volume of sawlogs and fuelwood in this study are estimated based on the initial forest inventory data for each polygon, and the shelf-life of pine in the area.

‘Shelf-life’ is defined as the length of time that a MPB killed tree will be usable for a specific product (herein, sawlog and fuelwood). Hughes et al. (2004) developed the shelf-life model to predict the effect of the MPB infestation. This model estimates the changes in the merchantability of killed timber in a given stand based on the biogeoclimatic specifications of the area. A narrative of the model is that the MPB killed trees degrade faster in wet climate and slower in the dryer climate (MacDonald 2006). The harvestable area is divided into three shelf-life classes: short, medium, and long according to biogeoclimatic zones and subzones, for each of which the model estimates the degradation in pine timber over time and divides it into sawlog and fuelwood portion as shown in Figure 3-1. For instance, the proportion of merchantable volume in a stand with short shelf-class, decreases from 100% in the first year to 5% in a period of 17 years and only a minimal of

5% is predicted to remain merchantable thereafter. For the long shelf-class, the degradation in the extractable fuelwood is comparably slower which indicate that the pine volume would remain merchantable for a longer period of time and the sawlog portion is about 10% in 20 years. Figure 3-2 provides a visualization of the data layers used in the simulations.

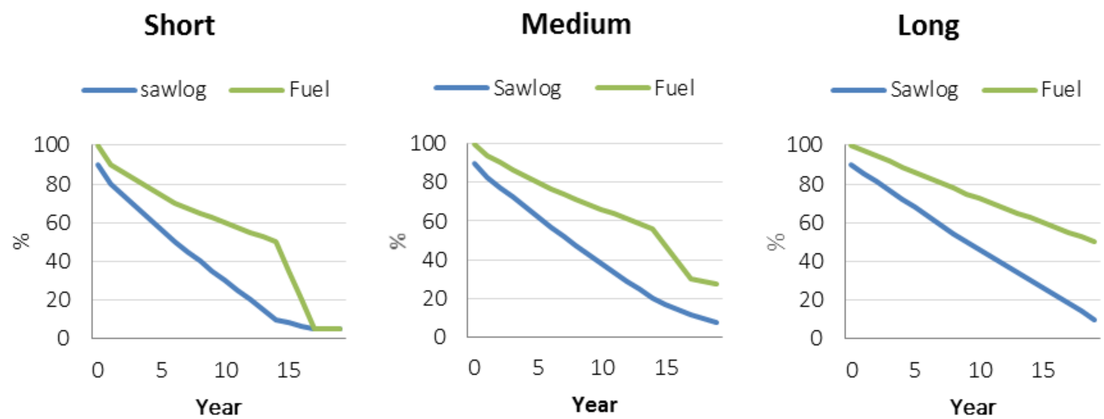

Figure 3-1. The projected proportion of sawlog and fuelwood for short, medium, and long shelf classes.

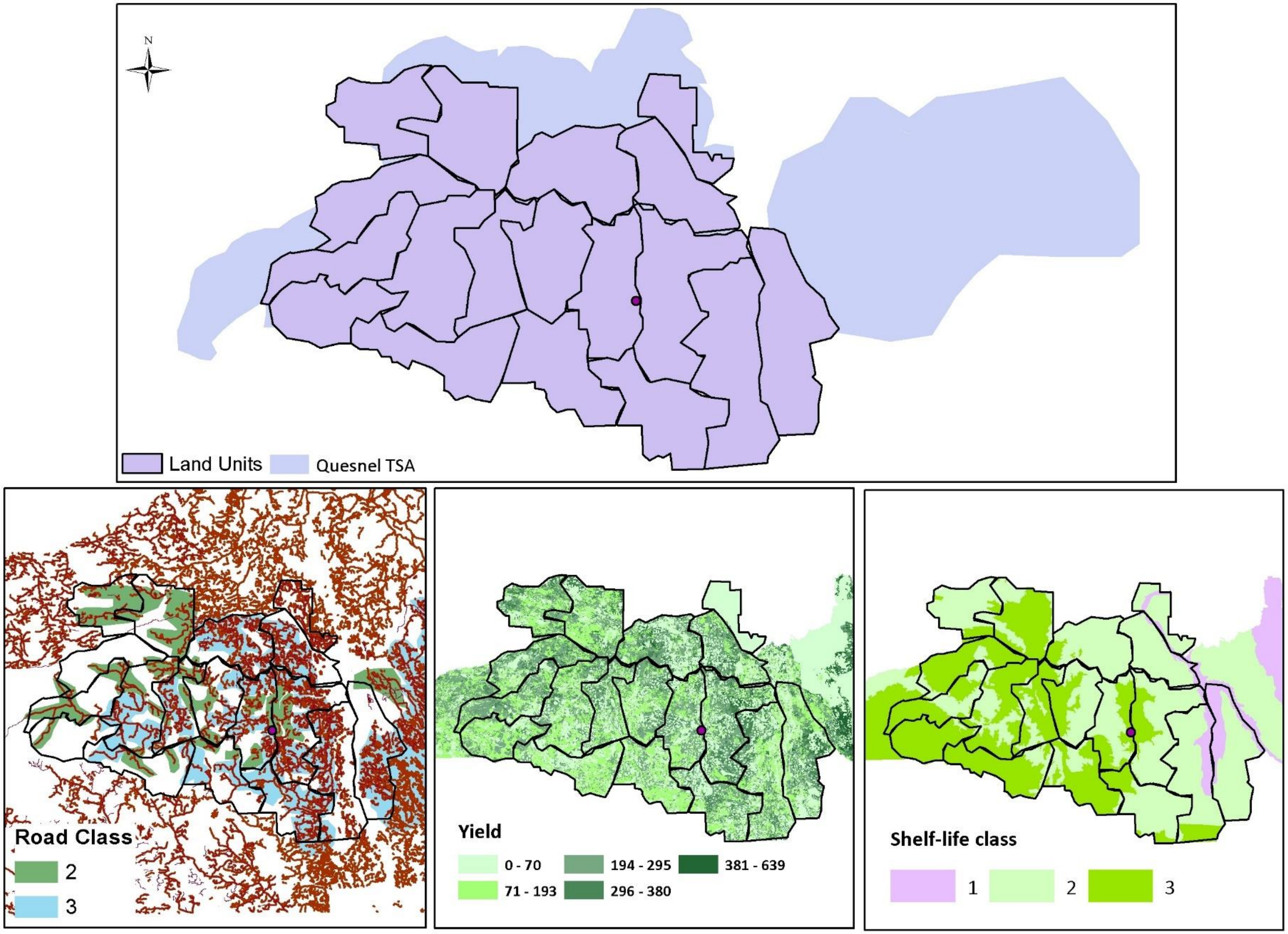

Figure 3-2. GIS data layers used in this study. Top: Quesnel TSA and land units considered in this study. Left: road network and classes, partial (2), dense (3). Middle: average yield in each cutblock as of 2006. Right: shelf-life classes, short (1), medium (2), long (3). Sources of data: FPInnovations (2009).

In this study, the annual available merchantable volume in the Quesnel TSA is estimated based on the availability in the beginning of the planing horizon (2006), proportion of the pine volume in each stand, and degradation of pine volume. Using the shelf-life model and the forest inventory data discussed above, the available timber volume is calculated for the study area and shown in Figure 3-3. There is a sharp decrease in the standing merchantable volume and the extractable sawlog volume over the 20 years. Availability of fuelwood peaks in 14 years and decreases as the pine trees fall and degrade over the next years.

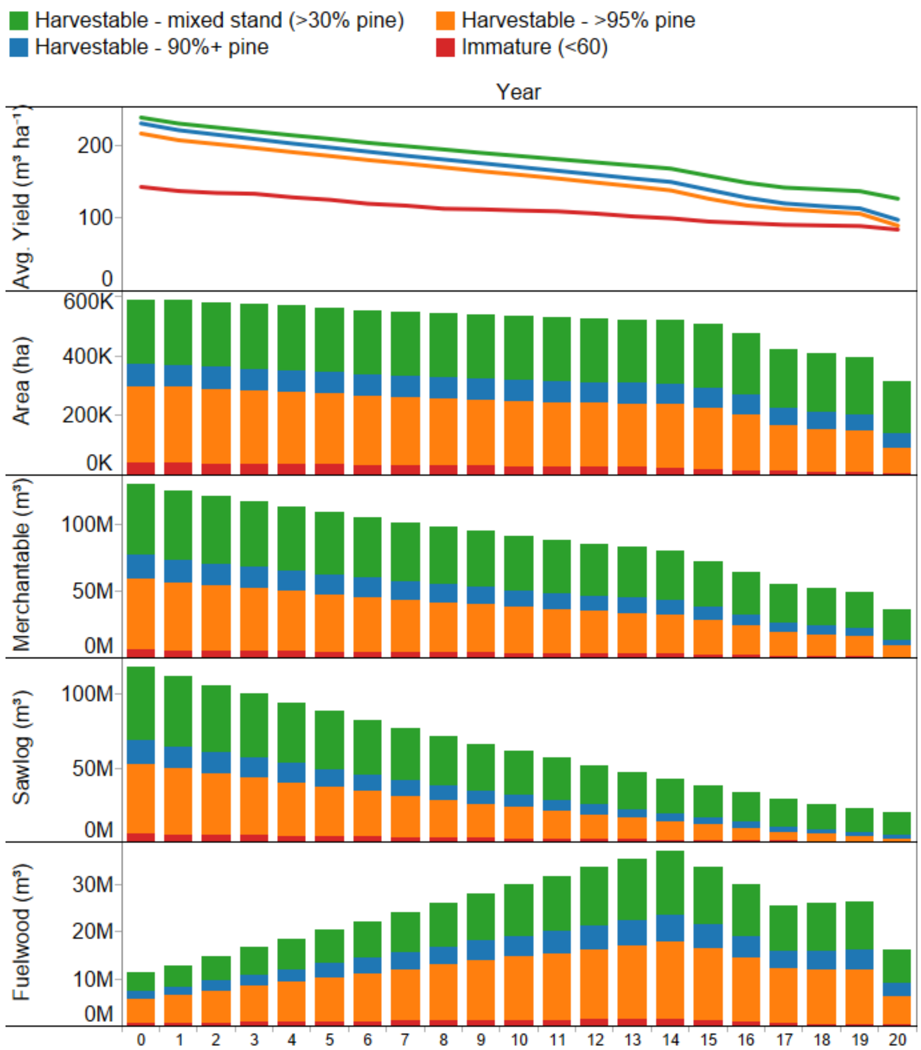

Figure 3-3. Estimated average yield, harvestable area, merchantable volume, and sawlog and fuelwood amounts in the study area over time.

3.2.2 Harvesting systems

The typical harvesting system used for logging practices in the Quesnel TSA is referred to as the conventional (mechanized) harvesting system, depicted in Figure 3-4. In the conventional harvesting system, trees are felled and skidded to the roadside where they are processed to sawlogs and transported to the mills. MacDonald (2006) suggested that the conventional harvesting system would remain the implemented system in the MPB affected areas as long as the licensees are able to generate profit (i.e. the delivered cost of logs from a cutblock is less than a certain amount depending on various factors). Residues from the logging operation along with stems not qualified as sawlog are piled at the roadside to be burnt at a proper time. To use the harvesting residues as a source for bioenergy, on-site size reduction (chipping or grinding) is required due to low bulk density of the biomass piles. It also needs to be conducted at the roadside using highly mobile equipment since the piles are located along the roads. A mountain goat chipper is considered that would need to be coupled with a small excavator to forward the piles to the reach of the chipper. Located on the tandem of the road, chippers process the piles and load the trucks directly. The set of equipment used in this system is listed in Table 3-2. Using the conventional harvesting system, the costs of felling, skidding and processing are covered by the logging companies and are not taken into account in the cost of delivered feedstock to the power plant, i.e. harvesting residues are available for bioenergy generation free of charge and only costs for chipping and hauling are considered.

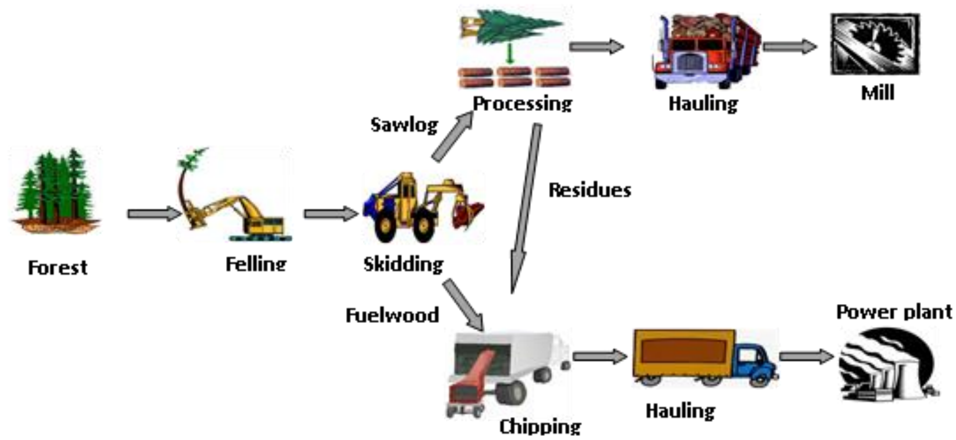

Figure 3-4. Conventional harvesting system: residues are chipped at the roadside and hauled to the power plant (Source: Mahmoudi et al. (2009)).

Table 3-2. Power and expected productivity of equipment normally used in a conventional harvesting system.

Type of equipment	Power (kW) [a]	Productivity/ payload [b]	No. assigned to each cutblock	Hourly cost ($ h^{-1})
Feller-buncher	149	50-70 m^3 h^{-1}	1	155
Grapple skidder	95	58-65 m^3 h^{-1}	1	105
Dangle-head processor	126	27-45 m^3 h^{-1}	2	130
Button-top loader	146	120-170 m^3 h^{-1}	1	125
Mountain goat chipper	575	20-30 dt h^{-1}	1	230
Semi-trailer chip-van	352	93 m^3	-	95
On-highway truck	550	80 m^3	-	110

[a] Caterpillar Equipment, http://www.cat.com/ 10 [October 2009]; [b](MacDonald 2006)

As time passes, the harvestable sawlog volume reduces due to the MPB infestation (inferior quality of the dead trees), also, the productivity of the harvesting equipment reduces when operating in post MPB stands (MacDonald 2006, Dyson and Sauder 2007). Therefore, the operation costs increase which makes the sawlog extraction not economical after a certain point. In this case, using a central location (so called as satellite yard) for storage of full trees and separation of sawlog and fuelwood was suggested by MacDonald (2006). In the satellite harvesting system (Figure 3-5) trees are felled, bunched and skidded to the roadside, then, transported to a satellite yard where the fuelwood and sawlogs are separated. Trees qualified as sawlog are processed into logs and sent to sawmills, while trees qualified as fuelwood, and residues from processed trees are chipped and sent to the power plant.

In the satellite harvesting system, unlike the conventional harvesting system, costs of felling, skidding, and processing are shared between the logging company and the power plant based on the fuelwood and sawlog proportions of the harvested volume, following the assumptions in (MacDonald 2006). The set of equipment used in this harvesting system, their hourly rate, and capacities are listed in Table 3-3. The satellite yard could be located either within a short distance of the cutblocks (several smaller remote satellite yards) or near the final destination (single in-town satellite yard). In the remote satellite system, trees are hauled by off-highway log trucks without being processed at the roadside. In the in-town satellite system, on the other hand, trees are delimbed and topped at the roadside and then hauled on the highway. The remote satellite system, located within a short distance (< 0.75 hour travel time) of the stand groups and 125 km away from the city of Quesnel, with access to all-weather roads (to allow year-round flow of bioenergy feedstock) is considered in this study.

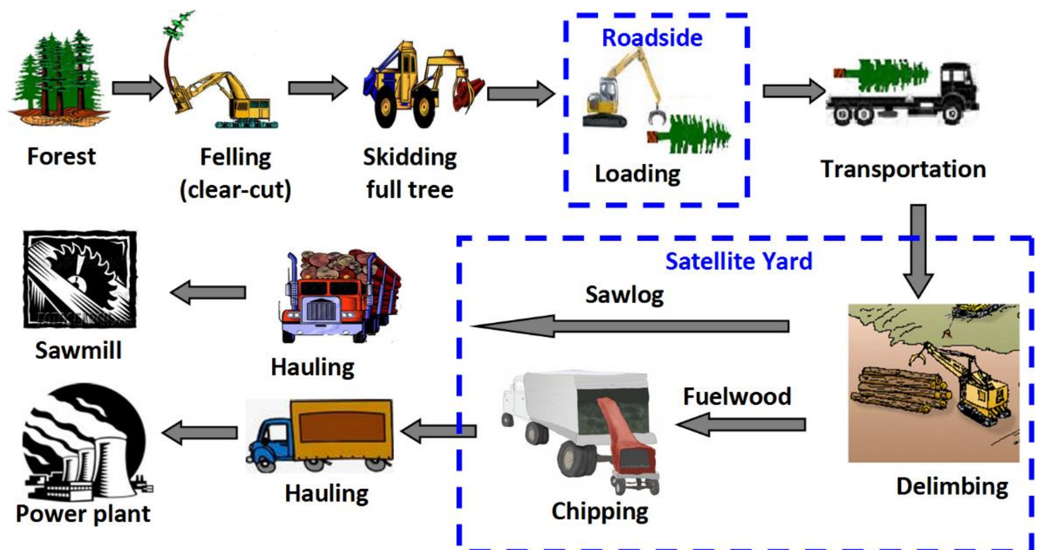

Figure 3-5. The satellite yard harvesting system in which full trees are hauled to the satellite yard where the flow of merchantable wood and fuelwood are separated.

Table 3-3. Power and productivity of equipment used in a satellite harvesting system.

Type of equipment	Power (kW)[a]	Productivity/ Payload [b]	No. assigned to each cutblock	Rate ($ h^{-1})
Feller-buncher	149	50-70 m^3 h^{-1}	1	155
Grapple skidder	95	58-65 m^3 h^{-1}	1	105
Off-highway truck	550	80 m^3	-	110
Wheel loader (loading)	210	250-320 m^3 h^{-1}	1	105
Wheel loader (unloading)	210	110-160 m^3 h^{-1}	-	105

Type of equipment	Power (kW)[a]	Productivity/ Payload [b]	No. assigned to each cutblock	Rate ($ h^{-1})
Log loader & delimber	197	120-170 m^3 h^{-1}	-	125
Chipper	130	20-30 dt h^{-1}	-	130
B-train chip-van	475	113 m^3	-	116

[a] Caterpillar Equipment, http://www.cat.com/ [10 October 2009]; [b] Productivity/payloads are based on productive machine (MacDonald 2006).

For the stands with severe defects, the cost of extracting sawlog from the harvested material in the satellite system exceeds the sawlog value, in this case, the full tree chipping system was suggested (MacDonald 2006). After felling and skidding, the full trees are chipped at the roadside and hauled to the power plant. The chipper used in this system is a mobile whole-tree chipper capable of moving along the roadside and between cutblocks. A loader is coupled with it for feeding the trees to the chipper situated in a convenient location along the road directly loading the feedstock to the trucks. The flow of biomass in this system is depicted in Figure 3-6. Table 3-4 lists the data on equipment used in this system.

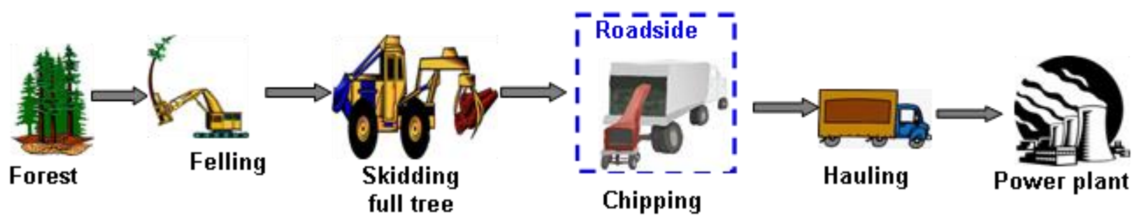

Figure 3-6. Flow of biomass in the full tree chipping harvesting system.

Table 3-4. Power and productivity of equipment used in a full tree harvesting system.

Type of equipment	Power (kW)[a]	Productivity/ Payload [b]	No. assigned to each cutblock	Rate ($ h^{-1})
Feller-buncher	149	50-70 m^3 h^{-1}	1	155
Grapple skidder	95	58-65 m^3 h^{-1}	1	105
Button top loader	197	120-170 m^3 h^{-1}	1	125
Mountain goat chipper	575	20-30 dt h^{-1}	1	230
Semi-trailer chip-van	352	60 m^3	-	116

[a] Caterpillar Equipment, http://www.cat.com/ 10 October 2009; [b] Productivity/payloads are based on (MacDonald 2006).

To make the selection between the harvesting systems, MacDonald (2006) assumed that the conventional harvesting system is only used in stands with fuelwood content less than 50%. The harvested volume from areas with more than 50% fuelwood still contain a significant proportion of sawlogs that must be separated from the fuelwood. However, once the proportion of fuelwood exceeds 95%, separation of sawlog was considered uneconomical and the full tree chipping system was proposed. The same thresholds are used in this simulation study.

3.3 The simulation model

The OOS approach is implemented using the ExtendSim software package (Imagine That 2011) to develop the supply chain model. Figure 3-7 shows the components of the simulation model. The *objects* are the equipment (and implicitly the personnel directly operating them) that are controlled by the decision making *entities* which define the 'harvest planning' and conduct 'resource allocations' to the plans over the simulation time. In this study, harvest planning is assumed to follow a set of priorities defining the order in which stands will be harvested. Furthermore, it is assumed that both the planning and resource allocation of the harvesting operations are centrally conducted for the whole harvest area. The input data include the GIS data layers that are used in the model to calculate the availability of the standing and merchantable volumes over time in 'Availability and Shelf-life' module. Annually, based on the initial volume, the shelf-life model predictions for the next year, and the harvested volume, the availabilities for the next year are updated.

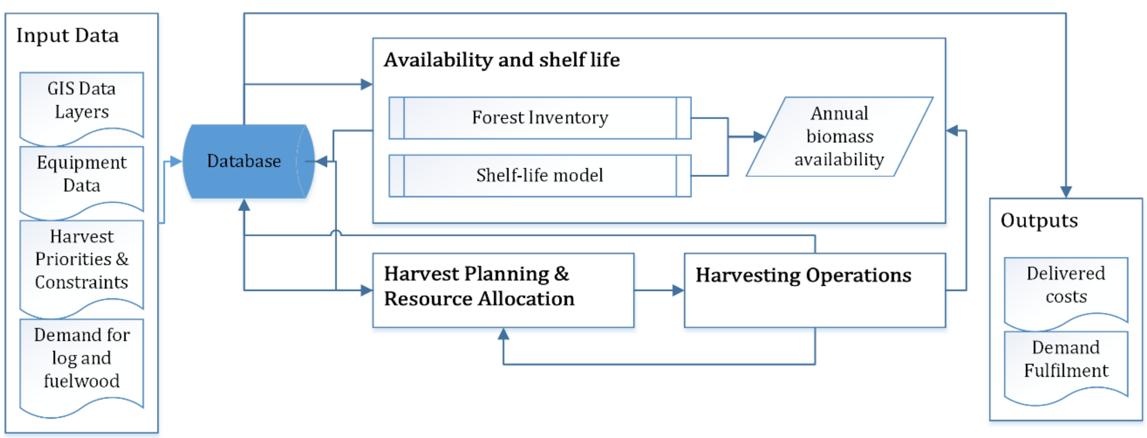

Figure 3-7. Components of the simulation model.

