THE SIMULATION MODELING OF SUPPLY LOGISTICS OF FOREST BIOMASS IN BRITISH COLUMBIA

by

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

(Forestry)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

June 2008

Abstract

The search for alternative energy sources has increased interests in forest biomass. During the last few years, the sever infestation of the Mountain Pine Beetle (MPB) within the Interior BC forests has led to huge volumes of dead wood that exceed the capacity of the lumber industry. One way to make the most value of the surplus wood is to use it as the feedstock for bioenergy. The forest biomass can be supplied through conventional (roadside residuals), full-tree chipping, or satellite yard systems. This thesis presents the development of a simulation model of supply logistics of forest biomass and its application to a case of supplying MPB-killed biomass from Quesnel Timber Supply Area (one of the most infested areas in the Interior BC) to a potential 300 MW power plant adjacent to the city of Quesnel. The model has the ability of providing estimates of quantity, delivery cost, and moisture content of biomass which are critical in feasibility study of any bioenergy project. The results obtained from simulation model showed a delivery cost of C$45 per oven dry tonne of wood chips to the power plant. The results also revealed that the feedstock recovered from roadside residues in one year meets about 30% of the annual demand of the power plant. Potential increase in the Allowable Annual Cut (AAC) for Quesnel TSA increases the quantity of biomass supplied from roadside residuals. However, as long as the biomass is supplied only through conventional harvesting, increasing the AAC even by 40% does not provide enough feedstock to meet the annual demand of the plant.

Using the simulation modeling, this research has the benefit of considering the logistics of forest biomass supply as an integrated and interacting system as well as providing different critical parameters over time. The model also has the potential of considering dynamic and random behavior of the logistics system of supplying forest biomass. The model can be modified and applied to similar cases of conventional forest biomass supply. It also can be extended to other harvesting systems including satellite yard and whole-tree chipping.

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Glossary

Allowable Annual Cut (AAC)	The rate of timber harvest permitted each year from a specified area of land, usually expressed as cubic meters of wood per year.
Biogeoclimatic zone	A geographic area (large ecosystem) with a relatively uniform and homogenous macroclimate, having similar patterns of vegetation and soils.
Cutblock	A specific area, with defined boundaries, authorized for harvest.
Dry weight	Weight of wood at zero percent of moisture content.
Fuel wood	Trees used for the production of firewood logs or other wood fuel.
Green weight	Weight of un-dried biomass.
Land unit	An area of land and water used for long-term planning of resource management activities. These units, which are typically 5000–400,000 ha in area, are important for designing strategies and patterns for landscape-level biodiversity and for managing a variety of resource values.

Merchantable volume	The amount of sound wood in a single tree or stand that is suitable for marketing under given economic conditions.
Moisture content	The weight of the water contained in wood, usually expressed as a percentage of weight.
Stand	A community of trees sufficiently uniform in species composition, age, arrangement, and condition to be distinguishable as a group from the forest or other growth on the adjoining area, and thus forming a silviculture or management entity.
Timber Supply Area (TSA)	A geographically based administrative area designated under Section 7 of the *Forest Act* (Ministry of Forestry and Range). Timber supply areas have an allowable annual cut as set by the Chief Forester, and are used to provide a sustainable flow of timber to both replaceable and non-replaceable forms of volume-based tenures.

Acknowledgements

I wish to thank my supervisor, Dr. Taraneh Sowlati for her constant support, understanding, patience, and guidance during the last three years. With her great attitude and excellent knowledge, she provided me with a wonderful opportunity to adjust to my new life in Canada as well as to accomplish my academic goals. Also, I wish to thank the members of my supervisory committee, Drs. Shahab Sokhansanj and Kevin Lyons who provided me with their excellent comments and guidance during this research. I also would like to appreciate Jack MacDonald and Tony Sauder from FPInnovation – FERIC Division for helping me on gathering data required for this research.

Co-Authorship Statement

The research project carried out in this thesis was identified and designed by Dr. Taraneh Sowlati (supervisor) and Dr. Shahab Sokhansanj. The case study of the research was also suggested by Dr. Sokhansanj. The research job including reviewing the related literature, gathering data on the case study, developing and running the simulation model, analysis of the results, and performing the sensitivity analyses were conducted by Mohammadhossein Mahmoudi. The thesis was prepared in manuscript style. A version of each of Chapters 2 and 3 has been submitted for publication. The preparation of manuscript chapters was performed by M. Mahmoudi. Also, Drs. Sowlati and Sokhansanj co-authored in manuscript chapters.

Chapter 1
Introduction

1.1. Background

During the last decade, the price of fossil fuels has raised globally. As Figure 1.1 shows, the price of natural gas and crude oil had increased by more than double from 1996 to 2006. This price increase along with political instability of the world oil and gas rich countries has raised a major concern among most of developed and many developing countries over their energy security and has led them to movements towards reducing dependency on fossil fuels through development of new energy sources.

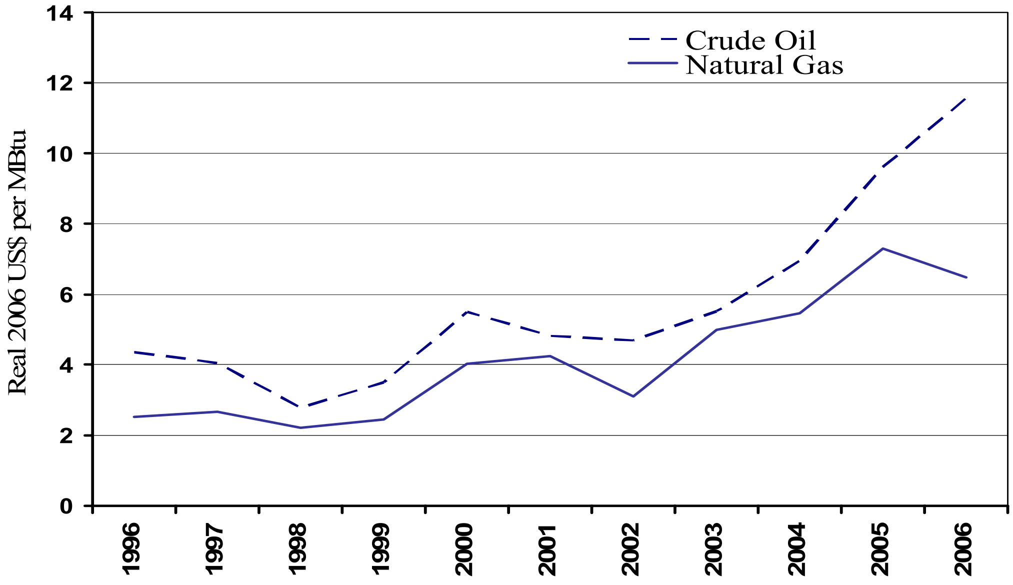

Figure 1.1. Annual Average Energy
Source: (EIA 2007)

In addition to economic and political incentives, other drivers of a global attention to renewable and clean sources of energy include the environmental impacts of fossil fuels. As shown in Figure 1.2, the world annual CO_2 emission has raised from 21,500 million tonnes in 1994 to 27,000 million tonnes in 2004. In December 2006, 169 countries and other governmental entities ratified the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC) to limit greenhouse gas emissions (UNFCCC 1997).

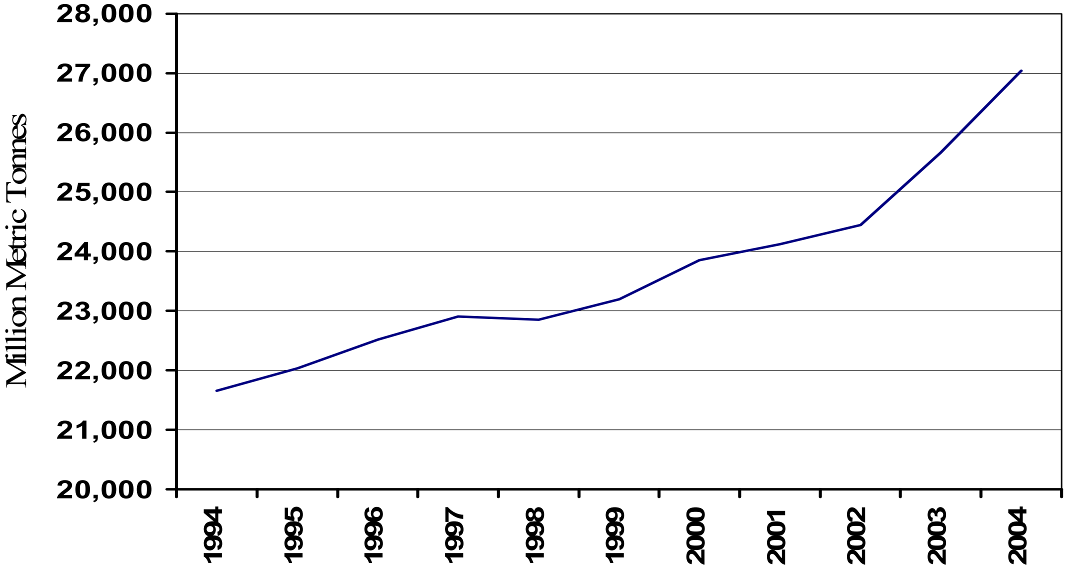

Figure 1.2. Annual World Carbon Dioxide Emission
Source: (EIA 2007)

Biomass, as a renewable source of energy has been receiving a worldwide attention. It is carbon-neutral, therefore, has the potential to mitigate emissions of greenhouse gases and the resulting environmental effects. The European Commission has issued a policy targeting to supply 10% of its overall energy demand from renewable energy resources by 2010 (Ericsson & Nilsson 2006). The US Department of Energy has conducted several projects on commercializing the electricity production from biomass (US DOE 2007). Also, the US production of ethanol from starchy grain (mainly corn) has increased substantially during the past 5-7 years from 1.5 billion gallons in 2001 to almost 5 billion gallons in 2007 (US DOE 2007). However, as it is shown in Figure 1.3, bioenergy still represents a small fraction of energy production in the whole world, especially in developed countries. In developing countries, bio-energy shares about 33% of the energy production which is mostly related to burning wood directly for cooking and heating.

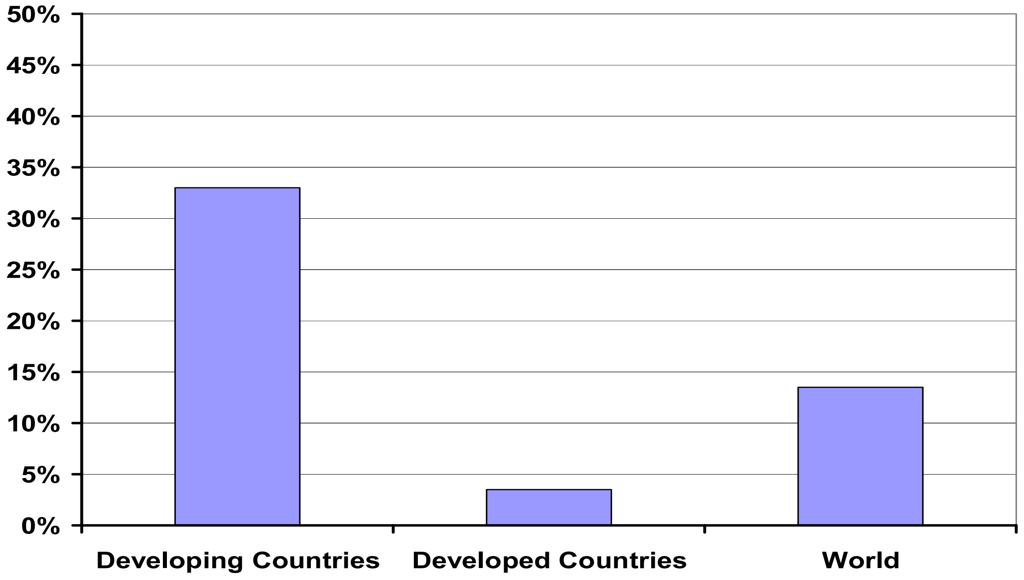

Figure 1.3. Contribution of Bioenergy to Total Energy Production for 2004
Source: (EIA 2005)

On the other hand, share of bioenergy in total energy production in developed countries is less than 5%. This is due to some non-technical factors plus technological requirements for bioenergy production that affect the growth of this industry. The first of these factors is the availability of biomass sources. The feasibility and success of a large scale bioenergy project is highly dependent on availability of biomass over the life time of the project. Another important factor affecting the growth of bioenergy industry is the finished cost of bioenergy which should be competitive with energy obtained from fossil fuels. The finished cost of bioenergy is affected by the cost of supplying biomass, quality characteristics of biomass (such as moisture content, uniformity, and energy content) and also cost of converting biomass to energy.

1.2. Biomass and Bioenergy in Canada

The bioenergy production capacity in Canada was estimated only about 8 million KW (Stennes & McBeth 2006) which represents about 6% of the total primary energy supply (EIA 2004). However, the abundance of biomass resources has provided Canada with a great opportunity to develop and sustain its bioenergy industry. Of the total land area in Canada (998 M ha), 25% is timber-productive forest (245 M ha) which has an energy content of 566 EJ equal to 69 times of Canada's annual energy demand (8.24 EJ) (Cunningham 2005). The Government of Canada has issued economic and environmental policies which provide incentives to use biomass as a new source of energy. In international level, Canada's commitment under the Kyoto protocol is to reduce greenhouse gas emissions to 94% of 1990 levels by 2012 (Williams 2005). In national level, the *Action on Climate Change and Air Pollution* announced in April 2007 by the Ministry of Environment sets mandatory targets for reduction of greenhouse gas emissions to 80% of 2006 levels by 2020 (Government of Canada 2007). Moreover, provinces require permits for industries emitting to the environment and the cost of these permits directly varies with the emission levels (Stennes & McBeth 2006). Also, under the regulations of Income Tax Act, industries using many types of renewable energies can benefit from an accelerated capital cost allowance (CCA) with a rate which has increased from 30% to 50% in 2005 (Stennes & McBeth 2006). In special case, British Columbia has a unique potential for generating energy from biomass. Of BC's total area, 26 Mha are estimated as productive and economically accessible forest land. These timber productive forests provide huge volumes of logs (feeding the BC's lumber industry) as well as residuals left after the logging operation. The logging residuals which are still burned after the operation and have no energy recovery are estimated about 1.6 million BDT (bone dry tonnes) (Stennes & McBeth 2006). With more than 600 MW of biomass-fuelled power generation (50% of the national total), British Columbia has the greatest capacity of producing electricity from biomass. The largest biomass-based power generation facility in Canada is located in Williams Lake in the Interior of British Columbia.

1.3. Mountain Pine Beetle killed Wood as a Source of Biomass

During the last few years, forests of Interior British Columbia have been experiencing the largest and severest infestation of Mountain Pine Beetle (MPB) (*Dendroctonus Ponderosa Hopkins*) recorded in the history (MacDonald 2006). This epidemic has led to huge volumes of wood which despite the raised levels of Allowable Annual Cut (AAC) exceed the current capacity of the lumber industry. In fact, the infested area is estimated to be more than 10 Mha as of 2005 which is expected to provide 960 million m^3 of dead wood by 2013 (Kumar et al. 2005). The volume of dead wood is so remarkable that one of the first objectives of the *British Columbia Mountain Pine Beetle Action Plan 2006-2011* submitted by the Ministry of Forests and Range has been stated as to recover the greatest value from MPB killed wood before it burns or decays (MoFR 2006). One of the possible ways of making value of the MPB killed wood is to use it as a source of bioenergy. Although the opportunity to use the MPB infested wood as the feedstock of the potential bioenergy projects seems very unique in British Columbia, little research has been conducted on feasibility of such projects.

The feasibility of a bioenergy project is highly dependent on the availability of biomass. In other words, in order to keep a bioenergy facility in operation over its lifetime, the quantity of biomass supplied should meet the quantity of biomass demanded by the facility. However, the quantity of biomass supplied at each point of time depends on available sources of biomass and time duration required for supplying it which is, in fact, a function of terrain conditions of the harvesting site(s), distance between the harvesting site(s) and the facility, and also the logistics system selected for collecting and transporting biomass.

