AN ABSTRACT OF THE DISSERTATION OF

René Arturo Zamora Cristales for the degree of Doctor of Philosophy in Forest Engineering presented on May 23, 2013.
Title: Economic Optimization of Forest Biomass Processing and Transport

Abstract approved:

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An economic analysis and optimization of forest biomass processing and transportation at the operational level is presented. Renewable sources of energy have captured the interest of public and private institutions to develop cost-effective supply chains to reduce dependence on fossil fuels. The production of energy from forest harvest residues constitutes an opportunity to develop a supply chain for producing heat, electricity and liquid fuels from renewable materials. Special interest has been directed to the production of aviation fuel given the characteristics of the commercial aircraft technology that cannot use other renewable sources such as electricity, nuclear power or wind turbines.

In economic terms, the production of energy from forest harvest residues at actual market prices requires efficient cost management and planning in order to compete with traditional fossil fuel supply chains. Efficient cost management requires an understanding of the operational stages in order to propose alternatives to improve

the planning process, reduce costs, and increase the chance of success of this emerging supply chain.

The main goal of this study is to improve cost-efficiency of an emerging energy supply chain from forest harvest residues. A general objective is the economic optimization of forest biomass processing and transportation at the operational level. We developed a model and frame-work to analyze the economics of forest biomass processing and transportation using mixed integer programming (MIP), simulation, Geographic Information Systems (GIS) and forest operation analysis. We developed an economic costing model that accounts for the cost of machinery and truck waiting time. The study is primarily focused on difficult access steep-land regions although it can also be applied to areas with less restricted road access.

A stochastic discrete-event simulation model was developed to estimate cost management strategies to improve economics of mobile chipping operations and analyze the effect of uncertainty in this type of operation. The model was successful in predicting productivity of actual forest biomass recovery operations. The model also allowed analyzing the economic effect of truck-machine interactions when using mobile equipment to process the forest residues

With stationary processing equipment, the economic effect of truck-machine interactions on closely coupled operations was analyzed through a simulation model. It was demonstrated that truck-machine interactions affect machine utilization rates and, thus, the economics of the operation. Truck-machine interaction must be accounted for when analyzing forest recovery operations to avoid inaccurate cost estimation.

Finally a mathematical solution procedure based on mixed integer programming, GIS and simulation was developed to support planning decisions in forest biomass recovery operations, including economic modeling of the effect of waiting times. The solution procedure was incorporated in the decision support system, Residue Evaluation and Network Optimization (RENO) developed in JAVA platform. The decision support system was demonstrated to be an accurate and effective tool to estimate the most cost effective processing machinery and transport configuration given road access, material physical properties, spatial location of the residue piles and accounting for truck-machine interactions. Additionally, an Ant Colony heuristic is included in the model to bring support to the MIP branch and bound solution method by providing an initial solution for objective function. The model is also flexible to user changes to allow the analyst to analyze the sensitivity of the results to main production variables.

Economic Optimization of Forest Biomass Processing and Transport

by

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I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request

René Arturo Zamora Cristales, Author

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CONTRIBUTION OF AUTHORS

Dr. John Sessions was involved in the design and writing of all the chapters cited in this document. Dr. Glen Murphy was involving in the costing analysis and modeling in Chapters 2 and 3. Dr. Kevin Boston made significant contributions in problem formulation and analysis on Chapters 2, 3 and 4. James Graham contributed in the design and development of the computer program that made possible the analysis and modeling in Chapter 4.

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

DEDICATION

This dissertation is dedicated to my parents,
Rene and Madelin, my wife Ingrid and my son Rene

ECONOMIC OPTIMIZATION OF FOREST BIOMASS PROCESSING AND TRANSPORT

CHAPTER 1 – GENERAL INTRODUCTION

The increase and volatility of fossil fuel prices in the last decade and the political instability of some exporting countries have raised the interest in renewable sources of energy to reduce dependence and increase energy security in the United States (CBO, 2012).

Forest residues are a renewable source of energy that can be used for electricity generation and liquid fuels production. Forest residues are left in the field following forest harvesting operations. They are a heterogeneous material composed of branches, tops, log-butts and pieces not meeting the utilization standards of actual markets (Reineke, 1965). In order to be used for energy purposes forest residues need to be processed using chippers or grinders to reduce the particle size and produce a more homogeneous material that can be transported more efficiently to a co-generation plant for electricity production or a bioenergy facility for chemical conversion and liquid fuels production (Hakkila, 1989). Material can be processed in-field, or at a centralized location. If material is processed in the field, machinery and trucks have to be able to reach the residue pile through the forest road network. Road accessibility becomes a restrictive factor in steep-terrain regions where road characteristics may increase truck-machine interactions reducing productivity and increasing cost. If material is processed in a centralized location then unprocessed residues need to be transported using small highly maneuverable bin or hook-lift trucks, however, low bulk density of residues has the potential to increase transportation cost and affect the overall profitability of the operation (Jackson et al., 2010) . Different systems are available for processing and transport of forest residues. Among all the feasible options, the forest manager or landowner has to decide which system is most cost-effective given road conditions, material physical properties, machine availability and operational performance. Cost effectiveness is the key in this emerging industry to guarantee its long term success. At the operational level the identification of factors affecting productivity and the development of a optimization model can help to improve economics of this industry.

1.1 Forest biomass energy markets

In recent years there has been an increase in the demand for woody biomass for energy purposes. This increase is partially derived from government policies that are focused on the reduction of energy dependence from foreign sources. Forest residues constitute a potential energy source that provides different advantages. Historically, forest residues have been considered a waste material with no value. Currently, forest residues are usually burned in order to clean the areas for replanting, reduce rodent habitat, and reduce fuel hazard.

One of the advantages of the use of forest residues for energy purposes is that they do not compete with human-food supply chains and most of them qualify under the renewable fuel standard (Bracemort, 2012). Additionally forest residues do not have actual alternative uses.

Biomass from forest residues have been used in the production of electricity. Several co-generation plants have been established in the United States to increase power supply. In 2011 Seneca Sustainable Energy opened a 19.8 MW co-generation plant in Lane County, Oregon and started production of electricity from mill and forest residues. The plant consumes approximately 135,000 bone dry tons (BDT) of residues annually (Seneca, 2012). For liquid fuels production softwood forest residues have become the primary source of raw material to develop a supply chain for jet fuel production in the Pacific Northwest (NARA, 2011).

1.2 Forest residues characteristics

Forest residues consist of a mixture of limbs, tops and different tree parts that do not meet the utilization standards for pulpwood and sawtimber. Forest residues are usually piled after logging operations. The volume in each pile is dependent upon the harvesting method, species mixture, and wood markets. The size of the available material is highly variable and dependent especially in pulpwood markets (Figure 1.1). In general, residue piles consist of pieces with a diameter ranging from 5 to 10 cm and 1 to 4 m long. Log-butts are also commonly found in some piles.

Depending upon the time between harvesting and the forest biomass processing operations, different amounts of leaves (or needles) can be found within the pile. As the pile dries, needles and leaves tend to fall apart from the woody stem.

Figure 1.1 Forest residue piles in Elkton, Oregon USA.

Moisture content of forest residues is dependent upon the time between the end of the forest harvesting and the start of the forest biomass operations, the species mixture and climatic conditions of the site. From the economic perspective, as moisture content of the residues decreases it is expected that after comminution, the truck can haul more solid material decreasing transportation costs.

1.3 Forest biomass processing machinery

Different machines are available to reduce the size and homogenize the forest residues in order to facilitate handling and transportation. In general, two categories of machines can be identified: chippers and grinders. Two types of chippers are most commonly found in the market: Disc and drum. Disc chippers consist of a rotating disc containing several knives that perform the wood cutting. Drum chippers consist in a large drum where the knives are mounted (Van Loo and Koppejan, 2007).

Stationary chippers have been used for many years in the pulp industry, however the main difference with respect to the processing of residues is that for the pulp and paper industry chips are produced from clean pulp logs containing a low percentage of bark. Instead, forest residues are a heterogeneous material containing bark and dirt, and other contaminants that affect the life of the knives (Hubbard et al., 2007).

As knives become dull, productivity decreases and fuel consumption increases impacting the overall cost of the operation. Nati et al., (2010) analyzed the wood chips size distribution in relation to the blade wear and screen size. Authors found that after processing 215 tons of chips, productivity was reduced by 15% and fuel consumption increased 46%. These two factors were mainly influenced by the knife wear. Although this study was performed on clean logs, it clearly shows how the wear in the cutting tools can impact productivity.

Mobile chippers are usually mounted on a forwarder and have an attached bin in which processed chips are placed (Figure 1.2). Mobile chippers can move between residue piles, process the material, and dump the contents of the bin in set-out trailers or containers. The use of the mobile chipper has the advantage of partially decoupling the processing from the transportation since the truck does not need to be at the site at the moment the loading process is performed.

Disadvantages are that mobile chippers are specialized machines with high fixed cost. Also productivity is highly affected by the degree of contamination of the material in relation to soil particles, rocks and other contaminants that increase the wear in the cutting tool.

Figure 1.2 Mobile chipper processing forest residues near Elkton, Oregon , USA. Processing a road-side pile (left); unloading a bin of chips into a set-out trailer.

Grinders consist on a set of rotating hammers that reduce the particle size by shredding the material. Unlike the chippers that require cleaner material to avoid rapid wear of the knives, grinders are less sensitive to the cleanness of the material since the material is being broken instead of being cut. Two types of grinders are commonly used in forest biomass recovery operations: Horizontal and tub grinders. The main difference between these two types of machinery is the in-feed system. In tub grinders, residues are placed in a rotating tub. The material is feed into the cutting rotor by gravity. The size of the piece is the main factor that drives the in-feed speed. The circular tub has the ability to rotate in order to prevent plugging of the residue inside the tub. The large cross-section of the tub also allows the processing of wood chunks and larger pieces compared to other types of grinders. In terms of safety, during the processing process particles of different sizes can be expelled from the tub representing a risk for persons and machinery working around the comminution site.

Figure 1.3 Stationary grinders performing in-field processing operations. Horizontal grinder (left) processing residues near Springfield, Oregon USA. Tub Grinder (right) processing residues near Medford, Oregon, USA.

Horizontal grinders have a mechanism to feed the residues horizontally instead of the vertical loading used in the tub grinders. The material is fed into the grinder using a feed conveyor which is followed by a cutting rotor that takes the material into the grinding compartment (Peterson Pacific Corp, 2012). The horizontal in-feed system requires a proper loading process to keep productivity and prevent plugging of the machine. After the material is comminuted, it is loaded into trucks using a continuous conveyor. In some cases the material can be directly dumped in piles and then loaded in trucks using front-loaders.

Stationary machinery has to be transported to centralized landings where the processing is carried out. Although these machines are usually track mounted, the ability to move within a processing site is limited by the low maneuverability and reduced speeds (1 km/h). Stationary equipment is tightly coupled to the chip truck transportation Stationary grinders need to be accompanied by a loader to feed the machine with residues.

Both chippers and grinders have engines ranging from 300kW to 800kW. Grinders usually require larger engines in order to provide the necessary force to comminute the material. A great amount of fuel is consumed while processing and therefore high variable cost is also expected.

A bundler is an alternative system to the in-field processing. A mobile bundler can produce compacted bundles of slash that is wrapped with standard baling twine and transported to a processing facility. USDA, Forest Service productivity tests of a mobile bundler indicate that a bundler is a feasible alternative to in-woods processing if the alternative cost of handling and burning the piles is taking into account (Rummer et al. 2004). The benefit that can be obtained from the use of the bundler is that the chipping or grinding of forest residues can be performed at the bioenergy facility and electricity instead of diesel can be used to power the machinery reducing the cost of comminution.

1.4 Transportation options

Transport of forest residues can be divided into two categories: first stage and second stage transportation. The first stage transportation consists in the transport of unprocessed forest residues from original sources to centralized locations. This process can be performed with the use of bin trucks, hook-lift trucks or dump-trucks (Figure 1.4). These trucks are usually highly maneuverable and small with capacities ranging between 30 to 40 cubic meters. They provide accessibility to locations where road conditions do not allow the access to larger trucks. However the cost of using small trucks such as hook-lift trucks is highly affected by slow speeds and low bulk density of the unprocessed material (Han, 2010). Also they require an additional loader to load the hook-lift.

Figure 1.4 Hook-lift trucks in biomass recovery operations near Eugene, Oregon, USA. The trucks were transporting residues to a centralized landing where a stationary grinder was located.

Second stage transportation consists in the transport of processed residues (chips or grindings) from the forest or centralized landings to a bioenergy facility. Chip vans are commonly used in the United States to transport chips for the pulp and paper industry and therefore they represent the preferred transport option for the transport of processed forest residues (Figure 1.5). Chip vans consist of a tractor (truck) and a trailer. Tractors are usually 6x4 tri-axles with engines sizes ranging from 260-370 kW. Some tractors have an additional drop axle to increase hauling capacity.

Trailers are usually light, open on top (to facilitate the loading) and contain an extension in the center of the trailer known as a drop-center or possum belly to increase load capacity.

Figure 1.5 Chip vans hauling processed forest residues. A 6x4 truck hauling a 16.5 m long drop center trailer in Rockaway, Oregon, USA (left). A 6x4 truck hauling a 9.75 m drop center trailer in Elkton, Oregon, USA (right).