3.3.1 Harvest planning

In the real system, the annual harvesting and logging schedules vary during the year in response to, e.g. the weather condition, roads condition, soil preservation policies, resource availabilities (personnel and equipment), inventory policies, and market demands.

In the simulation model presented here several assumptions are made regarding these fluctuations given the limited scope of the study.

In practice, the demand for forest biomass from the wood-processing facilities and the delivered costs define the actual amount of harvested volume and the licensees harvest from the areas that would fulfill their specific needs. For instance, when harvesting for sawlog, hauling distance to the harvest area, yield, and the quality requirement of available timber in the area are commonly considered to choose the cutblocks, while a different set of criteria will be in place when planning for fuelwood. In other words, the forest product industries harvest and consume wood selectively (Richardson 2002). These different decision making procedures create uncertainties in the actual harvest and in the available feedstock for bioenergy generation.

For the Quesnel TSA, with the objective of maximizing the utilized volume from the infested cutblocks before it degrades, BC MFLNRO (2009) suggested that the stands with shorter shelf-life class be harvested earlier in the planning horizon, while retaining a harvest target of 3.1 M m^3 over the time period of 2006-26. Herein, we assumed the same approach is taken and the stands which are expected to lose more yield per hectare (based on the results of the shelf-life model) are given a higher priority when planning the harvesting operations. The three harvesting systems, suggested by MacDonald (2006), are assumed to be applied to the planned harvest area with respect to its sawlog and fuelwood content as discussed before.

The annual harvesting schedule of a major logging company operating in the Quesnel TSA (Mahmoudi 2008) is used to distribute the harvesting operations (as a percentage of total annual harvest) over the year to reflect the limitations posed by the weather, road conditions, etc. Table 3-5 shows the share of the scheduled volume for each month. In May and April, when the rain precipitation is high, soil preservation constraints and road limitations restrict the operations and more than half of the operations take place during November to March.

Table 3-5. Monthly distribution of scheduled harvesting operations.

Month	Percent of annual target	Cumulative
May	2.6%	2.6%
June	8.1%	10.7%
July	7.8%	18.5%
August	9.7%	28.2%
September	8.8%	37.0%
October	5.2%	42.3%
November	10.6%	52.8%
December	12.1%	64.9%
January	13.0%	77.9%
February	11.7%	89.6%
March	10.2%	99.7%
April	0.3%	100.0%

Resource allocations are conducted daily, based on the availability of the equipment and the pre-defined harvest plan. The harvest plan indicates the stand(s) that are to be cut, and depending on the characteristics of the standing timber the harvesting system is selected. As long as the required resources are available the equipment pieces are allocated to the harvesting crew and dispatched to the area. Furthermore, it is assumed that resource allocations are non-pre-emptive, i.e. once a piece of equipment starts working in a stand group it cannot be allocated elsewhere until the operation is finished. When the operation is finished in a given stand group the equipment receives a delay depending on the location of the stand and its next destination (terminal/next stand group) to account for mobilization of the equipment between the stand groups.

The required time for each activity is calculated based on the productivity rate of the machines and the volume/mass that is processed. The expected productivity of the harvest equipment changes when operating in post MPB infestation areas. Time studies conducted in the interior BC in (Han and Renzie 2005, MacDonald 2006, Dyson and Sauder 2007) showed that there is a strong relationship between the average volume per tree in a harvested stand and the productivity of the fellers, skidders, loaders, and processors. Herein, the data from these studies are used to develop Eq. 3-1, which is used in the simulations to calculate an adjustment factor (δ). This factor is applied to the expected productivity of equipment (listed in Table 3-2, Table 3-3, and Table 3-4) and relates it to the average volume per tree in the stand ($\bar{v}_i$).

$$\delta = 0.04123 + 1.3169 \cdot (\bar{v}_i)^{0.46} \qquad \text{Eq. 3-1}$$

A regression model was developed by (Niquidet et al. 2012) that relates the yield (y) in a given stand to the average volume per tree, shown in Eq. 3-2.

$$y = 467.6 + 173.15 \cdot ln(\overline{v}_i) \quad \text{Eq. 3-2}$$

Eq. 3-1 and Eq. 3-2 are used in the simulation model to relate the productivity of the equipment to the characteristics of the harvested area. The required productive machine hour (PMH) and the costs are estimated accordingly. Through the simulations, the required schedule machine hour (SMH) for each cutblock is calculated considering the operating shifts, scheduled maintenance times (depending on the type of machine in the beginning and end of the shifts), and lunch breaks. Additionally, other unforeseen delays caused by machine failure, weather conditions, and interdependencies between different equipment are incorporated.

Ten scheduled machine hours per day and a half an hour lunch break are considered for all the operations. Half an hour (5% of the shift) scheduled maintenance at the beginning of a shift, and half an hour maintenance at the end of a shift are assumed for fellers, skidders, and loaders, while scheduled maintenance times of 1.2 hours at the beginning and end of each shift are considered for chippers and processors (Roser et al. 2014).

Weather conditions affect logging operations and transportation of biomass, and therefore are important in estimating the performance of the equipment. To consider these effects in the simulation, based on Mahmoudi (2008), it is assumed that one hour delay in the operations occurs per one mm of rain precipitation, and the entire operation is halted during any day that temperature falls below -40 °C. The equipment would be idle but occupied during the weather delays; this time interval is counted as machine hour. The daily weather shutdowns are assumed to occur randomly during the day and may overlap with the scheduled maintenance time and lunch breaks.

Moreover, the terrain conditions, species mix in the stand, and size of the operation cause uncertainties in the performance of the equipment. To account for these variables in the simulation model, the productivity rate of the equipment is defined as a range specified in Table 3-2, Table 3-3, and Table 3-4. An upper and lower limit of machine productivity was provided for each type of machine. It is assumed that the productivity of the equipment is normally distributed over the intervals.

Furthermore, an upper limit for the number of each type of equipment is taken as an input parameter that in addition to the number of pieces assigned to each cutblock (Table 3-2, Table 3-3, and Table 3-4) constraint generation and execution of the harvesting plans. To calculate the number of payloads that are transported from each cutblock, the bulk density and moisture content of material are taken into account. The payload is limited based on the volumetric capacity of the trucks, and considering a maximum 53 t for on-highway trucks and 45 t for off-highway trucks. Also, it is assumed that trucks are dispatched only if the estimated cycle travel time ends before the day-shift so that the trucks do not remain in the area overnight, i.e., time windows are considered in the transportation planning. Travel times are estimated based on average speeds of 80 km h^{-1} for highways, 60 km h^{-1} for main roads, and 45 km h^{-1} for branch roads and 10% coefficient of variation.

3.3.2 Moisture content and density of wood

The moisture content of wood changes as a result of changes in its ambient temperature and relative humidity; both mass and volume of wood change as a result of changes in moisture content. There is a great deal of inherent uncertainties in the moisture content of green (fresh), dead, and stored wood and how it changes over time, yet it is important to have an estimation of the moisture content and its effects on the physical properties of wood as they affect the performance of the supply chains (Acuna et al. 2012a). Moisture content of dead and stored wood change to reach balance with its ambient conditions and falls in a specific range called equilibrium moisture content (EMC) (Bergman et al. 2010). EMC varies depending on the relative humidity and temperature. Eq. 3-3 is used to calculate the equilibrium moisture content of biomass (Bergman et al. 2010):

$$EMC(\%) = \frac{1800}{W}\left[\frac{KH}{1-KH} + \frac{K_1KH + 2K_1K_2K^2H^2}{1 + K_1KH + 2K_1K_2K^2H^2}\right] \qquad \text{Eq. 3-3}$$

where H is the relative humidity and the parameters W, K, K_1 and K_2 depend on the temperature. With temperature (T) in °C the following equations give the value of these parameters.

$$W = 349 + 1.29T + 0.0135T^2 \qquad \text{Eq. 3-4}$$

$$K = 0.805 + 0.000736T - 0.00000273T^2 \quad \text{Eq. 3-5}$$

$$K_1 = 6.27 - 0.00938T - 0.000303T^2 \quad \text{Eq. 3-6}$$

$$K_2 = 1.91 + 0.0407T - 0.000293T^2 \quad \text{Eq. 3-7}$$

In the simulation model EMC is used as an estimate of the moisture content of biomass piles. The historical weather data is used to estimate the EMC based on Eq. 3-3. The average temperature and relative humidity for each day for the period of 1986 to 2006 for Quesnel[1] are collected and used in the model. In the beginning of the year, one of the 20 year of the weather data is randomly selected and used in the simulation model. Density and specific gravity (the dry mass per m^3 of solid wood at a given moisture content) are estimated by the following equations (Bergman et al. 2010):

$$\rho_{MC} = 1000 \cdot G_{MC}\left(1 + \frac{MC}{100}\right) \quad \text{Eq. 3-8}$$

$$G_{MC} = \frac{G_b}{\left(1 - 0.265 \cdot G_b \cdot \left(1 - \frac{MC}{MC_{fs}}\right)\right)}, MC < MC_{fs} \quad \text{Eq. 3-9}$$

where ρ_{MC} is the density of wood (including water) at moisture content *MC* (% dry basis), G_b is the basic specific gravity of the specie (dry mass of wood per m^3 green volume), G_{MC} is the specific gravity of the specie (dry mass of wood per m^3 at moisture content *MC*), and MC_{fs} is its fibre saturation point (moisture content above which physical properties of wood are not function of moisture content). For lodgepole pine MC_{fs} is 30% and G_b is 0.38 (Bergman et al. 2010). To calculate the bulk density of chipped biomass (required in estimating the payload of trucks) an average expansion factor of 3 is applied on the estimated density of roundwood; and in order to account for the variations it is assumed to follow a normal distribution with 10% coefficient of variation (Roser et al. 2014).

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[1] Retrieved 1 October 2014, from http://www.climate.weatheroffice.ec.gc.ca/climateData

3.4 Results and discussion

The simulation model was run with the abovementioned input data and assumptions for 10 iterations each of which consisted of 20 years in simulation time. Table 3-6 shows averages for harvested area, number of generated cutting plans (generated by the harvest planning module), total volumes, and total weight of delivered biomass over 20 years. Note that the target harvest volume was set to 3.2 M m^3 and based on that the delivered mass of bioenergy feedstock is estimated. Number of cutting plans and the harvested area show an increasing trend due to decrease in the yield over time (shown in Figure 3-3). There are considerable fluctuations in the amount of sawlog and fuelwood volume that can be extracted from the harvested timber as depicted in Figure 3-8. The fluctuations are due to the changes in the quality of the infested trees as predicted by the shelf-life model and the prioritization applied in harvest planning.

Table 3-6. Obtained results from the simulation model over 20 years.

Year	Harvested area (ha)	No. of cut plans	Volume (m^3)		Delivered feedstock mass (dt)	Demand fulfilment (%)
			Sawlog	Fuelwood		
1	14,988	770	2,892,122	1,110,129	401,496	26%
2	13,151	713	2,930,176	1,070,533	443,536	29%
3	14,523	729	2,763,373	1,235,926	524,497	34%
4	14,807	742	2,752,713	1,246,563	528,329	35%
5	14,792	767	2,709,154	1,291,631	538,344	35%
6	13,503	739	2,695,004	1,305,223	549,027	36%
7	15,987	837	2,449,311	1,551,154	662,458	43%
8	13,906	761	2,568,852	1,432,116	580,407	38%
9	17,416	857	2,259,979	1,737,026	737,328	48%
10	17,395	856	2,353,893	1,647,126	710,296	46%
11	18,474	938	2,173,575	1,827,504	748,977	49%
12	20,203	1,024	1,885,725	2,117,975	907,615	59%
13	20,330	1,020	2,043,924	1,959,263	817,622	53%
14	21,700	1,054	1,765,486	2,236,632	955,249	62%
15	20,709	1,033	1,813,489	2,187,817	929,877	61%
16	22,208	1,046	1,613,134	2,389,510	1,016,286	66%
17	25,940	1,225	1,479,964	2,518,929	1,068,373	70%
18	26,035	1,275	1,704,930	2,295,648	998,759	65%
19	23,592	1,183	1,869,732	2,134,871	921,431	60%
20	25,429	1,262	1,723,558	2,275,910	925,998	60%
Average	18,754	942	2,222,405	1,778,574	748,295	49%

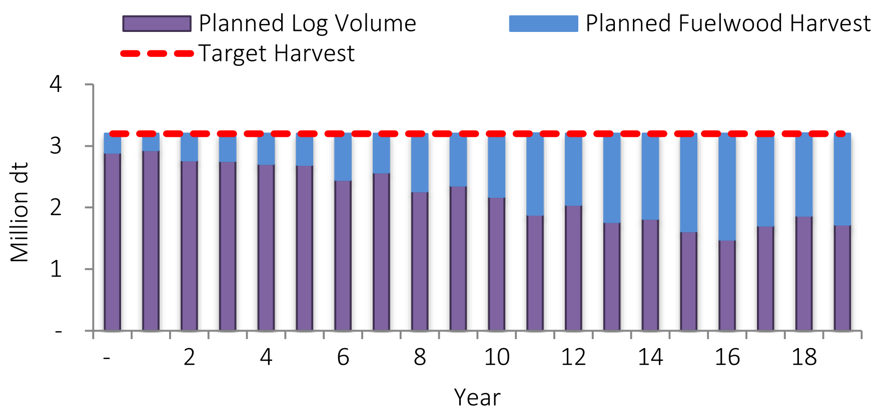

Figure 3-8. Share of sawlog and fuelwood in the harvested area.

Figure 3-9 shows the dry mass (dt) of biomass available to the power plant over 20 years. Dotted-line shows the annual demand of the power plant. The full capacity of the power plant is not fulfilled during the planning horizon. On average, the available feedstock covers 49% of the demand.

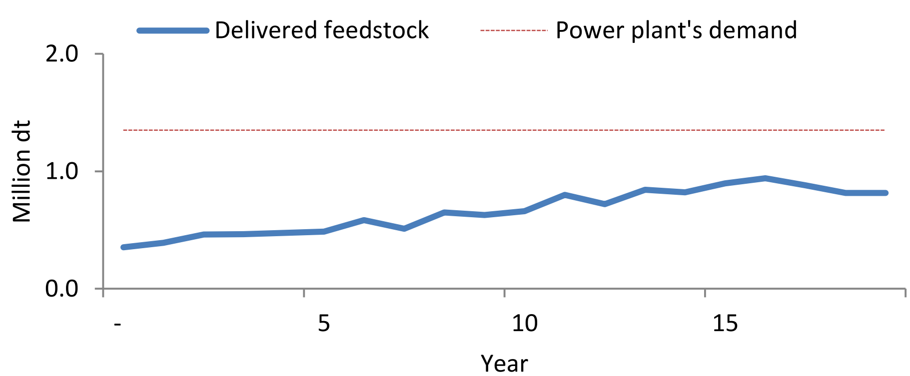

Figure 3-9. Estimated availability of feedstock for bioenergy generation during each year.

Figure 3-10 depicts the variation in the delivered mass of biomass to the power plant using each harvesting system. The changes in the proportion of delivered weight by conventional and satellite harvesting systems are due to the percentages of fuelwood and log volumes in the selected stands in each year that defines which system should be used. As shown in this graph, during the first 6 years, there is no feedstock supplied through the satellite and full tree harvesting systems; thereafter the majority of the harvesting operations are conducted using the satellite system and only in the 17-20th year a portion of the delivered mass was harvested by the full tree chipping system. This is because harvesting the areas with short-life class was scheduled in the beginning of the planning horizon.

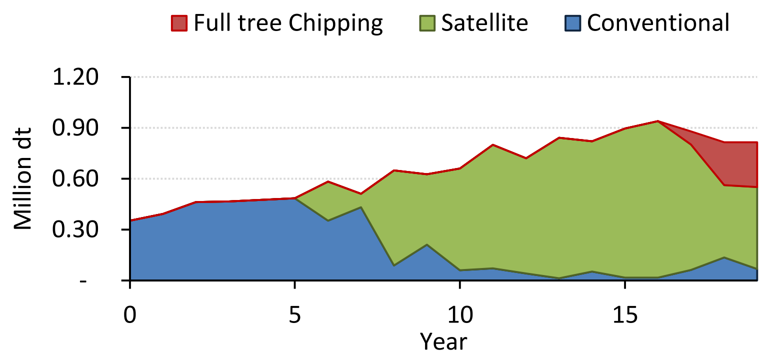

Figure 3-10. Delivered dry mass (dt) using each harvesting system.

The estimated average cost of each operation for the roadside harvesting residues used as bioenergy feedstock in the conventional harvesting system is shown in Table 3-7. In the conventional harvesting system, the costs of felling, skidding, and processing are not included in the delivered cost of feedstock since they are covered by the logging operations and allocated to sawlogs. Table 3-8 and Table 3-9 show the average bioenergy feedstock costs over 20 years supplied through the satellite yard and full tree chipping harvesting systems, respectively. The lowest cost is predictably estimated for harvesting residues in the conventional harvesting system at \$28 dt^{-1}, and the highest cost was estimated for the satellite system with \$56 dt^{-1}. In full tree chipping system, although felling and skidding costs are high, eliminating the processing and hauling to the satellite yard reduced the costs relative to satellite yard system. Table 3-10 and Table 3-11 show the estimate costs for sawlog delivered through conventional and satellite yard systems, respectively. The average estimated cost of sawlogs over 20 years in the conventional system is \$23 m^{-3} while the average cost for sawlog in the satellite system is about 20% less because costs of felling, skidding, loading and hauling to the satellite yard are shared with the bioenergy feedstock and sawlogs. The cost figures reported in Tables 3-7, 3-8, 3-9, 3-10 and 3-11 are the average costs over 20 years for 10 replications of the simulation model.

Table 3-7. Estimated average cost of operations over 20 years for harvesting residues left at the roadside in the conventional harvesting system (results from 10 iterations of the simulation model).

Loading & chipping ($ dt^{-1})	Hauling and unloading at the plant ($ dt^{-1})	Delivered cost to Quesnel ($ dt^{-1})
13.78	14.60	28.38

Table 3-8. Estimated average cost of operations over 20 years for bioenergy feedstock in the satellite yard harvesting system (results from 10 iterations of the simulation model).

Felling ($ dt^{-1})	Skidding ($ dt^{-1})	Loading, hauling, and unloading at the satellite yard ($ dt^{-1})	Processing ($ dt^{-1})	Loading & Chipping ($ dt^{-1})	Hauling and unloading ($ dt^{-1})	Delivered cost to Quesnel ($ dt^{-1})
14.97	9.68	8.70	13.45	3.68	5.81	56.31

Table 3-9. Estimated average cost of operations over 20 years for bioenergy feedstock in the full tree chipping system (results from 10 iterations of the simulation model).

Felling ($ dt^{-1})	Skidding ($ dt^{-1})	Loading & chipping ($ dt^{-1})	Hauling and unloading ($ dt^{-1})	Delivered cost to Quesnel ($ dt^{-1})
17.04	11.13	9.93	8.40	46.50

Table 3-10. Estimated average cost of operations over 20 years for sawlog harvested through conventional harvesting system (results from 10 iterations of the simulation model).

Felling ($ m^{-3})	Skidding ($ m^{-3})	Processing ($ m^{-3})	Loading, hauling, and unloading ($ m^{-3})	Delivered cost to Quesnel ($ m^{-3})
5.51	3.56	7.55	6.10	22.72

Table 3-11. Estimated average cost of operations over 20 years for sawlog harvested through satellite yard harvesting system (results from 10 iterations of the simulation model).

Felling ($ m^{-3})	Skidding ($ m^{-3})	Loading, hauling, and unloading at the satellite yard ($ m^{-3})	Processing ($ m^{-3})	Loading, hauling, and unloading ($ m^{-3})	Delivered cost to Quesnel ($ m^{-3})
3.15	2.03	3.81	3.14	5.87	18.00

The variations in the average annual cost of bioenergy feedstock delivered through each harvesting system are shown in Figure 3-11. In order to calculate the weighted average cost of delivered biomass to the power plant for each year, the proportions of the demand fulfilled by each harvesting system are used. The weighted average cost in each year is shown in Figure 3-12 along with the demand fulfilment at the plant. The weighted average cost varies between \$27 dt^{-1} and \$59 dt^{-1} and the weighted average over 20 years is about \$45 dt^{-1}.

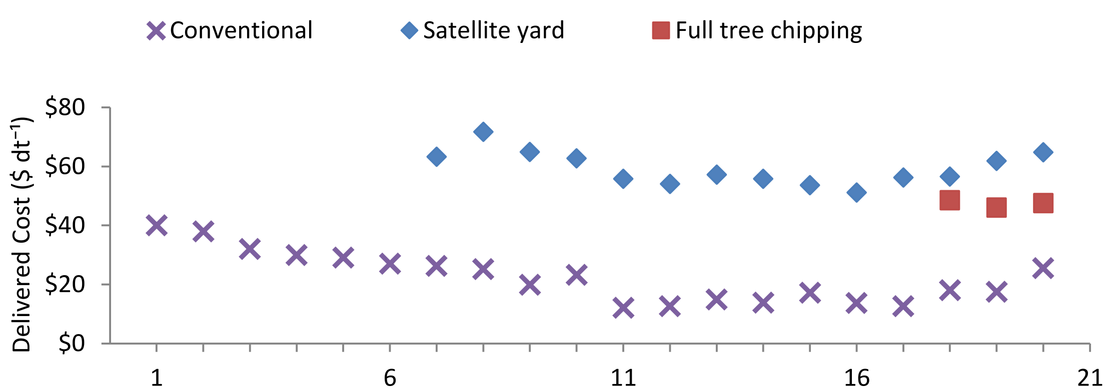

Figure 3-11. Variations in the delivered cost of feedstock over 20 years. Average delivered costs for each harvesting system per year from 10 iterations of the simulation model.

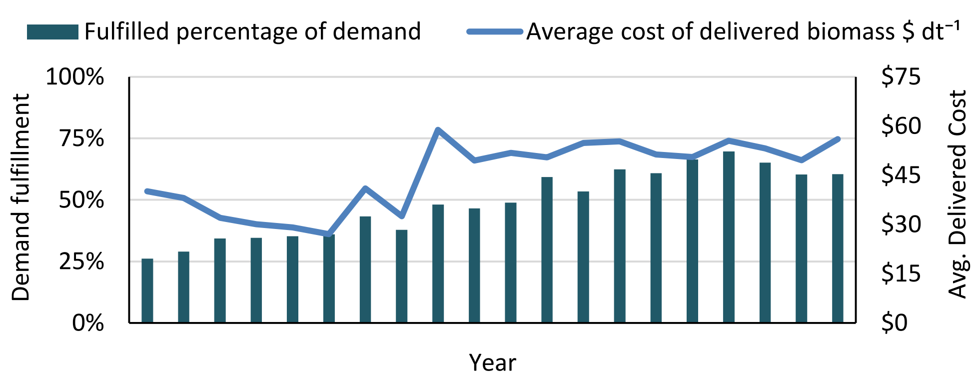

Figure 3-12. Annual demand fulfilment and weighted average cost of bioenergy feedstock.