In addition to availability of biomass and time required for supplying it, other parameters may affect the feasibility of a bioenergy project. These factors include finished cost of biomass, its quality, and also emissions due to logistics operations required for collecting and transporting biomass. However, all the mentioned parameters are affecting each other in an interacting way. For example, while the finished cost of oven dried biomass is affected by both quantity and quality (in terms of moisture content) of biomass supplied, the quantity (available volume) and quality (moisture content) are highly dependent on the harvesting time and the supply time frame in which the biomass is collected and transported. In addition to the interacting relationships between quantity, cost, time, quality and emissions, some external factors such as biomass yield of the harvesting area, production rate and number of equipment used for collecting and transporting operations, weather conditions and the distance between the harvesting area and the bioenergy facility affect each of the mentioned parameters. In a large scale biomass harvesting operation, which is usually the case for an industrial bioenergy project, each of the external factors behaves randomly.

1.4. Literature Review on Logistics of Forest Harvesting

Forest harvesting includes all activities needed for cutting the forest trees and getting them to the utilization facilities where they are manufactured to primary wood products such as lumber or pulp. Forest harvesting includes four main phases: 1) felling or cutting the trees from their stumps, 2) primary transportation which is the extracting of trees/logs from the stump to the roadside or a landing, 3) processing which is the manufacturing of the trees to logs or wood chips and may include delimbing, topping, bucking, slashing and chipping, and 4) transporting logs or wood chips to the utilization facilities. Forest harvesting is usually performed along with other operations such as construction of access roads as well as reforestation of the residual stands.

The combination of layouts, methods, and techniques used in forest operations is referred as *forest harvesting system* which is indicated by three main features: *cutting system*, *type of equipment*, and *operation technique*. The cutting system is the layout which shows which trees/areas of the forest zone designated for harvesting should be harvested and which parts should be remained un-harvested. The cutting system selected in each stand or forest zone usually depends on the tree size (height and diameter), type of species, the reforestation system, and economic factors. Typical cutting systems in British Columbia include single tree selection (felling the selected trees individually from all sizes of trees), group selection (cutting areas wide from 0.1 to 1 acre), and clear cutting (felling all the trees in an area in a single cut expecting a new even-aged forest to establish in the future) (MacDonald 1999).

The type of equipment used in forest operations depends on economic/business factors (ownership/operating costs, profitability, productivity, and quality of logs processed), operational factors (safety, terrain conditions, soil characteristics, tree size, timber quality, weather conditions and reforestation system), and environmental factors (soil disturbance, water quality and protection of residual and un-harvested stands). The forest equipment can be classified based on the forest operation phase. The felling equipment include chain saw (used for single tree cutting system) and different types of fellers (wheeled or tracked harvesters and feller-bunchers). Processing equipment may include chainsaw, delimber, different types of processors, slasher, hogger and chipper. Depending on the site terrain conditions, primary transportation might be done in three forms of *ground- based*, *cable,* and *aerial* each of which requires its special equipment. Ground-based equipment include different types of skidders (wheeled or tracked, grapple or line), clambunck, forwarder, loader and loader-forwarders. The cable equipment include high lead, grapple swing yarder, line swing yarder as well as single- and multi-span sky line. Aerial logging is performed by medium- or heavy-lift helicopters. Finally, transportation equipment include different types of loaders, log-trucks and chip-vans.

Operating techniques refer to the technical considerations for each phase of the forest operation. The goal of implementing these techniques is to increase the productivity of each phase and the whole operation as well as preventing possible damages to the stems. For felling, the main operating techniques refer to the orientation of felled trees, layouts of sorting/piling the felled trees, and travel direction of the felling equipment. Technical considerations for primary transportation may include the skidding pattern and the location of landing tress (landing vs. roadside). For processing, operating techniques include the location of processing (stump vs. landing or roadside), processing method (only tops, tops and branches, etc.), and log cutting method. Most typical log cutting methods in British Columbia include full-tree, tree-length, and cut-to-length (MacDonald 1999). In full tree method, the entire tree above the stump is extracted to the roadside or landing. The tree-length method is similar to full-tree method except that trees are delimbed and topped before extracting to the roadside or landing. In cut-to-length method, the felled trees are not only delimbed and topped but also cut to standard lengths required by sawmills and then extracted to the roadside.

Since forest harvesting is the main part of logistics of supplying forest biomass, the literature on forest harvesting systems will be reviewed here. However, the literature specifically related to biomass supply and logistics will be review later as well. The literature on logistics of forest harvesting is classified into those studies which used a mathematical method (such as parametric programming, linear programming, and engineering economic analysis), and studies using simulation modeling method.

1.4.1. Literature Using Mathematical Methods

Lambert and Howard (1990) conducted a study on the productivity and cost of an integrated harvesting and processing system operating in small-diameter forests in Washington. The harvesting system consisted of a steep-slope feller-buncher, a forwarder, a chain-flail debarker-delimber, a chipper, a conveyor system, and a shredder. Processed products in this system include saw-log, pulp chips and hogged fuel-wood. Two study blocks were selected for whole-tree harvesting during the study. Cost and production rates were recorded while the integrated harvesting and processing system operated normally in the study area. The results of the study showed that the system harvested and processed about 300 green tonnes of products per acre from 2,300 standing trees per acre at a production rate of 455 tons per day. The delivered product mix was 53% chips, 21% saw logs, and 26%

hogged fuel wood. Operation costs could not be assigned precisely to individual products because the processing system produced three distinct products simultaneously.

A study on controlling costs associated with forest harvesting and road construction operations was conducted by Heinrich et al. (1992). In first step of the study, they broke down each of harvesting and road construction operations into its consisting activities. The harvesting operation consists of activities including felling, bucking, skidding, loading and truck transporting. The road construction was broken down to surveying, clearing, piling, earthworking, finish grading and surfacing. Then, an engineering economic analysis was conducted based on labour cost as well as equipment ownership and operation costs to come up with unit cost for each activity. The analysis has covered all levels of mechanization ranging from basic to intermediate and advanced machinery. Finally, a computer program named as PACE (Production and Cost Evaluation) was developed to assist in calculating machine rates, road construction costs, and harvesting costs based on inputs including labour cost for each activity, ownership and operating costs for each type of machinery and the work volumes. The program was used to calculate costs associated with various options involving different combinations of harvesting equipment, skidding distance, skidding speed, load size, and skidding pattern.

Gingras and Favreau (1996) conducted a study on estimating delivered costs of round-wood and chips to primary wood-using industries and comparing these costs with costs for various scenarios of biomass harvesting and delivery. The harvesting costs for three harvesting systems on two representative forest types in eastern Canada were calculated and compared. The harvesting systems retained for the analysis included full tree to roadside system, cut-to-length system integrated with full-tree chipping and cut-to-length system. The representative forest types included Boreal softwood and Acadian mixed-wood. For each scenario, cost calculations were performed based on productivity rate of equipment (m^3/pmh) and unit cost of work performed by each equipment (\$/m^3). Each scenario also was tested on two levels of sensitivity using the two variables that contributed most to the total cost variations: biomass moisture content and the utilization rate of the biomass production machine. The results of the study showed that costs associated with all three harvesting systems were high comparing to the market value of biomass.

Epstein and Weintraub (2002) conducted a study on supply chain of the forestry sector in Chile. The supply chain in this study starts with logging operations in the forest and then continues with transporting logs to their initial destination which may be sawmills, plywood plants, pulp and paper mills, ports, stockyards or collection-transformation centers. From these initial destinations, products go to their secondary destinations which are either local markets or ports for export. Using linear programming, several mathematical models were developed to support decision making in different stages of the supply chain. These decisions included selection of stands to be harvested in each period, cutting/bucking method used for each stand, sizes (length and diameter) of logs sent to different destinations, types of logging machinery and trucks used, types and quantity of products sent to different local markets or ports.

Karlsson et al. (2004) developed a mixed integer linear programming model to optimize the annual harvest planning from the perspective of Swedish forest companies. The aim of the model was to assist the Swedish forest companies in making decision on which areas to harvest during the annual period so that the wood-processing facilities (saw-, pulp-, or paper-mills) receive their required demand from different assortments. The distance between the facilities and the harvesting areas directly affects the transportation costs. Each harvesting area considered in the study has a specific size and composition of assortments. Therefore, the choice of harvesting areas affects the production level of different assortments. The model also was aimed to help the companies to make decisions on which harvesting team should be assigned to each harvesting area. Each harvesting team has different skills, home base, and production capacities. Different combinations of teams and harvesting areas correspond to different harvesting costs. The model was solved with CPLEX 8.1 within a practical solution time limit and the results were applied in the case of a major Swedish forest company.

Table 1.1 represents a summary of the reviewed studies on logistics of forest harvesting which have used mathematical methods.

Table 1.1. Literature on Logistics of Forest Harvesting Using Mathematical Methods

Author(s)	Year	Operations	Country/Region	Objectives	Important Findings
Lambert & Howard	1990	Felling, forwarding, debarking, delimbing, chipping, and shredding	Western Washington, USA	Estimating cost and productivity associated with harvesting and processing system using plot sampling	The harvesting system had a production rate of 455 tons of mixed product per day. The product mix included 53% chips, 21% saw logs and 26% hogged fuel wood.
Heinrich et. al	1992	Logging, road construction	USA	Calculating costs associated with harvesting and road construction operations through an engineering economy analysis	A computer program named as PACE (Production and Cost Evaluation) was developed to assist in calculating machine rates, road construction costs, and harvesting costs. The program had the ability of considering different combinations of harvesting equipment, skidding distance, skidding speed, load size, and skidding pattern.
Gingras & Favreau	1996	Cut-to-length, full-tree harvesting and full-tree chipping	Eastern Canada	Calculating delivery cost of biomass based on productivity rate of equipment and unit cost of work performed ($\$/m^3$)	Costs associated with all harvesting systems were high comparing to the market value of biomass.
Epstein & Weintraub	2002	Logging, transporting logs to initial destinations, transporting products to secondary destinations.	Chile	Using linear programming to assist decision on selection of stands to be harvested, cutting/bucking method, size of logs, and type of machinery to be used.	Several mathematical models were developed to support decision making in different stages of the supply chain.
Karlsson et. al	2004	Harvesting forests	Sweden	Optimizing the annual harvest planning using mixed integer linear programming	A model was developed to assist the Swedish forest companies in making decision on which areas to harvest during the annual period so that the wood-processing facilities receive their required demand from different assortments.

1.4.2. Literature Using Simulation Modeling

Randhawa and Olsen (1989) developed a simulation model named as LOGSIM (Logging Simulator) for analyzing the tree-to-mill forest operations. The model was capable of simulating harvesting system including felling, processing, skidding, pre-hauling, sorting, loading, hauling, debarking, and chipping. The model was consisted of three major components: the network model written in SLAMSYSTEM simulation language for modeling the harvesting process and assigning attributes of time between failures and repair time to each machine, sub-routines written in FORTRAN which were used for initiating the simulation process and describing the statistical data and computing output results, and a FORTRAN-based user interface which was used for obtaining the input parameters for the harvesting system from the user. The simulation output included information on parameters such as average, minimum and maximum inventory levels, processing cost per volume of logs, processing cost per scheduled hour, time to process a specified amount of material, utilization of machines and machines' productive and breakdown hours.

Wang and Greene (1999) developed a graphical simulation model of forest harvesting operations. The objective of the model was to provide maps of original and residual stands, machines' running paths, machines' working and idle times, and production volumes at each stage of the operation. Using stand data inputs including species in the stand, stand age, stand density, dominant height, minimum and maximum diameter at breast height (dbh), and spatial pattern, a stand generator in the model creates a stand map indicating the location of each tree in a coordination system, its dbh, total height, volume and whether or not it is likely to be harvested. The harvesting operation considered in the model included felling trees in the stands and extraction of the felled trees. Three felling machines (chainsaw-feller-buncher and harvester) and two extracting machines (grapple skidder and forwarder) were implemented in the model. Each operation is simulated graphically based on production rates of machines and distances obtained from the stand map. Since the model was using an interactive technique, it was relatively time-consuming to run, particularly for simulating skidding and forwarding operations.

Wang and LeDoux (2003) modified the previous model (Wang and Greene 1999) with a numerical approach to reduce the running time of the model. The objective of the modified model was to estimate cost and productivity in ground-based timber harvesting systems. Data structure, input and output of this model was similar to the original interactive model. The stand generator was modified through considering three spatial patterns (random, uniform, and clustered) for planted stands and two spatial patterns (random and clustered) for natural stands. Felling and extracting operations were modeled numerically based on the distance and the speed of the machine. The model was validated by comparing the means of operational random variables achieved by the simulation with rates observed in field experiments.

Oinas and Sikanen (2000) developed a discrete-event simulation model of timber procurement process in Finland. The objective of the model was to provide estimates of log volumes available through thinning (single-tree cutting) and clear-cutting methods. Stands were generated from a database in order of descending quality. Attributes assigned to stands included cutting method (clear cutting or thinning), area and length of strip roads, average hauling distance, and timber volume per 100m of strip road. A database comprising 376 real-life logging stands was used to model the distribution of the stands according to their thinning and clear-cutting proportions. The harvesting machinery considered in the model consisted of one single-grip harvester and one forwarder in each stand. Simulation of harvesting operations was based on the moving time and time required to process trees for each machine. The transportation operation was simulated based on loading time, driving time for loading, time of driving loaded, time of driving unloaded, and unloading time. The constructed simulation model was validated to be suitable for training purposes rather than for professional research.

Barrett (2001) developed a simulation model in his Master's thesis to evaluate the impacts of log-truck turn-time on the productivity of timber harvesting system. The model was called as Log Trucking System Simulation (LTSS) and designed as a tool that can illustrate the magnitude of cost and productivity changes as the delivery capacity of the contractor's trucking system changes. The model simulated a harvesting system with up to eight products transported to different mills. Using an example contractor's cost and production rates, incremental analyses were performed to illustrate the nature of impacts associated with changes in the contractor's trucking system. The results revealed that the increased turn-times decreased number of loads per day and increased total cost per delivered tonne of logs. In case that truck turn-times significantly limited production, total cost per delivered tonne of logs decreased if additional trucks were added.

McDonagh (2002) developed two simulation models in his Master's thesis. The first model, called as Harvest System Assignment (HAS), was used to evaluate the impact of different harvesting systems, site conditions and stand characteristics on productivity and unit cost associated with the harvesting system. Four types of ground-based harvesting systems were incorporated in the model: manual chainsaw with cable skidding, mechanical felling with grapple skidding, shovel bunching with grapple skidding, and cut-to-length harvesting with forwarding. Inputs of the model included site and terrain condition such as slope, skidding distance, harvest intensity and stand size, as well as harvesting system characteristics like landing storage capacity, trucking capacity and typical system delays. Outputs of the model included volume and cost per unit of logs. The second model, called as Machine Allocation (MA), was used to evaluate the potential of a given machine combination and investigate the impact of machine interactions. The MA model can incorporate up to five machines for each of three phases in the harvesting operations: felling, skidding and processing. There are two types of inputs to the MA model: system input and general input. System input consisted of number and type of machines in the system along with the way in which these machines interact. General inputs to the MA model were site and terrain parameters that influence operation of machinery. Outputs of the MA model included productivity, delay, and utilization associated with each machine.

Myers and Richards (2003) developed a simulation model to assist decisions on wood supply chain for a sawmill owned by Pacific Inland Resources Ltd. in Northern BC. The objective of the model was to evaluate the impact of implementing cable logging and central tire inflation (CTIS) systems, either separately or collectively, on total costs of logs delivered to the mill, as well as inventory and storage costs at the mill. CTIS is a system used in trucks which gives the driver direct control over the air pressure in each tire and therefore increases the truck's maneuverability over different surfaces. The wood supply chain for the mentioned company was simulated by modeling the roadside, mill-yard, and inventories as queues, and harvesting, transportation and mill processing as activities. The results of the simulation showed that there was a significant saving in inventory costs for scenarios that used CTIS trucks, but no significant saving on overall costs for either of the two technologies used either individually or together.

Ziesak et al. (2004) used AutoMod simulation program (developed by Brooks Automation, USA) to create a model of log supply chain. The model had the ability to include three aspects of the supply chain: the forest environment, forest equipment, and characterizations of activities. The forest environment was modeled as a pattern of individual trees including forest roads and terrain conditions. For each tree, data including species, position, total height, diameter at breast height (dbh) and volume were obtained from a complete stand count or created based on the results of a stand simulator. The production resources consisted of type of forest equipment, their activities, description of standard movements and working pattern as well as information on interruption and break-down probability. Characterization of the activities included a detailed description of each operation. The model was tested for a forest stand in North Rhine Westphalia, Germany. The operation in this case included felling and processing with a harvester and a chainsaw and extracting logs with either a forwarder or a skidder. Comparing the results of the model with data obtained from the actual operation showed well functioning of the model. The model was successful in making decisions on changing equipment or their accessories and controlling the production volumes.