Although these trailer characteristics are beneficial in terms of increasing the payload, they also cause problems at the moment of transit along tight curves and steep roads. For example, the drop center extension in the trailer may increase the difficulty to cross vertical curves, and the light weight of the trailer on the driving axles may increase tire slip when driving unloaded on steep roads. Additionally off-tracking usually increases as length of the trailer increases (Sessions et al, 2010). Typical single chip trailers vary in length from 9.75 m to 16.5 m.

Different trailers can be coupled to one tractor to minimize the hauling cost (Figure 1.6). Double trailers are common in the transport of wood chips or grindings when the road conditions, in terms of geometry and grade, do not limit this type of configuration. The use of double trailers increase the total hauling capacity but individual trailers may not be at full capacity (depending on density and moisture content), due to road regulations in relation to the gross vehicle weight based on number and distance between axles. In Oregon, state regulations limit the maximum gross vehicle weight to 47,854 kg, with a special permit (ODOT, 2012).

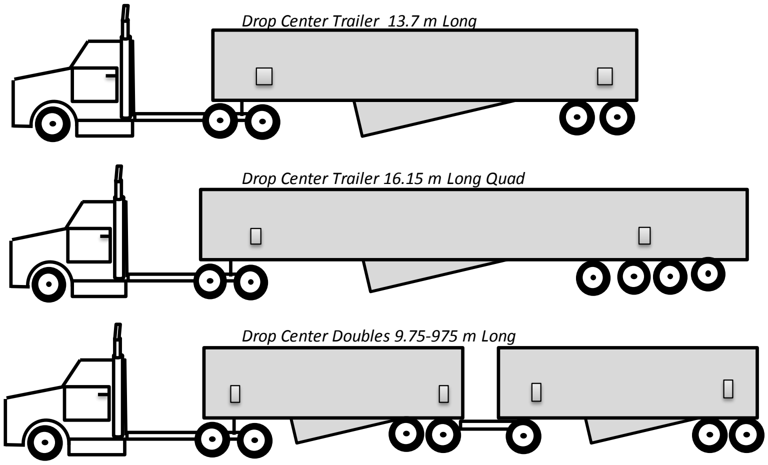

Figure 1.6 Tractor-trailer configurations commonly used in the United States.

Non-standard trailers options include a rear-steer axle trailers and stinger steer. A self-steering trailer contains two steering axles that allow the trailer to reduce off-tracking when driving around tight curves (Figure 1.7). It also increases the ability to turn-around in reduced spaces. The steering axles are controlled remotely by the driver. Western Trailers Company has developed a commercial rear steer model referred as a force steer chip trailer (Western Trailers, 2012). The available model is a 14.63 m long trailer. This type of trailer has been used in forest biomass recovery operations in Washington USA. A 6x6 is usually required to haul the trailer especially on steep roads.

Stinger steer trailers for forest biomass operations have been tested by the Forest Service Dan Dimas Technology and development center. This type of trailer is able to negotiate tight curves and difficult access roads (Haston and Fleming, 2006).

Figure 1.7 Rear-steer axle chip trailer operating in Port Angeles, Washington. This configuration is comprised of a tri-axle trailer (left) with two steering axles (right).

1.5 Forest biomass comminution and transportation systems

Different combinations of processing and transportation systems can be established depending on the road characteristics and spatial location of the residue piles. Residues can be processed at each pile, transported to centralized locations or processed at the bioenergy facility. Systems currently found in the Pacific Northwest are:

a) Stationary grinding processing each pile.

b) Stationary grinder at centralized landing supplied by hook-lift trucks with direct loading into trucks
c) Stationary grinder at centralized yard with direct dumping to piles and front loader reloading into trucks at processing site.
d) Mobile chipper with set-out trailers
e) Mobile bundler and processing at a bioenergy facility.

System a, (Figure 1.8) consists of the transportation of the stationary grinder to the processing site using a highway lowboy. Then the stationary grinder processes the material at the pile and after finishing, it moves to the adjacent piles. This system has the disadvantage that the movement is difficult and slow. Residue piles have to be close enough to each other to avoid significant decreases in productivity caused by the machine mobilization. Additionally, road characteristics often restrict the transit of the machine in the road network. Although the majority of machines are track mounted, some of them are wheeled, requiring an additional truck to move the machine between piles. This system is highly sensitive to the amount of volume in a pile. A large volume pile is preferred to maximize the grinding time and reduce the mobilization. The minimum equipment required is the stationary grinder and one loader.

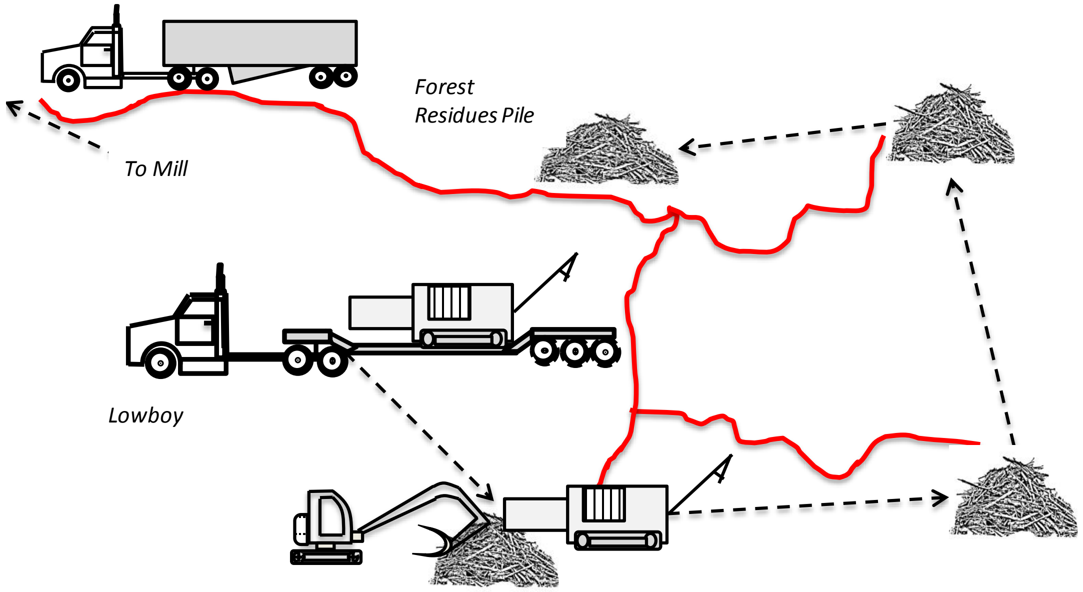

Figure 1.8 System (a), grinder processing at each pile.

In system b, (Figure 1.9) the grinder is placed at a centralized landing and hook-lift trucks supply the material from satellite sources with usually difficult access for chip vans. In this system grinder moving time is minimized. Disadvantages of this system are the additional cost of using the hook-lift trucks to transport the unprocessed material to the centralized location. Also the distance between the satellite and the centralized landing is the key factor to evaluate the potential use of short-trucks. In this system a minimum of two loaders, (one for the hook-lift trucks and one for the grinder) are required.

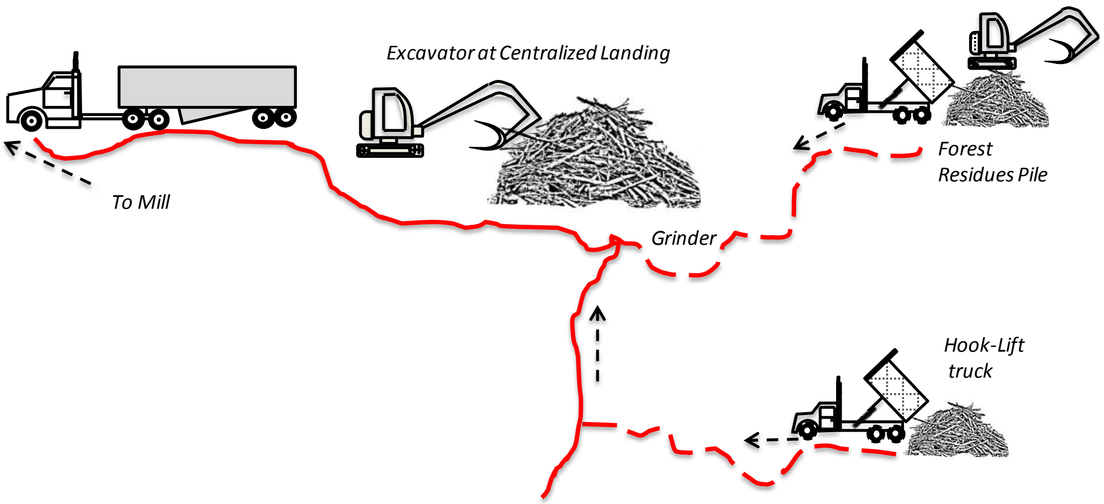

Figure 1.9 System (b), grinder processing at centralized landing with hook-lift trucks.

System c, (Figure 1.10) consists in the implementation of a centralized yard, typically outside the forest unit and with good access for high capacity trucks. Among the advantages of this system are that the grinder can be producing and dumping the material directly into piles to avoid truck dependence. Also the access to large truck can minimize transportation costs. Disadvantages are that the unprocessed residues need to be transported to the centralized yard increasing the overall cost of the operation by adding another stage in the collection process. Also the reloading process into large trucks requires the use of a front loader which represents another cost. In general the savings obtained by keeping the grinder producing and the use of large trucks must compensate for the additional cost of first stage transport and reloading.

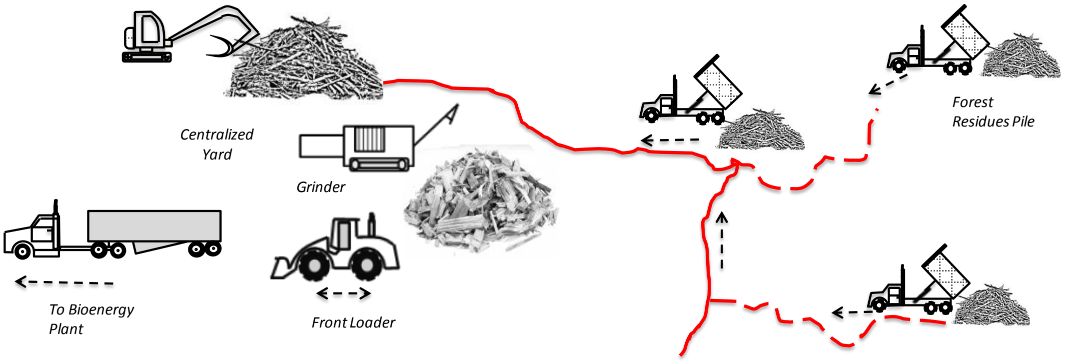

Figure 1.10 System (c), processing at centralized yard with a stationary grinder.

System d, (Figure 1.11) consists of a mobile drum chipper that moves between piles processing the material and filling an attached bin that when full is dumped into a set-out trailer or container. Reserve containers have to be utilized in order to keep the machine producing and to reduce truck dependence. The partially decoupled process reduces truck waiting time (when loading) but adds additional time to hook and unhook the set-out trailers. Disadvantages are the low productivity of the mobile chipper compared to stationary grinders and the sensitivity to the degree of contamination of the material. Also productivity decreases as distance between the pile and the trailers increases. The mobile chipper is also sensitive to metal pieces within the pile that can cause a significant damage to the drum and knives. Because it is a specialized machine, a skilled operator and a learning period are needed. If the amount of dirt within the pile is high, preprocessing of residues can be required to preselect cleaner material for the chipper, however this operation causes an additional cost.

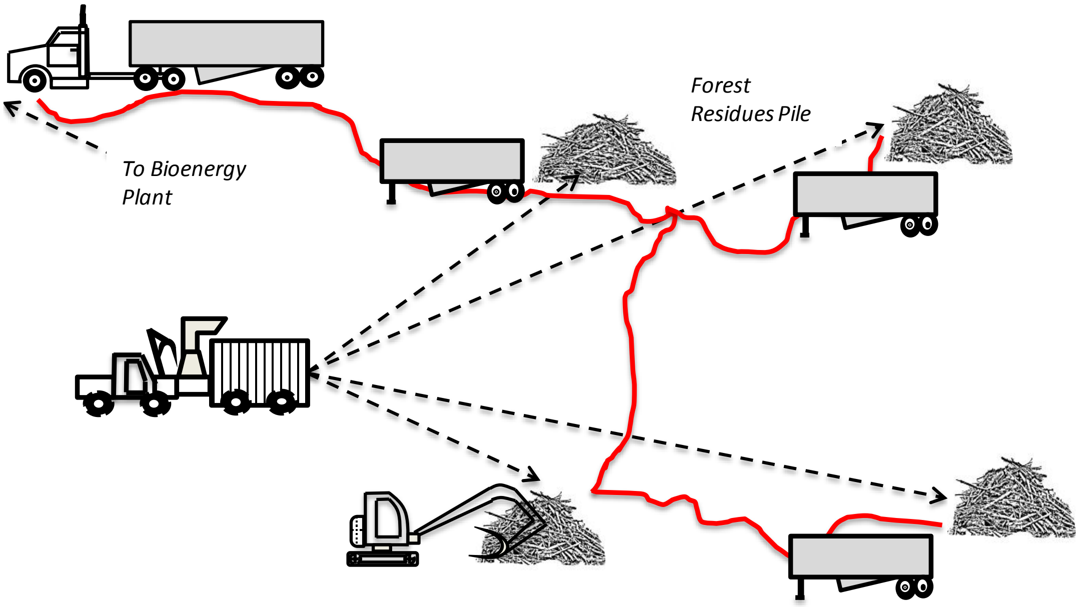

Figure 1.11 System (d) processing with mobile chipper and set-out trailers.