3.4.1 Sensitivity analysis

Quality of biomass piles

The delivered cost of bioenergy feedstock was estimated based on the input parameters and the assumptions. The minimum cost of the bioenergy feedstock was estimated for the roadside residues from the stands harvested with the conventional system. However, the estimated cost is highly sensitive to the bulk volume of the piles, and the moisture content of the material as these parameters affect the performance of the equipment and the time it takes to process the biomass. Moreover, the transportation costs are affected by the payload of the trucks which is basically related to the bulk volume of biomass after it is chipped. In other words, the costs depend on the dry mass (chipping time) and bulk volume (loaded to each trucks). To evaluate the effects of these uncertainties sensitivity analysis for moisture content of the harvesting residues is conducted.

Seven alternatives are considered to evaluate the effects of changes in MC. As mentioned before, when wood dries below the fibre saturation point its volume changes. EMC provides an estimate of the moisture content which is the expected moisture content in the wood when stored in a constant temperature and relative humidity. It is treated as a lower bound of the actual moisture content when stored at forest roadside, since the wood is exposed to precipitation that would increase its moisture content. The moisture content was estimated by EMC and the bulk density was estimated based on the density of roundwood after the chipping. To evaluate the difference in the estimated costs under each scenario, the parameters are changed as shown in Table 3-12. In the first alternative EMC is used which is increased by 5% in the next six alternatives.

Table 3-12. The parameters for moisture content used in the sensitivity analysis and the effects on estimated costs.

Alternative	Moisture content	Changes in the unit costs ($\$ dt^{-1}$)		
		Loading & chipping	Hauling	Delivered
1	EMC	$10.23	$24.66	$34.90
2	EMC + 5%	$10.14	$26.06	$36.19
3	EMC + 10%	$10.25	$27.69	$37.93
4	EMC + 15%	$10.24	$29.40	$39.63
5	EMC + 20%	$10.02	$31.11	$41.13
6	EMC + 25%	$10.19	$33.34	$43.54
7	EMC + 30%	$10.32	$36.70	$47.02

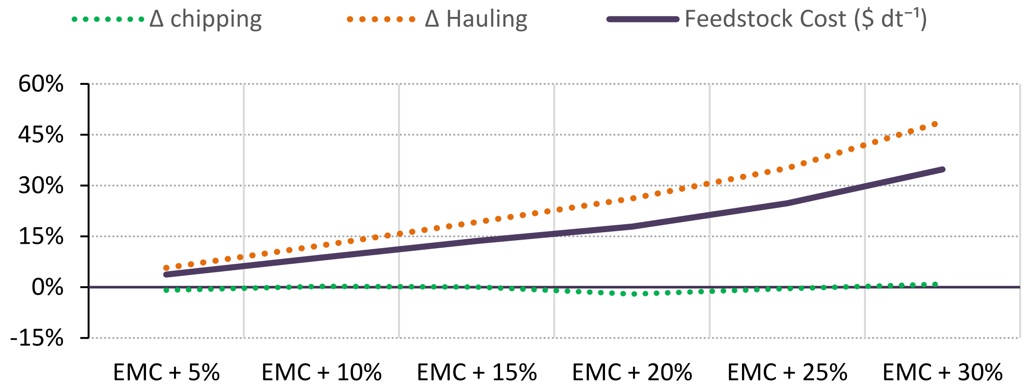

Figure 3-13. Sensitivity of the estimated cost of chipping and hauling harvest residues.

The results are shown in Figure 3-13 as a percentage change relative to the first alternative (EMC). The chipping times were estimated based on the productivity of the loader and the chipper. Since the productivity of the loader is more than the chipper, and the productivity of the chipper is based on the dry mass of processed wood, loading and chipping costs are not significantly changed when moisture content changes. However, the hauling costs are sharply increased which is due to the lower dry mass per payload. The significant changes in the results of these alternative runs of the simulation shows the importance of having an estimate of MC when estimating cost of the operations. Due to this, trial experiments are needed to confirm the obtained results of estimated costs as also suggested in (MacDonald 2006, Roser et al. 2014) for future research directions. Note that the results in the sensitivity analysis are based on a hypothetical situation in which the number of trucks (fleet size) and the number of available chippers were assumed non-limited. Since the interactions between the trucks and loaders were eliminated for sensitivity analysis, in the real case the variations in the costs are expected to be higher.

Weather delays

The delays caused by weather conditions were also modeled based on the data in the literature. Due to uncertainties in the assumptions, sensitivity analysis are conducted for different values of the delay per hour of rain. The delays were estimated for each activity based on an hour delay per mm of rain. Figure 3-14 shows the estimated delays (hours) for each of the processes with 2006-7 weather data and the distribution of the harvesting operations as shown in Table 3-5. All the scheduled cutblocks are selected from one single stand group to provide a basis for the comparison between the alternatives. In total, approximately 8,000 SMH, and on average 24 SMH per day was lost due to the rain precipitation based on this assumption.

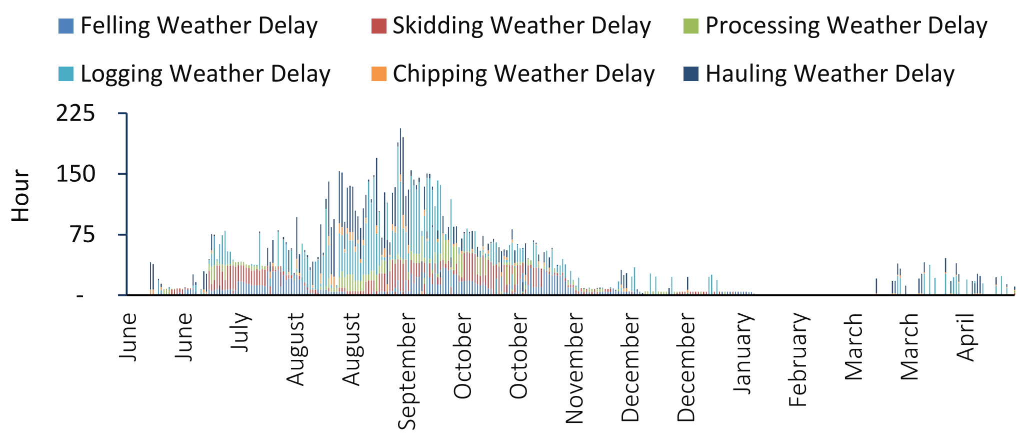

Figure 3-14. Estimated delays caused by rain precipitations.

Six other alternatives are considered each of which with different values for delay per mm of rain. The operations are scheduled for one year. Table 3-13 shows the parameters used in each alternative and the changes in the results for biomass cost ($ dt^{-1}) and sawlog ($ m^{-3}), and the average of all the operation costs per volume before divided for bioenergy and sawlog. The weather delays are eliminated in the first alternative to provide a basis for sensitivity analysis of the costs relative to the delay per hour of rain. The results from the simulations model are shown in Figure 3-15 as a percentage of change relative to the first alternative.

Table 3-13. The parameters for weather delays used in the sensitivity analysis and the effects on estimated costs.

Alternative	Delay (h/mm rain)	Changes in the unit costs		
		Feedstock ($ dt^{-1})	Sawlog ($ m^{-3})	Avg. ($ m^{-3})
1	0.0	$33.22	$23.75	$15.57
2	0.8	$34.28	$24.63	$16.15
3	0.9	$34.30	$24.77	$16.15
4	1.0	$34.03	$24.83	$16.24
5	1.1	$34.34	$24.96	$16.28
6	1.2	$34.34	$24.89	$16.19
7	1.3	$34.83	$25.12	$16.36

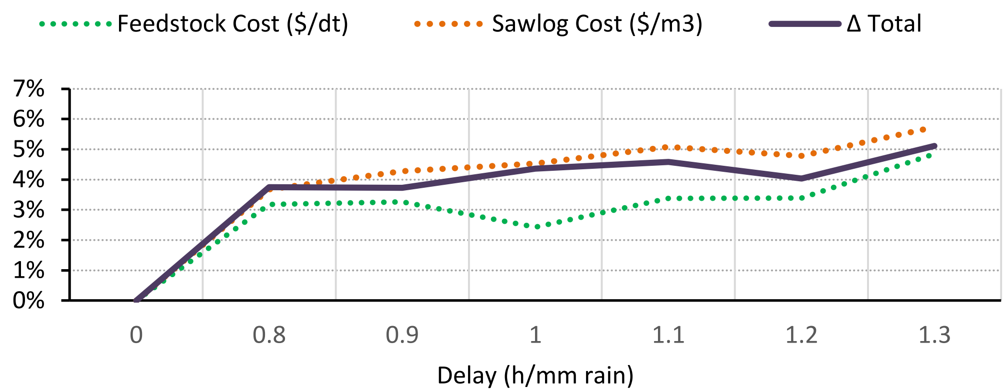

Figure 3-15. Changes in the costs with different weather delay parameters.

Disregarding the weather delays reduced the estimated costs by about 4%, while the costs show a slight upward trend as the result of increasing the hour delay per mm of rain. This indicates that there is a need to further analyze the effects of the weather delays on the operations in a trial of the real system, so that the parameters can be verified. It also points out that considering the weather delays in operations planning can lead to improved estimates of the costs.

Shelf-life model and feedstock availability

The shelf-life model developed by (Eng et al. 2005) was used in the simulation model to estimate the changes in merchantability of standing pine over time. However, the predictions are subject to uncertainties and in other studies modified versions of the shelf-life model are used (see e.g., (MacDonald 2006, Mobini et al. 2011, Niquidet et al. 2012)). The availability of bioenergy feedstock and also the proportion of the sawlog and fuelwood in the harvested volume were therefore different, pointing out another considerable uncertainty in the input data. Furthermore, the uncertainties in the actual feedstock availability would be more severe given that the already existing pulp and paper, and chip mills in Quesnel will be competing for wood chips. In 2006, according to the estimation provided by Kehbila (2010), there was about 0.5 M dt shortage of wood chips in the region, which would be partially, if not totally, supplied from the Quesnel TSA. On the other hand, the amount of sawdust, shavings, and wood chips produced as by-products of the lumber production in sawmills increases when processing MPB killed wood that also should be considered to more reliably estimate of the available bioenergy feedstock.

3.4.2 Estimated cost of generated bioenergy

Detailed analysis of the existing road network was out of the scope of this study, however, road construction, maintenance, and other overhead costs must be considered to provide an estimate of the real system. MacDonald (2006) estimated the costs for road management, administration, and silviculture in the Quesnel area at \$30 dt^{-1} in the satellite harvesting system (bioenergy's share) and \$41 dt^{-1} in the full tree chipping system; in conventional harvesting system these costs are assigned to the logging operations. This leads to a weighted average cost of \$70 dt^{-1} delivered to the power plant. This figure is calculated regarding the proportions of the demand that is fulfilled by each harvesting system plus the aforementioned costs.

From one dt wood delivered to the power plant approximately 1,398 kWh of electricity can be generated (Stennes and McBeath 2006). Therefore, considering \$70 dt^{-1} as the cost of delivered biomass, the estimated cost of generating electricity from biomass in this case study is estimated at \$50 MWh^{-1}. For this power plant, Kumar et al. (2005) calculated the capital, operation, and maintenance costs as shown in Table 3-14. Considering the cost of biomass and the costs of running the plant, an average cost of \$85 MWh^{-1} can be expected. The average price of wholesale electricity in the region (2006-10) was \$49 MWh^{-1} (Niquidet et al. 2012), which shows the important role of carbon mitigation subsidies and other outsource investment grants to make the project economically feasible to recover the underutilized available biomass in the Quesnel TSA.

Table 3-14. Capital, operation, and maintenance costs for the 300 MW power plant (Kumar et al. (2005)).

Item	(\$ MWh^{-1})
Capital cost recovery (10% pre-tax return on investment)	27.05
Storage cost at plant	00.61
Operating cost for plant	04.68
Maintenance cost for plant	01.43
Administration cost for plant	00.55
Ash disposal cost	00.48
Total capital, operation and maintenance cost (\$ MWh^{-1})	34.80

3.5 Conclusions

In this chapter, supply chain simulation was performed to evaluate the supply of biomass from MPB infested forest to a hypothetical power plant in Quesnel, BC. Three relevant harvesting systems were modelled. The harvesting systems were employed in a cutblock, respective to the portion of the fuelwood and sawlog which change overtime based on the biogeoclimatic specifications of the area. Other dynamics of the system in terms of spatial distribution and temporal variability of machine performance and weather conditions were incorporated.

The average cost of delivered feedstock through conventional, satellite yard and full tree harvesting systems are estimated at \$28 dt^{-1}, \$57 dt^{-1}, and \$47 dt^{-1}, respectively. The cost of bioenergy feedstock supplied from the harvesting residues (left at the roadside in the conventional harvesting system) are lower compared to that from the other two systems because the costs for logging operations were assigned to the sawlogs. Direct comparison of reported costs with the previous work is difficult due to the different input data and assumptions in the various studies. However, the estimated costs in this study are generally on the upper side of the reported costs in the literature. For instance, Kumar et al. (2005) reported the cost of harvesting residues from the Quesnel TSA based on 8 publications related to the interior BC between \$22 dt^{-1} to \$32 dt^{-1} (including the overhead costs and road construction and maintenance). In comparison, the operational costs for harvesting residues in the present study was 28 \$ dt^{-1} excluding the overhead and road construction and maintenance costs.

It is estimated that the weighted average cost of delivered biomass to the gate of the power plant over 20 years is about \$70 dt^{-1}, including the costs for road management (maintenance), administration, and silviculture. The estimated cost for the bioenergy generation is \$85 MWh^{-1}, about twice the average price of electricity in the region. This points out the importance of the subsidies and other investment grants to make this bioenergy project economically viable.

Limitations in the model developed in this chapter are as follows.

- The available volume of the standing timber was divided into sawlog and fuelwood portions based on the estimates of the shelf-life model. It was assumed that the demand of pulp mills and other existing facilities will be fulfilled from the by-products of sawmills and no pulp log harvest from the study area was considered. Kehbila (2010) estimate a deficit of 0.5 M dt of wood chips in the area that will further reduce the availability of bioenergy feedstock. Also, due to the competition between the bioenergy project and other applications the cost of bioenergy feedstock will likely increase above the estimations from the simulation model.

- The harvesting residues in the conventional harvesting system were assumed to be available free of charge for bioenergy generation. However, this may not be the realistic case and purchase costs may be associated with the available biomass, in which case higher costs for the delivered feedstock in the real system are expected.
- Available number of pieces of equipment and personnel were assumed to be unlimited (so that the annual target harvest level of 3.1 M m^3 is met). Delays and queues are therefore not included and the reported costs are optimistic. The operational costs are expected to be higher in the reality depending on the efficiency of the planning and execution of the operations.
- The seasonal variations in the harvesting operations, that occur due to the road conditions and limited access to the harvest areas, were based on the practice of a major company in Quesnel in 2006 (Table 3-5). Most likely this schedule changes from year-to-year in response to the weather conditions and the market demand for primary woody products. Also, the hourly delays due to rain precipitation were based on an arbitrary value of one h mm^{-1} that may deviate the estimated costs from the reality. This parameter needs to be validated based on the observations from the real system in order to provide more realistic estimates of the effects of the weather conditions on the operational costs.
- The selection of the harvesting system is made based on the proportion of the sawlog and fuelwood that can be extracted from the harvest area (Section 3.2.2).
- Switching between harvesting systems is set at arbitrary limits that may not necessarily reflect the decisions made in the reality. These will affect the availability of harvesting residues in the conventional harvesting system, the amount of feedstock supplied through each harvesting system, and the delivered cost of feedstock to the power plant.
- EMC is used as an approximation of the moisture content of wood that was estimated based on the relative humidity and temperature, regardless of passage of time, initial moisture content, and specimen size. Therefore, higher moisture content

of biomass are expected in the reality. Higher moisture content of the material will increase the transportation costs compared to the estimations obtained from the simulation model.

Chapter 4. A simulation model for the design and analysis of wood pellet supply chains

4.1 Introduction

During the past decade, wood pellets were traded globally. Rapid increases in the production and consumption of wood pellets, and predictions on its increased demand in the foreseeable future have formed a competitive global market. To remain competitive in this market business entities take advantage of the supply chain decision support tools. A simulation model is developed in this study to enhance and facilitate the studies concerning the design and analysis of wood pellet supply chains. Similar to the previously described model in Chapter 3, this model incorporates the resource constraints in terms of availability of raw materials, transportation means, and equipment. Uncertainties in the availability of and performance of these resources are also considered in the model, in addition to the uncertainties in the quality of biomass. The scope of the study covers the entire wood pellet supply chain from sources of raw materials to the end customers, so that the interdependencies between different stages of the supply chain are considered. The case study considered in this chapter is a pellet production plant located in BC. The model is applied to the case study and after verification and validation was used as a decision support tool.

4.1.1 Background

Wood pellets are densified form of biomass usually made from by-products of primary wood processing facilities (Cocchi et al. 2011, Hughes et al. 2014). Moisture content of wood pellets is less than 10% and its bulk density is around 650 kg m^{-3} (PFI Standards Committee 2011). Wood pellets have uniform cylindrical shape and are recognized as a standardized internationally traded commodity. The required infrastructure for handling, storage, and transportation of wood pellets are similar to other commonly traded commodities such as coal, wood chips, and grain. These properties make it easier to store, handle, and utilize wood pellets compared to other forms of biomass (Wolf et al. 2006). Rapid increases in the production and consumption of wood pellets, and predictions on its increased demand in the future have formed a competitive global market. The total global consumption of wood pellets in 2011 was 14.4 M t, from which about 80% were consumed in Europe (Murray 2012a). High fossil fuel prices, fossil fuel taxes, and incentives for renewable fuels in the European countries have led to a steady growth in the wood pellet market since 1990s. The European demand is expected to grow and could potentially reach to 20-50 M t per year by 2020 (Cocchi et al. 2011). Also, the North American and Asian markets are expected to substantially grow as a result of legislative supports and GHG reduction policies (Cocchi et al. 2011, Stelte et al. 2012).

In 2010, the total wood pellet production in Europe was 9.2 M t, which was equal to 61% of the global production. Canada is also a major producer with an annual production capacity of 3.3 M t (Cocchi et al. 2011). About 90% of pellets produced in Canada are exported to Europe where they are used for power and heat generation (Murray 2012b). The United States has been experiencing rapid expansions of wood pellet production in the southeast region to take advantage of the European market (Pirraglia et al. 2010). Furthermore, new potentials for the production and consumption of wood pellets are demonstrated in other biomass-rich regions, such as Russia, Brazil, Australia and New Zealand (Cocchi et al. 2011).

Different types of raw material have been tested and suggested for pellet production including wood residues (such as sawdust, shavings, wood chips, and bark), forest harvesting residues, and agricultural biomass (such as alfalfa, grain, etc.) (Melin 2008, Spelter and Toth 2009, Obernberger and Thek 2010, Sultana et al. 2010). Production of wood pellets in different geographical regions, using different types or mixtures of raw material and employing different technologies in the production, has been the focus of previous studies (Thek and Obernberger 2004, Mani et al. 2006, Obernberger and Thek 2010, Uasuf and Becker 2011). Mani et al. (2006) estimated 51 $\$ t^{-1}$ as the cost of pellet production when wet sawdust (40% moisture content) was used as raw material and dried shavings was used as the drying fuel. Additionally, economics of wood pellet production in BC, Canada were studied by Peng et al. (2010). The production cost was estimated when mill residues, harvesting residues, bark, or MPB infested wood was used as the raw material. It was shown that the final cost of pellets was significantly influenced by the type and cost of raw material and the size of the plant.

Economics of producing pellets from agricultural biomass in Western Canada has been studied by Sultana et al. (2010). Three scenarios based on the average yield of farms were developed and it was shown that the cost of energy from agricultural biomass was not competitive with that of natural gas. A multi-criteria decision making approach was used by Sultana et al. (2012) to choose the type of raw material for pellet production based on economic, environmental, and technical factors (11 criteria were defined). It was shown that pellets made from wood biomass were preferred based on the defined criteria. Many other studies including (Schmidt et al. 2010, Sikkema et al. 2011, Stelte et al. 2012, Duncan et al. 2013, Kohl et al. 2013) were concerned with utilization of wood pellets as a solid biofuel competing with other sources of energy.

Previous studies concerned with estimating the cost of wood pellet production, including those mentioned above, mostly used static deterministic modelling approaches that ignore the dynamics, interdependencies, and uncertainties along the supply chain; therefore, reduces the accuracy of their results. For example, neglecting the variations in moisture content might lead to incorrect estimations of available feedstock, and transportation and processing costs. The effects of a machine failure on the subsequent process cannot be included explicitly in a static model. Moreover, the design of a wood pellet supply chain is largely influenced by the geographical-dependent parameters, such as available types, cost, and quality of raw materials, market specifications, and access to the infrastructures. This limits the credibility of obtained results in each study to the specific case.

In this study, a simulation model, called Pellet Supply Chain (PSC) model, is developed to facilitate the design and analysis of the wood pellet supply chains, by overcoming the abovementioned limitations. Using the simulation model, it is made possible to incorporate uncertainties in the analysis. The model provides an integrated perspective of the chain that could be applied to any given area, provided that the input data with proper quality are available. The simulation model is intended as a customizable framework for designing the wood pellet supply chains. Decisions concerning the strategic design of the supply chain, such as choosing the best location of the pellet plant among a set of potential locations, could be supported by the model to evaluate the system under different configurations of the supply chain. Furthermore, the simulation model could be used to evaluate different alterations in the existing supply chains, e.g. changing the types of raw material or drying fuel, storage policies, number of loading/unloading stations, and number and size of the buffers between the processing stages.

4.1.2 Wood pellet supply chain

Figure 4-1 shows a typical wood pellet supply chain. It starts from sources of raw materials. Availability, quality, and cost of raw materials have decisive effects on the business viability and design of the supply chain (Lu and Rice 2011). Currently sawdust, a by-product of the sawmill industry, is the main raw material in the pellet production (Obernberger and Thek 2010). Shavings and sawdust are the most desired raw material due to their small particle size, low ash content, and low moisture content.

Transportation of raw material to the pellet plant is the next stage in the supply chain. Due to low bulk density and high moisture content of raw materials, transportation can significantly contribute to the final cost of wood pellets. In some instances, the pellet plants are located at sawmill gates and pipelines are used to convey the raw materials to the pellet plant, hence raw material transportation is eliminated. Covered and outdoor storage of raw materials are both used in the pellet production supply chains. Wet material could be stored outside, but drier materials such as shavings and dried sawdust are stored in covered storage areas or silos. Depending on the type of raw material, a series of processes are required for densification of biomass. Drying, size reduction, pelletizing, cooling, screening, and packaging processes are typically seen in pellet mills.