A summary of the reviewed studies on logistics of forest harvesting which have used simulation modeling is presented in Table 1.2.

Table 1.2. Literature on Logistics of Forest Harvesting Using Simulation Modeling

Author(s)	Year	Operations	Country/Region	Objectives	Important Findings
Randhawa & Olesen	1989	Felling, processing, skidding, pre-hauling, sorting, loading, hauling, debarking and chipping	USA	Estimating average, minimum and maximum inventory levels, production cost per volume of logs, and utilization of machines	The model showed a satisfactory potential to aid in improving the planning and operation of the log harvesting process.
Wang & Greene	1999	Felling , extracting logs	USA	Graphic simulation of logging operations	Maps of original and residual stands, machines' running paths, machines' working and idle times, and production volumes at each stage of the operation were developed.
Wang & LeDoux	2003	Felling, extracting logs	USA	Estimating cost and productivity in ground-based timber harvesting systems	The model was validated by comparing the means of operational random variables achieved by the simulation with rates observed in field experiments.
Oinas & Sikanen	2000	Thinning, clear-cutting	Finland	Estimating log volumes available through thinning and clear-cutting methods	The simulation model was validated to be suitable for training purposes rather than for professional research.
Barrett	2001	Truck transporting of logs	USA	Evaluating the impacts of log-truck turn-time on the productivity of timber harvesting system	As truck turn-times increased, number of loads per day decreased and, therefore, delivery times and total cost per delivered tonne of logs increased.
McDonagh	2002	Four ground-based systems	USA	Estimating unit cost of logs, productivity, and efficiency associated with each harvesting system.	The impact of different harvesting systems, site conditions, and stand characteristics on productivity, efficiency, and unit cost associated with the system were evaluated.
Myers & Richards	2003	Cable logging, Central tire inflation system (CTIS)	Northern BC, Canada	Estimating total cost of logs delivered to the sawmills	Using CTIS trucks causes significant saving in inventory costs, but neither cable logging nor CTIS causes significant saving on overall costs of logs.
Ziesak et al.	2004	Felling and processing with harvester and chainsaw, extracting logs with forwarder or skidder.	North Rhine Westphalia, Germany	Map of the original and residual stands, Volumes of logs available, Volumes of logs produced, total cost of logs produced	The model was successful in making decisions on changing equipment or their accessories and controlling the production volumes.

1.5. Literature Review on Biomass Supply and Logistics

The literature reviewed in this section covers studies that:

- consider forest or agricultural biomass:
    - Forest biomass includes the whole trees used as biomass (such as poplar, willow or MPB-killed trees) as well as residues left after forest operation
    - Agricultural biomass includes energy crops (such as switchgrass) which are planted for the purpose of using the whole crop as biomass and also residues left after harvesting of food crops (such as stover)
- include the biomass supply chain from source of biomass (forest or farm) to the gate of the conversion facilities and do not extend to the processes required for converting biomass to bioenergy or bio-fuels,
- focus on availability (quantity), productivity, cost, time and emissions associated with supply and logistics of biomass, and

Similar to the literature on logistics of forest harvesting, studies reviewed in this section are grouped into those using a mathematical method such as parametric programming, linear programming, engineering economic analysis and statistical analysis, and studies using simulation modeling method.

1.5.1. Literature Using Mathematical Methods

A study on economics of forest biomass supply was conducted by Sedjo (1997) to see if there was a large-scale future of biomass in industrial countries. The study examined the financial potential of forest biomass as a source of energy in competing with fossil fuels and also other industries using forest biomass as the raw material such as lumber or pulp and paper industries. The analysis was based on two key points of competition. First, the biomass must be priced low enough to compete with fossil fuels. Second, the financial return on forest-based bio-energy production must be high enough to bid wood away from alternative forest-based industries. However, after performing the mathematical analysis, the study concluded that forest-based bio-energy could not compete in either of the mentioned sectors and failed the financial test on both accounts.

A study was conducted by Allen et al. (1998) to assess the potential systems for the supply of biomass fuel to power plants in the UK through calculating the delivered costs associated with each supply system. Four types of biomass fuel including forest biomass, short rotation coppice, straw, and miscanthus (a perennial grass) were considered in the study. To identify the potential supply systems, the study concentrated on the logistic activities involved in supplying each type of biomass including harvesting, in field/forest handling and transport, processing biomass (to improve its handling efficiency), storage, and road transport to the power station. Then by using a spreadsheet package, a cost model was developed based on the potential supply chain systems in order to calculate the delivered cost through a detailed analysis of different cost components and activities. The results of the model showed a delivery cost ranging from £32 to £37 per dry tonne of forest fuel.

A study on barriers and drivers behind bioenergy market growth was conducted by Roos et al. (1999). The study investigates the problems related to bioenergy technology implementation from both a production structure and market structure perspectives. The barriers and drivers (as labeled as critical factors in the study) included: integration with other economic activities, impact of scales on bioenergy markets, competition in bioenergy markets, competition with other businesses, national policies, local policies and local opinion. Using economic concepts and models from transaction cost theory, investment risk management, information economics and industrial organization, they presented a framework for the analysis of both existing and projecting bioenergy market potential. Five real bioenergy markets including pellet residential heating in the US, pellet residential heating in Sweden, bioenergy power in the US, biomass district heating in Sweden and biomass district heating in Austria were demonstrated as case studies of the framework.

A study on possible contribution of biomass in the future global energy supply was conducted by Berndes et al. (2002). The study was a review of 17 earlier studies that had arrived at widely different conclusions on the subject (from below 100 EJ/yr to above 400 EJ/yr in 2050). The study showed that the reason for such wide differences was the high levels of uncertainty and variation associated with land availability, yield levels of energy crops and availability of forest wood and forestry/agricultural residues. The study also revealed that the bioenergy demand was sensitive not only to biomass supply potentials, but also to total energy demand and competitiveness of alternative energy options.

Kumar et al. (2003) conducted a study to determine power costs and optimum size of biomass-based power plant in western Canada for three types of biomass including agricultural residues (grain straw), whole forest biomass and forest harvest residues from existing lumber and pulp operations. For each type of biomass, cost components were estimated for production and delivery of biomass as well as capital investment and operating costs of the power plant. The results showed that both the yield of biomass per unit area and the location of biomass had an impact on power cost and optimum size of the power plant. The study also concluded that the forest harvest residues had the smallest economic size of the power plant (137MW) and the highest power cost (US$63 per MWh). The optimum sizes of the power plant for agricultural residues and whole forest biomass were 450 MW and 900 MW, respectively. Also, the power costs associated with agricultural residues and whole forest biomass were estimated as US$50.30 and US$47.16 per MWh. However, the study concluded that none of the projects were economic unless greenhouse gas credits were applied.

Gallagher et al. (2003) conducted a study to estimate supply and social costs associated with supplying biomass from different types of crop residues in the United States. Components of the marginal social costs considered in the supply analysis were 1) cash outlays and opportunity costs associated with harvest and alternative uses of residues, 2) potential environmental damages that are avoided by excluding unsuitable land, and 3) costs of transporting residues from farms to processing facilities. The results of the study revealed that crop residues would provide a moderate amount of the US fuel supply when biomass energy technologies were fully developed and adopted.

Gunnarsson et al. (2004) used mixed integer linear programming along with heuristic approach to conduct a study on forest biomass supply chain in Sweden with multiple sources (forest residues in harvest areas, sawmill residues and imported biomass at import harbours), multiple intermediate terminals and multiple demand nodes (heating plants). In this case, forest residues should be chipped to be used by the heating plant and chipping the residues could be made either directly at harvest areas or at intermediate terminals. The intermediate terminals were also needed to balance the seasonal demand fluctuations. The supply chain problem in this study included decisions on the type of fuel to use, locations of chipping, collecting and chipping times, storage levels at terminals and transportation pattern in order to minimize the total cost (objective of the supplying company). The model developed in this study was tested on a real industrial case and was proved acceptable as a decision support tool for strategic analysis as well as tactical planning of the supply of forest fuel in Sweden.

A study was conducted by Wahlund et al. (2004) to calculate the reduction of CO_2 emission and the cost associated with this reduction for several bioenergy processing options in Sweden. The processing alternatives considered in this study consisted of 1) combusting biomass to produce power (either directly or after drying/pelletizing) and 2) converting biomass to biomass-based motor fuels such as ethanol, methanol, or dimethyl ether (DME). The results of the study showed that the largest and most-long-term sustainable CO_2 reduction would be achieved by refining the woody biomass to fuel pellets for coal substitution. Analysis of the results also revealed that converting biomass to motor fuels gave only half of the reduction. Pelletizing biomass made transportation over long distances possible as well as seasonal storage which was crucial for further utilization of the woody biomass potential.

Hamelinck et al. (2005) conducted a technical-economic study on transporting biomass to Western Europe in an international scale. Types of biomass considered in this study included pellets produced from forest biomass and energy crops as well as liquid bio-derived fuels such as methanol. Using generic data, they analyzed chains of European and Latin American bioenergy carriers delivered to Western Europe. The results of the study showed that forest residues and energy crops supplied from Europe could be delivered at €90 and €70 per dry tonne (€4.7 and €3.7 per GJ_{HHV}) when shipped as pellets. However, despite the long shipping distance, crops supplied from South America had a much lower delivered cost of €40 per dry tonne (€2.1 per GJ_{HHV}). The results of the study also revealed that methanol produced in Latin America and delivered to Europe had a cost of €8-10 per GJ_{HHV}. When the conversion process was done in Europe, the delivered methanol costs were higher.

Caputo et al. (2005) studied the economic feasibility of biomass utilization for direct production of electricity in Italy. Two typical plant configurations were considered in the study: fluid bed combustion followed by steam power generation, and fluid bed gasification followed by a combined gas-system cycle power generation. The capacity of the power generation facility considered in this study ranged from 5 to 50 MW. The economic evaluation of analyzed plant configurations was carried out based on total capital investments, revenues from electricity sale and total operating costs including a detailed evaluation of logistic costs. Total operating costs were determined as the sum of operating labour costs, ash transport and disposal costs, purchased biomass costs, biomass transport costs, and maintenance and insurance costs. Also, in order to evaluate the impact of logistics on the profitability of the bioenergy facility, the effects of main logistic variables such as truck transport cost, truck capacity, and purchased biomass cost and distribution density were examined in terms of plant size (5-50MW). The analysis highlighted that sales effects were very significant for performance of considered bio-energy systems. More specifically, profitability of both plant configurations strongly improved with larger plant sizes. Finally the results showed that combustion-based configuration had a better profitability compared to gasification-based system.

Ericsson and Nilsson (2006) studied the short-term (10-20years), medium-term (20-40 years) and long-term (>40 years) potential of using biomass as source of energy in 15 European Union countries, its 8 new members and 2 candidates (collectively referred to as ACC10) plus Belarus and Ukraine. Biomass categories considered in the study included forest residues, forest industry by-products, crop residues (including straw from wheat, barley, rye and oats plus maize residues) and energy crops. The potential bioenergy supply was analyzed using a resource-focused approach. For forest residues and forest industry by-products, assessments were made based on forest biomass growth rather than on current national cuts and forest industry locations. Assessments of crop residues were based on average cereal and maize yields for 1998-2002. For energy crops, regardless of the type, assessments were made based on potential plantation areas as well as energy crop yields which assumed to be correlated with the national wheat yields. The results of the analysis showed that there were no resource limitations in meeting the biomass target (5.6 EJ/year) in 2010 which had been set by European Commission in 1997.

Kumar et al. (2005) conducted a study on using the unharvested Mountain Pine Beetle-infested trees in Quesnel Timber Supply Area for an electrical power plant. The objective of the study was to evaluate the feedstock availability and power costs associated with four scenarios including two sizes of power plant (220 and 300 MW) at each of two locations of Nazko and Quesnel. The power plant was assumed to be a stand alone condensing cycle power plant operating on a dedicated supply of the MPB-killed wood for a period of 20 years. The study assumed that trees were clear cut, skidded to the roadside and whole trees were chipped. The chips were transported to the plant by a chip van truck where they were combusted to produce power. The approach for estimating total power cost in this study was an engineering economic analysis considering delivered biomass cost as well as operation and maintenance costs. Components of the delivered biomass cost included harvesting cost, chipping cost, transportation cost, silviculture cost, and road construction cost. Operation and maintenance cost components included storage cost, operating cost, maintenance cost, administration cost, ash disposal cost, and transmission line cost. The result of the calculations showed that the 300 MW plant sited in Quesnel was the recommended scenario, and the leveled cost of power from this size of plant was about $70 per MW excluding any federal or provincial subsidies for green power and any carbon credits from the project. This power plant would use 63 million cubic meters of merchantable timber over its operating life which would be supplied from an estimated area of 145 km by 145 km.

MacDonald (2006) performed another research related to the study conducted by Kumar et al. (2005). Since the report prepared by Kumar et al. was based on some elementary estimates of pine volumes and harvesting and comminuting costs, this study was aimed to provide more accurate volume and cost estimates. The case study area considered in this research included the land units in the Quesnel TSA west of Fraser River, except for the three westernmost ones. Depending on proportions of merchantable and fuel wood, he suggested three harvesting system for MPB-infested stands. For stands with fuel-wood content less than 50%, the current salvage operation was considered as the appropriate system. In this system, the logging operation is the primary focus and fuel wood is limited to roadside residuals left after logging operation. For stands with fuel-wood content between 50% and 95%, he suggested a satellite system in which whole trees are transported to a satellite yard centered to the stands where they are sorted to merchantable and fuel-wood. After sorting merchantable wood will be sent to the mills and fuel-wood will be chipped. For stands with fuel-wood content more than 95%, whole trees are chipped in bush or at the roadside and nothing is used as merchantable wood. For each harvesting system, costs of merchantable wood ($\$/m^3$) and woodchips ($/dt) were calculated based on hourly rates and production rates of equipment used. The cost analysis was for direct harvesting and transportation costs and was not to include administration, road construction, maintenance, and reforestation costs.

Ralevic and Layzell (2006) carried out a study to provide an estimate of British Columbia's potential to produce renewable energy. The potential biomass sources considered in the study included municipal waste, animal manure, energy crops, forest residues from the existing forestry operations and unusable dead trees associated with mountain pine beetle. The results of the study revealed that the mentioned sources can supply 32 million oven dry tonnes of biomass per year which can provide British Columbia with over 50% of its current fossil energy needs (920 PJ/year). Forest residues and unusable MPB infested trees are estimated to be able to contribute 21% and 19% to the provinces energy needs, respectively.

Stennes and McBeath (2006) conducted a study on commercial bioenergy production from mountain pine beetle killed wood in British Columbia. Their study showed that although the increased harvests associated with the mountain pine beetle outbreak have caused much of surplus in residues in BC, this supply stream would be temporary and would decrease in next decade. They also studied the finished cost of direct harvesting of mountain pine killed wood and showed that the energy prices alone would not support energy production from direct harvest of woody biomass. They also used two case studies to examine the potential of using salvage-harvested pine for commercial energy production. In either case, they estimated the level of Carbon credits necessary to make bioenergy production feasible. The results showed that based on the energy prices and feedstock costs at time of the study, Carbon credit had to be more than \$35/tonne (CO_2) to make either option feasible. Their study also showed that, in case of electricity production in British

Columbia, the low cost of natural gas was a serious impediment to using biomass as a feedstock.

Yoshioka et al. (2006) conducted a research to examine the feasibility of a harvesting and transporting system for using logging residues in Japan. The feasibility of the system was studied from standpoints of cost, energy consumption, and CO_2 emission. The harvesting and transporting systems were constructed with reference to some European countries and were examined based on field experiments in Japanese forestry. The harvesting and transporting system included whole-tree yarding/skidding, delimbing, bucking, forwarding, truck transporting, and converting to energy. In addition to five processes listed above, chipper comminuting was incorporated into the system to enhance the transporting efficiency. Depending on where the logging residues were chipped, the system was classified into three types as “in-forest”, “landing”, and “plant” systems. While in the “in-forest” and “landing” systems mobile chippers were used, a large-sized chipper was used in the “plant” system. The total cost of each system was calculated by aggregating labour, machine and fuel costs. The results showed that with respect to the cost per unit weight of logging residues in each of the three systems considered in the study, the “in-forest” system is the lowest and the “plant” system is the highest. The “plant” system had the highest energy consumption and CO_2 emission per unit weight of logging residues compared to other systems.