System e, consist of a mobile bundler. The machine produces the bundles from the residues that are then transported to a bioenergy facility where an electric grinder or chipper can be used to process the bundles. The advantages of this system are that the comminution is not carried out in the field therefore no comminution machinery mobilization is needed and the processing of the bundles using electricity can lower the cost in places where electricity is cheaper than fossil fuels. Also, bundles are more compact and can be stored in the forest to favor a decrease in moisture content and maximize the hauling capacity of solid material. Disadvantages are the additional cost incurred to make the bundles, and the cost of log truck modification necessary to transport the bundles. Also some residues may not be accessible to the trucks or the mobile bundler and may require the use of hook-lift trucks and the development of a centralized landing, increasing cost.

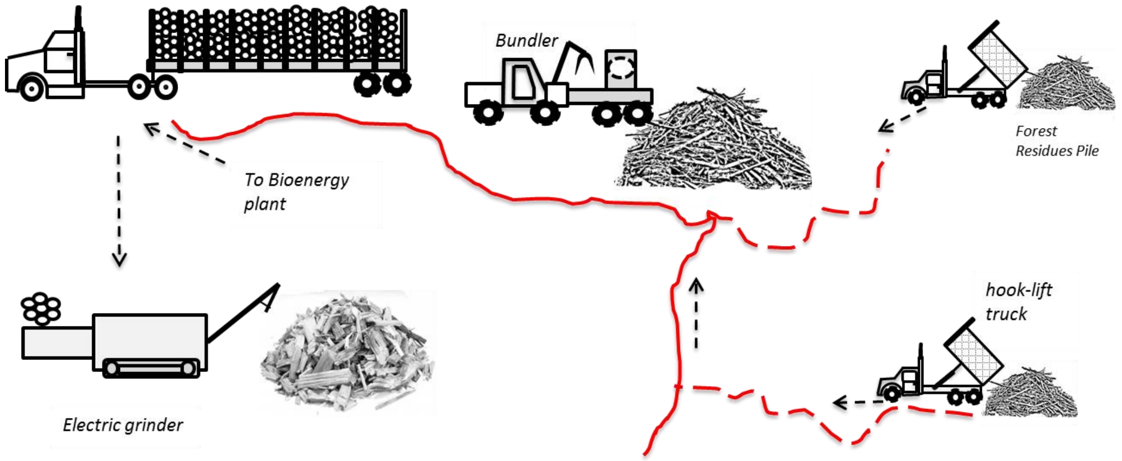

Figure 1.12 System (e), bundling at forest and processing at the bioenergy facility.

1.6 Economics of forest biomass processing and transportation

Miyata (1980) developed a procedure to estimate the fixed and operating costs in logging operations. According to this system, fixed cost is calculated based on the salvage value, depreciation, economic life, interest, insurance and taxes. Operating costs include labor, maintenance and repair, fuel and lubricants. Brinker et al., (2002) estimated machine rates for selected forest harvesting equipment. The authors also provide a procedure to estimate fixed and operative costs.

In terms of cost of biomass processing and transportation Harrill et al., (2009) estimated an hourly cost per scheduled machine hour (SMH) of $305/SMH for a Peterson Pacific 7400 grinder not including supporting equipment or loaders; an excavator cost of $113.94/SMH; and a hook-lift truck cost of $93.45/SMH. Costs were estimated using the standard fixed and operating costs methods of logging equipment reported in Miyata (1980). Average productivity of the grinder was estimated in 52.2 green tonnes (Gt) per productive machine hour (PMH). A total cost of the system including supporting equipment was $53 per bone dry metric tonne (BDMt) at 36% moisture content. Mitchell and Gallagher (2007) estimated productivity of chipping whole trees for fuel chips. They estimated an average chipper cost of $224.61/PMH for a Peterson 1858 chipper. The cost of a Prentice 210D loader was estimated as $162.82/PMH. Productivity of the stationary chipper was 60.4 Gt/PMH. Perez et al., (2012) estimated the hourly grinding cost in Washington State as ranging from, $300 to $400 /SMH. They also estimate a loader cost ranging from $125 to $150 per scheduled machine hour. Transportation cost ranged between $70 to $115 per SMH. Rawlings et al., (2004) estimated productivity of a 350kW horizontal grinder. Productivity averaged 32.5 Gt/PMH. Aman et al., (2010) reported average grinder productivity in processing forest residues of 70Gt/PMH. Ghaffariyan et al., (2012) reported and average productivity for a Bruks 805.2 of 43.88 green tonnes per PMH when processing residues. Anderson et al. (2012) estimate an hourly cost for a horizontal grinder Peterson 4710B tracked mounted of $240.53 per SMH assuming a utilization rate of 85% for in-field operations. The hourly cost of dump trucks was estimated as $62.46 per SMH assuming a utilization rate of 90%. Productivity was 34.5 green tons per PMH with average moisture content of 24%.

1.7 Mathematical programming optimization techniques

Mathematical programing involves the use of mathematical and computational algorithms for the solution of different problems (Dykstra, 1984) Different mathematical optimization techniques are available and applicable to forest operations. Linear programming is the most extensively used technique to solve planning problems. This technique involves the optimization of a linear objective function subject to several linear constraints. The objective function and constraint are directly related to the problem (e.g. maximization of net profit of a logging operation subject to volume and area constraints). The linear programming solution procedure is based on the effective solution method developed by Dantzig (1951) known as the simplex algorithm. The simplex algorithm starts at one extreme point and then it moves to neighboring extreme points in a hill climbing method until optimality is reached or the problem is found unbounded (Bazaraa et al., 2010).

Integer programming applies where decision variables must be an integer often 0/1. Although integer problems use a relaxed linear programing solution, they require a searching method to find the integer solution. The branch and bound method (Little et al., 1963) is a heuristic method capable of finding the optimal solution for integer-type problems by dividing the feasible region into pieces that together represent the original integer problem (Dykstra, 1984).

Simulation is another technique that allows representation of the dynamics of a system in order to solve a problem. The dynamic term indicates that the model is related to time variables (Kleijnen, 2008) Simulation can be deterministic or probabilistic. If simulation is probabilistic, then random variables are used to explain the degree and type of variability in a particular system. Simulation is particularly useful in forest operations because it allows the analyst to construct scenarios and analyze system performance when the main variables affecting the system are changed.

In the last few decades, several optimization algorithms have been developed to improve solution times especially when solution times of mathematical techniques are slow. These methods are commonly known as heuristic procedures that allow the calculation of an approximate solution for a problem. Among these methods Ant Colony Optimization (Dorigo et al., 1996) specializes in network type problems. The Ant Colony Optimization emulates the behavior and communication between ants when forming a colony. In a directed network with a source and destination, the algorithm starts by sending agents (ants) through different paths in a network. As the ants find the shortest (or least cost) paths they leave a pheromone that indicates to subsequent ants what is the best path to reach the destination (Figure 1.13)

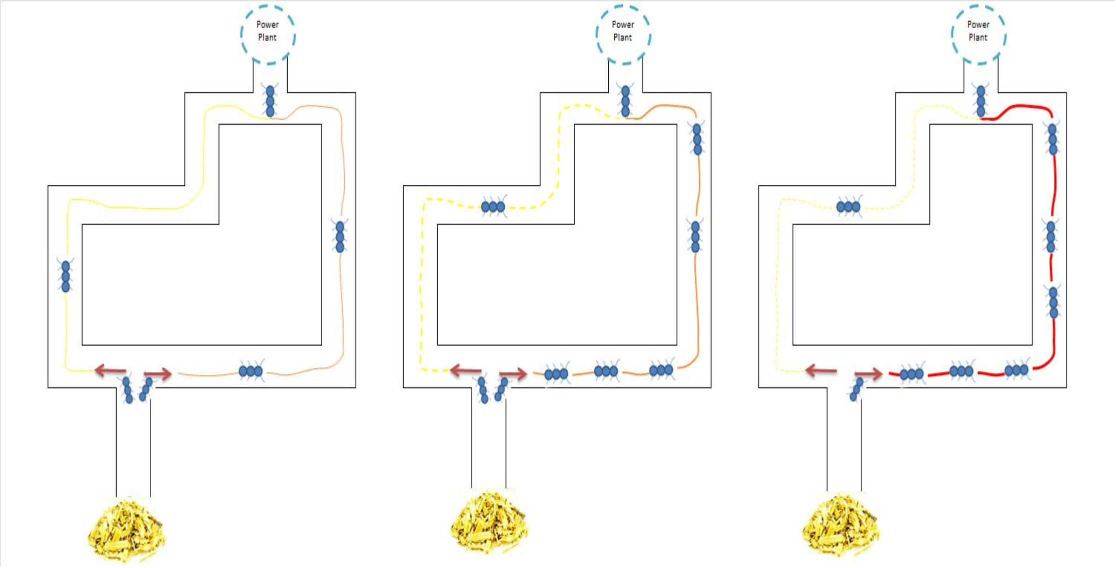

Figure 1.13 Ant Colony Optimization solution procedure.

1.8 Summary

The main goal of this research is to improve cost efficiency management in an emerging renewable energy supply chain from residues. A general objective is to achieve the economic optimization of forest biomass processing and transportation at the operational level by analyzing the most cost effective processing and transportation options given the residue pile location, available processing and transportation technologies and residue assortment. Specific objectives are (i) the development of a stochastic simulation model to analyze mobile chipping economics in processing and transportation of forest biomass from residues; (ii) to analyze and estimate the economic impact of truck-machine interaction in forest biomass recovery operations; (iii) to develop a costing methodology to improve cost estimation of forest biomass collection operation; (iv) to develop a mathematical programming solution procedure to economically optimize the processing and transportation of forest biomass at an operational level; and (v) to design and implement a computerized decision support system to help forest managers and landowners to improve efficiency in operations and to determine accurate cost estimates.

This thesis is composed of three manuscripts that analyze the economics and productivity of forest biomass processing and transport. The first paper (Chapter 2) addresses objective (i) and (iii). The cost methodology proposed in objective (iii) is analyzed for mobile chipping. This manuscript analyzes the economics of mobile chipping and develops a stochastic simulation model to analyze and optimize forest biomass recovery operations. The model proved to be accurate in simulating the economics and productivity of a mobile chipping operation on steep terrain. Additionally a new costing model is presented to account for operating and waiting costs.

The second paper (Chapter 3) addresses objectives (ii) and (iii) for stationary processing equipment. It discusses the economic effect of truck-machine interactions specially focused on stationary processing equipment. A deterministic model was developed to analyze operations, particularly in steep terrain operations. The model illustrates how road characteristics and pile location can affect machine utilization rates and economics when processing forest residues.

The last paper (Chapter 4) addresses objectives (iv) and (v) and makes use of the results obtained on previous manuscripts. This manuscript describes a solution procedure based on mixed-integer programming for the optimization of forest biomass recovery operations. The model was implemented in a computer program called RENO that combines the use of mathematical optimization, heuristic techniques, Geographic Information Systems (GIS), simulation and forest operation analysis.

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CHAPTER 2

STOCHASTIC SIMULATION AND OPTIMIZATION OF MOBILE CHIPPING ECONOMICS IN PROCESSING AND TRANSPORT OF FOREST BIOMASS FROM HARVEST RESIDUE

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2.1 Abstract

We analyzed the economics of mobile chipping and transport of biomass from forest residues for energy purposes under uncertainty. A discrete-event simulation model was developed and utilized to quantify the impacts of controllable and environmental variables on productivity in order to determine the most cost effective transportation options under steep terrain conditions. Truck-chipper interactions were analyzed to show their effect on truck and chipper standing time. A costing model was developed to account for operating and standing time cost (for the chipper and trucks). The model used information from time studies of each activity in the productive cycle and spatial-temporal information obtained from geographic information system (GIS) devices, and tracking analysis of machine and truck movements. The model was validated in field operations, and proved to be accurate in providing the expected productivity. A cost distribution was elaborated to support operational decisions of forest managers, landowners and risk-averse contractors. Different scenarios were developed to illustrate the economic effects due to changes in road characteristics such as in-highway transport distance, in-forest internal road distance and pile to trailer chipper traveling distances.

Keywords: Forest planning, simulation, decision analysis, economics, forest biomass, renewable energy.

2.2 Introduction

Forest residues, created as a byproduct of logging operations, are a renewable resource that can be used for electricity generation. These residues also have the potential to produce liquid fuels although conversion procedures are still experimental. In 2011, the Northwest Advanced Renewables Alliance (NARA), a group of US public universities, government laboratories and private industry was formed to build a sustainable supply chain for aviation fuel from forest and mill residues, municipal solid waste and energy forest crops (NARA 2011).

Forest residues consist of branches, tops, breakage, defect, and trees not meeting utilization specifications for timber and pulp (paper production). One of the most important distinctions of the use of forest residues for energy purposes, is that they are not currently used for other commercial purposes and do not compete with human food supply chains. Fuels derived from forest residues from non-federal lands and certain federal lands qualify as renewable energy sources under the current US Renewable Fuel Standard (Bracemort 2012).

After timber harvesting, most of the forest residues are piled and burned to clean the areas for replanting, and to reduce fuel loadings, and potential insect and rodent problems. It is estimated that a total of 127.4 million m3 of logging residues were produced in the United States in 2006 (Smith et al. 2009).