Prior to feeding the raw material into pelletizers, its moisture content and particle size should fall within appropriate ranges. As a general rule, the moisture content of raw materials should be in the range of 12% to 17% wet basis (Spelter and Toth 2009). The rotary dryer is the most commonly used technology in the drying of wood biomass since it can be used to dry high volumes of materials with wide range of initial moisture content (Thibault and Duchesne 2004, Pang and Mujumdar 2010, Li et al. 2012). The two most important drying process characteristics are the feed moisture content and the feed flow rate (Thibault and Duchesne 2004). In the real systems, the feed moisture content cannot be controlled since it depends on materials characteristics. It is usually the practice to keep the flow rate of materials as constant as possible and adjust other parameters, such as temperature of the heating media, in order to obtain a uniform moisture content in the discharged materials. Dried material is hammer milled using a 4 mm screen for producing pellets with 6 mm diameter (Obernberger and Thek 2010). Pellet mills (press) operate at a temperature of 90-100 °C (Di Giacomo and Taglieri 2009). Pellets are hot and soft upon exit from the pellet mill. Therefore, cooling is needed for hardening it. Wood pellets are usually stored in silos or warehouses or directly bagged for distribution.

According to the PFI standard, three types of pellets: premium, standard, and utility pellets are defined (PFI Standards Committee 2011). In the premium category, the maximum ash content is 1%. The maximum allowable ash content for the standard and utility categories are 2% and 6%, respectively. Since the ash content of raw materials does not change during the processes, the production of different types of wood pellets depends on the mixture of raw material.

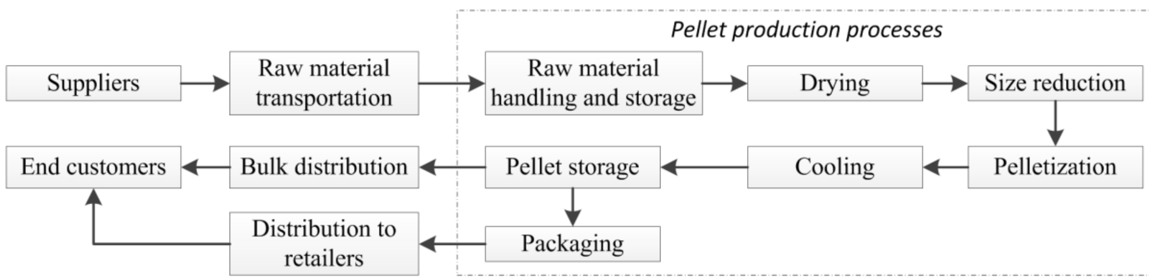

Figure 4-1. Schematic of a wood pellet supply chain.

Wood pellets are distributed in many forms including consumer-bags (15-18 kg), big-bags (500 kg), containers, railcars, and ocean vessels (Obernberger and Thek 2010). Also, residential market deliveries are done using tank trucks, especially in Europe where proper storage facilities are available in customers' locations (Obernberger and Thek 2010).

4.2 Case study

The case study considered in this work is a pellet producer in interior BC. The input data and information are mostly provided by the company. In case the required data were not available, complementary data from the literature are used. The supply chain includes five suppliers from which sawdust and shavings are transported to the pellet mill, a trucking company that handles the transportation of raw materials, a 20 t h^{-1} pellet mill, and an export port that handles incoming rail and outgoing sea transportation.

The pellet mill operates seven days a week and 24 hours per day. Sawdust is dried and then mixed with shavings before feeding to the grinders. The required heat for the drying process is provided by a burner fed with sawdust. The fuel consumption in the burner depends on the moisture content and heating value of the fuel and the required heat for the drying process, which in turn depends on the in-feed moisture content and target moisture content after drying. The electricity consumptions are estimated based on the corresponding nominal power of each piece of equipment, and the electricity price of 100.00 \$ MWh^{-1}. Simultaneity factors are considered to reflect the fluctuations in the performance of the equipment due to the processing conditions (Obernberger and Thek 2010).

4.2.1 Supply and demand

The pellet mill in this case study has five suppliers listed in Table 4-1. Suppliers are wood processing plants that provide two types of raw material: sawdust and shavings. They operate five days a week and two 8-hours shifts per day. Two of the suppliers are close to the pellet mill and the raw material is pneumatically conveyed to the pellet mill, while the materials from the other three suppliers are transported by trucks.

For each supplier and each type of raw material, a daily production rate is taken as the input in the model. Uniform distribution functions are used to reflect the fluctuations in the daily available amounts. Based on the supply contracts, the pellet mill has to take all the raw materials produced by the suppliers regardless of whether or not the pellet mill has the demand for the wood pellets. The suppliers are contracted in a way that the demand of the pellet mill during the full-load operation is satisfied. The costs are based on dt of materials (Table 4-1). The moisture content of each load is measured based on samples taken from it and the suppliers are paid based on the dried weight of delivered raw material.

Table 4-1. List of suppliers in the case study.

Supplier	Transportation mode	Distance to pellet mill (km)	Availability (t day^{-1})[a]		Cost (\$ dt^{-1})[a]	
			Sawdust	Shavings	Sawdust	Shavings
1	Truck	25.1	U(280, 300)[b]	U(100, 140)	10.00	15.00
2	Truck	52.4	--	U(50, 70)	--	15.00
3	Truck	55.4	--	U(30, 50)	--	15.00
4	Air Conveyed	--	--	U(20, 40)	--	15.00
5	Air Conveyed	--	U(240, 260)	--	10.00	--

[a] Data provided by the pellet company; [b] Uniform distribution function

The initial analysis on the obtained data (maximum likelihood estimates) show that the moisture content of sawdust delivered to the plant follows a Weibull distribution with a location value of 21, a scale value of 9.02, and a shape value of 3.39. For shavings, the best fitted distribution was a Weibull distribution with a location value of 8, a scale value of 3.32, and a shape value of 2.02 (Figure 4-2).

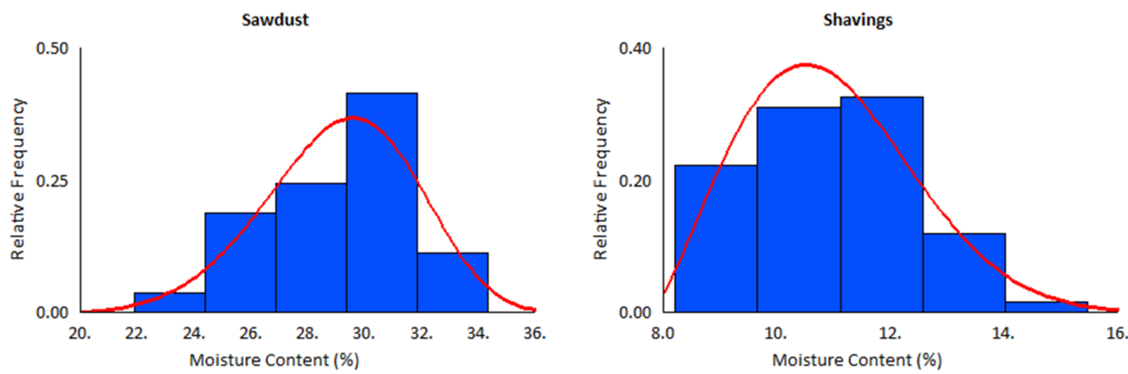

Figure 4-2. Random distribution functions fitted to the empirical data for moisture content of sawdust (left) and shavings (right).

The pellet company considered in this case study sells 90% of its products to European customers through long-term contracts. The wood pellets destined for European market are loaded into 90 t railcars at the pellet mill and transported 840 km to the North Vancouver port, where the pellets are stored and then transported by ocean vessels. In addition to the export market, the pellet mill sells about 15 k t of bagged pellets domestically. Pellet bags weigh about 18 kg and are palletized in 0.5 t batches. In this study, it is assumed that the pellets are delivered to two distribution centres in the area. Table 4-2 shows the input data regarding the customers in the case study.

Table 4-2. Input data for customers.

Customer	Distance (km)	Transportation mode	Annual demand (t)
Domestic1	125	Truck	7,300
Domestic2	205	Truck	7,300
Export	840	Railcar	146,000

4.2.2 Pellet mill

The general input data and assumption regarding the pellet mill are given in Table 4-3. The pellet plant (mill) operates seven days a week and 24 hours a day (365 days per year) with 20 t h^{-1} nominal capacity[1]. Sawdust is processed in a drum dryer and is fed into the hammer mill while shavings bypass the dryer and are directly fed to the hammer mill. The required heat for the drying process is generated in a 16 Mbtu furnace that burns wet sawdust. Ground materials are processed with four pelletizers and are fed into the coolers. After separating the fines in the shaker screens, the wood pellets are stored in the storage bins or packaged and then transported to the customers by railcars or trucks.

Table 4-3. The pellet plant input data and assumptions

Item	Value/Explanations
Nominal throughput	20 t h^{-1}
Working hours/days	24 hours 365 days a year
Electricity cost	100 \$ MWh^{-1}
Annual interest rate	8%
Cost of spare parts, lubricants, and other consumables	8 \$ t^{-1} [a]
Personnel needs and salary	There are fourteen full-time personnel, with the annual cost of \$60 k per person, operating the plant in three shifts. Also, two foreman and a supervisor are employed that cost \$75 k and \$90 k per person, respectively [b].

[a,b] data obtained from the pellet company.

The capital cost of the pellet mill is estimated based on the data provided by Sultana et al. (2010) as shown in Table 4-4. The cost figures are adjusted for currency exchange and inflation rate as of December 2012. The exchange rate of 1.12 (US\$/CAD\$) and the annual rate of inflation of 1.21% are used in the calculations (Bank of Canada 2013a, Bank

[1] Figures are reported based on the wet mass of materials (\$ t^{-1}) unless otherwise stated as \$ dt^{-1}.

of Canada 2013b). The total capital cost was estimated at $20 M for the nominal capacity of 20 t h^{-1}.

Table 4-4. Capital cost estimation for the pellet plant.

Item	Amortization period [a]	Capital cost for 6 t h^{-1} plant [b]	Estimated capital cost for 20 t h^{-1} plant	Number of pieces	Annualized cost
Dryer	15	$430,000.00	$1,788,924.31	1	$208,999.21
Hammer mill	15	$150,000.00	$978,565.74	2	$114,325.39
Pellet mill	15	$350,000.00	$2,878,614.31	4	$336,307.20
Cooler	15	$170,000.00	$1,097,768.33	2	$128,251.77
Screener	15	$18,300.00	$90,476.93	1	$10,570.38
Bagging system	15	$450,000.00	$2,306,670.85	1	$269,487.31
Conveyers, tanks, etc.	15	$1,113,000.00	$6,591,947.31	1	$770,134.20
Land, infrastructure, construction and other	25	--	$4,300,000	--	$402,818.75

[a] (Obernberger and Thek 2010); [b] (Sultana et al. 2010)

Specifications of the equipment are shown in Table 4-5. The heat recovery factor in the biomass burner is assumed to follow a Uniform distribution with 50% lower and 60% upper bounds (DeMeo and Galdo 1997). The repair and maintenance in the pellet plant have a significant impact on the plant up-time and the final cost of produced pellets (Obernberger and Thek 2010, Uasuf and Becker 2011). The data on the machine failure and required maintenance are scarce. Nilsson (Nilsson 1999) used exponential distribution functions to describe the failure of the bailers and loaders. In this research, the same approach is used to account for the down-time of equipment. It is assumed that the Time Between Failure (TBF) and Time To Repair (TTR) for the equipment follow probability functions shown in Table 4-5. The parameters are set after consultation with industry experts.

Table 4-5. Input data for the equipment

Specification of the dryer								
	Heat Demand (kWh t^{-1})	Feed Rate (t h^{-1})	Power (kWh)	Fuel	Burner efficiency (%)	Simultaneity Factor (%)	TBF [b]	TTR [c]
Drum dryer	1,300 [a]	25 [a]	270 [a]	Wet sawdust	U(50-60) [a]	U(85-100) [a]	Exp (25h)	Exp (1h)

Specification of size reduction, pelletization, and cooling equipment						
	No. of pieces	Capacity (t h^{-1})	Power (kW)	Simultaneity factor (%)	TBF	TTR
Hammer mill	2	10	370 [a]	U(85-100) [a]	Exp (15h)	Exp (0.5h)
Pellet mill	4	5	300 [a]	U(85-100) [a]	Exp (10h)	Exp (1h)
Cooler	2	10	25 [a]	U(85-100) [a]	Exp (30h)	Exp (0.5h)

[a] data obtained from the pellet company; [b] Time Between Failure; [c] Time To Repair.

4.2.3 Raw material transportation and wood pellet distribution

Transportation of raw materials from suppliers to the pellet plant and delivery of the wood pellets to the domestic customers is outsourced to a trucking company. The transportation company works seven days a week and two shifts per day (7 a.m. to 10 p.m.). It is assumed that there are 10 similar trucks available. The fuel consumption rate and the average speed of the trucks in each trip follow a Uniform distribution function with lower and upper bounds shown in Table 4-6.

Table 4-6. Trucks input data.

Weight Capacity (t)	Volume Capacity (m^3)	Fuel Cons. Rate (L km^{-1})	Average Speed (km h^{-1})	Unloading rate (m^3 h^{-1})	Loading Rate (m^3 h^{-1})	Cost (\$ h^{-1})
45	113	U(0.30, 0.35)	U(60,80)	200	200	114

Data obtained from the pellet company.

Rail transportation to the harbor costs 28 \$ t^{-1}, which includes all related fees such as railcar rentals and insurance. Railcars are filled and delivered to the port on a daily basis. The contract with the European customers is to deliver the wood pellets to the ocean vessels (free-on-board), after that the customers are responsible for ocean transport and costs.

In BC, the energy intensity factor of electricity is 24 g CO_2 kWh^{-1} (Environment Canada 2009) that is used to calculate the emissions due to electricity consumption at the plant. When burning biomass to generate the heat required in the drying process, a factor of 301.8 g kWh^{-1} is used to estimate the amount of CO_2 emissions (Environmental Protection Agency 1995). The energy consumed by trucks and generated emissions from it are considered based on the energy content of diesel (9.96 kWh l^{-1}) and CO_2 emissions of 2.7 kg from one l of diesel (Natural Resources Canada 2011). The energy consumption of 0.09 kWh $(t\ km)^{-1}$ and the generated CO_2 emission of 16.38 g $(t\ km)^{-1}$ are assumed for rail transportation (Magelli et al. 2009).

4.3 The simulation model

The scope of the model includes the whole supply chain, which starts from sources of raw materials (suppliers) and ends with the customers. Procurement, transportation and storage of raw material, pellet production, and distribution are the major activities along the supply chain that are included in the model. The estimates of time, cost, emission, and energy consumption associated with each of these activities are provided, while taking into account the dynamics of the system. The model is developed using the ExtendSim simulation software (Imagine That 2011), which is an OOS environment. The supply chain entities are developed as modules and contain several sub-modules. Depending on the module and its role, properties and interactions with other modules are defined. Model verification is done through walkthroughs, debugging of the codes, and rigorous test runs. In order to validate the model, its results are compared with those of the real system and confirmed by industry experts.

In the developed model, the discrete-event simulation approach is used to model the supply chain entities and their interactions; while the flow of materials inside the pellet mill is modelled using the discrete rate-approach. In ExtendSim (Imagine That 2011), the rate based capabilities of continuous simulation method are combined with discrete-event environment to form the discrete rate technology (Krahl 2009); the state variables of the system components only change at discrete points in time depending on the behavior of the system, as opposed to the continuous models that the whole state of the system is re-calculated at each time step (Damiron and Nastasi 2008). This type of simulation is particularly useful in modelling the systems that deal with flow of material, rates, breakages, storage capacity, and other constraints (Krahl 2009); such as the pellet mills where the flow of biomass between different processing stages is to be modelled. Adopting the discrete-rate method enables PSC to include the flow of material and to simulate the failure and repair times of the equipment and interdependencies between the processing stages inside the pellet mill.

4.3.1 Supply chain entities and modules

Raw material suppliers, pellet mills, customers, and transportation vehicles are considered as supply chain entities. A set of properties and interactions is defined for each entity according to their role in the supply chain. Figure 4-3 depicts the structure of the simulation model including the flow of information and interactions between the different modules. Table 4-7 lists the most important input parameters and outputs associated with each module in the simulation model. A relational database is used to communicate data between the modules. Activities and processes along the chain include the physical processes and activities in addition to the scheduling events leading to the occurrence of the activities.

The road transportation module is composed of three main activities (assignment of transportation orders to the vehicles, composition of routes for vehicles for which dispatch requirements are met, and transportation cost calculations) and a scheduling event. The scheduling event in the transportation module starts whenever there is a new transportation order, either for raw material transportation or for pellet distribution. Another occurrence that triggers a scheduling event is when a vehicle has been released from previously assigned trip and has become available. Also, periodic (hourly) scheduling events are considered. If a certain condition apply (number of available vehicles is more than zero, there are available vehicles capable of handling the order, and dispatch requirements are met) the route is composed and the vehicle is dispatched.

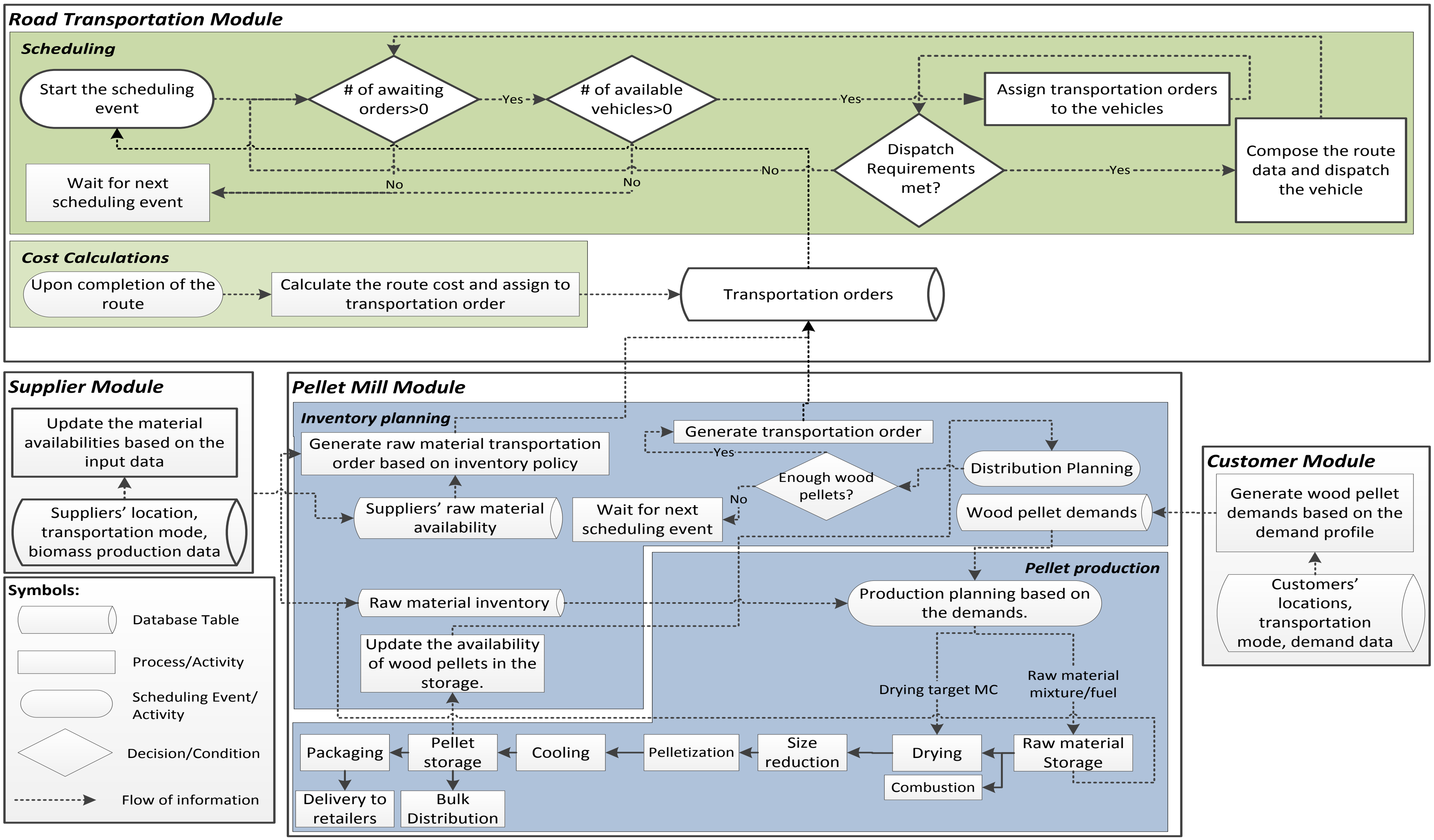

Figure 4-3. Structure of the simulation model; the model includes transportation, supplier, pellet mill, and customer modules. The flow of information and interactions between the modules are shown in the figure.

Table 4-7. Inputs and outputs of the simulation model.

Module	Input parameters	Outputs
Suppliers	• Biomass production rate • Quality measures of raw materials • Cost of raw materials • Location • Transportation mode	• Total wet and dried mass of purchased raw materials • Cost of purchased raw materials
Pellet plant	• Capacity (throughput) • Annual operating days • Location • Sequence of operations inside the plant • Equipment failure rates and repair time • Mixture of raw material • Fuel used for heat generation • Electricity cost • Investment cost	• Raw material consumption • Processing costs • Plant productivity • Total mass of each type of products • Energy consumption (electricity and heat)
Customers	• Demand profile • Location • Transportation mode	• Demanded mass of products • Delivered mass and average cost of delivered products • Demand fulfilment rate
Transportation company	• Unit cost of transportation per kilometer ($ km^{-1}) • Unit cost of transportation per hour ($ h^{-1}) • Number and type of trucks • Capacity of trucks • Fuel consumption rate (lit km^{-1})	• Total transportation distance/time • Total transportation costs of raw materials (from each supplier) and pellets (to each customer) • Total transportation costs of pellets • Mass and transportation cost of delivered raw materials from each supplier • Mass and transportation cost of delivered pellets to each customer • Emissions • Energy/ fuel consumption (cost)

4.3.1.1 Suppliers

A pellet mill may receive its raw materials from different types of suppliers. For each supplier, types of raw material, available quantity, and quality over time are inputs of the model. The location, production and capacity of suppliers, their operating shifts, transportation mode, storage capacity, and loading rate are other input parameters of the model. To keep track of the characteristics of the material moving through the system, each entity is associated with a material characteristic record. The data on mass, volume, moisture content, ash content, bulk density, heat value, and particle size are data fields maintained in this record. The main outputs of the suppliers' module are the amount and cost of purchased raw materials.