The last study using mathematical methods which is reviewed in this research was conducted by Van Belle (2006). He developed a model to quantify CO_2 emissions during the harvesting of forest residues for energy production in Belgium. In this model, the CO_2 emission per primary energy content of the biomass was calculated based on fuel consumption rate of the machine, CO_2 emission per litre of fuel, and operational productivity of the machine. He applied the model on the case of chipping with a chipper with two knives mounted on its disc. Fuel consumption and productivity of the chipper were measured over several trial runs. Productivity of the chipper was measured by weighting the forest residues before chipping and measuring the exact time needed to chip them. The energy content of the chipped samples was measured in the laboratory after a drying process. The results of the model showed that the diameter of the residues fed into the chipper had a significant influence on the CO_2 emissions per energy content of the chipped biomass. In fact, the smaller the diameter, the higher the emission ratio.

Table 1.3 represents a summary of the reviewed studies which have used mathematical methods.

Table 1.3. Literature on Biomass Supply and Logistics Using Mathematical Methods

Author(s)	Year	Biomass Type	Country/Region	Objectives	Important Findings
Sedjo	1997	Forest biomass	Industrial countries	Examining the financial potential of forest-based bioenergy in competition with fossil fuels and other industries	Forest-based bioenergy supply could not compete in either of the mentioned sectors.
Allen et. al	1998	Forest biomass, short rotation coppice, straw, miscanthus	UK	Calculating costs associated with the potential systems for the supply of biomass to power plants.	Cost of forest biomass ranged from £32 to £37 per dt. Using large baling method instead of small baling or roll baling reduced cost of agricultural fuels.
Roos et. al	1999	Pellets used for residential heating, forest biomass used for power plant	US, Sweden, Australia	Identifying critical factors in bioenergy technology implementation	The critical factors were identified as: integration with other economic activities, competition in bioenergy markets, and competition with other businesses, national and local policies, and scale effects.
Berndes et. al	2002	Biomass from a general point of view	The whole world	Examining the possible contribution of biomass in the future global energy supply.	Biomass was estimated to contribute from 100 to 400 EJ/yr in 2050. Bioenergy demand is sensitive to supply potentials, total energy demand and competitiveness of alternative energy options.
Kumar et. al	2003	Agricultural residues, whole forest biomass, and forest residues	Western Canada	Determining power costs and optimum size of biomass-based power plants.	Forest residues had the smallest optimum size of power plant (137 MW) and the highest power cost (US$63 per MWh).
Gallagher et al.	2003	Crop residues	USA	Estimating supply and social costs associated with supplying biomass.	Crop residues would provide a moderate amount of the US fuel supply when biomass energy technologies were fully developed and adopted.
Gunnarsson et al.	2004	Forest and sawmill residues	Sweden	Using linear programming to optimize decisions on type of fuel, location of chipping, operation start, storage levels and transportation patterns.	The model was tested on a real industrial case and was proved acceptable as a decision support tool for strategic and tactical planning of the supply of forest fuel in Sweden.
Wahlund et al.	2004	Woody biomass, pellets	Sweden	Determining the reduction of CO_2 emissions for bioenergy processing options.	Converting the woody biomass to fuel pellets for coal substitution gave the largest and most-long-term sustainable CO_2 reduction.
Hamelinck et al.	2005	Pellets produced from forest residues and energy crops, methanol	Western Europe	Estimating costs associated with transportation of biomass from Europe and Latin America to Western Europe.	Despite the long distance shipping, bio-fuels delivered from Latin America had a lower cost comparing to bio-fuels supplied from Europe.

Table 1.3. Studies on Biomass Supply and Logistics Using Mathematical Methods (Continued)

Author(s)	Year	Biomass Type	Country/Region	Objectives	Important Findings
Caputo et. al	2005	Wood, wood waste, agricultural crops, and their waste by-products	Italy	Examining economic feasibility of biomass utilization for direct production of electricity.	Combustion-based configuration had a better profitability comparing to gasification-based system.
Ericsson & Nilsson	2006	Forest residues, forest industry by-products, crop residues and energy crops	European Union, AAC10, Belarus and Ukraine	Assessing short, medium and long-term potential of using biomass as a source of energy.	There were no resource limitations in meeting the biomass target (5.6 EJ/year) for 2010 set by European Commission in 1997.
Kumar et. al	2005	MPB-killed pine	Interior BC, Canada	Determining power costs associated with using MPB-killed wood for bioenergy in British Columbia.	A 300 MW plant sited in Quesnel was the optimum scenario with an associated power cost of C$70 /MW
MacDonald	2006	MPB-killed pine	Interior BC, Canada	Estimating costs for harvesting, comminuting, and transporting the MPB-killed pine.	The conventional logging system had the lowest fuel-wood cost (C$ 45-54 /dt).
Ralevic & Layzell	2006	Municipal waste, animal manure, energy crops, forest residues, MPB-killed pine	BC, Canada	Estimating BC's potential to produce bioenergy.	The mentioned sources of biomass can supply 32M dt of biomass per year which can provide BC with over 50% of its current fossil energy needs.
Stennes & McBeath	2006	MPB-killed pine	BC, Canada	Studying the feasibility of commercial bioenergy production from MPB-killed pine.	The price of MPB-killed fuel will increase during the next decade as harvesting will decline.
Yoshioka et al.	2006	Logging residues	Japan	Examining the feasibility of harvesting and transporting biomass from standpoints of cost, energy consumption, and CO_2 emission.	In-forest chipping resulted to the lowest cost per dt of biomass. In-plant chipping had the highest cost, energy consumption and CO_2 emission per dt of biomass.
Van Belle	2006	Forest residues	Belgium	Calculating CO2 emissions during the harvesting of forest residues.	The diameter of the residues fed into the chipper had a significant influence on the CO2 emissions; the smaller the diameter, the higher the emission ratio.

1.5.2. Literature Using Simulation Modeling

De Mol et al. (1997) conducted a study on costs and energy consumption associated with the logistics of biomass fuel collection in Netherlands. Using a network structure, they developed two models (a simulation model and an optimization model) to estimate the logistics cost of the biomass fuel supply. The logistic system considered in the study included pre-treatment (size reduction and/or drying), transport, storage, and handling. In the network structure, nodes corresponded with locations (including source locations, collection sites, transshipment sites, pre-treatment sites, and the energy plant) and arcs represented transport (road, water, or rail transport). To simulate the logistics, the flow of biomass in the network was divided into lots and each lot was followed on its way through the network from source location to the energy plant. Costs and energy consumptions were calculated for each lot and accumulated during simulation. The results of the simulation model included the amount of biomass, total and average costs of logistic operations, and energy consumption. An optimization model was also developed to optimize both the network structure (inclusion/exclusion of possible nodes and situation of pre-treatment), and the mixture of biomass types supplied to the energy plant. The results of the optimization model revealed that the optimal location of pre-treatment site was one located centrally to the collection sites. The model also showed that a mixture of road transport (on short distances) and water transport (on long distances) was optimum. Finally, the results of the optimization model showed that the optimum location to chip biomass was at the energy plant.

Hall et al. (2001) used simulation modeling to estimate and compare costs associated with different logistics systems for delivering forest residues to an energy plant in New Zealand. The delivery systems considered in this study consisted of harvesting, storage, processing, and transportation. Three sample forest sites were defined to represent the most typical and important areas of forest operations in New Zealand. The simulation results showed that for the landing residues, a delivery system consisting of loading residues to the truck, hauling to the plant, unloading trucks and chipping residues at the plant was the cheapest system at all three sites. For cutover residues, a delivery system consisting of forwarding residues to landing, unloading forwarder, storing residues for 3 months, loading into the truck, hauling to the plant, unloading and chipping residues at the plant was the cheapest system. Generally, landing residues had lower delivery costs than cutover residues because the latter needed to be collected and then transported to landings. The results of the sensitivity analysis showed that delivery cost in all systems was significantly sensitive to the initial moisture content and bulk density of residues. While increasing the initial moisture content increased the delivery cost of dry biomass, a higher bulk density had a reducing effect on the delivery cost because each truck could contain a larger amount of dry matter.

Sims and Venturi (2004) used simulation modeling to study harvesting, processing and transport system for delivering short rotation coppice crop in North Island of New Zealand to a 10 MW bioenergy plant 25 km away. The objective of the study was to compare the delivered costs of biomass associated with two harvesting systems: conventional short season harvesting and all-year-round harvesting. In conventional system, the crop was harvested during one short seasonal period of 8-10 weeks and, therefore, needed to be stored from one to 12 months in order to provide a continuous supply of feedstock. In all-year-round system, small areas were harvested every few weeks throughout the year and, hence, a continuous supply of biomass feedstock was provided. Two alternatives of all-year-round harvesting and four alternatives of conventional harvesting were simulated and compared.

The results of the simulation showed that all-year-round harvesting systems had economic advantages in terms of \$/GJ over the short season harvesting systems, partly because of the reduction in dry matter losses due to the short storage period, and partly as a result of cheaper harvesting costs due to the use of smaller scale equipment.

Sokhansanj et al. (2006) developed a dynamic simulation model of agricultural biomass collection and transport called as the Integrated Biomass Supply and Logistics (IBSAL). The objective of the model was to estimate cost, energy input, CO_2 emissions and moisture content of biomass associated with collecting and transporting biomass. The model was developed using EXTNED v.6 (Imaginethat Inc. 2006) which is an object oriented high-level simulation language. The model consisted of a network of operational modules and connectors threading the modules into a complete supply chain. Operational modules represented processes such as grain combining, swathing, baling, loading, hauling, stacking, grinding, sizing, and storing. Modules also represented processes like drying, wetting and chemical reactions leading to dry matter loss. The supply chain was divided in two main activities: 1) collecting and storing the biomass at the collection sites and 2) preprocessing and transporting biomass from collections sites to a bio-refinery. The IBSAL model was applied to collection and transport of corn, stover, straw, and swithcgrass in Idaho and Iowa. For conventional baling system, the results of the model showed collection costs of US\$15.80, US\$16.54, and US\$15.80 for 1 dry tonne of stover, cereal straw and swithcgrass respectively. These costs were decreased when a loafer replaced a baler in the collection operation. The results also revealed that transport costs for a given distance and suite of equipment depend on bulk density. Analysis of the results showed that the minimum cost for a 40-mile distance was US\$16 per dry tone.

Mukunda et al. (2006) used discrete-event simulation and GIS tools to model the logistics system of supplying corn stover from on-farm storage to an existing ethanol plant in Indiana with a capacity of 102 million gallon per year. The objective of the study was to investigate the logistical challenges that were likely to occur in such supply system and also analyze various logistics scenarios. The logistics system in this case included on-farm storage of stover bales, loading bales on the trailers, transporting bales to the ethanol plant, unloading bales at unloading stations, and handling (weighing and sampling) bales. The model parameters included number of trucks, travel distances, and capacity of stations considered for loading, unloading, and handling bales. Variables of the model included feedstock inventory as well as average trip time, waiting time and unloading time for each trailer. The results of the model showed that unloading bales from trailers was the bottleneck of the system, thus, the capacity of the unloading stations was a critical factor in the design of similar plants in future. To perform a sensitivity analysis, the model was run for different scenarios of number of trailers and capacity of unloading station. The results of the sensitivity analysis showed that reduction in the capacity of the unloading stations significantly increased the trailers' requirement as well as average waiting time, but increasing the unloading station capacity did not yield significant reduction in number of trailers or average waiting times.

Ravula et al. (2007) developed a discrete-event simulation model to compare logistics costs associated with two strategies for supplying seed cotton feedstock from satellite storage locations (SSLs) to a bio-processing plant located in Virginia. The logistics system in this study included loading loads of seed cotton at the SSLs, hauling to the plant and unloading at the plant. In the first strategy, half of the loaders were assigned to the SSLs with the shortest travel times and half of them to the SSLs with the longest travel times. In the second strategy, the supply region was divided to five sectors and two loaders were assigned to each sector. For both strategies, it was assumed that feedstock was grown on 50%, 45% and 40% of all pasture land within a 3.2-km radius of an individual SSL. The results of the model showed that although the second strategy had lower travel distances than the first strategy, the decrease in loader transport cost was not large enough to recover the cost of additional trucks. The results also revealed that decreasing the land use rate from 50% to 40% increased the number of SSLs needed from 105 to 125 and increased the delivered cost by 6.3%.

A summary of the literature using simulation modeling is presented in Table 1.4.

Table 1.4. Literature on Biomass Supply and Logistics Using Simulation Modeling

Author(s)	Year	Biomass Type	Country/Region	Objectives	Important Findings
De Mol et. al	1997	Agricultural residues, energy crops, waste wood, waste paper	Netherlands	Determining the optimum logistics system of biomass fuel collection.	The optimal location of pre-treatment site is one located centrally to the collection sites. The optimum transport plan is a mixture of road transport (on short distances) and water transport (on long distances). The optimum location of chipping biomass is at the energy plant.
Hall et al.	2001	Forest residues	New Zealand	Comparing costs associated with different logistics system of supplying forest biomass.	Landing residues had lower delivery costs than cutover residues. Delivery cost was significantly sensitive to the initial moisture content and bulk density of residues.
Sims & Venturi	2004	Short rotation coppice	North Island, New Zealand	Comparing the delivered cost of biomass for conventional short-season and all-year-round harvesting systems.	All-year-round harvesting systems had economic advantages in terms of $/GJ over the short season harvesting systems, partly because of the reduction in dry matter losses due to the short storage period, and partly as a result of cheaper harvesting costs due to the use of smaller scale equipment.
Sokhansanj et al.	2006	Corn stover, straw, and switchgrass	Iowa and Idaho, USA	Estimating cost, energy input, CO_2 emissions and moisture content associated with collecting and transporting biomass.	Using conventional baling system, the collection costs were US$15.80, US$16.54, and US$15.80 per dry tonne of stover, straw and swithcgrass respectively. Replacing the baler with a loafer reduced the costs. Transport costs for a given distance and suite of equipment depend on bulk density.
Mukunda et al.	2006	Corn stover	Indiana, USA	Investigating the logistical challenges of supplying biomass from an-farm storage to a power plant.	Unloading was the bottleneck of the system. Reduction in the unloading capacity significantly increased number of trailers required and average waiting time.
Ravula et al.	2007	Seed cotton	Virginia, USA	Comparing logistics costs associated with two strategies for allocating loaders to the satellite storage locations.	Although the second strategy had lower loader transport cost, the first strategy had a lower total cost due to the lower truck transportation cost.

1.6. Research Objectives

This research is an attempt of using simulation modeling in estimating the critical parameters of logistics of forest biomass supply. The model is applied to a case study on supplying the MPB-killed wood from the Quesnel Timber Supply Area (TSA) to a potential power plant near the city of Quesnel. Focusing on the logistics system, this research is an integrated study on supply of the MPB-killed biomass for the above mentioned case. Thus, the objectives of this research are to:

- Developing a simulation model of the logistics of forest biomass and applying it to the case study mentioned above
- Evaluate the amount of fuel-wood available as the feedstock for the power plant
- Assess the cost of supplied biomass (C$ per dry tonne)
- Evaluate the supply time
- Calculate Carbon emissions due to operations associated with the supplied biomass.

1.7. Thesis Outline

This thesis is written in a manuscript style and, accordingly, the organization of the rest of this document is as follows. In Chapter 2, the case study, structure, and logic of the simulation model, data, assumptions and equations used in the model as well as the results obtained from the model will be explained. Chapter 3 will present a sensitivity analysis of some of the results obtained from the simulation model based on some alternative scenarios. Although Chapters 2 and 3 include the main body of the thesis, each of them is a complete manuscript chapter and has its own background, literature review, analysis, discussion, and conclusion. Finally, in Chapter 4, main conclusions of the thesis, future works and limitations of the research will be explained.

1.8. References

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Chapter 2

The Simulation Modeling of Logistics of Forest Biomass Supply in British Columbia [1]

2.1. Background

During the last decade, the increase in fossil fuel prices along with the environmental impacts from their combustion has raised a global attention to biomass as a renewable and clean source of energy. In Canada, the abundance of biomass resources including especially those from forests and agricultural lands has presented an attractive alternative to fossil based feedstock for bioenergy. Within Canada, British Columbia (BC) with a timber productive area estimated at 26 Mha (Cunningham 2005) has a unique opportunity to take the lead in bioenergy industry. The recent infestation of Mountain Pine Beetle (MPB) (*Dendroctonus Ponderosa Hopkins*) within the forests of nterior BC requires the removal of some of dead wood from forest to prevent incidental fires. The MPB-infested area is estimated at more than 8 million ha of forests in central and southern Interior BC amounting to bout 400 million m^3 of merchantable timber (MoFR 2006).