To economically handle and transport forest residues, biomass has to be mechanically reduced in particle size (comminution). This process reduces the heterogeneous composition of the material and facilitates the handling and delivery process (Hakkila 1989). Residues can be processed using chippers or grinders (Staudhammer et al. 2011). After comminution, processed residues are transported using chips-vans for long distance transportation.

The use of a mobile chipper for processing forest residues for energy purposes represents an alternative to the use of stationary grinding machines currently used in the US Pacific Northwest. The advantages of mobile chippers are the mobility to reach different locations within the forest where the forest residue piles remain following harvesting, flexibility to unload the material into different types of containers and a self-feeding system. Also the use of independent containers partially disconnects processing from trucking reducing truck dependence. However productivity is highly sensitive to the size, cleanness, and type of harvest residue material. And, the number of stages involved in the chipping process (chipping, moving, and dumping into trailers) gives more complexity to this process compared with stationary equipment. Consequently, uncertainties might arise at each stage of the process and can have a significant effect in the overall productivity. Uncertainty in this paper is analyzed in non-controllable factors that are usually environmental variables in which the decisions are not in control of the operator or planner (Taguchi 1987). Examples of these variables in mobile chipping include the size, shape and location of the forest residue piles, degree of heterogeneity of the material within the pile, machine driving speed between the piles due to terrain and maneuverability conditions and interactions between trucks and machine-truck.

Biomass from forest residues is a low value product in the forest supply chain. Processing in the field requires the use of expensive machinery with usually high fixed costs. Transportation costs are highly dependent on the travel time between the forest unit and the plant and the moisture content and bulk density of the processed residues. Given the reduced marginal income of this operation, efficient planning and cost management is needed to ensure the long term success of this emerging renewable source of energy. A careful analysis of each operational stage is necessary to understand the elements that affect productivity and consequent profitability of the operation. Due to the low margin of profit of this operation, sources of uncertainty need to be understood to produce an accurate estimation of the net profit variability and to support the decision process for forest managers, landowners and risk adverse contractors. At the operational level optimization is necessary to determine the most cost-effective transportation option given the chipper productivity, road and landing access and residue assortment.

In mobile chipping, equipment balancing can be an issue if there is not sufficient availability of trucks to replace the trailers in the forest. Truck-chipper interactions occur when the behavior of trucks (e.g. truck inter-arrival times) affect chipper productivity increasing standing times. If there are not available trailers to unload the chipper bin, then the chipper has to wait until a truck arrives and places an empty trailer on the landing. Similarly, if the trailer is not full with chips when a truck arrives to the site, then the truck has to wait until the trailer is full. Truck interference can also occur due to single lane passage and limited turn-around locations. Therefore, if a truck arrives to the site and a second truck is still in the chipping area, then the truck that is arriving must wait further down the road until the other truck passes the point where the first truck is waiting. Additionally the variability on productivity of the mobile chipper adds complexity to the problem. Adding more reserve trailers to reduce chipper dependence on the trucks is often not a feasible option due to the limited available space in forest roads under steep slope conditions to locate the trailers.

Most of the modeling studies in forest biomass recovery operations are based on deterministic approaches and only a few studies consider uncertainty. Also the analysis of truck-machine interaction requires the representation of the system dynamics that is only achievable through simulation. Baumgrass et al. (1993) discussed the use of simulation to estimate and validate harvest production. Although their paper did not specifically mention the use of simulation in forest biomass recovery operations, it described how simulation can be a useful method to analyze relationships and effect of different equipment in forest operations. In relation to forest biomass collection, Gallis (1995) simulated a forest biomass harvesting and transportation system in Greece using activity oriented stochastic simulation. 1Also no details were provided about the costing process that was used to evaluate the operations. Additionally no information about the robustness or validity of the probability density functions is reported and the simulation system did not account for standing times related to equipment balancing. Mobini et al. (2011) developed a discrete-event simulation model to evaluate the biomass delivery cost to a potential power plant. The authors discussed several processing and transportation systems at the tactical level but no details are giving about the effect of truck-machine interactions or road access on productivity. The variability of productivity was analyzed as an overall system not segregated into different operational stages. Little information is given about the productivity distributions used within the study and its applicability to other processing systems such as mobile chipping. Macdonagh (2002) developed two simulation systems to analyze forest harvesting operations. The author also discussed the impact of machine interactions on productivity of the system, however the study is not directly related to biomass recovery operations and no methodology is developed in relation to the standing cost. Talbot and Suadicani (2005) developed a deterministic simulation model to analyze in-field chipping and extraction systems in spruce thinnings. They discussed strategies for decoupling the chipping operation from bin forwarding to maximize chipper productivity. Although the cost of chipper bin forwarder interactions is accounted for in the study, few details are giving about the effect of truck configuration and road accessibility on chipping performance and truck-machine interactions

The main goal of this study is to improve the efficiency of the forest biomass supply by minimizing mobile chipping processing and transportation costs at the operational level under uncertainty. Processing and transportation costs include the mobile chipper and tractor–trailer variable and fixed cost, the mobilization cost to transport the machinery between different forest units and the overhead costs. Although this study has a general application in different terrain conditions, we concentrate our analysis in steep slope terrain due to the operational constraints in relation to forest road and landing access that have not been addressed in previous studies.

This paper is focused in the analysis of productivity and economics at the operational level of forest biomass processing and transport harvest residues with a mobile chipper having the central role in the operation. Our methodological approach is to develop a highly detailed discrete-event simulation model based on the operational activities in the productive cycle to understand and measure the effect of truck-machine interactions expressed as standing times for chipping and transport. A costing model is proposed to account for the standing cost for the mobile chipper and trucks. Also the model is intended to improve the understanding of the effect of road characteristics and accessibility on productivity and economics of forest biomass collection activities in steep terrain conditions.

We chose an activity-based analysis to reduce the overall variability of the system and predict only the variation that is related to environmental factors in each stage of the operation thus we modeled the planning decisions as different scenarios but not as sources of variability.

2.3 Materials and Methods

The model is based on chipping and transportation data collected in four different locations during August and September, 2011 in Oregon, USA, all under steep slope terrain conditions. Field conditions differed between harvest units in the type, quality and size of forest residues, species, distance between piles, road conditions, round-trip distance from the forest to the bioenergy facility, and truck-chipper interactions. We divided the modeling in three stages: (i) data collection-tracking analysis; (ii) distribution fitting and parameter estimation; and (iii) discrete-event stochastic simulation.

The model simulates the processing of a mobile drum (800mm diameter, 2 knives) Bruks Chipper 805.2 with a 331kW diesel engine (Bruks 2010), mounted on a Valmet Forwarder 890.3 (Figure 2.1). The chipper bin has a capacity of 21 m3. The trucking model simulates transport using single 9.75m and double trailers (FigureFigure 2.2) although it can be adjusted to other configurations.

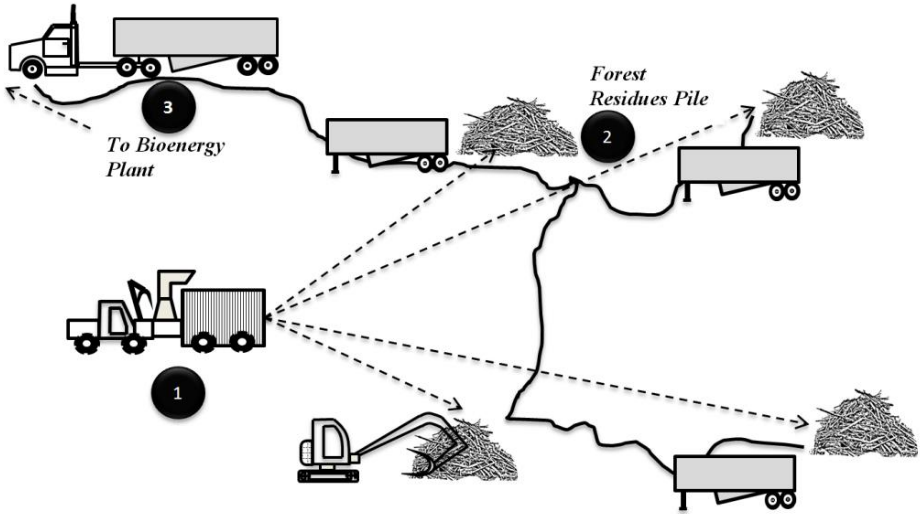

Figure 2.1 Comminution and transportation using a mobile chipper. The Mobile chipper processing forest residues at each pile and dump the chips into trailers

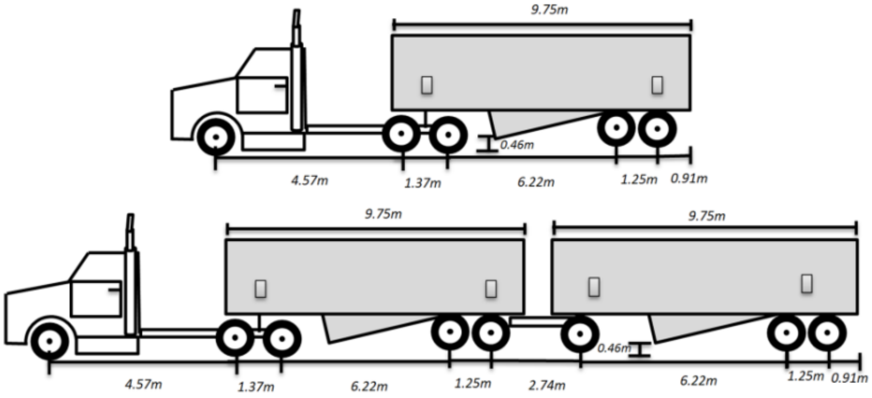

Figure 2.2 Two typical tractor-trailer configurations single and double trailers. a) 6x4 tri-axle truck and single trailer approximately 15 tonnes of capacity; b) 6x4 tri- axle truck and double trailer (9.75 and 9.75 m in length).

2.3.1 Data collection and tracking analysis

We used the continuous time study method (Pfeiffer 1967), to determine the time consumed chipping and transporting the residues. We combined manually timing, video recording and spatial-temporal tracking analysis of machine and truck movements to accurately collect the data. One hundred and twenty cycle times for chipping and twenty round-trips for transportation were recorded.

Four chipping elements were identified and timed to determine the total delay free cycle time: (i) chipping includes the conversion of forest residues into chips; (ii) traveling begins at the end of the chipping process when the chipper bin is full with chips and moving to the trailer to dump the load and ends before the dumping process is performed; (iii) dumping begins at the end of traveling and ends when the load has been dumped in the trailer; (iv) returning begins at the end of the dumping process and ends when the machine is back to the pile before the start of a new chipping process.

The amount of chips processed in each cycle was also recorded from the internal weight scale of the mobile chipper. In addition to the total cycle time, delay times were considered. Scheduled and un-scheduled downtimes for chipping were also recorded.

For the transportation systems the following variables were recorded: (i) unloaded travel time, is the time spent by the truck travelling between the plant and the forest when the truck is unloaded; (ii) loaded travel time, is the time spent by the truck traveling between the forest and the plant when the truck is loaded; (iii) dumping time spent by the truck while is being unloaded at the plant; (iv) truck turning around; and (v) hook and unhook time in the forest is the time spent by the truck while the empty trailer (or trailers when running double trailers) is unhooked and the loaded trailer is hooked in the forest. Non-scheduled downtime in transportation was considered although none occurred during the study period.

GPS receivers Visiontac® were placed in the chipper and trucks in order to collect spatial and temporal information of their movements. The GPS devices recorded the position and time at a rate of one coordinate per second. In a normal shift of 10 hours, we recorded an average of 28,800 points. No significant problems with satellite reception related to tree canopy interference were found since all the study areas were cleared (clear-cut harvesting) before the biomass recovery operation was carried-out.

Collected data from the GPS devices was pre-processed using a digital toolbox based on an algorithm developed in Python programming language for ArcGIS 10 software (ESRI 2012). In the preprocessing procedure we filtered the data to reduce the amount of identical coordinates and produce a spatial-temporal layer suitable for tracking analysis. Tracking analysis, an extension from ArcGIS 10, was used to recreate the movement patterns of the chipper and trucks. We also calculated travel distances from the spatial data.

Average cycle time for the chipper per activity for the four units analyzed is shown on Table 2.1. On average, about 76% of the time the machine was chipping or waiting for the next piece to be fed. About 18% of the time the chipper was moving to the dumping site and travelling back to the forest residues pile. The rest of the time was spent in dumping. The range of values for chipping time is wide, 8.07 to 40.78 minutes (Table 2.1). Since this range is based on the average values of all units, it was considered an indicator of the high sensitivity of this process to the type of material and site characteristics. Average productivity for the four units was estimated as 12 green tonnes per productive machine hour.

2.3.2 Distribution fitting and parameter estimation

Distributions were fitted for each activity in the chipping productive cycle (Table 2.2). The Input Analyzer from Rockwell Arena Simulation Software (Rockwell Automation 2012) was used to estimate the distribution and parameters that fit best to each dataset. We evaluated the p-values of the chi-squared goodness of fit test and squared errors to determine if enough evidence has been provided to say that the data is well represented by the suggested distribution. We fitted distributions to time spent (minutes) in the chipping and dumping process. Chipper travelling time was modeled as a function of the distance between the trailer and the pile. We calculated the chipper speed variability while the machine was travelling. Diagnosis was performed for all distributions using quantile-quantile (Q-Q) and probability-probability (P-P) plots and the results were approximately linear for all the selected distributions.