4.3.1.2 Pellet mill

The raw material storage, drying, size reduction, pelletizing, cooling, and wood pellet storage processes are included in the pellet mill module. The plant capacity depends on the installed number and capacity of equipment pieces which are inputs of the simulation model. Furthermore, the model takes the sequence of operations as an input to the model that could be different for different types of materials.

The costs related to the pellet plant are composed of several elements: capital cost, operating (e.g., costs of energy, fuel, lubricants, consumables, and labour) and maintenance costs. The capital cost is annualized using the capital recovery factor formula (Eq. 4-1), where *ACC* is the annual capital cost, *TCC* is the total capital cost, *i* is the annual interest rate (%), and *N* is the service life of the plant. To estimate the capital cost of a piece of equipment, the power law suggested by Perry et al. (1997) is used. Eq. 4-2 shows the relationship used to calculate the capital cost of a piece of equipment with $capacity_2$ relative to a given cost of a piece of equipment with $capacity_1$.

$$ACC = TCC\left(\frac{i(1+i)^N}{(1+i)^N - 1}\right) \qquad \text{Eq. 4-1}$$

$$Cost_2 = Cost_1\left(\frac{Capacity_2}{Capacity_1}\right)^{scale\ factor} \qquad \text{Eq. 4-2}$$

Operating costs are calculated separately for each process. Depending on the case, the labor and overhead costs are estimated and used in the calculations.

Raw material storage

The storage of raw materials is modelled by incorporating the storage capacity, number of unloading stations, unloading rates, and tracking in/out flows. The storage capacity for each type of raw material is an input parameter of the model. Queues might form in front of the unloading station and the in-line time of the vehicles are estimated in this case.

Drying process

The drying process diagram, Figure 4-4, describes how the drying process is modelled. The input rate of materials is kept constant as long as the raw materials are available, and the variations in the feed moisture content are dealt with by controlling the weight of the fuel materials fed to the burner.

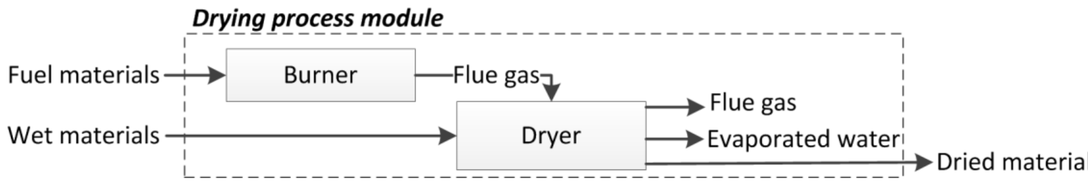

Figure 4-4. The drying process flowchart.

Electricity and heat are used in the drying process. Electricity is consumed by the belt drive, fans and other electrical components of the dryer. In the simulation model, the dryer's total power is used to calculate the electricity consumption over time interval of Δt as shown in Eq. 4-3, where E is the price of electricity (\$ kWh^{-1}), P is the equipment power (kW), SF is the simultaneity factor of the equipment (%), and W is the processed mass (t) during the time interval. The simultaneity factor (%) is an empirical value that adjusts the power consumption of the equipment according to the nominal power and the operating conditions (Thek and Obernberger 2004, Obernberger and Thek 2010).

$$\text{Electricity cost} = \frac{E \cdot P \cdot SF \cdot \Delta t}{W} \qquad \text{Eq. 4-3}$$

Pellet mills in BC usually burn biomass to generate the required heat. The required amount of heat depends on the amount of water that should be evaporated which in turn depends on the initial and target moisture contents of the material. Eq. 4-4 is used in the simulation model to estimate the amount of water that should be evaporated in order to reach the target moisture content. In this equation, $W_{eva.}$ is the mass of water that should be evaporated (t), W_{in} is the mass of material fed into the dryer (t), dW_{in} is the dried mass of in-feed materials (dt), and MC_t is the target moisture content after the dryer (%). The heat demand of the dryer (HD) is defined as the amount of heat required to evaporate one t of water (kWh t^{-1}), which is introduced as a specification of the dryer system and is provided by the manufacturers (Obernberger and Thek 2010). Eq. 4-5 is used to calculate the required heat (R_{Heat}) to obtain the target moisture content.

$$W_{eva.} = W_{in} - \frac{dW_{in}}{1\text{-}MC_t} \qquad \text{Eq. 4-4}$$

$$R_{Heat} = W_{eva.} \cdot HD \qquad \text{Eq. 4-5}$$

The cost of consumed heat during a given time interval is calculated by multiplying the heat requirement by the unit cost of the energy (\$ kWh^{-1}). When biomass is used as the drying fuel, the required mass of fuel during Δt is calculated based on the heat demand of the dryer, heat value and moisture content of the fuel, and the efficiency of the burner as expressed in Eq. 4-6, wherein, W_{Fuel} is the required mass of fuel (t), HV_{Fuel} is the higher heat value of the fuel (kWh dt^{-1}), MC_{Fuel} is the moisture content of the fuel, and γ is the efficiency of the burner (%).

$$W_{Fuel} = \frac{R_{Heat}}{HV_{Fuel}\ (1\text{-}MC_{Fuel})\ \gamma} \qquad \text{Eq. 4-6}$$

Size reduction (grinding), pelletizing, and cooling

The size reduction process is usually performed by hammer mills when sawdust and shavings are used in pellet production. Pelletization of the ground materials is performed in pelletizers (pellet mills). Counter flow coolers are commonly used in the pellet production industry. Eq. 4-3 is used in the simulation model to estimate the energy consumption and cost in the processes.

4.3.1.3 Customers

The input data of the model include the demand profile of the customer, its location, and available transportation mode. Delivered cost of wood pellets is estimated for each customer in addition to the related energy input and CO_2 emissions.

4.3.1.4 Transportation

The location and available transportation mode for each supplier and customer are inputs of the model. Travel distances are calculated using MS MapPoint (Microsoft Corporation 2010). Travel times are calculated based on travel distances and vehicle's speed. The fuel consumption of vehicles is calculated based on the consumption rate (lit km^{-1}). The energy consumption and generated emissions due to road transportation are calculated based on the fuel consumption. Scheduling of the road transportation is performed considering the vehicles status (idle, busy, off-shift), capacity (volume and weight), hours of operations, and restrictions (e.g. type of materials that can be transported), and also type of raw material (different types cannot be mixed during transportation). Road transportation costs are based on an hourly rate. When a trip is made between several suppliers or customers, the transportation cost is shared between them based on their share of the load weight. Schedule of the rail transportation is dictated by the rail transportation company and the same is true for ship transportation. Therefore, the schedules are inputs of the simulation model. Cost calculations for rail and ship transportation costs are calculated using transportation rates per unit of mass ($\$ \ t^{-1}$).

Transportation orders generated by the pellet mill module (for delivering the raw materials to the plant or delivering pellets to the customers) are given a due data that is used for scheduling the transportation orders. As previously mentioned, the scheduling events are triggered whenever a truck becomes available, a new transportation order is received, a specific amount of time since the last scheduling time is elapsed, or availability of materials (raw materials or wood pellets) are changed (more than a minimum level). At each scheduling event, the orders are sorted based on the due dates and customers priorities. Orders are then allocated to the available trucks and trucks are dispatched when the required materials are available at the source(s) within the time-window of the operating shifts.

4.4 Regular pellet production and distribution

The simulation time is set to one year and the model was run for 50 iterations. The number of iterations was calculated based on the 95% confidence level in the estimated value of the annual production.

4.4.1 Supply chain costs

The average annual production was estimated at 156.87 kt of pellets with a standard deviation of 370 (95% confidence interval: 156.87 kt ± 725.20). This equals to 89.54% of the nominal capacity which complies with the values reported by other authors for plant availability in a year. In the literature, 85-91% plant availability factor is commonly reported (Thek and Obernberger 2004, Obernberger and Thek 2010, Uasuf and Becker

2011). The contribution of different cost items in the aggregate cost structure of the supply chain is shown in Table 4-8.

Table 4-8. Supply chain costs

Item	Annual Cost (1000 $)	Stn. Dev.	Unit cost ($ dt^{-1})	Unit cost ($ GJ^{-1})
Raw material	1,839.78	2,679.80	$11.83	$0.59
Raw material transportation	2,427.51	4,850.32	$15.61	$0.78
Pellet production				
Auxiliary drying equipment	109.53	253.15	$0.78	$0.04
Size reduction	491.94	1,106.31	$3.50	$0.17
Pelletization	797.56	1,745.47	$5.67	$0.28
Cooling	35.48	54.96	$0.25	$0.01
Annualized capital investment	2,240.89	0.00	$15.94	$0.80
Personnel	1,080.00	0.00	$7.68	$0.38
Spare parts and other consumables	1,124.67	2,643.88	$8.00	$0.40
Pellets distribution	4,484.98	9,902.64	$32.06	$1.60
Total	14,632.34	20,148.87	$101.33	$5.06

The histogram of the estimated annual cost of the supply chain drawn from 50 runs of the simulation model is shown in Figure 4-5. The annual cost of the supply chain was estimated within a range of 14.59 M$ and 14.67 M$ at 95% confidence level. The small standard deviations (Table 4-8) for this case study are due to the long-term contracts of the pellet mill with suppliers and customers, which may not be the case for many small sized pellet mills.

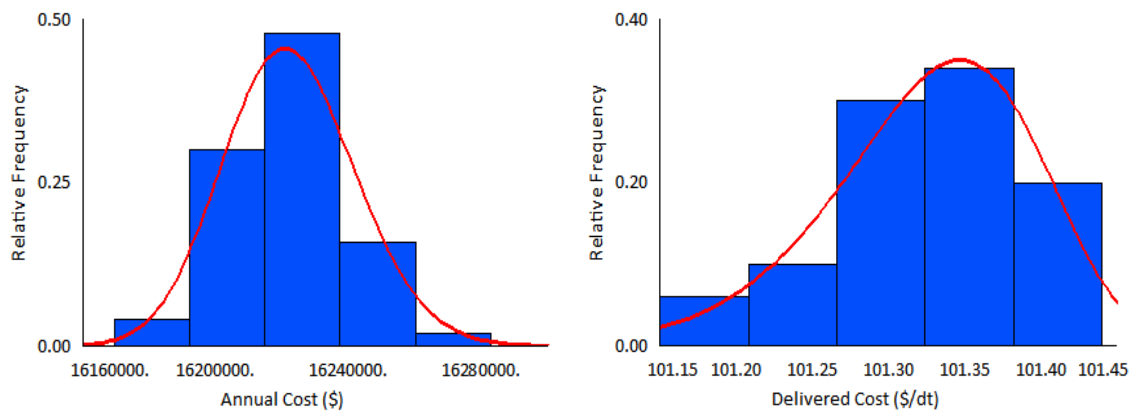

Figure 4-5. Histograms and best fitted distribution functions for the annual cost of the supply chain (left) and the delivered cost (right) of wood pellets

Raw material procurement and transportation accounted for 29% of the total cost. Total mass of delivered raw materials to the pellet mill was about 203.02 kt (155.52 kt dried mass). Table 4-9 shows the aggregated results in terms of mass and cost of supplied raw materials from each supplier. On average, one t of raw materials delivered to the plant costs \$21.02 t^{-1} (equivalent to \$27.44 dt^{-1}). Delivered sawdust and shavings cost \$14.33 t^{-1} and \$35.59 t^{-1}, respectively.

Drying, size reduction, pelletization, and cooling processes cost \$10.20 dt^{-1} of wood pellets, which compose 10% of the total costs. The production cost of wood pellets (including processing, capital investment, personnel, and consumables) is \$41.83 t^{-1}, which is 40% of the final cost. The estimated cost of wood pellets at the gate of the pellet mill is \$69.27 dt^{-1}. Distribution of wood pellets accounts for 31% of the total cost, on average \$32.06 t^{-1} (Table 4-8). Table 4-10 lists the delivered mass and distribution cost of wood pellets for each customer. Delivered wood pellets to the export port costs \$97.27 t^{-1}. The cost of delivered wood pellets to domestic customers depends on the distance from the pellet.

Table 4-9. Quantities and cost of raw material delivered to the pellet plant.

Supplier	Sawdust Mass (kt)	Sawdust Material (k$)	Sawdust Trans. (k$)	Shavings Mass (kt)	Shavings Cost (k$)	Shavings Trans. (k$)	Total Mass (kt)	Total Material (k$)	Total Trans. (k$)	Total Ave. Cost ($ t^{-1})
1	73.86	523.50	1,007.03	30.02	401.04	651.08	103.88	924.54	1,658.11	24.86
2	0	0.00	0.00	15.63	208.82	454.63	15.63	208.82	454.63	42.44
3	0	0.00	0.00	10.43	139.34	314.77	10.43	139.34	314.77	43.55
4	0	0.00	0.00	7.83	104.62	0.00	7.83	104.62	0.00	13.36
5	65.25	462.46	0.00	0.00	0.00	0.00	65.25	462.46	0.00	7.09
Total	139.11	985.96	1,007.03	63.91	853.82	1,420.48	203.02	1,839.78	2,427.51	21.02

Table 4-10. Outputs regarding the distribution of wood pellets

Customer	Delivered Mass (t)	Transportation cost ($)	Unit trans. cost ($ t^{-1})	Delivered cost ($ t^{-1})	Delivered cost ($ GJ^{-1})
Domestic1	7,300.00	205,353.22	28.13	97.40	5.43
Domestic2	7,300.00	317,781.99	43.53	112.80	6.28
Export	141,494.40	3,961,843.20	28.00	97.27	5.42

4.4.2 Energy consumption and CO_2 emissions

The energy consumption and CO_2 emissions along the supply chain are listed in Table 4-11. The total annual energy consumption was 89.19 GWh. On average, the energy input was 568.42 kWh t^{-1}. The total annual CO_2 emission was 21.46 t, an average of 136.76 kg per t of wood pellets.

Table 4-11. Energy consumption and CO_2 emissions

Item	Energy use (kWh)	Energy use (kWh t^{-1})	CO_2 Emission (t)	CO_2 (kg t^{-1})
Drying	62,591,069.80	399.00	18,585.70	118.48
Grinding	4,919,408.34	31.36	118.07	0.75
Pelletization	7,975,567.67	50.84	191.41	1.22
Cooling	354,754.66	2.26	8.51	0.05
Trucking	2,314,441.10	14.75	627.41	4.00
Rail transportation	11,093,160.56	70.71	1,946.85	12.41
Total	89,248,402.14	568.93	21,477.95	136.91

The most energy intensive part of the supply chain was the drying process with an average of 398.38 kWh t^{-1} including heat and electricity. Table 4-12 lists the results for the drying process. It was estimated that 26.02 kt of water is evaporated that requires 61.50 GWh of energy. The consumed fuel mass and estimated CO_2 emissions due to drying process are shown in Table 12.

Table 4-12. Outputs of the drying process

Heat (GWh)	Electricity (GWh)	CO_2 Emissions (t)	Processed Mass (kt)	Evap. Water (kt)	Fuel Mass (kt)
61.50	1.10	18.59	93.30	26.02	17.45

Truck and rail transportation was also an important contributor to the supply chain CO_2 emissions. Table 4-13 lists the outputs of the model for truck transportation. The total travel distance was 774,579 km and total travel time was 25,883 hours. The total fuel consumption was 232, 374 liters. The emission generated due to the truck transportation was 627.41 t CO_2 and the total energy consumption was 2.31 GWh. The CO_2 emission due to rail transportation was 1950 t and the energy consumption was about 11.10 GWh.

Table 4-13. Truck transportation outputs

Cost (M$)	Fuel (Lit)	Distance (km)	Travel time (h)	CO_2 emission (t)	Energy (GWh)
2.95	232,373.60	774,578.68	25,882.87	627.41	2.31

4.4.3 Scenario analysis

Two potential modifications to the supply chain were investigated in this study: (1) changing the drying fuel from sawdust to bark and hog fuel, and (2) producing lower quality pellets for the international market. These two alternations were suggested by the pellet company president. In order to evaluate the effects of these modifications, three scenarios were developed.

Changing the drying fuel

The sawdust which is burnt and used as the drying fuel could be converted to wood pellets to generate more profit for the company, if a sensible and low cost drying fuel was available. One option is to burn bark. The pellet mill considered in this study could receive bark from adjacent sawmills free of charge. However, in order to make the transition to use bark, the company has to improve its combustor and emission control system. To do so, a capital investment of $1.5 M is required. The simulation model was used to evaluate this option.

In order to run this scenario, the input parameters of the model were modified. The moisture content of bark is assumed to follow a Uniform distribution function with lower bound of 40% and upper bound of 55% (Kehbila 2010). When consuming bark as the drying fuel, the total amount of required sawdust and shavings would be less than those for the base case. There were two possible scenarios: (a) to purchase less sawdust, or (b) to purchase less shavings. There is a trade-off between the changes in the material procurement cost and transportation cost, which depend on the moisture content and bulk density, from one hand, and the cost of raw material on the other hand. Sawdust is cheaper than shavings per delivered dried t, but has a higher moisture content that increases the transportation cost. The lower bulk density of shavings (on average 130.83 kg m^{-3}) compared with sawdust (on average 226.21 kg m^{-3}) is another factor that is taken into account. To quantify the differences between these two options, two scenarios were run using the simulation model. In Scenario 1, the amount of sawdust procurement from Supplier 1 is reduced. In Scenario 2, it is assumed that the amount of purchased shavings is reduced and more sawdust is used in the mixture of raw materials. Table 4-14 shows the input parameters for Scenarios 1 and 2. The daily availabilities of sawdust and shavings at the suppliers' locations are changed and bark is supplied from Supplier 5.

Table 4-14. Suppliers input data for Scenario1 and Scenario 2.

	Supplier	Production (t day^{-1})		
		Sawdust	Shavings	Bark
Scenario 1	1	U(210, 230)	U(100, 140)	--
	2	--	U(50, 70)	--
	3	--	U(30, 50)	--
	4	--	U(20, 40)	--
	5	U(240, 260)	--	U(80,90)
Scenario 2	1	U(280, 300)	U(100, 140)	--
	2	--	U(60, 80)	--
	3	--	--	--
	4	--	--	--
	5	U(240, 260)	--	U(90,110)

The obtained results for the base case and Scenarios 1 and 2 are compared in Table 4-15. The amount of bark consumed in Scenario 1 and Scenario 2 were about 21.71 kt and 25.10 kt, respectively. More bark was required in Scenario 2 due to the higher moisture in the sawdust. Compared to the base case scenario, the final cost of delivered pellets would be slightly reduced by about 1% and 1.5% in Scenario 1 and Scenario 2, respectively. The energy consumption and CO_2 emissions in Scenario 1 were not significantly different than the base case scenario. However, the energy consumption and CO_2 emissions in Scenario 2 compared to the base case were increased by 11% and 13%, respectively. The increases were due to the higher drying process needed as more sawdust was used in the mixture of raw material.

Producing lower quality pellets

BC wood pellet producers have traditionally been located in close proximity of sawmills and other wood processing plants. Thus, they have had easy access to abundant sawdust and shavings and have produced premium quality pellets (Tumuluru et al. 2010). Bark is less expensive than sawdust and shavings and using bark in the blend of raw materials for pellet production increases the heat value and mechanical strength of the pellets (Melin 2008). The PFI standard for wood pellets allows utility grade wood pellets to contain less than 6% ash content. In Scenario 3, it is assumed that the pellet plant uses 10% bark in its raw material composition to produce lower quality wood pellets; the required bark material is supplied from the adjacent sawmills without any truck transportation.

The simulation results show that adding bark to the raw material mixture in addition to using bark as the fuel in the drying process leads to a cost saving of about 5% (\$4.82 t^{-1}) in the final cost of wood pellets. This reduction is due to lower procurement and transportation of raw materials as shown in Table 4-15. The energy consumption and CO_2 emissions in Scenario 3 were, respectively, 27% and 34% higher than those in the base case scenario due to the additional drying requirement for added bark in the raw material mixture.

Table 4-15. Costs of raw material procurement and transportation

Scenario	Fuel Mass (kt)	Annualized capital ($ t^{-1})	Raw material cost ($ t^{-1})	Raw material trans. cost ($ t^{-1})	Final cost ($ t^{-1})	Energy consumption (kWh t^{-1})	CO_2 emissions (kg t^{-1})
Base case	17.45	$15.94	$11.83	$15.61	$101.33	568.93	136.91
Scenario 1	21.71	$16.94	$11.10	$14.30	$100.31	567.63	136.54
Scenario 2	25.10	$16.92	$10.52	$14.30	$99.81	629.61	154.93
Scenario 3	30.34	$16.93	$9.37	$12.54	$96.51	724.73	183.46

4.5 Torrefied pellet production and distribution

To further improve the properties of wood pellets, torrefaction of biomass prior to densification has been suggested as a pre-treatment step (Gold and Seuring 2011, Miao et al. 2012). Torrefaction is a thermal treatment that increases bulk and energy densities by removing oxygen and other volatiles (van der Stelt et al. 2011, Peng 2012). Production of torrefied pellets is, however, more complex and capital intensive than the production of regular pellets, and the thermal treatment leads to a dry matter loss. The evaluation of torrefaction as a pre-treatment approach in a supply chain context has been identified as a research gap in the literature (Trattner 2009). The case study presented above is considered here to evaluate the production of the torrefied wood pellets in the existing wood pellet supply chain. Delivered costs at selected destinations are estimated by simulation models and used to compare regular and torrefied pellets.

When integrated into the pellet mill, the torrefaction process usually takes place before the pelletization of biomass. Different torrefaction process designs have been suggested. The basic torrefaction reactor design selected in this study is the Andritz ACB© Process (Trattner 2009), the only design that is commercialized, to the best of the author's knowledge. Before being fed to the torrefaction reactor, biomass is dried to a target moisture content of 15%. The biomass is processed in an indirectly heated drum reactor at temperatures of about 280 °C for about 20 minutes. Part of the biomass is gasified and yields the so called torrefaction gas which is combusted with ambient air to supply the thermal energy for the torrefaction process. The torrefied biomass has a higher specific heating value compared to the dried biomass. An example set of mass and energy balances for the torrefaction process are given in Table 4-16 (Prins et al. 2006). Torrefied biomass contains most of the energy content of the dried biomass. The energy content of the torrefaction gas is sufficient to supply the thermal energy for the torrefaction process and also a share of the thermal energy demand in the upstream drying process.

Table 4-16. Mass and energy balance for torrefaction of 1 kg biomass (Prins et al. (2006)).

	Biomass	Torrefaction gas	Torrefied biomass
Dry matter (kg)	0.850	0.159	0.615
Water (kg)	0.150	0.226	0.000
Higher heating value (GJ dt^{-1})	17.70	11.19	21.55
Energy content (%)	100.00	11.83	88.17

4.5.1 Torrefaction module

The PSC model is extended by developing the torrefaction module to be able to simulate the production and distribution of torrefied wood pellets in a supply chain context. The quality of biomass affects the torrefaction process. The amount of energy contained in the in-feed biomass depends on the heating value and moisture content. Ash content of the material affects the amount of energy required for the torrefaction process. Figure 4-6 shows the schematic of the torrefaction module developed in this study. Preconditioned biomass from the dryer is fed to the torrefaction reactor and is heated by the flue gas from the gas burner. Torrefaction gas resulting from the reaction is fed to the gas burner where it is combusted with ambient air. The flue gas from the reactor is used in the drying process. Torrefied biomass is fed to the next process.