One possible way to generate energy from the MPB-killed wood is to use it as fuel for a biomass-based power plant. The feasibility of such project depends on the availability of biomass over the life time of the power plant (20-25 years) at a competitive cost and

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[1] : A version of this chapter has been submitted for publication.
Mahmoudi, M., Sowlati, T., and Sokhansanj, S. "The Logistics of Supplying Biomass from a Mountain Pine Beetle Infested Forest to a Power Plant in British Columbia."

acceptable quality (mainly moisture content). The availability and cost depend upon quantity of biomass in the forest (before harvest), seasonality of access to biomass, and the logistics for collecting preprocessing, storing, and transporting of biomass.

Several studies have been conducted during the last few years on supply of forest and agricultural biomass in Canada. Kumar et al. (2003) conducted a study to determine power costs and optimum size of a biomass-based power plant with a life time of 30 years in western Canada. Their study showed that power cost and optimum size of the power plant depend on the yield of biomass as well as the location of biomass sources. They also showed that forest harvest residues had the smallest economic size of the power plant and the highest power cost compared to agricultural residues.

A study on the potential commercial energy production from MPB-killed wood in British Columbia was conducted by Stennes and McBeath (2006). Their study showed that despite the increased harvests associated with the recent epidemic which had caused much of surplus in residues in BC, the supply stream would be temporary and would decrease in the next decade.

Also, Kumar et al. (2005) evaluated the feedstock availability and power costs associated with using the un-harvested MPB-killed trees in Quesnel Timber Supply Area (TSA) for power production. Two sizes of power plant (220 and 300 MW) were considered at each of two locations of Nazko and Quesnel over a life time of 20 years. They concluded that the 300 MW plant in Quesnel would be the best scenario. The power cost associated with this size of plant was estimated about $70 per MWh. MacDonald (2006) followed the work of Kumar et al. (2005) to determine accurately the amount of MPB-killed wood available in the region and through several harvest scenarios. He calculated the unit costs of produced merchantable and fuel wood (delivered to the power plant) for the conventional roadside residues, satellite, and whole-tree chipping harvesting systems.

A simulation model called the Integrated Biomass Supply and Logistics (IBSAL) was developed by Sokhansanj et al. (2006) to estimate cost, energy input, CO_2 emissions, and moisture content associated with collection and transport of biomass. The model was applied to collection and transport of corn stover, wheat straw, and swithcgrass in Idaho and Iowa. The results showed that transport costs for a given distance and suite of equipment depend on bulk density and the total delivered cost ranged from US$30 to US$60 per dry tonne depending on the harvest option and distance traveled (0 to 100 km).

2.2. Objectives

The objective of this study is to develop a simulation model of the logistics of forest biomass and applying it to a case of supplying MPB-killed fuel-wood in British Columbia. The model is developed using EXTEND v.6 (Imagine That Inc. 2006) which is an object oriented high-level simulation language and has the potential of providing estimates of the quantity, unit cost, supply time, moisture content, and equipment Carbon emissions associated with this type of biomass. Using simulation technique, the model also has advantage of considering the logistic system required for supplying forest biomass as an integrated and interacting system.

2.3. Case Study

The case study considered in this thesis is the logistics system required for supplying the MPB-killed fuel-wood from Quesnel TSA to a potential power plant near to the city of

Quesnel. The case is explained in three parts: the harvesting system, the harvesting area, and the power plant.

2.3.1. The Harvesting System

As explained in Chapter 1, three harvesting systems were suggested by FERIC (MacDonald 2006) for MPB-infested stands based on proportions of merchantable and fuel wood volumes. Merchantable volume is the amount of sound wood in a stand or a tree that is suitable for marketing (MoFR 2008). In fact, merchantable volume is the volume that contributes to the Annual Allowable Cut (AAC) and is estimated based on trees with minimum dbh (diameter at breast height) of 12cm, from roughly 30cm above the stump to a 10cm diameter at top (MoFR 2007). For MPB-infested stands, fuel-wood occurs in two classes: residuals left after conventional logging operations that are piled at the roadside (tops, butts, and limbs) as well as small, broken and dead standing trees that are not considered as merchantable (MacDonald 2006). For stands with fuel-wood content less than 50%, the current salvage operation is considered as the appropriate system. In this system, the conventional logging operation is the primary focus and fuel-wood is limited to roadside residuals. For stands with fuel-wood content between 50% and 95%, a satellite harvesting system was suggested by FERIC in which whole trees are transported to a satellite yard where they are sorted to merchantable and fuel-wood. After sorting, merchantable wood will be sent to the mills and fuel-wood will be chipped. For stands with fuel-wood content more than 95%, FERIC suggested a full-tree chipping system. In this system, whole trees are chipped in bush or at the roadside and nothing is used as merchantable wood.

The harvesting system considered in the simulation model is limited to the conventional system. Also, it is assumed that the operation is limited to ground-based and no cable or aerial logging equipment is required. For this system, it is assumed that cutblocks of 20-40 ha are felled by a feller-buncher. Then, whole trees are skidded by a grapple skidder to the roadside where they are processed (delimbed and topped) into logs by two dangle-head processors. The residuals left after processing are moved by a butt-and-top loader closer to the road where the residual are fed into a mobile chipper that would throw the chips into a semi-trailer chip-van. Finally, the chip-van will transport wood chip to the power plant, unloads them, and returns to the site. Figure 2.1 illustrates the roadside residual system.

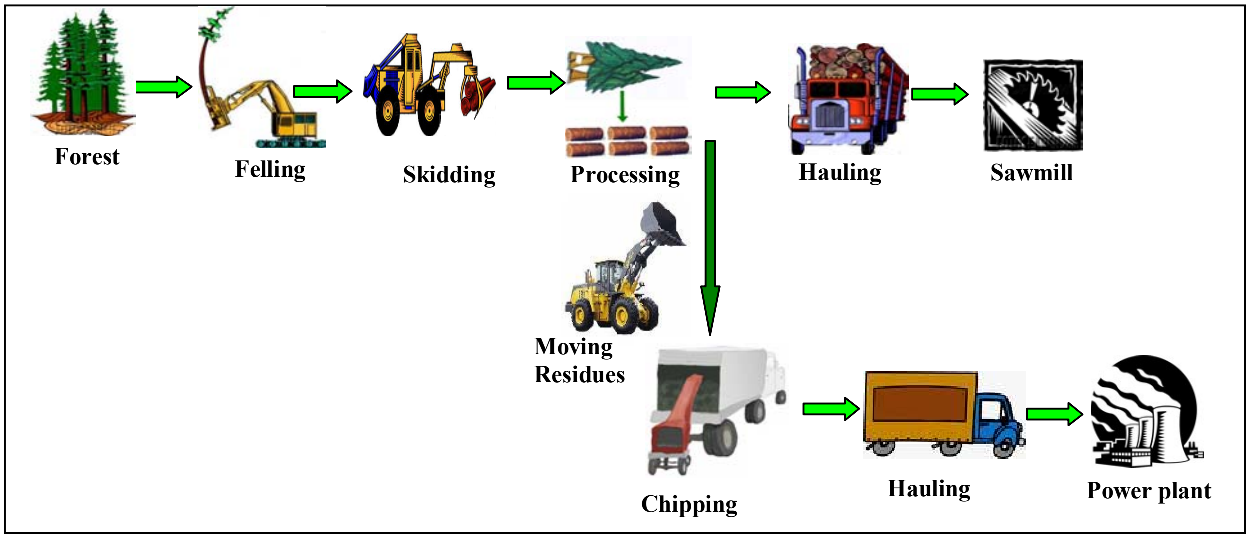

Figure 2.1. Roadside Residual Harvesting System

2.3.2. The Harvesting Area

The Quesnel TSA is located in the Fraser Basin and Interior Plateau between the Coast Mountains on the west and the Cariboo Mountains on the east. The TSA covers approximately 1.6 million hectares and includes the communities of Quesnel, Red Bluff, Barlow Creek, Dragon Lake, and Bouchie Lake. The current Annual Allowable Cut (AAC) for the Quesnel TSA is 5,280,000 m^3 (MoFR 2007). Figure 2.2 shows a map the Quesnel TSA and its location in BC.

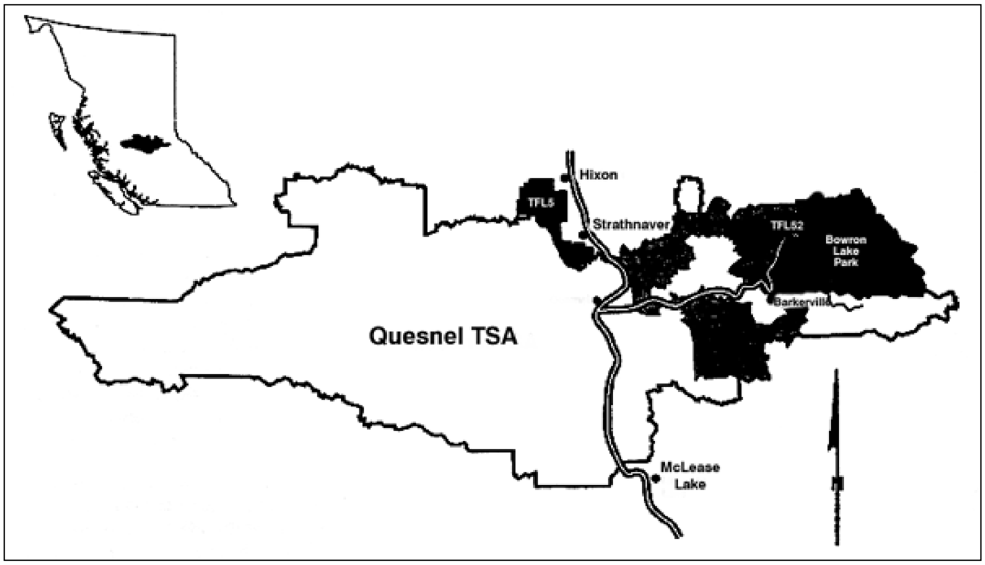

Figure 2.2. The Quesnel TSA
Source: (MoFR 2007)

The forest area selected in the study is the same area considered in MacDonald (2006) which comprises all the land units in the Quesnel TSA except for the three westernmost land units. Table 2.1 shows a list of these 18 land units and their estimated area.

Table 2.1. Land Units in the Quesnel TSA Considered for the Case Study

Land Unit Name	Estimated Area (ha)	Land Unit Name	Estimated Area (ha)
Euchiniko	30,708	Kluskus	34,731
Pelican	41,777	Baker	46,923
Whittier	15,065	Tibbles	39,235
Pantage	38,673	Narcosli	19,082
Chine	32,908	Toil	16,688
Marmot	27,065	Wentworth	37,973
Snaking	40,897	Clisbako	34,807
Baezaeko	46,553	Ramsey	37,757
Coglistiko	37,212	Twan	11,274
Source: (FERIC) Forest Engineering Research Institute of Canada (2006)			

FERIC provided a dataset of these land units. In this dataset, each land unit is divided to three classes of stands with proportions of fuel-wood less than 50%, between 50% and 95% and more than 95%. Also, each of three classes in each land unit is divided to smaller groups of stands based on density of roads and mixture of species. For each group of stands, FERIC estimated area and volumes of merchantable and fuel-wood for current situation as well as for 5, 10, 15, and 20 years from now. To estimate area and volumes of merchantable and fuel wood for each stand groups at 5, 10, 15 and 20 years from now, FERIC created a shelf-life model in which MPB-infested pine deteriorated from merchantable wood to fuel wood to non-recoverable at a rate that depends on biogeoclimatic zone (MacDonald 2006). However, area and volumes of merchantable/fuel wood used in the simulation model developed in this study are limited to those data for current situation. Also, stand groups considered in this study are limited to the first class (with fuel-wood content less than 50%). In fact, as it will be explained later, entities in the simulation model are cutblocks which are randomly selected from stand groups with fuel-wood content less than 50%. For each land unit, the dataset also provides estimates of average hauling distance to Quesnel on highway, mainline and branch roads which are used in the simulation model to calculate the hauling times.

2.3.3. The Power Plant

The power plant considered in this study is assumed to have a capacity of 300 MW with an operating life of 20 years. The potential location of the power plant is near the city of Quesnel. The power plant is estimated to consume 27 million dry tonnes of wood chips over its operating life or an average of 1,350,000 dt per year (Kumar et al. 2005).

2.4. The Simulation Model

The simulation model will be described in two parts. First, data, assumptions, and equations used in the model will be defined and then the logic of the model and how the logistic system is simulated will be explained.

2.4.1. Data, Assumptions and Equations

2.4.1.1.Data on Yield and Percents of Merchantable and Fuel Wood

The harvesting system considered in this study is the conventional system in which fuel-wood is recovered only from roadside residuals left after logging operations. Therefore, data for the first class of stands (with fuel-wood content less than 50%) from dataset provided by FERIC was used to calculate data for the simulation model. In FERIC's dataset, as mentioned before, each class is also divided to smaller groups of stands. According to the dataset, at current situation there are 184 groups of stands with fuel-wood content less than 50% in all the land units under the study. To use in the simulation model, yield (m^3/ha) and percents of merchantable and fuel wood were calculated for each of the stand groups based on current area and volumes of merchantable and fuel wood obtained from FERIC's dataset.

2.4.1.2. Hauling Distances

Hauling distances used in the simulation model are the same as average distances to Quesnel estimated by FERIC for each land unit on highway, main and branch roads as shown in Table 2.2. Thus, as it will be explained later, hauling distances and hauling times in the simulation model are the same for all the cutblocks within each land unit.

Table 2.2. Average Hauling Distances to Quesnel

Land Unit Name	Hauling Distances (Km)			Land Unit Name	Hauling Distances (Km)		
	Highway	Main	Branch		Highway	Main	Branch
Euchiniko	0	35	46	Kluskus	0	15	27
Pelican	0	39	8	Baker	0	22	14
Whittier	20	15	5	Tibbles	18	3	30
Pantage	0	16	20	Narcosli	25	17	10
Chine	2	35	24	Toil	0	10	10
Marmot	0	10	2	Wentworth	0	45	26
Snaking	30	0	10	Clisbako	2	10	15
Baezaeko	0	18	15	Ramsey	50	25	20
Coglistiko	0	10	10	Twan	62	0	20

Source: (FERIC) Forest Engineering Research Institute of Canada (2006)

2.4.1.3. AAC, Seasonal Schedule of Operation

The current Allowable Annual Cut (AAC) for the Quesnel TSA is 5,280,000 m^3. Since data on the AAC for each land unit was not available and the land units considered in the study almost cover the whole TSA, it is assumed that total merchantable volume recovered from land units under the study would be equal to the AAC for the Quesnel TSA. Also, to apply the seasonal fluctuations of logging operations due to forest roads conditions and market demand (MacDonald 1999), the total volume of the AAC was distributed on a monthly basis. This monthly distribution is presented in Table 2.3. Monthly percents of the AAC are calculated based on volumes of merchantable wood produced in the Quesnel TSA by one of the major licensees operating in the area (West Frazer Co.) between May 2006 and April 2007. In fact, we assumed that the schedule followed by this company is representative for schedule of operations in whole TSA.

Table 2.3. Monthly Distribution of the AAC in the Quesnel TSA

Month	Percent of AAC[1] (%)	Cumulative Percent of AAC (%)	Monthly Volume (m^3)	Cum. Volume (m^3)
May	2.6	2.6	136641	136641
June	8.1	10.7	428304	564944
July	7.8	18.5	411202	976146
August	9.7	28.2	511236	1487383
September	8.8	37.0	466983	1954365
October	5.2	42.3	277020	2231385
November	10.6	52.8	558645	2790030
December	12.1	64.9	636733	3426764
January	13.0	77.9	686245	4113009
February	11.7	89.6	615293	4728302
March	10.2	99.7	537105	5265407
April	0.3	100.0	14593	5280000

1: Monthly percentages of the AAC are calculated based on data received from West Fraser Co. for volumes of logs harvested by this company in the Quesnel TSA between May 2006 and April 2007.