Table 2.1 Statistics of time spent in each activity of the productive chipping cycle.

Process	Mean	Min	Max	SD	%
Chipping (min)	16.45	8.07	40.78	5.52	75.80
Travelling to Trailer (min)	1.83	0.47	6.73	1.12	8.44
Dumping (min)	1.46	0.45	3.07	0.51	6.74
Returning to Pile (min)	1.96	0.25	6.62	1.30	9.02
Total (min)	21.70	9.24	57.20	8.46	100.00
Bin-load (t)	4.09	2.09	6.01	0.70	

For the transportation part of the model, the dumping time (normal distribution μ=59.4, σ=15, in minutes), hook and unhooking time (Erlang λ=1.91, k=1, a=2, in minutes), were considered stochastic components. Truck travel loaded and unloaded travel time was modeled deterministically using the relation between the average driving speed and the distance since no significant sources of uncertainty were identified in this stage of the

Table 2.2 Fitted distributions for each operational process

Process	Probability Distribution	Location Parameter	Scale Parameter	Shape Parameter	Squared Error and p-values
Chipping sorted (min)	Erlang	8	1.63	4	0.0056; p>0.75
Chipping unsorted (min)	Gamma	11	5.91	1.53	0.0023; p=0.31
Travelling to Trailer (m/min)	Weibull	1	44.3	1.66	0.0048; p=0.51
Dumping (min)	Log-Normal	0.18	1.28	0.527	0.0042; p=0.38
Returning to Pile (m/min)	Gamma	6	14.7	2.16	0.0011; p=0.73
Bin-load (kg)	Normal	4090	692	0	0.0116; p=0.05

2.3.3 Discrete-event simulation model

The discrete-event simulation model was designed in the Rockwell Arena Software environment. A two component model was developed. The first component expresses the different stages involved in the mobile chipping productive cycle. The second component simulates trucks arriving to the processing site and transporting the material to the bioenergy facility. Both components start with the creation of entities. Entities are objects that flow through the system and produce a change in the output or state of the system (Kelton et al. 2001). The mobile chipper represents an entity for the chipper model. Trucks arriving to the system are the entities of the transportation model. Entities are recycled in the model until the scheduled time is reached. Inputs for the chipping model are the scheduled machine hours in a day including scheduled downtimes, and the average distance between the trailers and the piles. The trucking model assumes that the planner has the complete control of the number of trucks, trailers, and truck arrival schedule. The transportation model's inputs are the average speed of the truck on highway paved roads (from the bioenergy facility to the entrance of the unit), and within the harvest unit driving on the forest roads (gravel or dirt roads), the distance between the entrance of the unit and the processing site, and the average distance between the residue piles and the turn-around.

For the mobile chipper model, the first stage in the model occurs when an empty trailer is available and the chipper begins to travel to the pile (Figure 2.3a). This stage captures the variability of the chipper driving at different speeds. Then, the chipper proceeds to process the residue in a pile. The next stage involves a decision module that is linked with the transportation model. If an empty trailer is available to dump the load, then the chipper continues to the next stage which is travelling to the trailer, and then unloading the processed material. If a trailer is not available then the chipper has to wait until an empty trailer is available. The trailer is modeled as a tank with a fixed capacity depending on the size of the trailer.

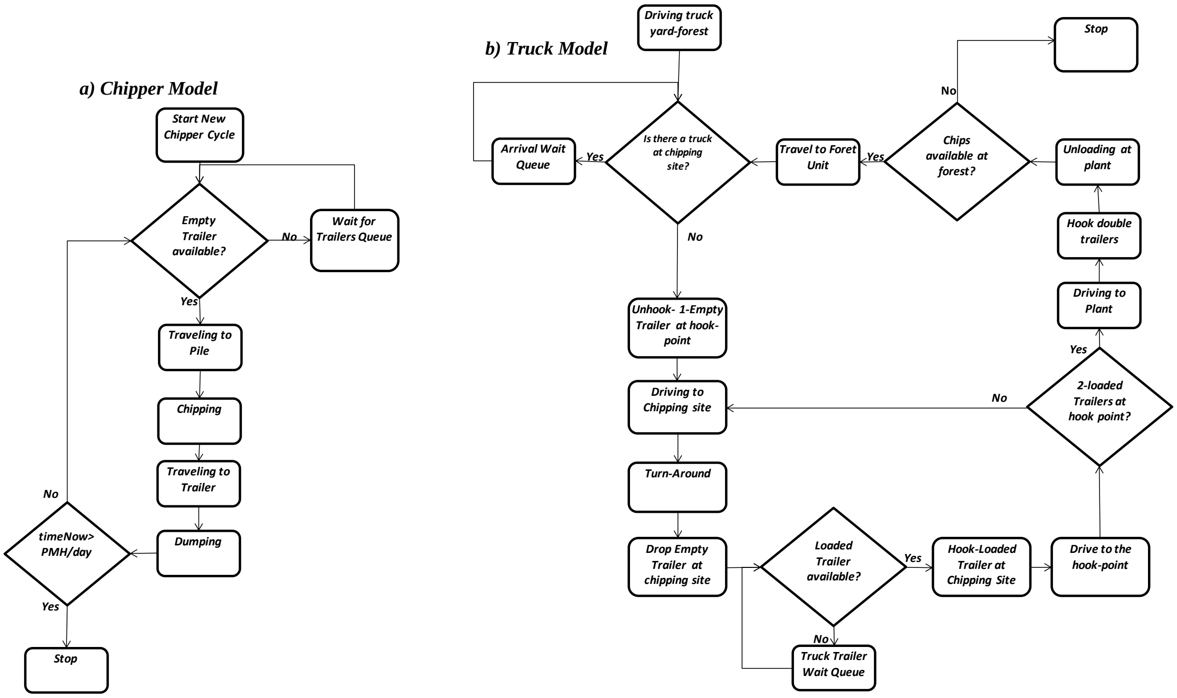

Figure 2.3 Model logic: a) chipper; b) truck-double trailer configuration

The amount of processed chips (metric tonnes) in each productive cycle has a partial positive correlation with the chipping time and was estimated using the procedure proposed by Mykytka and Cheng (1994) to generate correlated random variables obtained from independent distributions. The mathematical expression to calculate the bin load size, Y2, as a function of the chipping time, X, given the Pearson correlation coefficient ρ is expressed as follows:

$$Y_2 = \frac{\rho\sigma_y}{\sigma_x} X + \sqrt{1-\rho^2}\,Y - \frac{\rho\sigma_y\mu_x}{\sigma_x} + \left(1-\sqrt{1-\rho^2}\right)\mu_y \quad (2.1)$$

where

Y_2	correlated random variable of the amount of chips produced in each cycle time,(kg)
Y	uncorrelated random variable of the amount of chips produced in each cycle time,(kg)
X	random variable representing the chipping time,(min)
μ_x	mean of the chipping time distribution,(min)
μ_y	mean produced chips per cycle distribution,(kg)
σ_x	standard deviation of chipping time distribution,(min)
σ_y	standard deviation of chips produced per cycle distribution,(kg)
ρ	Pearson correlation coefficient between chipping time and chips per cycle

Chipper downtime was divided into two categories: the scheduled downtime, which has to be made on a daily-basis to change the knives, warm the engine and clean the filters, and the unscheduled downtime that is caused by unplanned mechanical problems. One of the most common causes of mechanical downtime is related to the presence of metal cables or debris inside the pile. We modeled unscheduled delay using a Poisson distribution with parameter λ=550, which represents the number of processed chipper bins before a downtime occurred. This parameter was estimated using the average of incidence of this problem in the last 6 months.

The logic for the transportation model (Figure 2.3b) begins when an empty truck leaves the truck yard to go to the forest unit. The truck then drives to the processing site, turns around and places the empty trailer. The next step is to drive to the loaded trailer, hook it and travel back to the mill. In the double trailer setting, due to road accessibility, the truck must drop one of the empty trailers before continuing to the pile location. The mobilization within the unit is modeled deterministically as a function of the internal distances and the speed of the truck. The first truck arrives one hour after the chipper starts the chipping process (it is assumed that reserve empty trailers are left in the unit the day before the operation starts, the second truck arrives 30 minutes after the first truck has arrived. The model assumes single passage forest roads which limits one truck to enter into the system at each time. If double trailers are used the truck must pick up each trailer one at a time. This factor increase the cycle time considerably compared to single trailer configuration. An increase in round-trip time of around 30% is expected when using double trailers (for a round-trip distance of 120km on paved roads and 5 km in gravel roads). The time to setting up double trailers increases as the distance between the hook-up point and processing site increases. Also the dumping time at the bioenergy facility increases for double trailers.

2.3.4 Model limitations

The proposed simulation model attempts to explain complexity of a real mobile chipping system by simplifying it into discrete parts. Simplification can lead to some sources of error and the analyst has to be aware of them. The model simulates chipping operations as if the residues were located in one single location. In reality, residues are distributed among different piles and locations. To compensate for the time the machine spends moving from one pile to another we added as an input the time spent moving from pile to pile in a working day. At each site the analyst has to calculate the number of piles and the average distance between them and relate this value to the average speed of the chipper (5km/h). Also we have a fixed capacity of trailers (13,650 kg for each trailer in a doubles configuration and 15,500 kg for singles), but in reality the maximum amount of chips dumped in each trailer varies. This causes some amount of chips to remain in the reserve trailers after a working shift without being transported. To minimize this problem we assumed that those chips will remain in the reserve trailers and eventually will be transported the next day when the trailers are full. We input the average of the distance to the turn-around and between the trailer and the pile, but in a harvest unit where the standard deviation is high, using the average value may lead to inaccurate results. Also, the model does not consider that productivity and knife sharpness are correlated; i.e. productivity should be highest after a knife change and become lower as more chips are processed (Nati et al. 2010). Additionally the model does not consider the loss in productivity due to operator fatigue. Finally the model is intended to support the decision making process but not remove the final decision from the analyst.

2.3.5 Costing Model

Costs were estimated using information from the different stakeholders in the forest biomass supply chain. This includes consultation with contractors, trucking companies, forest managers, landowners and bioenergy facilities. Costs were calculated for the mobile chipper and trucks described in section 2. The cost model accounts for standing times due to truck-machine interactions.

Processing and transportation costs were separated into two main categories: fixed and variable costs. We first calculated the hourly variable and fixed cost in order to be able to model the cost in each activity based on the time spent. Operational and standing costs were then calculated for the chipper and trucks.

Fixed cost of mobile chipping and transportation was based on salvage value, annual depreciation, average yearly investment, interest, insurance and taxes. We assumed 2000 scheduled machine hours per year for the chipper based on historical machine records. For transportation, we assumed 2200 scheduled machine hours per year.

Variable costs for chipping comprised labor, fuel, repair and maintenance. Additionally to fixed and variable costs, operational costs for chipping include overhead and profit and risk costs. Overhead cost ($19.67/h) included supervision (assuming that general supervisors spend 10% of the total working time in chipping operations), communications (radio and cell phones) and administration cost (secretary and office consumables). Supportive equipment includes one water truck (\$7.33/h), service truck (\$9.47/h) and operator's pickup truck (\$11.37/h). These costs are incurred whether the chipper is operating or standing. Profit and Risk was estimated as 7% of the sum of fixed, variable, supportive equipment and overhead costs. Chipping operational costs were calculated based on Eq. 2.2.

$$OC_{ch} = Fx_{ch} + Va_{ch} + Rp_{ch} + Su_{ch} + Ov_{ch} \qquad (2.2)$$

Where

OC_{ch} hourly processing cost while the machine is operating (\$/h)

Fx_{ch} fixed costs for chipping, (\$/h)

Va_{ch} variable costs for chipping, (\$/h)

Rp_{ch} risk and profit for chipping, (\$/h)

Su_{ch} supportive equipment hourly cost for chipping, (\$/h)

Ov_{ch} overhead hourly cost for chipping (\$/h)

Chipper standing costs were calculated as the sum of an opportunity cost based on the expected profit the chipper would have earned if it had been operating, plus labor, interest, insurance, supporting equipment and overhead (Eq. 2.3). Since the machine is assumed to be idle during waiting, no depreciation cost was included, given that the machine is not being used. Obsolescence is not considered in this study, since we assumed that the useful life of forest machinery is dependent on the hours worked, not the passage of time as it occurs in the software industry or electronics for example.

$$IC_{ch} = Int_{ch} + ins_{ch} + La_{ch} + Su_{ch} + Ov_{ch} + Rp_{ch} \qquad (2.3)$$

where

IC_{ch}	hourly chipper standing cost, ($/h)
Int_{ch}	hourly interest cost for chipping ($/h)
Ins_{ch}	hourly insurance and taxes cost for chipping ($/h)
La_{ch}	hourly insurance and taxes cost for chipping ($/h)

For Transportation, variable cost includes labor, repair and maintenance, fuel and lubricants. Variable cost is a function of distance, road surface (gravel, paved dirt), speed and weight of the truck and trailer (loaded or unloaded). Only one driver is required per truck. Fuel cost was estimated as a function of the truck power necessary to overcome rolling and air resistance forces. Rolling and air resistance are dependent upon the speed, weight (empty or loaded) and roundtrip distance. Variable transportation costs for transportation were calculated in the following section for the validation unit, based on the traveled distance, and weight (loaded unloaded), on different road surfaces.