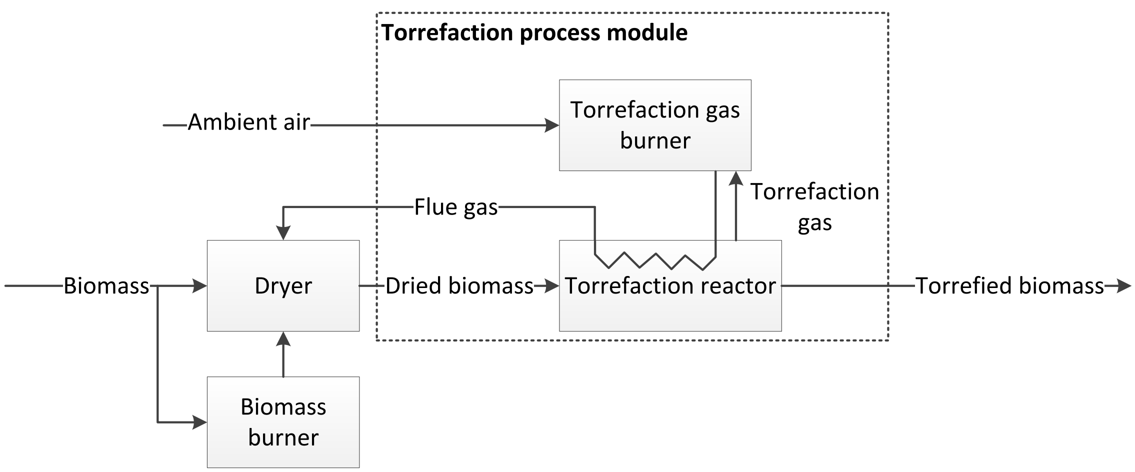

Figure 4-6. Drying and torrefaction processes flowchart.

The following equations along with the energy and mass balance shown in Table 4-16 were used in the simulation model to estimate the thermal energy supplied from the combustion of torrefaction gas, the thermal energy demand in the torrefaction reactor, and the excess of thermal energy that can be used in the upstream drying process. The equations take into account the moisture content, ash content and heating value as well as process temperature and burner efficiencies.

$$Q_{supply} = w_{in}(1 - MC)HV \cdot \partial \cdot \eta \quad \text{Eq. 4-7}$$

$$\begin{aligned} Q_{demand} = w_{in}\Big(MC\,\Big(\theta\big(t_{boiling} - t_{in}\big) + lh \\ + \theta'\big(t_{torrefaction} - t_{boiling}\big)\Big) \\ + (1 - MC)\,\Big((1 - AC)\sigma\big(t_{torrefaction} - t_{in}\big) + AC \\ \cdot \varrho\big(t_{torrefaction} - t_{in}\big) + \varphi\Big)\Big) \end{aligned} \quad \text{Eq. 4-8}$$

$$Q_{excess} = (w_{in}(1 - MC)HV \cdot \partial - Q_{demand})\delta \quad \text{Eq. 4-9}$$

Where w_{in} is the total input mass (t), MC represents the moisture content (%), HV is the higher heating value (GJ dt^{-1}), and AC is the ash content per dt (%). The supplied thermal energy (Q_{supply}) is calculated by multiplying the total energy input with the fraction of the heating value contained in the torrefaction gas (∂) and the efficiency of the combination of torrefaction gas burner and heat exchange to the torrefaction reactor (η) which is assumed to be equal to 81% (Trippe et al. 2010).

The thermal energy demand of the torrefaction reactor (Q_{demand}) is calculated based on the thermal energy demand for heating and evaporating the water contained in the feed, heating the biomass including ash, and the actual torrefaction of dry biomass. The heat capacities for water (θ) and steam (θ') as well as the evaporation enthalpy (lh) are taken from (Lucas 2006) and are equal to 4.2 kJ kg^{-1} K^{-1}, 2 kJ kg^{-1} K^{-1}, and 2,250 kJ kg^{-1}, respectively. Heat capacities for dry biomass (σ) and ash (ϱ) as well as the heat demand for torrefaction (φ) are equal to 1.7 kJ kg^{-1} K^{-1}, 1.2 kJ kg^{-1} K^{-1}, and 530 kJ kg^{-1}, respectively (Kornmayer 2009). Temperature of the dried biomass input (t_{in}) and the torrefaction reaction temperature ($t_{torrefaction}$) are assumed to be 70 and 280 °C, respectively (Mani 2005).

The excess heat of the torrefaction process (Q_{excess}) which can be used in the upstream drying process is estimated as follows. The total energy content of the torrefaction gas is reduced by the thermal energy demand of the torrefaction process and the useable fraction for the drying process is δ, which is assumed 70%. The required heat energy (R_{heat}) in the drying process is calculated based on the initial wet mass (W_{in}) and dried mass (dW_{in}), target moisture content after drying (MC_t), heat demand of the dryer (HD), and excess heat provided from torrefaction as shown in Eq. 4-10. The heat demand of the dryer (HD) is expressed as required energy to evaporate one t of water and is a specification of the dryer provided by the manufacturer (Obernberger and Thek 2010). Eq. 4-11 shows the relationship used in the simulation model to calculate the required weight of fuel (W_{fuel}) to reach the target moisture content. Herein, the heating value and moisture content of fuel are denoted by HV_{fuel} and MC_{fuel}, respectively. γ is the efficiency of the biomass burner.

$$R_{heat} = \left(W_{in} - \frac{dW_{in}}{1 - MC_t}\right) HD - Q_{excess} \qquad \text{Eq. 4-10}$$

$$W_{fuel} = \frac{R_{heat}}{HV_{fuel}(1 - MC_{fuel})\gamma} \qquad \text{Eq. 4-11}$$

Consequently, the developed torrefaction module estimates the dry matter loss due to the torrefaction based on the energy and mass balance while taking into account the quality of biomass as described in Eq. 4-7 to Eq. 4-11. The processing rate at any given time during the simulation run is defined based on the availability of biomass, upstream drying process, and specification of the equipment while considering the possible failures and required maintenances. The energy demand and cost of the torrefaction are calculated based on the power consumption of process equipment and operating hours.

The nominal capacity of the existing pellet plant in this case study is 20 t h^{-1} of conventional wood pellets; which is equivalent to 15.7 t h^{-1} of torrefied wood pellets when considering the higher heating value of 18 GJ dt^{-1} and 21.2 GJ dt^{-1} for regular and torrefied wood pellets, respectively (regular wood pellets with 10% moisture content and torrefied wood pellets with 3% moisture content). It is assumed that the current demand of the pellet supply chain would be the same in energy terms when torrefaction is added.

The dimensioning of the required equipment for the torrefaction process is based on mass and energy balances and takes minimum and maximum capacities of equipment into account to estimate the required capital investment. Equipment costs and total capital investment for the torrefaction process are estimated using the Total Capital Investment (TCI) method (Peters et al. 2002), shown in Table 4-17. The electricity consumption of the required torrefaction equipment is estimated at 1100 kW.

Table 4-17. Estimated investment required for the torrefaction equipment with 15.7 t h^{-1} capacity.

Equipment	Cost (Million $)
Torrefaction reactor	8.309
Burner	6.036
Heat exchanger	0.700
Turbo blower flue gas	2.578
Turbo blower torrefaction gas	0.154
Precipitator	1.472
Torrefied biomass cooler	0.316
Total	19.565

In addition to the current practice of shipping wood pellets from North Vancouver to Northwestern Europe, representative ports in Japan, Korea and China in proximity to coal power plants were selected to estimate delivered costs to potential markets for torrefied wood pellets from BC. Port handling and storage costs as well as costs for ocean transport were obtained from (Suurs 2002, Peng et al. 2010) and personal industry contacts. The same unit cost for ocean transportation of pellets to Europe and Asia is assumed. Shipping route distances to these locations were estimated from (Farnel Soft Inc. 2014) and are shown in Table 4-18. The energy demand and CO_2 emissions for ocean transportation are calculated based on consumption of 3.7 g diesel t^{-1} km^{-1}, diesel higher heating value of 45.9 GJ kg^{-1}, and 3.6 kg CO_2 kg^{-1} consumed diesel (Magelli et al. 2009).

Table 4-18. Shipping distances, and transport and logistics costs for different markets.

	Regular pellets ($ t^{-1})	Torrefied pellets ($ t^{-1})
Transport costs from Vancouver to Rotterdam, Europe	50.00	41.00
Handling and storage at Vancouver port	13.00	10.00
Handling and storage at destination port	13.00	10.00
Shipping distance Vancouver to Rotterdam, Europe	16,580 km	
Shipping distance Vancouver to Onahama, Japan	7,433 km	
Shipping distance Vancouver to Incheon, Korea	9,112 km	
Shipping distance Vancouver to Shanghai, China	9,266 km	

4.5.2 Results and discussion

While plant productivity was estimated at 89.54% for producing regular pellets, it drops to 84.85% when torrefaction is added to the studied supply chain. Failure of the torrefaction equipment and shortage in the raw material are the reasons for the lower productivity of the plant when torrefaction is added in this case study. The torrefaction process unit becomes the bottleneck and failure of the equipment halts the downstream processes, hence, reducing the productivity. The shortage in the raw material is due to the dry matter loss in the torrefaction process, considering that the availability of raw materials at the suppliers' locations was not increased while higher amount of biomass is required to produce the torrefied pellets with the identical energy content. On average 1.29 t of raw materials were consumed to produce one t of regular pellets; while for producing one t of torrefied pellets 1.73 t of raw materials was required. Considering the energy content of 18 and 21.2 GJ t^{-1} of regular and torrefied pellets, respectively, the additional biomass input on mass basis to achieve the same energy output for torrefied pellets is about 14%.

4.5.3 Supply chain costs

The cost structure of the supply chain is estimated using the simulation model. The contribution of each stage of the supply chain is shown in Figure 4-7. Raw material procurement and transportation compose 27% of the annual costs and similar to regular wood pellets contribute significantly to the cost structure of the supply chain. The production cost of torrefied pellets, which includes processing, maintenance, personnel and investment costs, represents 53% of the total cost. The break-down of the production cost is shown in the right hand side pie chart of Figure 4-7. Rail transportation of torrefied pellets to the export port in North Vancouver accounts for 20% of the total cost.

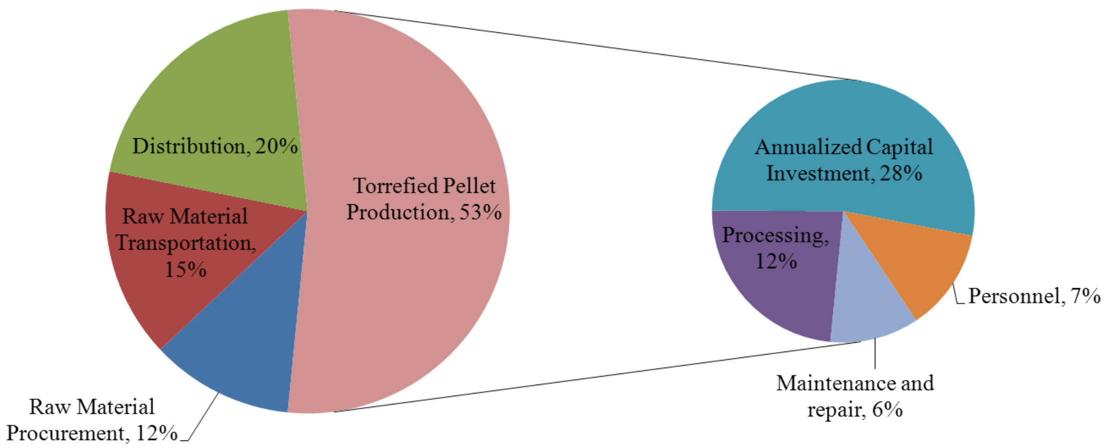

Figure 4-7. Estimated cost structure of torrefied wood pellet supply chain.

The cost structure of the supply chain for regular and torrefied pellets are compared in Table 4-19. The cost estimations associated with each section of the supply chain are provided in terms of the weight basis ($\$\ dt^{-1}$) and the energy ($\$\ GJ^{-1}$) of wood pellets. The delivered cost of torrefied pellets at the North Vancouver port is \$142 dt^{-1}, which represents 36% increase in the \$ dt^{-1} cost of torrefied pellets compared with that of regular pellets. In energy terms, the estimated cost of delivered torrefied pellets to the North Vancouver port is \$6.67 GJ^{-1}, while it is \$5.81 GJ^{-1} for regular pellets, showing about 13% higher cost for torrefied pellets.

Table 4-19. Cost structure of the supply chain for regular and torrefied wood pellets.

	Regular pellets		Torrefied pellets	
	Unit cost ($\$\ dt^{-1}$)	Unit cost ($\$\ GJ^{-1}$)	Unit cost ($\$\ dt^{-1}$)	Unit cost ($\$\ GJ^{-1}$)
Raw material purchase	$13.09	$0.73	$16.20	$0.76
Raw material transportation	$17.27	$0.96	$21.48	$1.01
Pellet production				
Processing	$19.13	$1.07	$25.96	$1.21
Repair and maintenance, Personnel	$15.94	$0.89	$39.85	$1.87
Annualized capital investment	$7.68	$0.43	$9.51	$0.45
Transportation to North Vancouver	$31.24	$1.74	$28.87	$1.36
Total	$104.35	$5.81	$141.86	$6.67

4.5.4 Energy consumption and CO_2 emissions

The energy demand at different stages of the supply chain is estimated and shown in Table 4-20. The highest input energy was required in the drying process with 395 kWh t^{-1}. In the production stage, 162 kWh t^{-1} electric energy was consumed for torrefaction, grinding, pelletization, and cooling. The energy consumed for raw material transportation (trucking) was 14 kWh t^{-1} and it was 78 kWh t^{-1} for rail transportation of the wood pellets. The energy input along the supply chain was estimated at 648 kWh t^{-1} that equals to 11.3% of the energy content of one t of torrefied wood pellets. About 137.62 kg CO_2 t^{-1} was emitted to produce and deliver torrefied pellets to the port, which is equivalent to 0.024 kg CO_2 kWh^{-1}. For regular pellets, the estimated input energy along the supply chain was 569 kWh t^{-1} (Table 4-11), which is about 12.7% of the energy content. The amount of emissions along the supply chain for regular pellets was estimated at 136.91 kg CO_2 t^{-1} (0.027 kg CO_2 kWh^{-1}). These results indicate that torrefied pellets are superior to regular pellets in terms of consumed energy and emitted CO_2 along the supply chain.

Table 4-20. Energy consumption and CO_2 emissions along the supply chain of torrefied wood pellets.

Item	Input energy (kWh t^{-1})	CO_2 emissions (kg CO_2 t^{-1})
Raw material transportation (trucking)	14	4
Drying	385 (thermal energy) 10 (electric energy)	116
Torrefaction	66	2
Grinding	37	1
Pelletization	56	1
Cooling	2	0
Rail Transportation of torrefied pellets	78	14
Total	648	138

4.5.5 Effects of uncertainties

The uncertainties in the raw materials availability and quality together with those in the performance of the vehicle and equipment cause fluctuations in the outputs. The histogram and best fitted probability distribution function (PDF) for annual raw material procurement cost, annual raw material transportation cost, annual produced weight of pellets, and total annual costs are shown in Figure 4-8. The fluctuations are shown for 50 runs of the simulation. The annual raw material procurement and transportation costs vary due to the uncertainties in the moisture content and bulk density of sawdust and shavings. The best fitted PDF for the raw material procurement cost is Normal with \$1.84 M average and \$0.003 M standard deviation. The raw material transportation cost follows a Normal PDF with \$2.44 M average and \$0.004 M standard deviation. The uncertainties in the quality measures and availability of raw materials at the pellet mill, plus the uncertainties in the equipment performance leads to the fluctuations in the annual production of the pellet mill. The estimated total annual cost follows a Normal distribution with an average of \$16.10 M and a standard deviation of \$0.02 M.

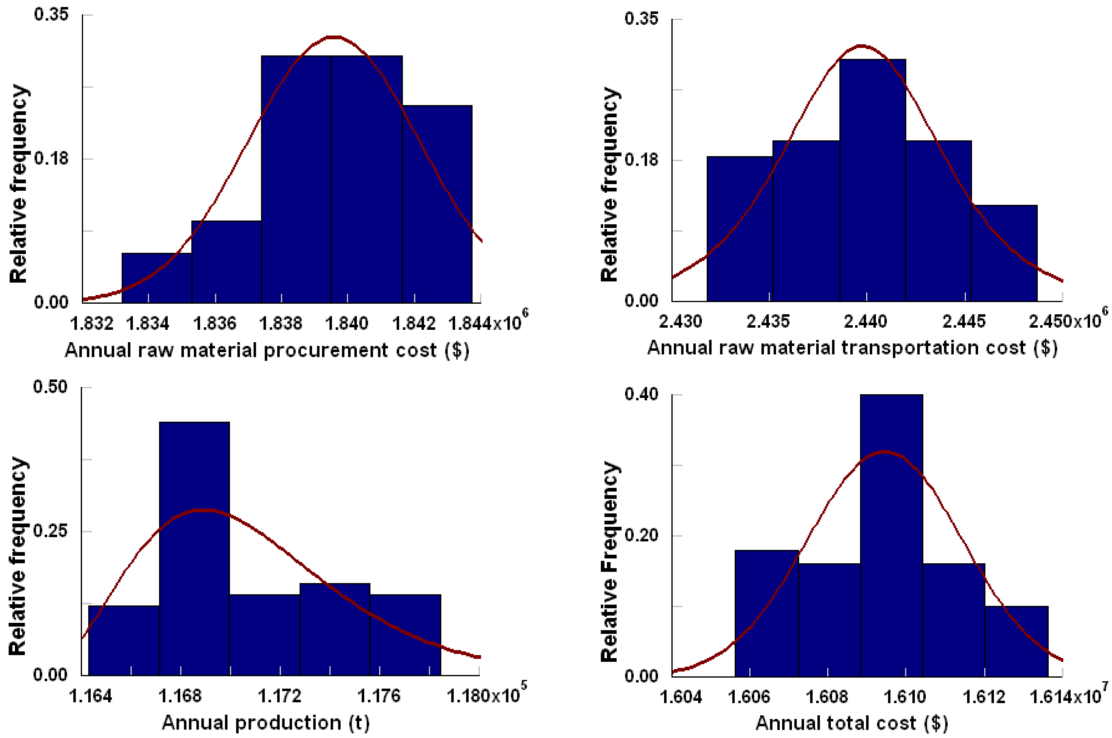

Figure 4-8. Histograms and best fitted PDF to the simulation outputs.

Sensitivity analysis of the results with respect to the moisture content of sawdust is performed to further evaluate the effects of biomass quality on the performance of the supply chain. Table 4-21 shows the effects of changes in sawdust moisture content on the procurement and transportation costs, required fuel in the drying process, the total production of the plant, and the final cost of torrefied pellets. The average moisture content is changed by ±5%.

Sawdust transportation cost and the required drying fuel were positively correlated with the moisture content while raw material procurement cost and production weight were negatively correlated with the sawdust moisture content. As moisture content increases, the trucks carry more water which increases the transportation cost per dry t and because more water is to be evaporated from the raw material, the drying process becomes more energy intensive and requires more fuel. The raw material procurement cost is based on the dried weight delivered to the pellet mill, therefore, when moisture content is increased less dried material is delivered to the plant and procurement cost decreases (Note that the availability of raw materials, i.e. the wet weight of raw materials available at each supplier, was not changed when the moisture content was changed in the sensitivity analysis, in order to reflect the effects of the moisture content variations on the production at the pellet mill). Production increases when moisture content decreases because more dried mass would be available to be converted to pellets. The total cost decreases when moisture content decreases as a result of reduction in drying fuel requirements, reduced transportation cost, and increased produced weight. When more wood pellets are produced, the specific capital cost decreases.

Table 4-21. Effects of variations in sawdust moisture content on the supply chain.

	5% lower moisture content	Base case	5% higher moisture content
Procurement Cost (k $)	1,903	1,839	1,763
Difference	3%	--	-4%
Transportation Cost ($ dt^{-1})	20	21	23
Difference	-5%	--	10%
Required Drying Fuel (t)	1,026	6,535	12,237
Difference	-84%	--	87%
Produced (t)	122,630	117,082	108,849
Difference	5%	--	-7%
Total cost ($ t^{-1})	138	142	148
Difference	-3%	--	4%

4.5.6 Cost comparison for different markets

The increased energy density of torrefied pellets make them more appealing when long transportation distances are involved, such as delivering pellets from BC Canada to the markets in Europe, Japan, Korea, and China. Table 4-22 shows the estimated cost of regular and torrefied pellets delivered to these locations. It is noted that these cost figures include handling and storage costs at the Vancouver port and destination ports and are presented in $ t^{-1}, while the costs in Table 4-19 do not include handling and storage costs and are in $ dt^{-1}. The delivered cost of torrefied pellets on weight basis ($ t^{-1}) is higher for all the candidate locations. In energy terms ($ GJ^{-1}) the cost of delivered torrefied pellets is similar to that of regular pellets at North Vancouver port after 840 km rail transportation. Including the ocean transportation to Europe makes energy from torrefied pellets about 8% cheaper than regular pellets. For Japan, Korea, and China, delivered cost of torrefied pellets is similar to that of regular pellets on energy basis. The comparison shows that the increased capital investment and increased processing costs are compensated by reduced transportation costs of the products. Furthermore, the higher energy density of the torrefied pellets leads to less energy input and CO_2 emissions along the supply chain when compared to regular pellets on energy basis. For regular pellets delivered to Northwestern Europe, 17% of their energy content was used along the supply chain while, for torrefied pellets 14% of their energy content was required. The amount of CO_2 emissions per GJ of delivered energy content was estimated at 11 kg and 14 kg for torrefied and regular pellets, respectively.

Table 4-22. Cost comparison of delivered regular and torrefied pellets to different markets.