2.4.1.4. Weather Data

Weather conditions may affect the speed of biomass supply operation. In fact, while frozen and snow conditions provide a better soil surface for maneuverability of equipment, rainy weather can reduce the productivity of equipment due to decreasing bearing strength of soil. However, very cold temperature may cause shutting down the whole operation due to possible hazards for operators. In developing the simulation model, it is assumed that the operation carried out by each machine will be delayed for 1 hour per each mm of rain. It is also assumed that the whole operation will be shut down on any day that temperature goes under -40°C. The approach for applying the weather delay will be described in more detail later when the logic of the model is explained. Daily weather data consisting of average temperature, rain and snow precipitations as well as relative humidity were obtained for Williams Lake which is located almost at the center of the Quesnel TSA for the period of

May 1, 2006 to April 30, 2007 (Environment Canada 2007). Daily weather data is also used for calculating the moisture content of delivered wood chips which will be explained later.

2.4.1.5. Harvesting Units

Harvesting units considered in the simulation model are assumed as cutblock of 20-40 ha.

2.4.1.6. Operation Times

It is assumed that the operation is carried out for 1 year (May 1 to April 30), 6 days a week and 9 hours a day.

2.4.1.7. Equipment Data

All stands in the study are assumed to have smooth terrain conditions and, therefore, forest operations can be carried out by ground-based equipment. Each cutblock receives one tracked feller-buncher, one wheeled grapple skidder, two dangle-head processors, one butt-and-top loader, and one mobile drum chipper. Hauling of wood chips to the power plant is carried out by semi-trailer chip-vans which are available as soon as needed. Data on production rates of equipment (cubic meter or dry tonne per productive machine hour) and payload of chip-van are obtained from MacDonald (2006). These production rates are average values for most typical equipment used in similar site conditions based on an average stem volume of 0.3m^3, an average skidding distance of 200m and a smooth terrain condition with slopes less than 20% (MacDonald 2006.) Data on rated power of equipment are obtained for similar equipment from Equipment Rental Guide (2006-2007) which is published annually by BC Road Builders and Heavy Construction Association. A list of equipment and mentioned data is presented in Table 2.4.

Table 2.4. Equipment Data Used in the Simulation Model

Type of Equipment	Power (Kw)[1]	Productivity/ Payload [2]	Number Allocated to Each Cutblock
Tracked feller-buncher	149	50-70 m^3/pmh	1
Wheeled grapple Skidder	95	58-65 m^3/pmh	1
Dangle-head Processor	126	27-45 m^3/pmh	2
Butt-and-top Loader	146	120-170 m^3/pmh	1
Mobile chipper	592	20-30 dt/pmh	1
Semi-trailer chip-van	352	13 dt	Available when needed

1: Source: Equipment Rental Rate Guide 2006-2007 (BC Road Builders and Heavy Construction Association)
2 : Source: MacDonald (2006)

Data on average speed of chip-van on highway, main and branch roads are also obtained from MacDonald (2006) which are 80, 60, and 45 km/h, respectively.

2.4.1.8. Cost Data

Calculation of operation costs in the simulation model is based on hourly rate of equipment (C$/hr). For roadside residual harvesting system, it is assumed that costs associated with felling, skidding, and processing operations are covered by logging contractors and does not contribute to delivery cost of fuel-wood. Thus, delivery cost of the feedstock is calculated only based on moving, chipping, and hauling operations which are directly related to handling and supplying fuel-wood. Data on hourly rate of equipment carrying out moving, chipping, and for hauling are received from FERIC (MacDonald 2006) as shown in Table 2.5.

Table 2.5. Hourly Cost of Equipment Used in the Simulation Model

Type of Equipment	Hourly Rate (C$/hr)
Loader	131
Mobile chipper	130
Chip-van	95
Source: MacDonald (2006)	

2.4.1.9. Equations for Moisture Content, Density and Green/Dry Weight

Moisture content of the fuel-wood is calculated at different stags of operation based on relative humidity and daily temperature obtained from weather data. The following Equation (2.1) is used for this calculation (Kumar et al. 2005).

$$MC = \frac{1800}{W} x \left[\frac{Kh}{1 - Kh} + \frac{(K_1Kh + 2K_1K_2K^2h^2}{1 + K_1Kh + K_1K_2K^2h^2} \right] \tag{2.1}$$

In this equation, MC, h and T represent the moisture content of wood chips (% wet basis), relative humidity (decimal fraction) of the surrounding air and temperature (º C) respectively. W, K, K_1 and K_2 are calculated using (2.2) to (2.5).

$$W = 349 + 1.29T + 0.0135T^2 \tag{2.2}$$

$$K = 0.805 + 0.000736T - 0.00000273T^2 \tag{2.3}$$

$$K_1 = 6.27 - 0.00938T - 0.000303T^2 \tag{2.4}$$

$$K_2 = 1.91 + 0.0407T - 0.000293T^2 \tag{2.5}$$

Equation (2.6) is suggested for calculating density of pine wood from its moisture content (Kumar et al, 2005).

$$\rho = 1000\ G_m (1 + MC / 100) \tag{2.6}$$

In this equation, ρ is the density of wood in Kg/m^3, MC is the moisture content (% wet basis) and G_m is the specific gravity of wood. G_m is calculated from (2.7).

$$G_m = \frac{G_b}{(1 - 0.265\, aG_b)} \tag{2.7}$$

G_b is the basic specific gravity based on green volume (for pine G_b=0.38) and a is calculated from (2.8).

$$a = \frac{(30 - MC)}{30} \tag{2.8}$$

Value of density obtained from Equation (2.6) is used at different stages in the simulation model to calculate dry weight of fuel-wood from (2.9) and (2.10).

$$GreenWeight = \rho.Volume \tag{2.9}$$

$$DryWeight = GreenWeight.(1 - MC) \tag{2.10}$$

2.4.1.10. Equation for Carbon Emission of Equipment

Carbon emission due to each operation is calculated from (2.11) (West and Marland 2002.)

$$C = (21.95)E \tag{2.11}$$

C is the carbon emission for diesel equipment (kg) and E is the energy input of the equipment in GJ. Energy consumption by the equipment can be calculated from equation (2.12) based on fuel consumption rate of the equipment (F) in and its machine working hours (MH) (ASAE 2001.)

$$E = (0.0364)(F)(MH) \tag{2.12}$$

Rate of fuel consumption for the equipment in lit./hr is calculated from equation (2.13), in which P represents the rated power of the equipment in horse power (ASAE 2001)

$$F = (0.2254)(P) \tag{2.13}$$

2.4.2. Logic of the Simulation Model

The simulation model simulates the flow of fuel-wood from cutblocks to the power plant through the logistics system over one year of operation. Figure 2.3 shows a flowchart of the model.

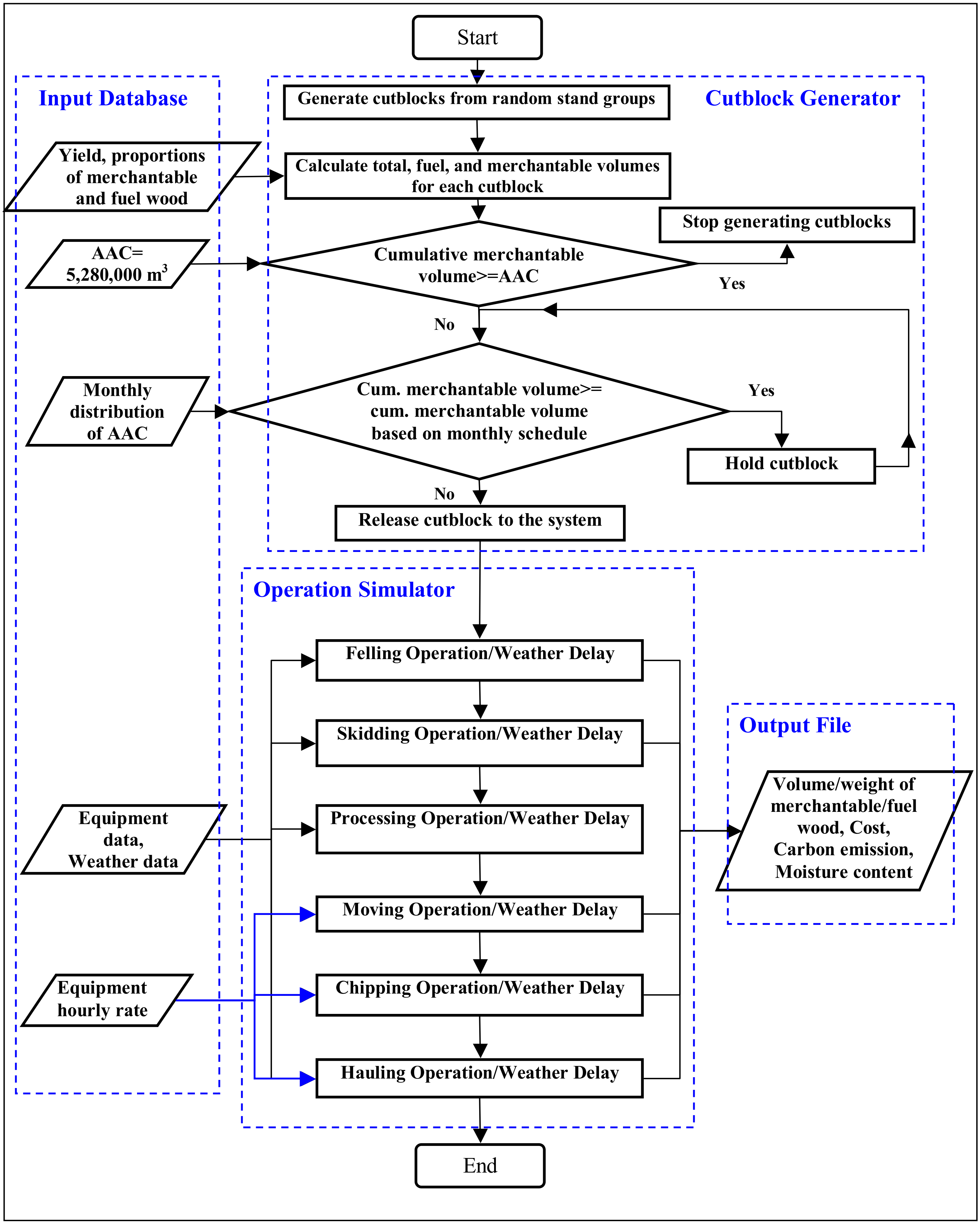

Figure 2.3. Flowchart of the Simulation Model

As shown in this flowchart, the model consists of four main parts: input database, cutblock generator, operation simulator, and the output file. Each of these parts will be explained in detail. The Cutblock generator and operation simulator constitute the main body of the model which is developed in EXTEND v.6 (Imaginethat Inc. 2006) and consists of a network of operational modules and connectors threading the modules into the complete logistics system. Input database and output file are in EXCEL format and are used for importing inputs and exporting outputs while the model is running.

2.4.2.1. Input Database

Input database is developed in Excel spreadsheets and contains all data explained in section 2.4.1. These data include yield, area, and percents of merchantable and fuel wood for each stand group as well as average hauling distances, the AAC, monthly distribution of the AAC, weather data, equipment data, and hourly rates of equipment.

2.4.2.2. Cutblock Generator

Initially, entities in the simulation model are considered as cutblock; however, as it will be explained later, each cutblock is split into smaller entities (chip-van payloads) at chipping/hauling phase. Each cutblock is selected randomly from all 184 groups of stands under the study. To simulate this process, a generator module generates entities continuously, then a random integer number from a uniform distribution between 1 and 184 (total number of stand groups) is allocated to each cutblock as attribute of stand group number. Since each of 184 stand groups is located in one of the 18 land units, an attribute of land unit number (a number between 1 and 18) will be allocated to each cutblock as well. Using attributes of stand group number and land unit number, each cutblock can be identified through the whole model. Each cutblock has an area between 20 and 40 ha; therefore, a random real number from a uniform distribution between 20 and 40 is allocated as attribute of area to each entity. A module controls the cumulative area of cutblocks selected from each stand group and stops picking cutblocks from each stand group for which the cumulative area meets the total area of the stand group. According to yield and percents of merchantable/fuel wood for stand group the cutblock is selected from, the model calculates attributes of total, merchantable and fuel wood volume for each cutblock. Since volume of merchantable wood produced in one year cannot exceed the AAC for the Quesnel TSA, a module continuously controls the flow of cutblocks sent through the model and stops generating cutblock when cumulative volume of merchantable wood collected from cutblocks meets or exceeds the AAC. Also, a similar module controls the cumulative volume of merchantable wood for each month according to current date of operation (based on calendar of the simulation software) and monthly distribution of the AAC (presented in Table 2.3). In fact, this module lets cutblocks go through the system unless the cumulative volume of merchantable wood meets or exceeds the cumulative volume of the month according to the monthly distribution of the AAC.

2.4.2.3. Operation Simulator

After being released from the cutblock generator, entities go through each of felling, skidding, processing, moving, chipping, and hauling operations. The general logic used in simulating all these operations is the same. Before starting each operation, the related equipment is allocated to each entity (cutblock or chip-van payloads) from a resource pool considered for the operation (each operation has its own resource pool). Data on number of equipment allocated to each entity is obtained from equipment data in the input database. In case of this study, it is assumed that number of equipment in each resource pool is unlimited (a very large number in practice); therefore, number of cutblocks which are simultaneously under operation is not limited by number of available resources. In fact, number of cutblocks which are under operation at the same time only depends on the flow of cutblocks released from the cutblock generator which is a function of monthly distribution of the AAC.

For each entity, each phase of operation is simulated through applying the related operation time which consists of both productive machine time and possible delay due to bad weather conditions. Due to lack of data, no repair or breakage downtime is considered for equipment; however, the model has the potential of applying equipment downtimes as random distributions or as a function of machine working hours. At each phase of operation, productive machine times and weather delays are calculated and allocated as attributes to entities. Productive machine time for each entity is calculated based on production rate of the related equipment (cubic meter or dry tonne per hour); number of equipment allocated to the entity and volume/weight of merchantable/fuel wood in the entity. Productive machine times are applied through a module that has the feature of holding multiple entities (entities under the same operation at the same time) and releasing each of them based on the machine time it needs to be processed. Weather delay for each entity under each operation is calculated based on total rainfall and total number of days with temperature less than -40°C in the period of days it has been under that operation. Rainfall and temperature for each day of operation are obtained from the weather data in the input database. As mentioned before, it is assumed that each operation will be delayed for 1 hour per each millimeter of rain and will be shutdown on any day that temperature goes under -40°C. Similar to productive machine times, weather delay is applied through a module that holds entities simultaneously and releases them based on their weather delay attributes. For each operation, once both machine time and weather delay are applied, equipment are released and returned to the resource pool and the entity goes through the next phase of operation.

In addition to the machine times and weather delay applied for each operation, the whole operation is stopped at non-working times/days through a clock/calendar module that stops the whole system at those times and shift the time to the beginning of the next working day.

At the end of each operation, variables including start and finish times, operation time, volumes/weights of merchantable and/or fuel wood processed, moisture content, equipment carbon emission and cost (only for moving, chipping and hauling) are calculated for each entity. Moisture content for each entity is calculated based on relative humidity and temperature on the day the operation has finished which is obtained from weather data and equation (2.1) presented in section 2.4.1.9. For each entity, cost of the operation is calculated by multiplying the sum of productive machine time and weather delay by hourly rate of the related equipment obtained from cost data and number of equipment allocated to the entity. Equipment carbon emission for each entity is calculated from equation (2.11) presented in section 2.4.1.10 based on productive machine time, the rated power of the related equipment and number of equipment allocated to the entity.

For each and the whole operation, the model also calculates total operation times, total volume/weight of merchantable/fuel wood processed, total cost and total carbon emission for all the entities processed through the system. As mentioned before, in this model, cost and carbon emissions are only estimated for moving, chipping and hauling operations. This means that only moving, chipping and hauling costs contribute to total cost and total Carbon emission of operation. After calculating total values for cost and carbon emission, average cost (C$/dt) and average carbon emission (Kg C/dt) are calculated for each and the whole operation. The model also presents graphs for variations of dry weight and moisture content of fuel wood delivered to the plant over one year of operation.

Although a similar approach is used in simulating all phases of operation, some operations are simulated differently in terms of calculating machine times, type of entities, and resource allocation method. These differences are explained here:

- For each cutblock, production rates for felling, skidding, and processing operations are calculated based on volume of merchantable wood, but production rate for moving operation is calculated based on volume of fuel wood (roadside residuals) because moving operation is carried out only for roadside residuals left after processing.
- As mentioned before, entities generated by the generator are considered as cutblocks. Theses cutblocks will move through felling, skidding, processing, and moving operations. After moving operation, each cutblock is split to smaller entities which are loadable to a semi-trailer chip-van. For each cutblock, number of new entities (chip-van payloads) is calculated by dividing dry weight of fuel wood (roadside residuals) by average payload of a chip-van. Dry weight of fuel wood is calculated based its volume, density, and moisture content from equation (2.10) presented in section 2.4.1.9. Each new entity has a new attribute of dry weight which is almost equal to chip-van’s payload and will be used for calculating productive machine time of the chipper.