Transport operational cost (Eq. 2.4) includes 7% percent of risk and profit of variable fixed and overhead costs. Overhead transportation cost was calculated based on dispatching, communications and administration costs. Transportation standing costs were calculated following Eq. 2.5.

$$OCT_{rwz} = Fx_t + Va_{rwz} + Rp_t \qquad (2.4)$$

$$OC_t = Int_t + ins_t + La_t + Su_t + Ov_t + Rp_t \qquad (2.5)$$

where

Fx_t	truck hourly fixed costs, ($/h)
Va_{rwz}	truck hourly variable costs, ($/h)
Rp_t	truck hourly risk and profit, ($/h)
OCT_{rwz}	operating truck hourly processing cost on road surface r with a load w and speed z ($/h)
OC_t	truck hourly standing cost, ($/h)
Int_t	truck hourly interest cost ($/h)
Ins_t	truck hourly insurance and taxes cost ($/h)
La_t	truck hourly labor cost ($/h)
Su_t	truck supportive equipment hourly cost, ($/h)
Ov_t	truck overhead hourly cost ($/h)

Total chipping (Eq. 2.6) and transportation (Eq. 2.7) cost per tonne of chips (\$/t) were calculated taking into account the time spent in each activity listed in the simulation model. A final cost equation includes previous costs, the mobilization cost of the machinery to the forest unit using a highway legal lowboy, mobilization cost to drop the extra trailers at the site and stumpage price of the piled material if any (Eq. 2.8).

$$TC_{ch} = \frac{\left(tc + tp + tm + td\right)OC_{ch} + \left(tw + tb + tl\right)IC_{ch}}{Q} \qquad (2.6)$$

$$TC_{t} = \frac{\sum_{rwz}\left(t_{rwz}\right)OCT_{rwz} + \left(tx + ty + th + ti\right)OI_{t}}{Q} \qquad (2.7)$$

$$COST = TC_{ch} + TC_{t} + \frac{MV_{u}}{Q} + Stp \qquad (2.8)$$

Where

TC_{ch}	total chipping cost as a function of the amount of processed chips, (\$/t)
tc	time spent chipping, (h)
tp	time spent moving to pile, (h)
tm	time spent moving to trailer, (h)
td	time spent dumping in trailer, (h)
tw	chipper standing time, (h)
tb	standing time due to unscheduled machine breakdowns,(h)
tl	standing time due to scheduled machine downtimes,(h)

Q	amount of chips processed, (t)
TC_t	processing cost as a function of the amount of processed chips in unit u, (\$/t)
t_{rwz}	truck time spent traveling on road surface r with a load w at a speed z (h)
tx	truck standing time waiting for loaded containers, (h)
ty	truck standing time due to forest road traffic interference, (h)
th	time spent to hook a single or double containers, (h)
ti	time spent to dump at the bioenergy facility, (h)
Mvu	mobilization cost of the machinery to the unit, (\$)
Stp	stumpage cost, (\$/t)
$COST$	total cost per tonne, (\$/t)

Assumptions and supportive equations for fixed and variable chipping and transportation cost calculations are shown in Appendix 1.

2.4 Results

2.4.1 Model Validation

We made an independent validation of the model (additional to the previous four evaluated units) to estimate the degree of accuracy of the model to represent the chipper and truck productivity. The validation was performed in a forest unit with an area of 16.2 ha located in the Coast Range in western Oregon, United States 123°28’5”W, 43°28’13”N. The access to the unit was characterized by steep loose-gravel roads with road gradients ranging from 8 to 20%. The area was harvested in late April 2012 using cable-logging equipment. Piles of forest residues were left in the forest around the landings as a by-product from the logging operation. The residue piles were composed of a mixture *Pseudotsuga menziesii* (Douglas-fir), *Abies concolor* (white-fir) and *Libocedrus decurrens* (incense-cedar) with pieces ranging from 10 to 20cm in diameter and 0.9 to 3m in length. The distance from the main road entrance to the processing site was 2.57 km. Average distance between the trailer locations and the piles was 40 m. Fifteen piles were distributed within the unit with an average distance between piles of 70.6 m. Turn-around average distance to the piles was 150 m. Double trailers as shown on Figure 2.2b, were used in the transportation of chips. Two trucks transported the chips to the plant. The distance between the forest unit entrance (hook-up point) and the plant was 50 km.

We compared the results of the simulation against the actual data obtained from a time and motion study (Table 2.3). Thirty independent repetitions were made to evaluate the performance of the model; the average was compared to the actual value. Welch's t-test was used to assess if there was statistical significant difference between modeled and actual data. Given the multiple outputs of the simulation model (chipping time, traveling to trailer, chips produced, etc.), the Bonferroni inequality was used to calculate the critical t-value for multiple responses. The critical value using this approach is tm-1;α/2T, where m is the degrees of freedom (30-1), T is the number of responses (5) and α is the significance. We combined the Bonferroni inequality with a significance value of α=0.20, suggested by Kleijnen (1995) for simulation models with multiple responses. Critical value t29;0.02 = 2.46. No statistical difference was found between the model and the actual data for each of the components of the chipper cycle time and the amount of chips produced. All their respective t values were below the critical value of 2.46

Table 2.3 Modeled and actual results for the validation study.

Process	Real	Model	% Difference
Chipping (min)	882.99	893.59 ± 18.00	1.20, t_{29}= 1.492
Travelling to Trailer (min)	101.52	107.75 ± 8.84	6.14, t_{29}= 1.734
Dumping & Record Keeping (min)	89.28	89.53 ± 3.50	0.28, t_{29}= 0.174
Returning to Pile (min)	91.10	88.24 ± 4.14	3.14, t_{29}=1.700
Chips Produced (t)	277.72	279.36 ± 7.57	0.59, t_{29}= 2.329
Total productive Time (min)	1164.88	1153.53	1.22
Productivity (t/PMH)	14.30	14.22	0.62

2.4.2 Economics of mobile chipping under uncertainty

The economics of mobile chipping is a function of the chipper productive time, transportation time and machine interactions that may cause delays in processing or transporting. Specifically, costs in mobile chipping are affected by chipper and truck standing times, distance between the forest unit and the plant, internal road distances and conditions (i.e. gravel and single passage road), pile location, physical properties and characteristics (size) of the forest residues. To illustrate the effect of these variables on productivity we calculated the cost for the forest area used in the validation using the cost model.

Chipping costs were separated for each of the activities in the productive cycle of the chipper. We considered chipping, moving to trailer, moving to pile and dumping as operational stages, therefore the operational cost is calculated by multiplying the operating cost by the accumulated time spent in the unit (Table 2.4).

Table 2.4 Estimated hourly cost for the Bruks chipper under the study conditions.

Cost $/hour	Operating	Standing
Interest, insurance, and taxes	116.75	36.75
Labor	37.50	37.50
Knife Cost	16.00	-
Repair and Maintenance	56.00	-
Fuel Cost	48.00	-
Oil and Lubricants	17.64	-
Total Variable Cost	175.14	37.50
Supportive Equipment	28.18	28.18
Overhead	19.67	19.67
Profit and Risk (7%)	23.78	23.78
Total $/hour	363.51	145.87

Operational transportation cost was calculated as a function of the time spent: (i) arriving to the site; (ii) driving in forest roads empty and loaded; and (iii) turning-around. Standing transportation costs were calculated based on: (i) hook and unhook time; (ii) unloading at the plant and (iii) standing time due to chipper-truck interactions (Table 2.5).

Table 2.5 Hourly transportation costs based on road standard for the loaded and empty truck. Single trailer is 9.8m and double trailer is composed of two 9.8m trailers.

Truck-Trailer Configuration ($/h)	Paved	Gravel	Dirt	Standing
Single Empty	80.32	68.37	65.73	45.34
Single Loaded	96.06	76.72	73.44	45.34
Double Empty	98.53	78.97	75.03	50.87
Double Loaded	126.19	92.11	89.03	50.87

Maximum allowable tractor-trailer weight (Table 2.6) was calculated using a linear programming model proposed by Sessions and Balcom (1989), that it is based on axle-load group limits for the single and double trailer options. Double trailers required an additional axle (dolly) to connect both trailers. This axle adds weight and cost to this configuration.

Cost per hour of double trailers is 30% more than a single trailer configuration but the maximum allowable load increases by 76%. However, the use of double trailers requires the additional time to hook and unhook the trailer combination and a suitable location to do so. Transportation cost per hour decreases on gravel and dirt roads because it is assumed that at low speeds in gravel (15 km/h) and dirt (5 km/h) roads fuel consumption per hour decreases even though rolling resistance increases. We assumed an average speed in paved roads of 70 km/h.

Table 2.6 Truck and trailer specifications.

Truck Specifications	Single	Double
Truck Weight (t)	9.1	9.1
Trailer Weight (t)	3.9	10.2
Trailer capacity (m^3)	76.5	152.9
Maximum Capacity (t)	15.5	27.3
Number of Axles	5	9

Hourly cost was then related to the total amount of chips produced in order to calculate the cost per tonne. We incorporated the moisture content of the chips to obtain the rate per dry tonne of chips since the product was used in power generation. Moisture content was estimated as 30% (wet basis). Estimated costs per bone dry metric tonne (BDMt) were \$37.94/BDMt for chipping, \$3.60/BDMt for machinery mobilization and placement of reserve trailers at the chipping site (assuming six hours of a highway lowboy with an hourly cost of \$100 and 2 hours of truck waiting time), and \$18.13/BDMt for transportation giving a total of \$59.66/BDMt (Figure 2.4).

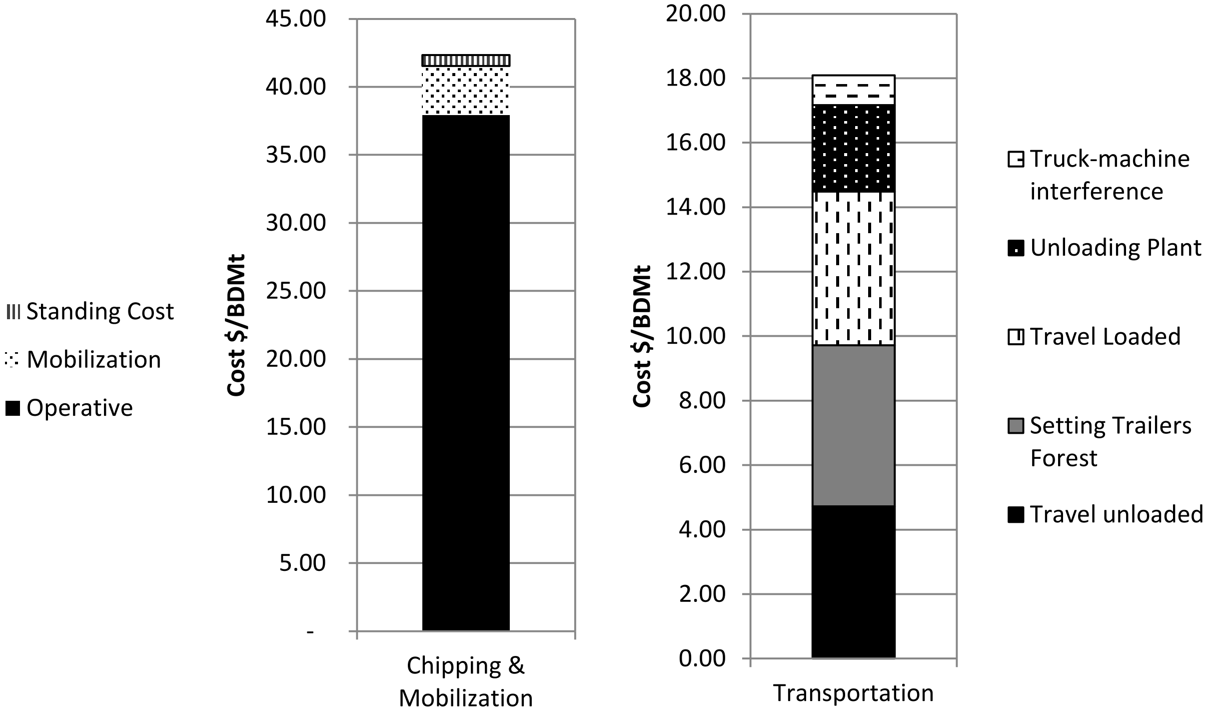

Figure 2.4 Total cost of chipping and transportation for the validation forest unit.

Using the simulated data we created a probability histogram for the total cost per bone dry metric ton given the variability of the system (Figure 2.5). This histogram can help risk adverse managers to analyze the probability of occurrence of each cost for a particular unit and evaluate if it is profitable or not to do an operation.

In this case, there is a 76% probability to have a cost between \$55 and \$61/BDMt and 24% probability to have a cost between \$61/BDMt and \$69/BDMt.