Location	Regular pellets		Torrefied pellets		Difference (%)	
	$ GJ^{-1}	$ t^{-1}	$ GJ^{-1}	$ t^{-1}	$ GJ^{-1}	$ t^{-1}
Plant's gate	4.07	65.80	5.31	109.61	30%	67%
North Vancouver	6.61	106.80	7.15	147.61	8%	38%
Rotterdam, Europe	10.51	169.80	9.62	198.61	-8%	17%
Onahama , Japan	8.89	143.61	8.53	176.00	-4%	23%
Incheon, Korea	9.18	148.37	8.73	180.14	-5%	21%
Shanghai, China	9.18	148.37	8.75	180.52	-5%	22%

4.6 Conclusions

A simulation model was developed to facilitate the design and analysis of the wood pellet supply chains. Different aspects of the system, including procurement and transportation of raw material, processes inside the pellet plant, and distribution of the pellets, are captured in the model, allowing to create a customizable representation of the supply chain to analyse its dynamics. An existing wood pellet production and distribution supply chain was considered as a case study. The developed simulation model was used as a tactical-level decision support tool in the presented case study. It was used to estimate the delivered cost of the wood pellets to domestic customers and an international port. The average cost of delivered pellets was estimated at $101 t^{-1}. Raw material procurement and transportation accounted for 29% of the cost. Processing, capital investment, spare parts and consumables, and personnel costs constituted 40% of the total supply chain costs. The distribution of wood pellets contributed 31% to the total cost. To assess improvement potentials in the supply chain, three scenarios were developed and analyzed to evaluate the effects of changing the drying fuel in the pellet mill and changing the mixture of raw materials used for pellet production. It was estimated that about 5% reduction in the final cost of delivered fuel was achievable by changing the type of fuel for the drying process and the mix of raw material, however, the total energy consumption and CO_2 emissions would be expected to increase by 27% and 34%, respectively.

Torrefaction has gained attention as a pre-treatment technology in the solid biofuel industry. The simulation results were used to compare the torrefied and regular wood. Estimated cost of torrefied pellets stored at the international port in North Vancouver was \$148 t^{-1}, which is 38% more expensive than regular pellets on mass basis. Including the ocean transportation of wood pellets to the existing and potential markets, however, showed that the higher energy density of torrefied pellets in addition to the lower handling and storage costs make the cost of delivered torrefied pellets comparable or lower than that of regular pellets. This indicates the higher capital investment and processing costs of torrefaction is compensated by lower distribution, storage and handling costs.

The results show that torrefied pellets are preferred compared to the regular pellets in terms of the cost of the delivered energy content when long transportation distances are involved. It is noted that whether or not this reduction would make economic sense for the pellet manufacturers to add the torrefaction processing unit into their supply chain depends on different factors, such as availability of the associated capital cost, interest rates, market readiness and fluctuating price of wood pellets, and requires further investigations. The effects of the changes in the moisture content, in the sensitivity analysis, indicate the importance of considering the type and quality of the raw materials in the design of the supply chain, as well as the importance of controlling the moisture content along the supply chain.

The simulation results could be made more accurate by using improved functional relationships that are used in the model. By developing functions that represent the relationship between the performance of different equipment and the type of raw material used in the process, it would be possible to simulate the production of wood pellets from other types of biomass. Additionally, the sources of uncertainties in real systems are not limited to those considered in this case study. As an instance, the annual demand for wood pellets in the case study was guaranteed through long-term contracts between the producer located in BC, Canada and large utility producers in Europe. In case of wood pellet production in other regions, there might be higher uncertainties in the demand and high seasonal fluctuations would be expected in small-scale projects.

As a suggested direction for further research, simulation of small scale market for wood pellets in other biomass-reach regions in BC and risk analysis for such investments could be investigated through simulation. Also, collaboration between several small-scale pellet plants geographically scattered in a given region in order to reduce the distribution costs could be simulated and analyzed using the supply chain simulation models.

Chapter 5. Supply chain analysis in combined heat and power generation from forest biomass

5.1 Introduction

Economic feasibility and environmental footprints of energy generation depend on the performance of the supply chains as well as the employed conversion technologies. Bioenergy projects which rely on supply chains with the lowest possible financial and environmental costs and highest stability of supply are likely to be the most readily implemented and successful (Ruiz et al. 2013). Several studies examined the economic viability of energy generation (heat and/or power) from forest biomass under different conditions. Nicholls and Crimp (Nicholls and Crimp 2002) reasoned that low wood fuel costs, low wood moisture content and high alternative fuel costs increase the profitability of heat generation from wood biomass. Fuel cost impacted the profitability of the project more than the moisture content. Van den Broek et al. (2001) and Yagi and Nakata (2011) concluded that feasibility of energy generation in a small scaled CHP plant from forest biomass was significantly depended on the type of forest biomass. In Van den Broek et al. (2001) electricity generation from forest residues and sawmill wastes were less expensive than electricity generation from willow plantations, due to the high cost of running a willow plantation.

The many different alternatives imaginable when designing the biomass supply chains make the use of decision support tools necessary. This chapter examines the supply of forest biomass for CHP generation. Review of the literature shows that strategic planning of the biomass supply chain in CHP applications has attracted more attention compared with tactical and operational planning (Iakovou et al. 2010). Although effects of biomass types and its quality has been pointed out as a significant factor in previous studies, the uncertainties in these parameters are often neglected and deterministic parameters has been used in the developed models. Stochastic simulation of the supply chains allows incorporating the uncertainties in the quality measures of biomass and other uncertainties in the supply chain, thereby providing better estimates of the performance criteria.

A simulation model is presented in this chapter which is developed to analyze the supply chain of urban wood waste to energy. The model included an inventory planning procedure for the CHP plant to provide a proper tool for evaluating different inventory levels and demand fulfilment at the plant. The estimations of cost, input energy, and CO_2 emissions are provided to evaluate two alteration in an existing system. Changing the source of raw materials and adding the drying process at the collection yard are evaluated through scenario analysis. In addition to the previously developed modules (presented in Chapter 3, and 4), simulation modules are developed for the CHP plant and collection yards as discussed in the followings.

5.2 Case study

The studied system includes suppliers of raw materials, a collection yard situated approximately 60 km from a CHP plant. Figure 5-1 shows the geographical distribution of the supply chain. Biomass suppliers include wood processing mills, pulp chip mills, and pallet producing plants. Each supplier provides limited quantities of specific species, with varying quality. There are five major suppliers from which the feedstock delivered to the CHP plant is procured. Raw materials are transported to the collection yard where temporary storage and pre-processing are carried out. Multi-modal transportation of biomass from different suppliers to the collection yard, and from collection yard to the CHP plant is outsourced to a contractor. The contractor is responsible for purchasing raw materials from suppliers, carrying the materials to the collection yard, pre-processing, and delivering the required quantity with required quality to the CHP plant. The contractor owns a number of bins located at the suppliers' locations. These bins are carried to the collection yard once they are filled. The mixed biomass (feedstock) is transported from collection yard to the plant using moving floor trailers. Table 5-1 lists the type and cost of materials for each supplier and the distance from the suppliers to the collection yard.

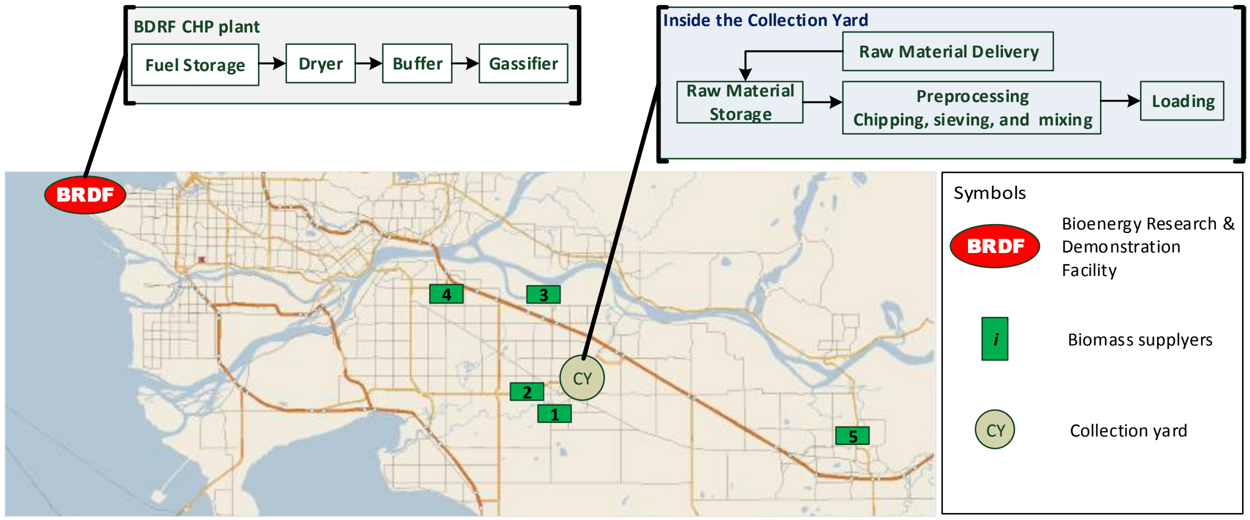

Figure 5-1. Geographic distribution of the supply chain entities and processes inside the CHP plant and the collection yard.

Table 5-1. List of suppliers of raw materials.

Supplier	Type of material	Cost ($ dt^{-1})	Distance from collection yard (km)
1	Wood chips	40	17
2	Trim ends	20	5
3	Trim ends	20	6
4	Trim ends	20	12
5	Trim ends	20	33

Pre-processing at the collection yard includes size reduction (chipping), sieving, and blending. A large stationary electric-powered grinder carries out the size reduction process for the trim ends. The sieving process intends to separate the undersized and oversized pieces of ground material. Blending is performed by the loaders when the trucks are being filled. The materials are loaded to the moving bed trucks and delivered to the CHP plant. The volumetric capacity of moving bed trucks is 110 m^3 and the maximum allowed weight is 63 t. Table 5-2 lists the specifications of the trucks that are used for transporting the raw materials from the suppliers to the collection yard (bin-trucks) and for transporting feedstock from the collection yard to the CHP plant (moving floor trucks). Hourly rates of the trucks shown in Table 5-2 are used to calculate the transportation costs. The volumetric capacity, traveling speed, fuel consumption rates, and loading and unloading rates for each type of truck are the other input parameters associated with each type of truck.

Table 5-2. Specifications of the vehicles used in the logistics system.

Vehicle type	Capacity (m^3)	Hourly rate ($ h^{-1})	Fuel con. (l km^{-1})	Ave. speed (km h^{-1})	Loading rate (m^3 h^{-1})	Unloading rate (m^3 h^{-1})
Bin-truck	30	100	0.34	65	-	330
Moving floor	110	125	0.37	55	660	330

A mix of woody biomass from a variety of species with different sizes, and moisture contents can be used in CHP plants. Biomass characterization becomes essential as it helps predicting the quality of syngas and the subsequent effects on the plant's overall performance. Physical and chemical characteristics of the feedstock vary significantly due to different biomass sources, seasonality, ambient conditions, and the inherent biological variability of biomass. Variations in these parameters can significantly affect the performance. Data used to model these parameters were gathered from the plant from July 2012 to November 2012. The daily supply of biomass to the plant was a mix of 'hog fuel' and wood chips. Methods of measuring fuel quality used in this study are outlined in European Standard EN 14961-1. This standard mandates the characterization of wood fuel properties including moisture content (MC), heating value (HV), particle size (PS), and ash content (AC). Upon each delivery to the plant, a 5 kg sample was collected and the quality measures were recorded for a total of 188 samples. Table 5-3 lists statistics on the quality measures. Best fitted PDF for MC, BD, and HV were Rayleigh (Figure 5-2), Pearson 5 (Figure 5-3), and Johnson SU (Figure 5-4), respectively.

Table 5-3. Quality measures of the raw materials delivered to the CHP plant

Stat.	MC (%)	BD (kg m^{-3})	HV (GJ dt^{-1})
Mean	31.29	160.46	19.43
Standard Deviation	11.33	32.77	0.37
Minimum	9.99	97.29	18.46
Maximum	54.93	251.27	20.71

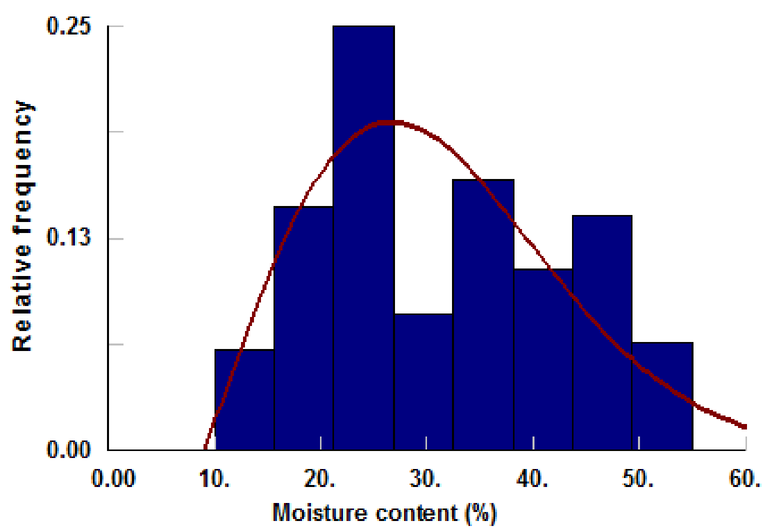

Figure 5-2. Best fitted distribution function for MC was Rayleigh with minimum value of 9.12 and sigma value of 17.6.

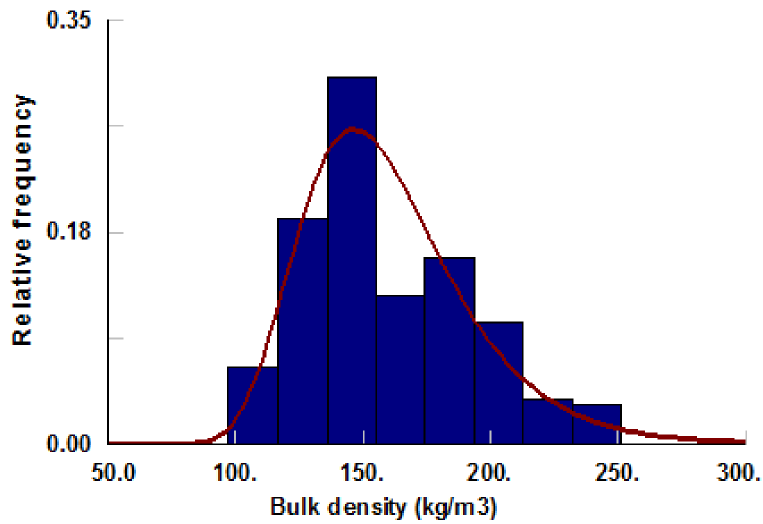

Figure 5-3. Best fitted distribution for bulk density was Pearson 5 with minimum value of 21.37, alpha value of 19.05, and beta value of 2511.66.

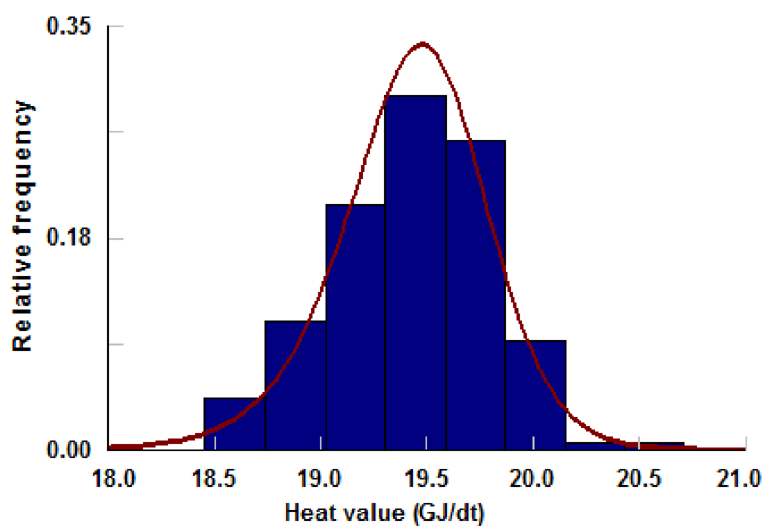

Figure 5-4. Best fitted distribution for heat value was Johnson SU with xi 19.66, lamda 0.79, gamma 0.66, and delta 2.43.

Fuel storage, drying, and gasification are performed within the CHP plant. A covered area at the CHP plant is designated for fuel storage. Also, temporary storage is used after drying process with a capacity of 150 m^3 to decouple drying and gasification. The plant is equipped with a fully automated monitoring and control system that is administered by operators. The inside temperature and the oxygen level of the gasifier are the most important parameters controlled by the automation system. Assuming constant level of oxygen, a fixed amount of heat value in the in-feed fuel is required in order to keep the temperature at a specific level which is important for preventing tar formation in the processes and maximizing the efficiency of the gasifier. According to the design specifications of the plant, the heat demand of the gasifier is 34.63 GJ h^{-1} when operating in the steady state. The heat demand is related to the required wet weight of biomass that needs drying using Eq. 5-1 and Eq. 5-2.

$$W_{\Delta t}=\frac{HD_g}{HV\,(1\text{-}MC_{in})} \quad \text{Eq. 5-1}$$

$$W'_{\Delta t}=\frac{W_{\Delta t}\,(1-MC_{in})}{(1-MC_t)} \quad \text{Eq. 5-2}$$

where $W_{\Delta t}$ is the wet mass fed to dryer during the time interval of Δt, $W'_{\Delta t}$ is the wet mass fed to the gasifier during the time interval of Δt, HD_g is the gasifier's heat demand during Δt, MC_t is the target moisture content after drying, HV is the heating value of the fuel, and MC_{in} is the initial moisture content.

5.3 Supply chain simulation model

Simulation modeling is conducted to estimate the performance of the supply chain in terms of the delivered cost of biomass, the emitted CO_2, and the energy consumption. The effects of switching to harvesting residues as the source of raw materials, and also drying the biomass prior to delivering to the CHP plant are evaluated.

An overview of the structure of the model is shown in Figure 5-5. The simulation model includes the suppliers of raw materials, transportation of biomass to the collection yard, pre-processing at the collection yard, delivery to the CHP plant, feedstock storage, drying, and gasification. Each module is designed with a set of roles, based on which data fields, properties, and functions are added.

The suppliers' module and the truck transportation module are similar to those presented in Chapter 4. Modifications are made in their functions regarding the case study and the structure of the supply chain, the input parameters, and interactions of the modules. In the supplier module, data on the availability and quality of raw materials are recorded and updated. The availability of raw materials is updated based on the daily production rate associated with each supplier that is taken as an input parameter. The type of material and the quality measures are also based on the input data associated with each of suppliers.

The transportation orders are generated by the suppliers' module when the bins are filled with materials. The orders are processed by the transportation module and are assigned to available trucks; the transportation orders are processed at specific "*scheduling events*". The scheduling events occur every hour in a working day plus whenever a new transportation order is received or a truck is done with the previously assigned trip. Upon completion of each trip and before the truck returns to the garage, it is considered as an available resource so that it can be used instead of backhauling. Also, restrictions are applied to the type of biomass that can be handled by each type of truck.

The level of feedstock inventory at the CHP plant is used as an indicator to decide when a truckload of feedstock should be ordered. In the CHP plant module (plant manager), raw material (feedstock) orders are placed, and they are converted to transportation orders in the logistics manager module (contractor) upon availability of required biomass at the collection yard. A Re-Order Point (ROP) parameter is taken as input to the model. Whenever the available feedstock weight plus the awaiting orders weight is below the ROP, a request for a truckload of feedstock is placed.

The suppliers input data include the locations, type of materials, and the amount of material that is available in a given time period. For each supplier the model estimates the amount of purchased material, the transportation cost, and the delivered cost to the collection yard. The input data for each vehicle type includes the total available number and the specifications of the vehicles, such as traveling speed, loading and unloading rates, fuel consumption rate, and hourly operation costs. The outputs that are gathered from the transportation module include the traveling times for each vehicle, transportation costs, total feedstock consumption, and the amount of emitted CO_2. Equipment data include the nominal power of each piece of equipment, the maintenance and repair costs, and processing capacity. For each piece of equipment the operation hours are estimated to project fuel costs. The annual and unit costs are estimated based on the repair and maintenance costs plus the operational costs.

Microsoft MapPoint (Microsoft Corporation 2010) is integrated with the simulation model to calculate the real distances between every pair of locations in the supply chain. The distances and the traveling speed of the vehicles are used to estimate the travel times. Loading and unloading delays are calculated based on the volume of the truck and the loading and unloading rates specific to each type of truck. The outputs of the model are gathered from each module and exported to Microsoft Excel for presentation and further calculations.

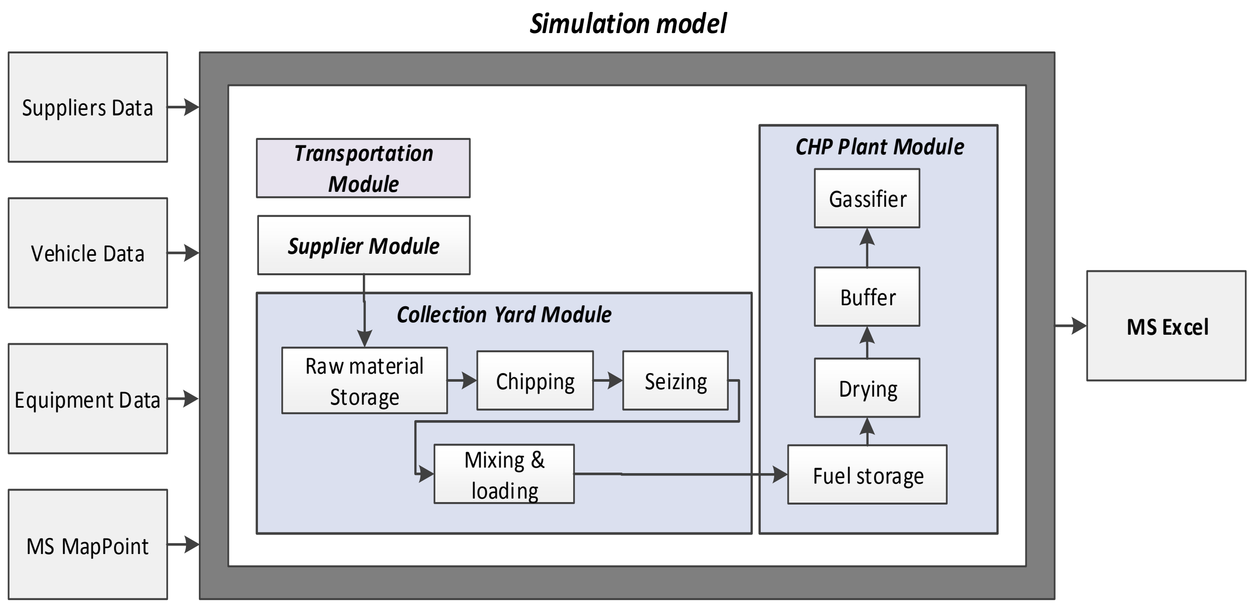

Figure 5-5. Structure of the developed simulation model.

5.4 Results

The simulation model is run for 20 iterations of one year. The outputs regarding the supply of raw materials to the collection yard are shown in Table 5-4. The amount of purchased raw materials, the annual procurement cost, and delivered cost from each supplier are shown. The average delivered cost from each supplier varies due to the different distances between the supplier and the collection yard and also because of the difference in the bulk density and moisture content of the purchased materials. The most expensive raw material was from supplier 1 that provides wood chips. The annual raw material cost was estimated at \$563 k per year, the annual transportation cost at \$257 k per year and the average cost of delivered raw materials was estimated at \$38.18 dt^{-1}.

Table 5-4. Outputs of simulation runs regarding the supply of raw materials to the collection yard.