- The method of resource allocation in chipping and hauling operations is different from that in other operations. Since chipping and loading of wood chips are carried out at the same time, both chipper and chip-van should be allocated before starting chipping. The important point in simulating this operation is that while the chipper is allocated to each cutblock (and will be released when the chipping operation is finished for the whole cutblock), the chip-van should be allocated to each payload of fuel wood. To simulate this structure, a chipper is allocated to each cutblock and then, the entity is split to smaller entities (with fuel wood amount equal to payload) each of which receives a chip-van. After chipping/loading of each payload, the chip-van is sent to the power plant, unloads the wood chips, and returns to the resource pool. No unloading time is considered for the chip-van because semi-trailer chip-vans are usually equipped with automatic hydraulic unloading system which makes the unloading process very quick. As mentioned above, once chipping for the whole cutblock is finished, the chipper will be released and sent to its resource pool.
- For each of felling, skidding, processing, moving, and chipping operations, production rates are selected from a random uniform distribution with minimum and maximum values for the related equipment as shown in Table 2.4 in page 57. Machine times for each entity under each of these operations is calculated based on volume/weight of merchantable/fuel wood available in the entity and the random production rate selected from the related uniform distribution. For hauling operation, hauling times are calculated based on average speeds of a semi-trailer chip-van on highway, main and branch roads and average hauling distances for the land unit the cutblock is located as shown in Table 2.2 in page 56. For each payload, total

transportation time which will be used for calculating transportation cost consists of loading time (which is equal to chipping time), hauling time and, and weather delay.

2.4.2.4. Output File

Once the model is run for one year, all calculated variables are exported to a file in Excel format. The model was run for 20 times and outputs for each run were exported to the output file. After finishing all runs, averages were calculated over 20 sets of outputs for all variables of interest. These averages are used as the results of the model which are explained and analyzed in next section.

2.5. Analysis and Results

The simulation model was run 20 times for one year. Table 2.6 represents averages of the results obtained from 20 runs for total harvest area, number of cutblocks, total dry weight of wood chips, average delivered cost and average Carbon emission due to operations.

Table 2.6. Averages of Variables of Interest for 20 Runs of Simulation

Variable of Interest	Harvest Area (ha)	Number of Cutblocks	Total Weight of Wood Chips (dt)	Average Cost (C$/dt)	Average Carbon Emission (kg C/dt)
Average	29,870	1,195	365,160	44.8	12.7

Model estimations for the total harvesting area showed that to meet the annual AAC in the Quesnel TSA, 30,000 ha which is equivalent to 1,200 cutblocks should be harvested. Although this area can provide enough merchantable volume to meet the AAC (5,280,000 m^3), it will not provide enough fuel-wood to meet the annual demand of the power plant. The total quantity of wood chips supplied over one year is estimated around 365,000 (dt) which is less than 30% of the annual demand of the power plant (1,350,000 dt).

Several scenarios might be the possible options to supply the required feedstock shortfall. One option is to supply shortfall from TSAs other than the Quesnel TSA. Another scenario is to use other harvesting methods (satellite and full-tree chipping systems). Co-firing of wood chips with natural gas or other types of biomass such as wood pellets is another option that might be considered. In this case, the choice for combustion system of the power plant should be reevaluated. However, to evaluate the feasibility of each of the mentioned or other scenarios, a complete study on availability, finished cost, time, and carbon emissions associated with the related scenario is required.

Figure 2.4 illustrates the simulated daily weight of wood chips delivered to the power plant. As shown in this graph, daily amount of wood chips delivered to the power plant in months of April and May is low compared to other months. This was predictable because according to the monthly distribution of AAC presented in Table 2.3, the logging operation is almost shut down in April and May, and consequently the volume of roadside residues available at the roadside is very low.

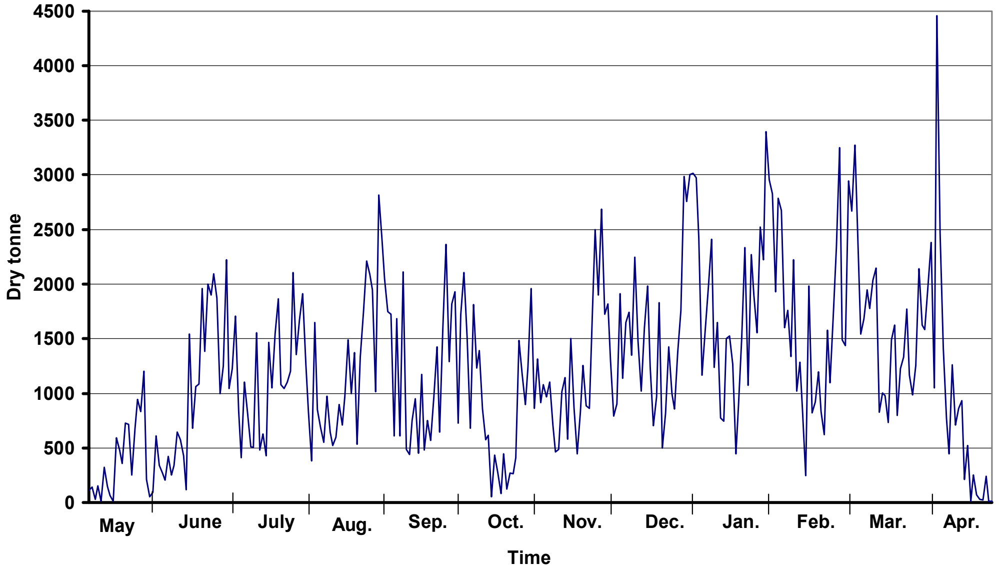

Figure 2.4. Daily Weight of Wood Chips Delivered to the Plant

Therefore, in case of supplying the feedstock from other sources which was discussed above as a possible scenario to meet the demand, April and May will be the months with the highest amount of outsource feedstock required. Figure 2.4 also shows that daily weight of supplied biomass has a large variance and may change between less than 500 to around 4,500 tonnes. Besides the logging schedule, another factor that may affect the operation is the weather condition.

The results obtained for time durations of operations show that for each cutblock, the logging operations (felling, skidding and processing) takes about 1 month, but operations related to supplying biomass (moving residues, chipping and transportation) only takes 1 or 2 days to be completed. This means that in conventional system most of the time required for supplying biomass from forest to the bioenergy facility is the time that takes logging contractors to fell the trees, skid them to the roadside, process them to logs and leave the residues at the roadside. A close coordination with logging contractors is necessary in order to allocate the equipment required for supplying biomass at the right time and prevent additional equipment costs due to unavailability of residues at the roadside.

Results obtained from the simulation model for finished cost of wood chips and Carbon emissions due to operation are presented in Table 2.7.

Table 2.7. Results of Simulation for Cost and Carbon Emission

	Moving	Chipping	Hauling	Total
Total Cost (C$)	1,088,698	6,096,829	7,969,867	15,155,394
Average Cost (C$/dt)	2	19	25	45
Total Carbon Emission (kg C)	175,147	1,618,036	2,881,535	4,664,718
Average Carbon Emission (kg C/dt)	1	4	8	13

It should be mentioned that both parameters (cost and Carbon emission) are calculated only for moving, chipping and transportation operation. Costs and Carbon emissions associated with logging operations are not included in calculations.

The results obtained for cost shows a sum of $15 million for the whole supply operation during one year. The average cost for one dry tonne of wood chips delivered to the power plant is C$45.00 which is slightly more than the finished cost estimated for moving, chipping and hauling of roadside residues estimated by MacDonald (2006) (C$42/dt). This is because MacDonald only considered the productive machine hours to calculate the costs, but the simulation model in this study also considers the weather delay as part of the time for which the equipment are charged. The results also reveal that moving, chipping and transportation contribute to almost 4%, 40%, and 56% of the supply cost, respectively. This means that while changing moving equipment would not remarkably affect the supply cost, changing the location of the power plant or trying to get most of the biomass from Land Units closer to the city of Quesnel will impact the delivered cost of biomass.

Carbon emission due to the whole operation over one year is estimated to be more than 4,500 tonnes. Similar to cost distribution, transportation contributes to a large portion of the total Carbon emissions (more than 60%).

The results for moisture content of wood chips over time are illustrated in Figure 2.5. As shown in this graph, moisture content varies between about 7% and 25%. This might be helpful in estimating the energy content of the fuel delivered to the power plant as well as type and size of storage or drying facilities. Also, the graph shows that while the maximum moisture content is related to supply in the months between November and February, wood chips supplied in months between April and June have the minimum moisture content

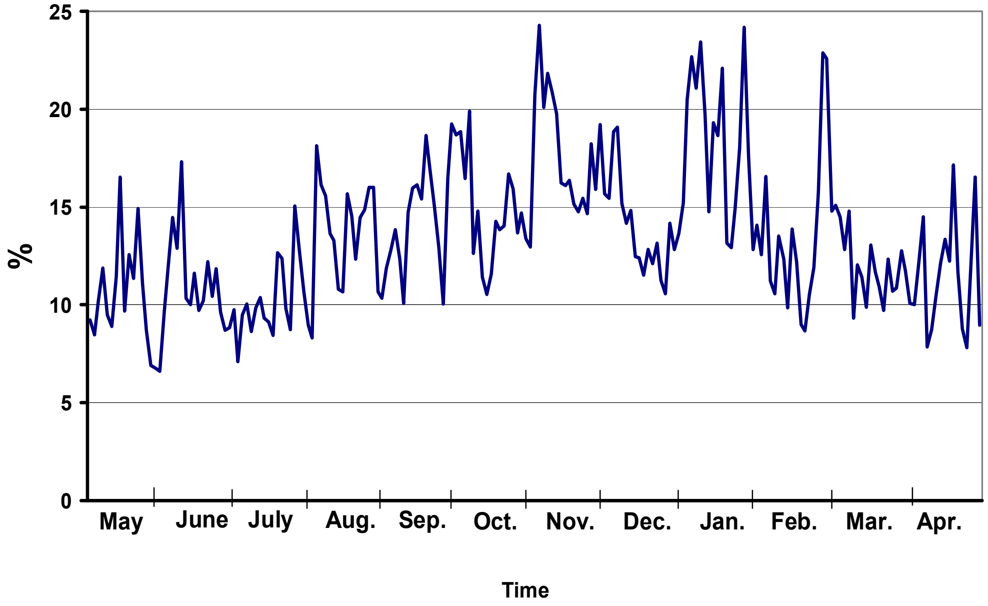

Figure 2.5. Moisture Content of Wood Chips Delivered to the Plant

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2.6. Conclusion

A simulation model of logistics system of supplying forest biomass was developed and applied to a case study of supplying the feedstock from roadside residuals in the Quesnel TSA to a potential 300MW power plant near the city of Quesnel. Estimations for amount of the feedstock available, its moisture content, total and average cost of operation and total and average equipment carbon emission were provided. The amount of feedstock available in this case was estimated about 365,000 dry tonnes of wood chips which only contributes to 27% of the annual feedstock demanded by such bioenergy facility. Therefore, supplying the feedstock from other sources (like other TSAs in Interior BC) and/or other harvesting systems such as full-tree chipping should be considered and studied. Another possible scenario is to shift to a smaller size of the power plant. Moisture content of the feedstock was estimated to vary between 7% and 25%. Finished cost of the feedstock supplied through the conventional system (C$45/dt) seems to be reasonable comparing to previous studies, although further studies are essential to estimate the finished cost of the power (C$/MWh) delivered to the network.

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Chapter 3

Sensitivity Analysis of Logistics of Forest Biomass Supply in British Columbia[2]

3.1. Background

The current epidemic of the Mountain Pine Beetle within the forests of Interior British Columbia is the largest recorded outbreak in North America and is estimated to kill 80% of the merchantable pine in central and southern Interior of the province by 2013 (MoFR 2006). One possible option to make value of the dead pine is to use it as the feedstock for a biomass-based power plant. In the previous chapter, a simulation model of logistics of forest biomass supply was developed and applied to a case on the supply of MPB-killed wood from the Quesnel TSA in Interior BC to a potential 300MW biomass-based power plant near the city of Quesnel. The power plant was estimated to consume 27M tonnes of wood chips over its 20-year operating life or an average of 1,350,000 tonnes per year (Kumar et al. 2005.) Type of forest biomass in this study was limited to the roadside residuals left after the conventional logging operations and, thus, the logistics system consisted of conventional logging operations (felling, skidding to the roadside and processing at the roadside) as well as moving, chipping and transporting of roadside residuals to the power plant. The simulation model was developed in EXTEND v.6 (Imaginethat Inc. 2006)

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[2] : A version of this chapter has been submitted for publication.
Mahmoudi, M., Sowlati, T., and Sokhansanj, S. “Sensitivity Analysis of Supply Logistics of Mountain Pine Beetle Killed Wood for Bioenergy in British Columbia.”

and quantity, supply time, cost, carbon emission and moisture content associated with delivered fuel wood were estimated. The simulation results showed that the amount of the supplied feedstock could only contribute to less than 30% of the power plant's annual demand. The results also showed a logistic cost of C$45/dt of biomass delivered to the plant. However, the results of the model were based on some uncertain inputs and inputs which might change in the future. These inputs mostly include weather conditions, seasonal distribution of the AAC, and the Allowable Annual Cut (AAC). This chapter presents a sensitivity analysis for the case study to assess the impacts of changes in the mentioned inputs on quantity, supply time, delivery cost, and moisture content of the feedstock.

Sensitivity analysis is a well-known systematic investigation of the reaction of the simulation response to changes in input variables (Kleijnen 1997). Several studies on biomass supply and logistics have used simulation modeling along with sensitivity analysis as their methodology. Hall et al. (2001) developed a simulation model to estimate and compare costs associated with logistics systems for delivering two types of forest residues (landing residues and cutover residues) to an energy plant in New Zealand. They also performed a sensitivity analysis to assess the impact of moisture content and bulk density on delivery cost of biomass. The results of the sensitivity analysis showed that delivery cost in both systems and for all sites was significantly sensitive to the initial moisture content and bulk density of residues. While increasing the initial moisture content increased the delivery cost of dry biomass, a higher bulk density had a reducing effect on the delivery cost.

A simulation model was developed by Sims and Venturi (2004) to estimate costs associated with supplying short rotation coppice crop in North Island of New Zealand. Also, a sensitivity analysis was conducted to assess the response of biomass delivered cost to changes in purchase price, direct harvesting costs, transport distance, and drying rate. The results of the analysis showed that using all-year-round harvesting system, the purchase price of biomass had a significant effect on the delivered cost, but drying rates were of little significance. In conventional harvesting system, changing direct harvesting costs significantly affected the delivered cost of biomass.

Sokhansanj et al (2006) used dynamic simulation modeling to study logistics systems associated with supplying agricultural biomass. A sensitivity analysis of collection operations showed that collection costs were sensitive to efficiency, performance of equipment, bulk density of biomass and yield. The results of the sensitivity analysis also showed that cost of biomass grinding increased with decreased particle size as throughput of the grinder decreases. Transport costs for a given distance and suite of equipment were sensitive to bulk density of biomass. In fact, cost of transport increased with an increase in particle size because bulk density was decreased as less mass was transported.

Mukunda et al. (2006) used discrete-event simulation and GIS tools to model the logistics system of supplying corn stover from on-farm storage to an existing ethanol plant in Indiana. To perform a sensitivity analysis, the model was run for different numbers of trailers and different capacities of unloading station. The results of the sensitivity analysis showed that reduction in the capacity of the unloading station significantly increased the trailers' requirement as well as average waiting time, but increasing the unloading station capacity did not yield significant reduction in number of trailers or average waiting times.

3.2. Sensitivity Analysis of the Case Study

As mentioned above, some inputs of the simulation model such as distribution of the AAC over the year, weather conditions, and level of the AAC either represent uncertain quantities or are subject to change over the life time of the power plant. To address the question about how the variability of these inputs may affect quantity, supply time, delivered cost, and moisture content of the feedstock, several sensitivity analyses are performed and the related results are discussed.