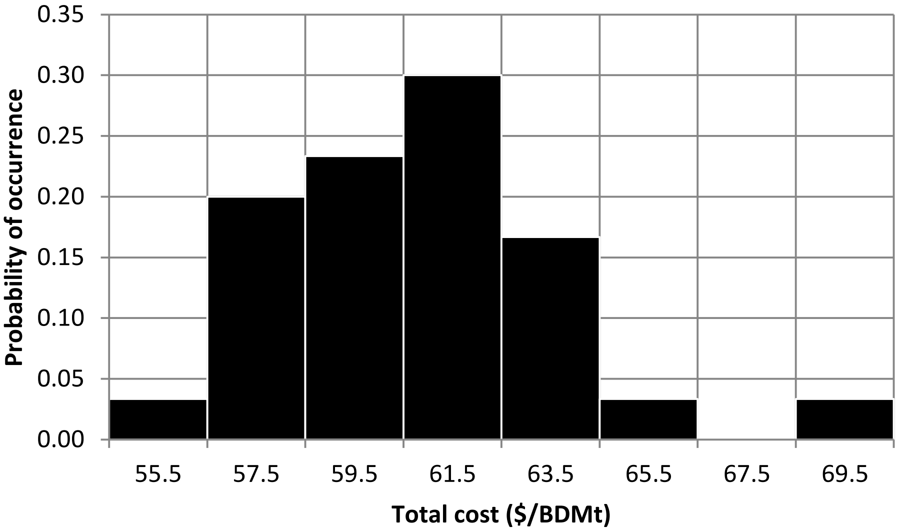

Figure 2.5 Probability distribution of total cost for the validation forest unit

2.4.3 Optimization of mobile chipping and truck-chipper interactions

In this section, we present a series of scenarios using the simulation model to analyze the effect of the main variables on productivity and strategies to reduce the cost and increment the marginal net profit under uncertainty. We focused our analysis on the effect of truck-chipper interactions on productivity. In all scenarios we modeled productivity and cost for a 10-hour mobile chipper shift. Other assumptions include: (i) all forest roads were single passage; (ii) only two reserve trailers were available for the chipper; (iii) the average distance from the trailer to the pile was 40 m; (iv) the average distance from pile to turn-around was150 m; (v) The hook-point for double trailers was located in the entrance of the unit; and (vi) the moisture content was 30% (wet basis).

Available transportation options were: (a) two single trailer trucks, (b) three single trailer trucks, (c) two double trailer trucks and (d) three double trailer trucks. Longer trailers (>9.75m) are available but forest road conditions constraint their access. Other double trailer configurations are available (i.e. 6.1-12.2 m in length) but the option 9.75-9.75m maximizes the maximum allowable weight (47,854 kg) and the tractor-trailers length (24.38 m), under the current road regulations.

In the first scenario we modeled the chipper and truck productivity as a function of the distance between the entrance forest unit and the bioenergy facility (highway distance). We ran three simulations for round-trip highway distances ranging between 40 km and 280 km. We assumed a fixed round-trip distance in forest roads of 6 km from the entrance of the unit to the pile location

Results showed that for transportation options (a), and (c) chipping cost ($/BDMt) increases as distance increases (Figure 2.6). This trend is caused by the increasing standing time of the chipper (Figure 2.7). As distance increases the truck has to spend more time traveling loaded and unloaded to the plant and back to the unit and therefore it is difficult to reach the forest site in time to replace the loaded trailers. The cost impact is higher when using only two single trailer trucks because the amount of transported chips per trip is less than the double trailer configuration. Using three double trailer trucks or three single trailer trucks has the minimum impact on the chipping cost per tonne because the standing time of the chipper is minimized, however transportation cost increases.

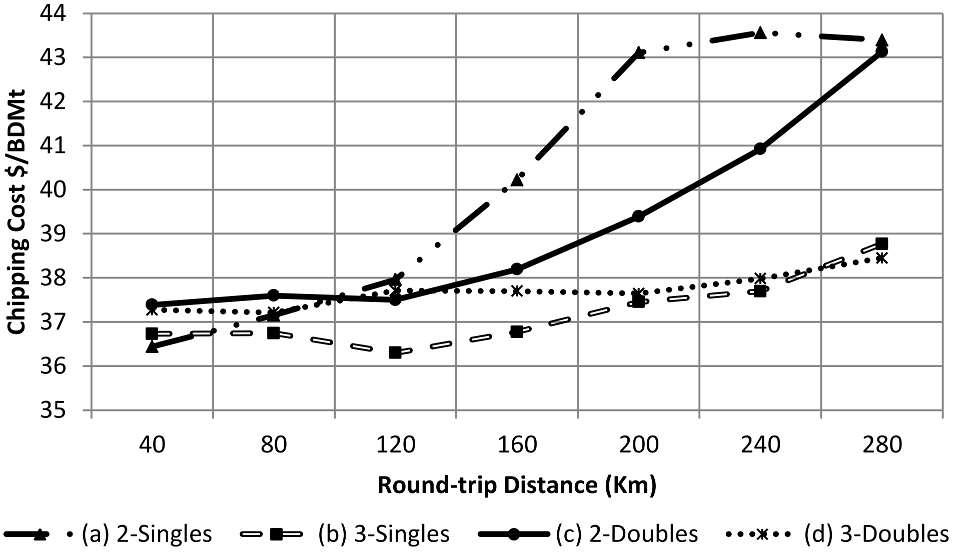

Figure 2.6 Chipping cost as a function of the round-trip highway distance to bioenergy plant. Internal forest round-trip distance was fixed at 6 km.

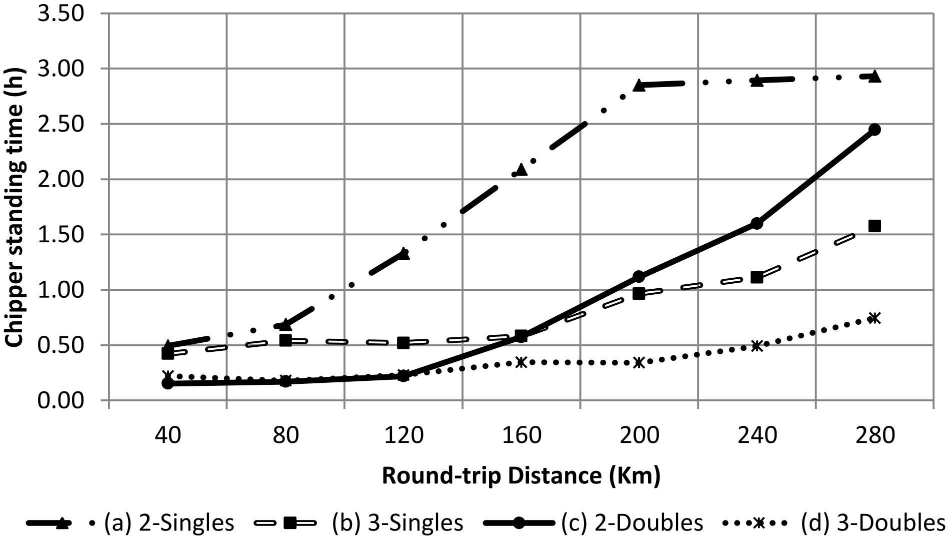

Figure 2.7 Chipper standing time as a function of round-trip highway distance to bioenergy facility. Internal forest round-trip distance was fixed at 6 km.

Transportation cost is mainly affected by the increase in round-trip distance and number of trucks. As the number of trucks increases there is a high probability of truck congestion in the single passage roads. Each truck has to wait for other trucks and loaded trailers. Transportation cost in options (a) and (b) are mainly affected by the maximum allowable weight for singles. Due to their reduced capacity, the number of trips is higher compared to the double trailer truck configuration. Options (c) and (d) are lower cost because the double trailer configuration can carry more per trip (Figure 2.8). Options (b) and (d) are more affected by standing times. The additional truck under this configuration adds more congestion at the arrival to the unit (Figure 2.9).

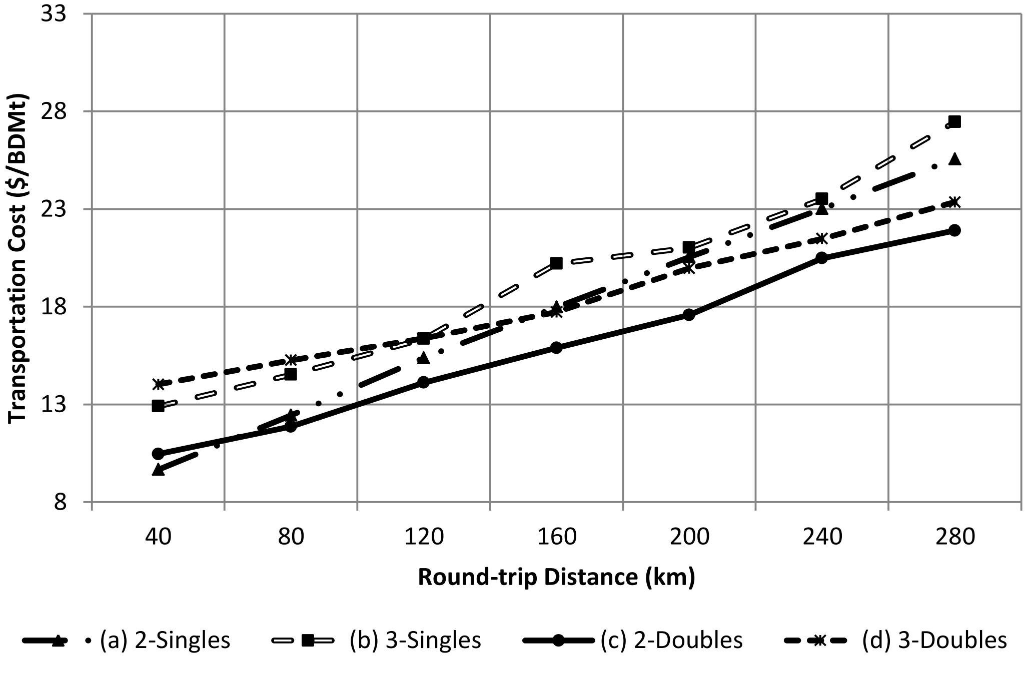

Figure 2.8 Transportation cost as a function as a function for round-trip highway distance to the bioenergy facility. Internal forest round-trip distance was fixed at 6 km.

Although adding a truck can minimize the standing time of the chipper, the additional truck may not be able to complete the number of trips necessary to satisfy a normal working shift for the trucks (8-hours). The under-utilized truck cost was calculated by multiplying the hourly standing cost of the truck and the hours necessary to complete a minimum working shift of 8 h. Focusing only on the chipping cost, the manager may choose option (d), 3 doubles, as the most cost effective for the operation since that is the one that appears less expensive and less sensitive to the distance. However, total transportation cost indicates that the less expensive option is (c), 2 doubles.

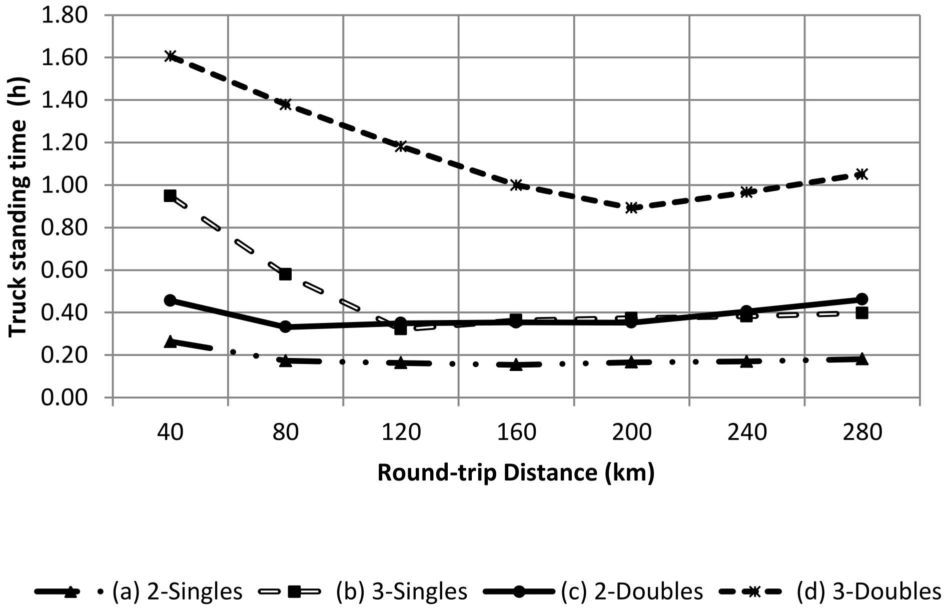

Figure 2.9 Truck standing time due to truck-chipper interaction and road truck congestion as a function of highway distance. Standing time include at arrival queue wait due to road congestion and waiting for loaded trailers.

Adding chipping and transportation cost to account for truck-chipper interactions (Figure 2.10) we determined that the use of two double trailer trucks is the most cost-effective option for round-trip distances of less than 220 km. For round-trip distances greater than 220 km the use of three double trailer trucks seems to be more effective. For round-trip distances around 40 km options (a) and (c) appear to have the similar costs.