Supplier	Purchased mass (t)	Procurement cost ($)	Transportation cost ($)	Delivered cost ($ dt^{-1})
1	12,182	267,508	117,423	57.56
2	6,278	100,388	27,194	25.42
3	5,955	95,243	28,469	25.98
4	3,542	56,699	28,537	30.07
5	2,716	43,435	55,145	45.39
Total	30,672	563,273	256,768	38.18

The processing costs at the collection yard are summarized in Table 5-5. The annual cost of preprocessing at the collection yard is $86 k, and the unit processing cost is $5.51 dt^{-1}.

Table 5-5. Simulation outputs for processing at the collection yard.

Process	Total processed mass	Annual cost ($ dt^{-1})	Unit cost ($ dt^{-1})
Grinding	18,613	40,923	2.62
Screening	18,600	29,460	1.89
Blending and loading	23,140	15,658	1.00

The simulation results for delivering the feedstock to the CHP plant are shown in Table 5-6. On average 23,138 t of biomass is delivered to the CHP plant that is equal to 15,620 dt and contains 303.6 k GJ heat value. The annual transportation cost is estimated at $433 k that equals to $27.75 dt^{-1}. Results shows that 1314 truck loads of biomass were delivered annually and 3.6 truckloads per day.

Table 5-6. Simulation outputs for the feedstock delivery to the CHP plant.

Delivered mass (t)	Delivered mass (dt)	Delivered heat value (GJ)	Annual transportation cost ($)
23,138	15,620	303,602	433,322

Figure 5-6 depicts the histogram and the best fitted distribution function for the hourly feedstock consumption and the amount of available biomass, or the inventory level, at the CHP plant. The inventory level follows a Normal distribution with a mean of 47.4 t and a standard deviation of 13.5. The feedstock consumption at the CHP plant had an estimated average of 2.63 t and standard deviation of 0.15 t and ranges between 2.2 to 3.33 t h^{-1}. As shown in Figure 5-6, the CHP plant's demand is always fulfilled because the inventory level at the plant is rarely less than 20 t.

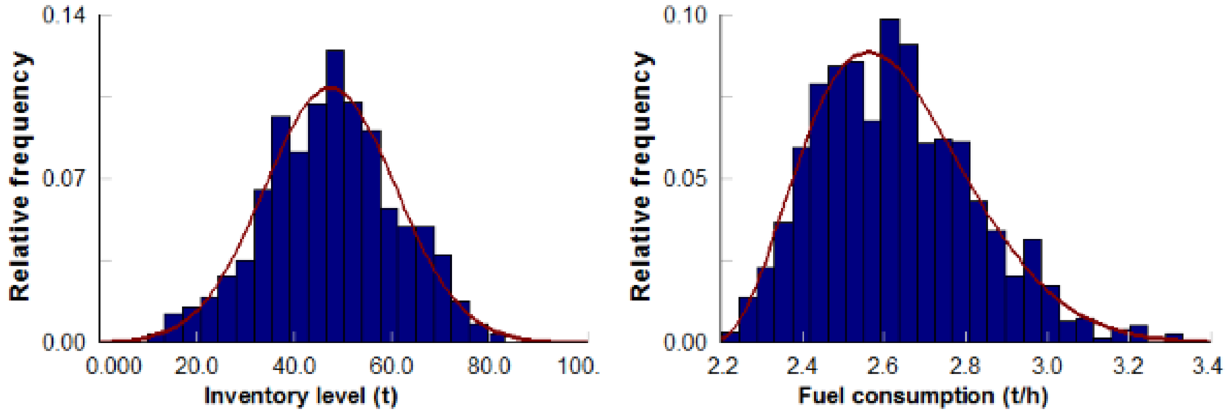

Figure 5-6. The histogram of inventory level and hourly feedstock consumption at the plant.

The cost structure of the supply chain is summarized in Table 5-7 and depicted in Figure 5-7. The total annual cost of the system was estimated at \$1.7 M. The estimated cost of delivered feedstock to the CHP plant was \$93 dt^{-1}, which is equivalent to \$5.52 GJ^{-1}. The largest share of the cost belongs to the raw material procurement which constitutes 34% of the annual cost with \$563 k per year. Raw material delivery to the collection yard costs \$257 k per year that is 15% of the annual cost. Personnel and maintenance costs and preprocessing the raw materials at the collection yard constitute 20% and 5% of the annual cost, respectively. Delivering the feedstock to the CHP plant costs \$433 k per year equal to 26% of the annual cost. It was estimated that 118.6 kWh energy was consumed to deliver one dt of biomass to the collection yard. The amount of emitted CO_2 was estimated at 21.02 kg per dt.

Table 5-7. Simulation results for costs, input energy, and emissions along the supply chain.

Item	Cost ($ year^{-1})	Cost ($ dt^{-1})	Cost ($ GJ^{-1})	In. Energy (kWh dt^{-1})	Emissions (kg CO_2 dt^{-1})
Raw Material Procurement	563.2 k	26.23	1.86	-	-
Raw Material Transportation	256.8 k	11.96	0.85	29.40	7.97
Pre-processing & Loading	86.1 k	5.51	0.28	52.74	3.16
Personnel & Maintenance	337.5 k	21.61	1.11	-	-
Fuel Delivery	433.3 k	27.74	1.43	36.46	9.88
Total	1,668 k	93.04	5.52	118.60	21.02

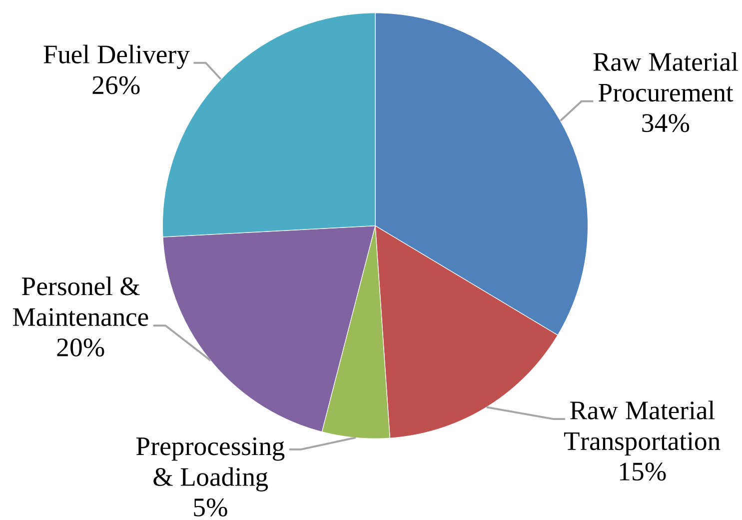

Figure 5-7. The cost structure of the supply chain.

5.4.1 Adjusting the model for analysis of forest biomass residues

The high cost of raw materials motivated the evaluation of using harvesting residues as the raw materials, which was performed with alterations to the simulation model. Data used in parameterization were obtained from the experts and the collection yard's manager. Harvesting residues were available from a distance of 60 to 70 km away from the collection yard. The moisture content of harvested residues was assumed to follow the normal distribution with a mean of 40% and a standard deviation of 3%. The bulk density of the material was assumed to follow a normal distribution with a mean of 150 kg m^{-3} and a standard deviation of 15 kg m^{-3}. It was assumed that the harvesting residues were available free of charge.

Transportation was augmented with a loader which was required to fill the trucks with harvesting residues at a cost of $80 per hour (Roser et al. 2014). Bin-trucks with volumetric capacity of 90 m^3, average speed of 50 km h^{-1}, and hourly cost of $100 h^{-1} would be used to transport the biomass to the collection yard. Loading each bin takes on average 20 minutes and unloading takes about 15 minutes. With these assumptions and assuming no limitation on the available amount of residues (the demand is very small compared to the availability of harvesting residues) the simulation model was re-run to estimate the delivered cost of biomass to the collection yard and compare that with the estimated cost in the previous scenario where the raw materials were purchased from wood processing facilities.

The results indicated average costs of $5.5 dt^{-1} and $39.5 dt^{-1} for loading and transportation, respectively. The estimated delivered cost of harvesting residues to the collection yard was $45 dt^{-1}. In comparison with the waste wood from the wood processing facilities, the delivered cost of harvesting residues is 15% higher. However, the cost of harvesting residues is less than the cost of wood chips purchased from supplier 1 (see Table 5-4). The delivered cost of wood chips from the supplier was $57.56 dt^{-1} and annually about 40% of the required raw materials were purchased from it. Replacing the material purchased from this supplier with the harvesting residues would reduce material costs to $34.27 dt^{-1} a 10% reduction. However, the higher amount of ash content and other contaminations in the harvesting residues would require further analysis of the quality of the delivered feedstock and the effects on the gasification process.

5.4.2 Drying at the collection yard in place of the CHP plant

Drying the biomass at the collection yard was assessed because it reduces the moisture content of the delivered feedstock and increases the efficiency of the CHP plant. Transportation costs would also decrease as less weight is transported. To estimate the delivered costs, it was assumed that a drum dryer with evaporative capacity of 5 t h^{-1} would be located at the collection yard and biomass is used as the drying fuel. The efficiency factor of the burner is assumed to follow a uniform distribution between 50% and 60%, the heat demand of the dryer is assumed to be 1200 kWh for evaporating one t of water. Nominal power consumption of the dryer is assumed 140 kW, and capital cost of $430 k and service life of 15 years are considered. The simulation model was used to estimate the amount of required fuel. The burner is assumed to be fed with hog fuel with average moisture content of 30% and average heat value of 18.5 GJ dt^{-1} and unit cost of $10 dt^{-1}. The cost of biomass that is used as the drying fuel was estimated and added to the preprocessing costs.

The average moisture content of the biomass delivered to the CHP plant was 31.3%. Reducing the moisture content to 20% at the collection yard through the drying process would also reduce the bulk density of the material. It was assumed that after the drying the moisture content of the material follows a normal distribution with a mean 20% and a small standard deviation of 1% based on the observations from the similar drum dryers. The empirical data on the dry bulk density of the material, calculated during the experiments, along with the moisture content are used to estimate the wet bulk density of material after the drying process. The bulk density has an average of 140 kg m^{-3} and standard deviation of 24 after drying.

Using these inputs in the simulation model showed that the delivered mass of feedstock to the CHP plant was reduced to 19,558, a reduction of 15% due to the less moisture content in the delivered material. Transportation costs from the collection yard to the CHP plant were reduced by 4% to $26.6 dt^{-1}. Table 5-8 lists the outputs of the drying process at the collection yard. It was estimated that 3,580 t of water was evaporated for which 2,171 t of feedstock was required. The estimated cost of the drying process was \$4.45 dt^{-1} that increases the pre-processing costs to \$9.95 dt^{-1}. Therefore, the reduction in the transportation cost was less than the added cost of drying. The estimated cost of delivered fuel when dried at the collection yard was 8% higher than when drying is conducted at the plant.

Table 5-8. Simulation outputs for the drying process at the collection yard.

Evaporated water (t)	Biomass fuel (t)	Electricity demand (kWh)	Drying cost (\$ dt^{-1})
3580	2171	100,240	4.45

5.5 Discussion and conclusions

A simulation model was built for modeling an existing supply chain of urban woody biomass to a CHP plant. The required input data for the simulation model were gathered through literature, site visits, experimental analysis, and communications with the experts. The model was applied to the case study and was used to estimate the performance criteria of the supply chain in terms of cost, energy consumption, and CO_2 emission. The cost of delivered biomass to the CHP plant was estimated at \$93.04 dt^{-1}. Raw material procurement and transportation to the collection yard constituted 49% of the total cost. Pre-processing, personnel and maintenance costs constituted 25% of the annual cost and delivering the mixed biomass to the CHP plant covered 26% of the annual costs. The estimated cost of delivered biomass in terms of the energy content was \$5.52 GJ^{-1}.

As with every model, there are a number of caveats which need to be mentioned. The capital cost of the collection yard was not included in the case study (Table 5-7) because the collection yard was previously established. The collection yard serves many other customers and the CHP plant's demand required a small portion of its capacity. Generated emissions and consumed energy due to the logistics system were estimated from the suppliers to the CHP plant's gate. Therefore, the estimations do not include the upstream operations (harvesting, hauling, milling, etc.) and it would be necessary to include those to provide a more thorough perspective to compare biomass-based energy generation with other alternatives.

The drying and gasification processes in the CHP plant were modelled under the steady state only. In the case study, the output energy from the CHP plant was assumed to be constant and the amount of required feedstock was calculated considering the fluctuations in the MC, and HV of the feedstock. This chapter presented an on-going research and future iterations of the model will include fluctuations in the CHP's output and the effects on the feedstock consumption, drying and gasification and the effects of quality measures of biomass on the performance of gasifier and boiler.

Chapter 6. Conclusions, strengths, limitations and future research

6.1 Conclusions

The efficient design and management of the biomass supply chain plays an important role in the successful implementation of bioenergy projects. Hence, decision support tools are needed to provide the decision makers with detailed and accurate information. Simulation modelling of the supply chain was the adapted approach in this research where the complexities and uncertainties of the supply chains are considered in an integrated representation of the real system. The interdependencies between different stages of the supply chain are captured in the simulation models. Moreover, considering the uncertainties inherent in the biomass supply chains that are related to the market demand, biomass availability, performance of the equipment, and properties of biomass are made possible by simulation models.

The overall objective of this research was to study the design and analyze the forest biomass supply chains while considering the uncertainties, interdependencies, and resource constraints in three case studies. In the first case study supply of different types of forest biomass from harvesting areas to a power plant was considered. Due to the large volume of leftover harvesting residues and high degree of mountain pine infestation in interior BC the establishment of a 300 MW power plant was suggested by Kumar et al. (2005). Reliability of the biomass supply for demand fulfilment at the power plant, and the delivered cost of biomass were examined through simulation of the supply chain over 20 years. Three harvesting systems were suggested for the supply of biomass from the Quesnel TSA to the power plant and were incorporated in the simulation model.

Lack of secured supply of raw material was found to be the foremost challenge in the implementation of this project. The most economical way to supply the required feedstock was to use the harvesting residues piled at the roadside in the conventional harvesting system. However, the availability of this source is limited to the practice of the existing facilities and their willingness to harvest from MPB killed forests. Hence, to fulfill the demand customized harvesting systems intended for fuelwood harvest are needed. Employing the satellite yard and full tree chipping system in areas that were more severely affected by the infestation increases the delivered costs of raw materials to the power plant, which will make the project entirely dependent on the carbon mitigation subsidies and other contingencies such as stumpage costs. Downsizing or re-locating the plant based on the spatial distribution of the available raw material are the possible options to reduce the cost of generated energy.

The second part of this research was focused on the supply chain of wood pellet production and distribution. An existing wood pellet production and distribution supply chain located in interior BC, serving domestic and international markets was the case study. Simulation was used to conduct scenario based analysis on the configurations of the supply chain. Specifically, two alterations in the system were investigated; first, changing the type of biomass that was used as the drying fuel; and second, producing lower quality wood pellets for large utility customers that are capable of handling the higher ash contents. Moreover, the simulation model was extended to assess integration of torrefaction process into the supply chain. The advantage of torrefied wood pellets was involved with long distance sea transportation to the international markets. Increased capital investment and processing due to torrefaction are compensated by reduced transportation and handling costs of the products when distributed to international markets. The estimated delivered cost of torrefied wood pellets to European and Asian markets was 4-8% lower on the energy basis. Besides, the energy consumption and CO_2 emissions along the supply chain were decreased by integration of torrefaction into the production line.

The third part of this research was to analyze the supply chain of CHP generation from biomass, discussed in Chapter 5. Two alterations in an existing supply chain were evaluated through simulation. Changing the source of raw materials from the waste of wood processing facilities to the harvesting residues was of interest. The simulations result indicated that the added costs, which were due to handling the biomass and loading the trucks at the forest roadside and longer transportation distances to the collection yard, were compensated with the lower cost of biomass. As a potential for improvement, replacing the wood chips purchased from one of the existing suppliers with the harvesting residues could lead to a saving of about 10% in the delivered cost of fuel. The second change in the supply chain was to add drying process to the pre-processing at the collection yard to provide the CHP plant with more consistent moisture content in the delivered fuel. A biomass burner and a drum dryer were considered for the drying process. It was estimated that doing so adds about \$5 dt^{-1} to the pre-processing costs and increases the delivered cost of fuel by 8%. Which provides a basis for comparison of the incremental costs of drying with the increased efficiency of the gasifier when processing dryer material.

Specific features of biomass supply chains in large-scale bioenergy, small-scale bioenergy, and regular and torrefied wood pellets were apprehended in the three case studies and the developed models were used as decision support tools to address some of the decisions involved in the respective case. The contributions of this research in the area of biomass supply chain rely on the simultaneous consideration of three major sources of complexity, namely: uncertainties (in the biomass availability and quality, equipment performance, and weather conditions, etc.), interdependencies between different stages of the supply chain, and the resource constraints.

6.2 Strengths

Integrating the GIS data layers with the simulation model in Chapter 3, which allowed to capture the spatial distribution of the cutblocks in the Quesnel TSA, was a strength of the developed model.

In Chapters 4 and 5, the main strength is that the required data for the simulation models were obtained from real cases and in collaboration with industrial experts. The simulation modules were designed based on the observations of the real systems. This allowed to provide a relatively realistic perspective of the supply chains. The required data regarding the structure of the supply chains were obtained through several site visits and personal communications with industry experts and in collaboration with other research groups. The input data regarding the quality of biomass were provided based on the samples from the actual systems, which was important in the reliability of the obtained results from the simulation experiments.

Simulation modelling has been utilized in many aspects of forest biomass supply chains. However, majority of previously developed models are focused on isolated stages of the supply chains. In this research, the whole supply chains in each case study were considered. Discrete rate simulation approach was used in order to consider the flow of biomass inside the processing facilities and between the equipment. In this way, it was possible to consider the raw material availability at the plant, failure of equipment, and the consequent effects on the up/downstream activities. Additionally, this approach allowed consideration of the effects of biomass qualities on the performance of the equipment.

The modular design of the models presented in Chapters 3, 4, and 5 makes it easier to construct different configurations of the supply chains and reduces the model development efforts in the future research. The developed models could be applied to other cases provided that the required input data are available. Additionally, the modular design of the models make it very convenient to change/improve the modules for example by modifying the relationships that are used to represent the different aspects of each module. To manage the extensive amount of data involved in the supply chain models a relational database was embedded that helps in decreasing the simulation time. This database provides a structured set of data that could be used in order to go to the details for each stage of the supply chain and evaluate the performance during the simulation runs.

Consequently, the modular design of the simulation models and the capabilities provided in ExtendSim (Imagine That 2011) provide a suitable framework for developing such decision support tools. These features of the models allow fast prototyping for different conditions.

6.3 Limitations

In Chapter 3, it was assumed that the harvest planning and resource allocations are conducted centrally for the whole Quesnel TSA, however, in the reality each licensee decides about the location and the level of harvesting independently. Hence, obtaining information and data regarding the various decision making entities in this area is necessary to realistically simulate the flow of fiber amongst the wood processing facilities and the power plant. Also, more data and information regarding the existing wood processing facilities, such as pulp mills and chip mills, are required in order to have a more realistic representation of the system and better estimate the portion of the harvested volume which will be available as fuelwood. Moreover, the distances between the roadside residue piles and the effects of the slope and terrain conditions were not considered in estimating the performance of the equipment, instead random numbers based on ranges in the literature were used. The data and assumptions that were based on the literature, e.g. productivity of equipment and its variations, need to be verified for the case study area. Moreover, more empirical data on the effects of the weather conditions and storage time on the moisture content and bulk density of forest biomass are required to have a more accurate cost estimation in the simulation model. Changes in the physical properties of biomass after chipping were simulated based on the expert opinions and further investigations are required to confirm the obtained results. The weather delays due to the precipitations and theirs effects on the harvesting operations were modelled based on the best available data in the literature, however, it is necessary to obtain data from the actual practice to have more accurate results.

In Chapter 4, the obtained data regarding the quality of raw materials belong to a limited time interval of one week. More variation in the quality measures is expected in data for longer period of time. In the case study considered in this chapter the sources of raw materials were sawmills in close proximity of the pellet mill. Therefore, the only process that was associated with the suppliers was loading the biomass to the trucks. Due to the unavailability of historic data regarding the variations in the supply of raw materials from the suppliers in the case study, assumptions were made based on the expert opinion and limited variations in the availability of raw materials were assumed in the simulation experiments. This limitation could be overcome by gathering more data and information to better reflect the uncertainties in the supply of raw materials. Also, the variation in the demand for the wood pellets was very limited in this case study since most of the products were exported and the long-term contracts eliminated considerable variation in this regard. This might not be true for domestic markets and applying the simulation to this case would require more data on the demand patterns and consideration of anomalies such as seasonal fluctuations.

In Chapter 5, very limited data were available regarding the quality of the raw materials purchased from the suppliers and input values were obtained from the collection yard's manager. Conducting experiments on the raw materials could provide more reliable data for the simulation and improve the quality of the results. Also, the demand for steam and power from the CHP plant were assumed to be constant in this chapter due to the fact that this plant only operates as a supplementary source for an existing natural gas boiler. Therefore, no fluctuations were considered in the heat and power demand. This would not be the case if the system was used as a stand-alone source of steam and power. For example changes in the ambient temperature would affect the demand. The operating conditions of the gasifier depends on many factors such as oxygen level, temperature, ash content, moisture content, etc. in this work, however, it is assumed that the oxygen level is constant and the fluctuations in the temperature of the gasifier are dealt with by manipulating the amount of biomass that is fed to the gasifier. Although this assumption holds true for longer periods of time, detailed data gathering and improvements in the equations used in the model are required in order to incorporate fluctuations in the gasification process.

The simulation models presented in this thesis are developed based on the data and information that were gathered from different sources and the abovementioned limitations in the data are also reflected in the structure and applications of the models. For example, detailed analysis of the existing road network and the required forest road development in Chapter 3 is required to refine the estimated costs and also to better simulate the movement of the equipment within and between the cutblocks. As another instance, when the demand for wood pellets are not guaranteed through long-term contracts with the customers and the seasonal fluctuations are expected, a forecasting procedure is needed for planning the raw material procurement and the production of the wood pellets which could be embedded into the simulation model presented in Chapter 4.

6.4 Future research

A direction for future research relates to the improvement of the underlying equations used in the simulation modules. Conducting experiments and statistical analysis for improving the equations that are developed based on the simplifications and assumptions is suggested. For example, the energy consumption in the pelletizers should be related to the characteristics of infeed material. Another example is consideration changes due to storage of biomass that require experimental analysis based on the obtained data from the real system.

Another area for further research is to extend the scope of the analysis to simultaneously consider planning for several collaborating facilities and supply chains and to capture the interactions and competitions between them. This allows to construct the simulation models that can be used for the planning of the forest product industry including the conventional forest products (such as lumber, paper, etc.) along with the biofuel and bioenergy sectors. The results of the simulation studies presented in this thesis along with numerous previous studies affirm that to realize the maximum potential of bioenergy and biofuels in BC requires coordinated design and planning of the forest products supply chains as a whole.

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