3.2.1. Sensitivity to the Seasonal Distribution of the AAC

Since the biomass in this case study is supplied from residues left after the logging operation, any change in the seasonal distribution of the AAC affects the biomass collection and transportation schedule and, therefore, may affect quantity, delivery cost, and moisture content of the feedstock. To assess the possible effects, the model is run for an alternative distribution of the AAC and the results are compared to those for the original distribution. The seasonal distribution of the AAC in the base case was shown in Table 2.3 in page 57. In Interior BC, winter is the peak operating season because ground-based equipment causes the least soil disturbance on snow or frozen ground. Operations are often shut down completely during spring breakup (when the frost is leaving the ground) and during fall freeze up (before the ground is frozen) (MacDonald 1999). Thus, in the alternative case, it is assumed that the logging operation is completely shut down in months of March, April, September, and October and the AAC is produced uniformly over the other 8 months. This alternative distribution of the AAC is shown in Table 3.1. The total weight obtained for the alternative case is almost the same as the original case (365,000 dt) but the average delivered cost of biomass decreased by almost 10% from C$45 to C$40. This is basically because most of the operation happens in months with least rain precipitation and less is paid for unproductive machine hours.

Table 3.1. Monthly Distribution of the AAC in the Quesnel TSA: Alternative Case

Month	Percent of AAC (%)	Cumulative Percent of AAC (%)	Monthly Volume (m3)	Cum. Volume (m3)
May	12.5	12.5	660,000	660,000
June	12.5	25	660,000	1,320,000
July	12.5	37.5	660,000	1,980,000
August	12.5	50	660,000	2,640,000
September	0	50	0	2,640,000
October	0	50	0	2,640,000
November	12.5	62.5	660,000	3,330,000
December	12.5	75	660,000	3,960,000
January	12.5	87.5	660,000	4,620,000
February	12.5	100	660,000	5,280,000
March	0	100	0	5,280,000
April	0	100	0	5,280,000

Figure 3.1 shows variations of daily weight of feedstock delivered to the plant under the original and alternative scenarios of logging schedule. Comparing graphs reveals that generally daily weight of biomass supplied in 8-month logging schedule is more than that in continuous logging. However, there will be no supply during September, October, March, and April when the operation is completely shut down.

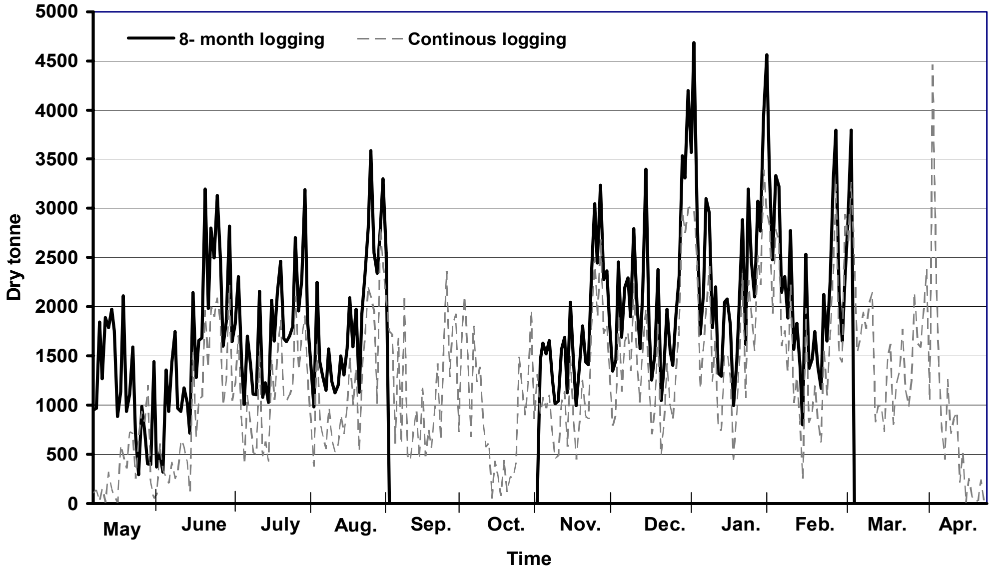

Figure 3.1. Daily Weight of Wood Chips for 8-month Logging Schedule

3.2.2. Sensitivity of Quantity and Unit Cost of Feedstock to the AAC

The results of the model for the original scenario showed that under the current AAC (5,280,000 m3) the quantity of the feedstock supplied was less than 30% of plant's annual demand. A sensitivity analysis was performed to investigate how the quantity and cost of the feedstock is sensitive to increase of the AAC. In alternative scenarios, the AAC was increased from its current level (5,280,000 cubic meters) by 10, 20, 30, and 40 percents. The results of the analysis are shown in Table 3.2.

Table 3.2. Sensitivity of Quantity and Unit Cost to the AAC

AAC	Quantity (dt)		Unit Cost (C$/dt)	
	Value	%	Value	%
5,280,000 m^3 (base case)	365,000	-	45	-
+ 10%	402,000	+10.1	44.2	-1.7
+ 20%	438,000	+19.8	44.6	-1
+ 30%	459,000	+25.5	45.2	0.4
+ 40%	461,000	27	45.3	0.6

The results show that increasing the AAC will increase the amount of feedstock delivered over one year. However, the feedstock supplied will not meet the demand even when the AAC is raised by 40%. Also, we can see that increasing the AAC more than 30% does not significantly increase quantity of the supplied feedstock. This is because in the conventional system only stands with fuel-wood proportions less than 50% are harvested, and therefore as the AAC increases the overall proportion of fuel-wood in the whole harvest area decreases. This means that even in the case of raising the AAC levels for the Quesnel TSA by Ministry of Forestry and Range, roadside residues will not supply enough feedstock to meet the annual demand of the power plant. The results of the analysis did not show a significant change in the unit cost of the feedstock when the AAC is raised. This is because the unit cost of biomass basically is a function of hourly rate and productivity of equipment and does not change with total volume of fuel wood processed.

3.2.3. Sensitivity of Quantity, Cost and Moisture Content to Weather Conditions

Weather conditions including rain, snow, temperature, and relative humidity affect not only speed of operation and consequently quantity and cost of the feedstock but also its moisture content. In the base case, the weather data was selected for the period from May 1, 2006 to April 30, 2007 for Williams Lake. Alternative cases for weather conditions were considered for the same area based on a colder (May 1996-April 1997) and a warmer (May 1998-April 1999) year than the base year. Average daily temperature, relative humidity, and rain precipitation for the base year and alternative years are presented in Table 3.3. Figures in the table show that although the warmer year has a higher average temperature than the base year, it is not dryer than the base year due to more rain and snow precipitations.

Table 3.3. Weather Data for Base, Warm and Cold Years

Year	Average Daily Temperature (°C)	Relative Humidity (%)	Rain (mm)
Base year (2006-2007)	4	65	241
Cold (1996-1997)	2.5	71	449
Warm (1997-1998)	6.2	68	273

Table 3.4 shows the results of the model for quantity and unit cost of feedstock under base case and each of the alternative cases. As shown in the table, the total amount of supplied feedstock is not sensitive to weather conditions, but unit cost of the feedstock is relatively sensitive to amount of rain precipitation. This is basically because the total amount of feedstock is already limited by the AAC. In fact, even in case of a colder year with more rainy, the amount of available roadside residues is that low that can be handled easily by the suggested allocation of equipment and during the good-weather days of year. However, since the unit cost of the feedstock depends on the scheduled machine hours (working hours plus weather delay hours), it is sensitive to rain and snow precipitations.

Table 3.4. Sensitivity of Quantity and Unit Cost to Weather Conditions

Year	Quantity (dt)		Unit Cost (C$/dt)	
	Value	%	Value	%
Base year (2006-2007)	365,000	-	45	-
Cold (1996-1997)	363,800	-0.4	48	+6.7
Warm (1997-1998)	364,700	-0.1	46	+2.2

Figures 3.2 and 3.3 in the next page illustrate changes of moisture content over one year for the colder and warmer years comparing to the base year. As graphs show, moisture content of the feedstock in most of the days of both colder and warmer years is relatively higher than moisture content of the feedstock in the base year, but it almost remains in the same range (7%-27%).

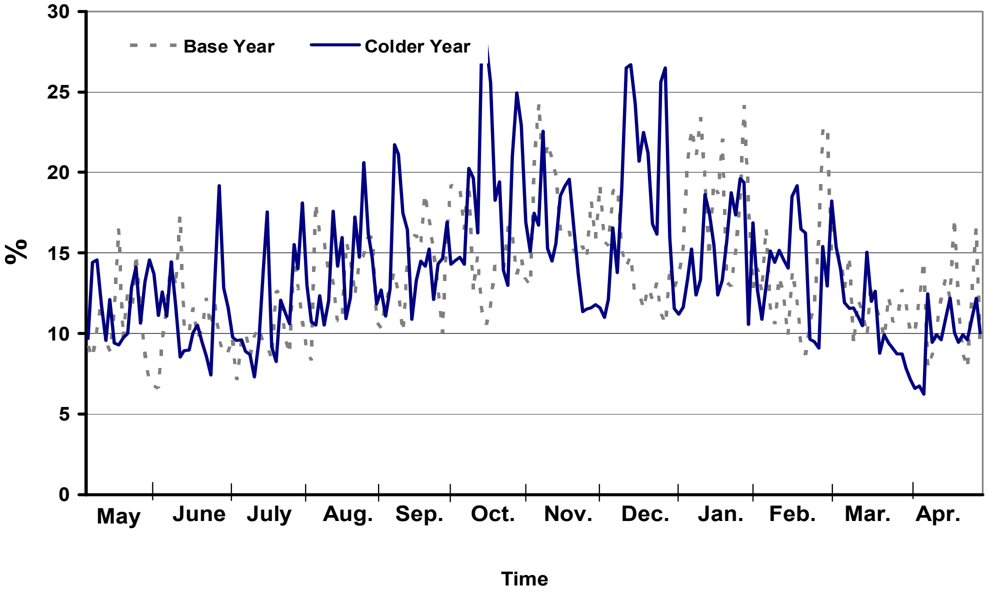

Figure 3.2. Moisture Content of Wood Chips in Cold Weather Conditions

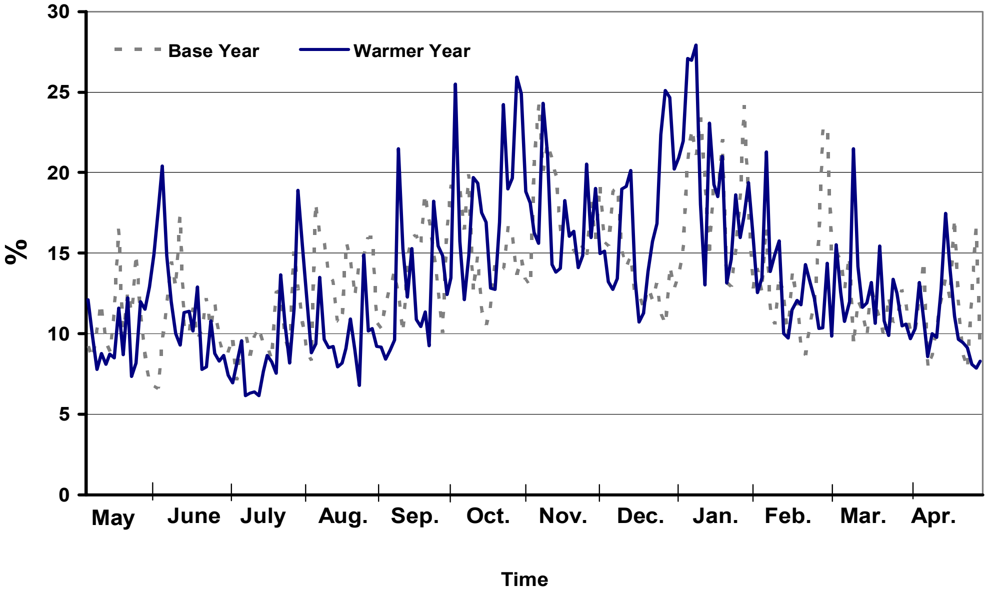

Figure 3.3. Moisture Content of Wood Chips in Warm Weather Conditions

3.3. Conclusion

Result of the sensitivity analysis showed that as long as the feedstock is limited to the roadside residuals in the Quesnel TSA, increasing the AAC levels even by 40% will not provide enough feedstock to meet the annual demand of the power plant. However, raising the AAC levels will relatively increase the annual amount of supplied feedstock and will reduce the feedstock shortfall which should be supplied from other sources and/or other harvesting systems. Weather conditions also affect the quality of biomass in terms of moisture content. Dry weather conditions will decrease the moisture content and consequently reduce the storage/drying costs.

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Chapter 4

Conclusions, Limitations, and Future Works

4.1. Conclusions

The abundance of forest biomass resources has provided British Columbia with a unique opportunity to take the lead in bioenergy industry. The feasibility of bioenergy projects highly depends on factors such as availability, supply time, delivery cost, and moisture content associated with the feedstock. To provide estimates of the mentioned factors, the logistic system used for supplying forest biomass should be investigated carefully. This thesis presents a study on logistics of forest biomass supply through simulation modeling. Using EXTEND v.6 simulation program (Imaginethat Inc. 2006), a simulation model was developed and applied to the case study on supplying forest biomass from Quesnel TSA to a potential 300MW power plant near to the city of Quesnel. Type of forest biomass considered in this study was limited to logging residues left at the roadside after conventional logging operations. The logistic system considered in the simulation model included felling, skidding, and processing of whole trees as well as moving, chipping, and hauling roadside residuals. Results of the model included quantity (dry weight), delivery cost, supply time, moisture content and carbon emission associated with the supplied feedstock. The quantity of feedstock supplied through conventional harvesting over one year was estimated around 365,000 dry tonnes which was less than 30% of the annual demand of the plant. The delivered cost of biomass was estimated about C$45 per dry tonne of wood chips. Also, a sensitivity analysis for the case study was performed to assess the impacts of changes in the seasonal distribution of the AAC, level of the AAC, and weather conditions on quantity, delivery cost, and moisture content of the feedstock. The sensitivity analysis showed that as long as the biomass is supplied through roadside residuals from conventional harvesting, increasing the AAC even by 40% will not provide enough feedstock to meet the annual demand of the plant. The delivery cost of feedstock is sensitive to monthly distribution of the AAC and weather conditions. Weather conditions also affect the quality of biomass in terms of moisture content. Dry weather conditions will reduce the moisture content of the feedstock and consequently decrease the storage/drying costs.

The model developed in this thesis can be applied to other cases of forest biomass supply logistics such as other supply areas or other harvesting scenarios. It has the potential of considering the supply logistics as an integrated and interacting system which enables the user to study the random behavior of the system over time and under different scenarios. Also, the model has the ability of calculating all important logistic parameters in one single run which helps the user in saving time.

4.2. Limitations

The focus of this thesis was on developing a simulation model of logistic system of forest biomass supply. Although the model has the potential of considering different features of simulation modeling, its application was limited to data available for the case study. Also, application of the model was limited to one harvesting system (conventional harvesting using ground-based equipment). It was also assumed that the number of resources were unlimited.

In other words, none of the cutblock had to wait for releasing the equipment from other cutblocks. Data on area and volumes of merchantable and fuel wood for stand groups in the Quesnel TSA were obtained from a dataset provided by FERIC (MacDonald 2006) based on a shelf life model of MPB infested wood. However, the method used in calculating area and the mentioned volumes for stand groups in the Quesnel TSA is not stated in MacDonald (2006). Thus, the validity of the results obtained for the quantity of biomass from the simulation model developed highly depends on the accuracy of the mentioned data. Since volumes of merchantable and fuel wood available in Quesnel TSA change each year based on the shelf life model, the simulation was run only for one year (volumes used in the model were based on current situation).

The model did not consider some features of simulation modeling such as generating queues or randomness for operation times, travel times, and hauling distances. Also, no breakage or maintenance was assumed for equipment.

4.3. Future Works

Providing data on road networks and real locations of harvesting areas in the Quesnel TSA and data on production volumes/weights, productive times, idle times, and breakage time for real equipment working in the Quesnel TSA, the model can be modified and applied again to the case study to provide more accurate estimates of variables of interest. Also, using data on area and volumes of merchantable and fuel wood for stand groups in the Quesnel TSA from the shelf life model suggested by FERIC (MacDonald 2006), the model should be modified to be run for 20 years to estimate quantity and cost of the feedstock over the operating life of the power plant. Also, supplying biomass from other sources (like other

TSAs in Interior BC) and/or other harvesting systems such as whole-tree chipping or satellite yard can be studied as possible solutions to the availability problem. Also, a study on optimum size of the power plant based on the amount of biomass available in this TSA will be relevant. The simulation model developed in this thesis can be modified accordingly and used in either of these potential studies.

4.4. References

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