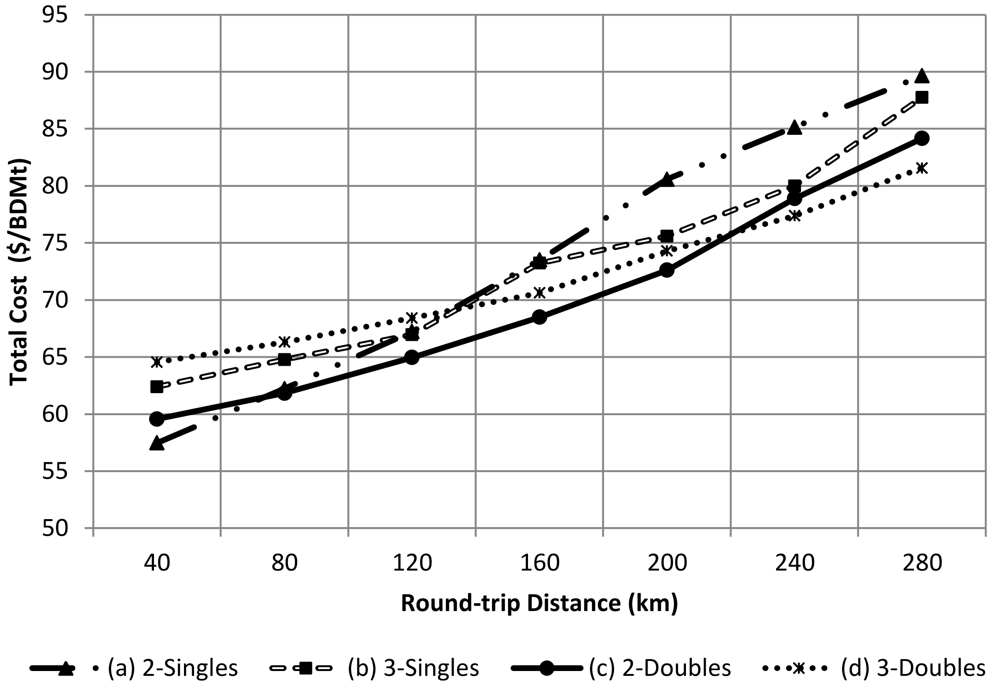

Figure 2.10 Total costs as a function of the round-trip highway distance to the bioenergy plant. Internal forest round-trip distance was fixed at 6 km.

In the second scenario we estimated productivity and cost as a function of the forest road distance from the entrance of the unit (trailer hook-up point) to the residue pile location. In this scenario we set the round-trip distance to the bioenergy plant equal to 120 km, and changed the round-trip internal distance from 2 to 12 km. All other inputs remained the same as in scenario 1.

Total costs of processing and transport are significantly more sensitive to the in-forest road distance than to the highway road distance (Figure 2.11). For the two double trailer trucks configuration, a change in the forest road distance from one to six kilometers caused an increase of 18% in the total cost. This change is caused by the low travel speed on forest roads (steep roads and tight curves) and the time the truck spends turning-around, hooking and unhooking trailers.

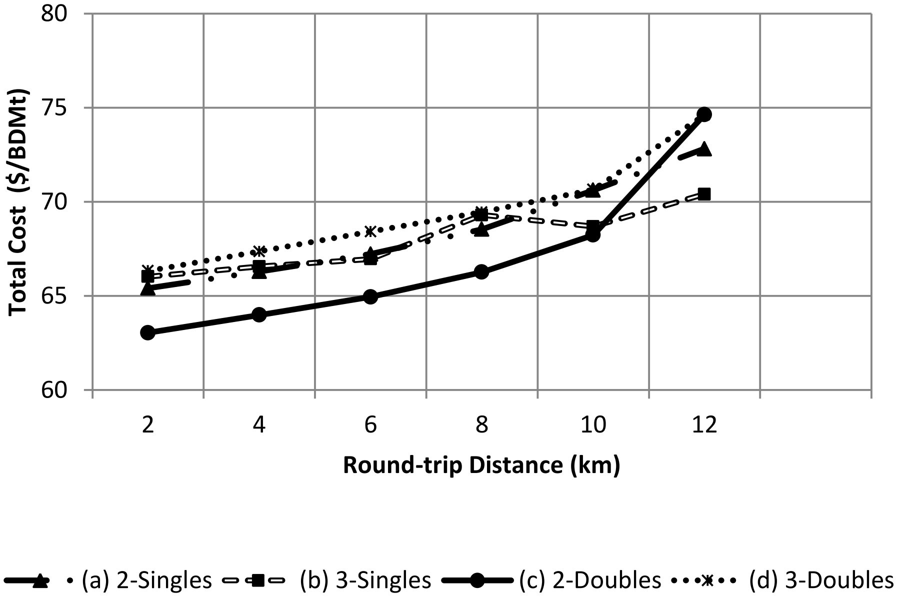

Figure 2.11 Total costs as a function forest road distance. Cost were estimated for a highway haul round-trip distance of 120 km to the bioenergy plant

Double trailer trucks are more sensitive than single trailer trucks to increases of internal road distance, due to significant increases in chipper standing time (steeper curves on Figure 2.11). However, the use of two double trucks appears to be the most cost effective configuration because fewer trips to the plant are required compared to single trailer configurations for round-trip in-forest distance of less than 10 km. For in-forest distances greater than 10 km the use of three single trucks is cheaper that the all the other options

The third scenario estimates the effect of reducing chipper moving time (traveling to pile and trailer) on productivity and cost. Trailer-to-pile distance was set to zero. We modeled the estimated productivity dumping directly into the trailer or blowing into the trailer using an extension accessory on the chip tube. We assumed bulk density of the dumped and blown chips in the trailer would be the same.

The mobile chipper spends around 17% of the productive cycle, moving between the trailer and the pile. Reducing the moving time may increase the productivity by allowing the chipper to spend more time chipping or feeding the machine. Cost and productivity were modeled under these considerations for Scenario 3. Results show that eliminating the moving time but dumping into the trailer decreases the overall cost about 7% (Figure 2.12). Blowing the material directly into the trailers reduces the cost about 8% and this option becomes limited by the availability of trailers. Adding one more double trailer truck minimizes the chipper standing time and decreases the overall cost by 22% with respect to the actual value (Figure 2.12, Centralized, Blowing, 3-Doubles). Any machinery or trucks necessary to transport the material to a centralized landing must cost \$5.40 to \$15.92/BDMt or less to be a feasible option as compared to the base scenario. Additionally a centralized landing may require clearing a large area to allow for the placement of trailers and residues and to allow the trucks to turn-around.

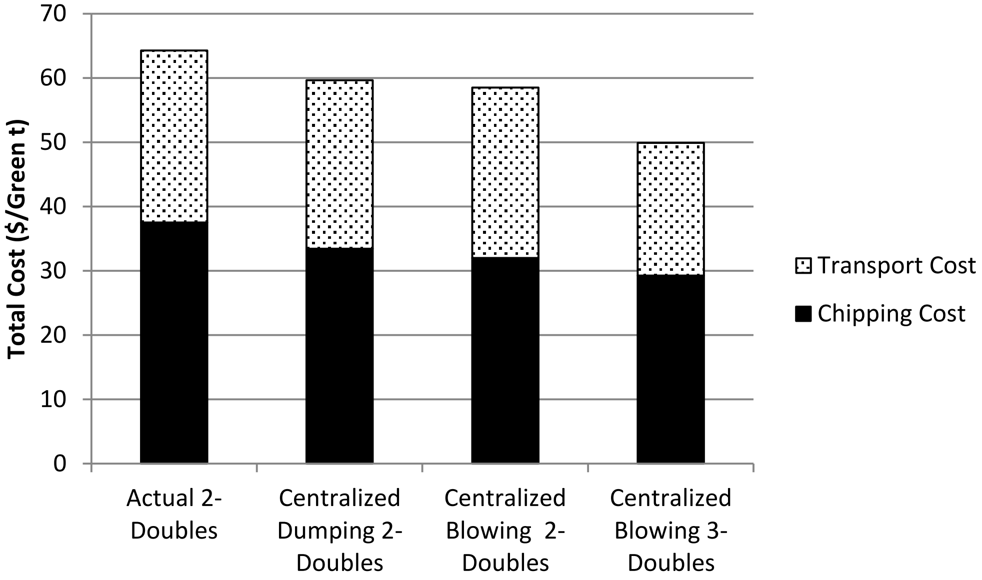

Figure 2.12 Total costs for chipping at centralized landing

2.5 Discussion and Conclusions

We presented a stochastic simulation model and optimization procedure applied to forest biomass recovery operations for energy purposes. The proposed stochastic simulation model has been shown to be an accurate tool to support decisions related to the estimation of productivity under uncertainty. The forest biomass processing and transportation was modeled as a dynamic system, providing productivity estimates of each activity in the productive cycle accounting for truck-machine interactions.

On steep terrain conditions it is important to consider the impact of road characteristics that can affect truck-machine interactions. Important road characteristics to considering when planning operations on steep slopes are internal forest distance, type of road surface, road width, road grade and curve radii that can limit the access to high capacity trucks due to off-tracking.

Standing times for the chipper and trucks due to truck-chipper interactions must be considered and quantified when analyzing economics and productivity of the forest biomass collection. A costing method was developed to account for the cost while the machine or trucks are operating or standing. Assigning value to the standing cost of the chipper and trucks allowed the economic optimization by minimizing chipper and trucks standing costs. Reducing the chipper standing time may require additional trucks but as number of trucks increases the probability of truck congestion at arrival to the forest unit increases. Additionally some trucks cannot be fully utilized incurring in higher transportation cost. In this study trucks had to be paid for a minimum day. In other situations, truck dispatching to other jobs may improve truck efficiency.

Single passage road distances may limit the number of trucks that can reach the processing site at each time, thus affecting costs and productivity of the chipper and trucks. Total cost is highly sensitive to small increases in distance especially for double trailer configurations that require several internal trips to drop off, collect, and assemble the double trailer configuration.

For the study site the use of double trailers is the most cost-effective option on steep terrain. The capacity of this configuration compensates the additional time spent in the forest. This configuration was selected by comparing its productivity and cost with alternative transportation systems and number of trucks.

The model was able to estimate a cost distribution that can be used to assess the risk of operating in some forest units. In cases where delivery prices were close to expected cost estimations a deep analysis of the distribution can improve decision making process and analyze the potential trade-offs of operating in some units

Future work could evaluate establishing a centralized yard to reduce chipper standing time, reduce chipper moving time and increase large trailer access. However, benefits must also consider the additional costs of aggregating the material.

Finally, combining the use of GPS, geographical information systems, spatial-temporal analysis and discrete-event simulation proved to be effective in constructing a robust model to estimate the economics of mobile chipping. These methods can be applied to analyze other forest operations.

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CHAPTER 3

ECONOMIC IMPACT OF TRUCK-MACHINE INTERFERENCE IN FOREST BIOMASS RECOVERY OPERATIONS ON STEEP TERRAIN

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3.1 Abstract

A deterministic simulation model was developed to estimate the economic effect of truck-grinder interference in forest biomass processing and transport operations on steep terrain. Truck-machine interference can occur in situations where the stationary grinder is waiting for trucks or vice versa. We analyzed how the number of available trucks and road characteristics affect grinder utilization rate and their impact in the biomass delivery cost. Three cases based on different road characteristics were designed and applied to actual operations in order to illustrate how particular road features in relation to the spatial location of the grinder can affect the economics of the operation. An economic model was also developed to estimate the waiting cost of trucks and machinery due to truck-machine interferences. Grinder location in relation to available truck turn-around, turn-outs, truck turning-around time, truck positioning time and distance traveled in each road surface are considered influencing factors affecting forest residues processing and transport economics.

Keywords: Simulation, economics, renewable energy, optimization.

3.2 Introduction

A growing market for forest biomass from logging residues is being developed due to the increasing interest in developing renewable sources of energy as replacements for liquid fuels and electricity. Logging residues are one of the few available renewable sources of material with no competing uses. Currently, logging residues are often piled and burned to assist in reforestation. The amount of available residues is a function of the physical characteristics of the species, forest composition, type of logging operation (cable logging or ground-based equipment) and timber-pulp market requirements. The US Department of Energy, DOE, (2011), estimates that approximately 40 million metric tonnes of forest residues are available following timber harvest each year in the US.

Forest residues in the US Pacific Northwest, PNW, are typically comminuted during field operations following timber harvesting using stationary grinders at roadside. Grinders reduce the particle size of the residues (limbs, tops and other byproducts) by hammering the material with a cutting rotor (Staudhammer, 2011). Grinders are expensive machines with engines producing between 500 and 1000 horsepower that result in high purchase and operating costs.

Processed material is usually discharged directly into trailers using a discharge conveyor. Truck loading occurs following a FIFO (first in first out) loading scheme. Processing operations are tightly coupled to transportation. For example, if no truck is available, the grinder must cease operations and wait until the next truck arrives to be loaded. Grinder utilization decreases as waiting time increases, reducing productivity and lowering the profitability of the operation.

Forested steep lands create an additional problems related to road accessibility. Available truck turn-around spaces are usually reduced in number and limited in space. Distance between the processing location and available truck turn-around spaces may affect truck productivity and consequently grinder economics. Additionally single-lane roads further limit the number of trucks that can reach the area where residues are located. Therefore, trucks cannot simply wait in a line, one behind the other. Instead a truck must wait in a turn-out or turn-around space that must be located as close as possible to the grinding site. Availability and location of truck turn-out and turn-around spaces are important factors to consider when planning biomass recovery operations on steep terrain.

High capacity trucks are preferred to smaller trucks due to their ability to lower transportation cost. However, curves with small radii and steep road grades limit their accessibility on steep terrain (Sessions et al., 2010). The problem is further hampered by the drop-center often used in the trailer to increase its capacity. The result is a lower vertical clearance of the trailer that affects truck capacity to cross vertical curves. Finally, when trucks are traveling empty, the reduced weight on the driving axles, results in low normal forces on the wheels that lessen traction and the ability of the truck to climb steep roads.

Spinelli and Visser (2009) used literature related to in-field wood chipping operations to analyze and estimate delays in wood chipping operations of different machines and different operating conditions. They found an average chipper utilization rate of 73.8%. According to the authors, two thirds of delays reported (16.6%) are caused by organizational type delays related to truck interference, waiting for the biomass, and refueling. Acuna et al., (2012), optimized transport scheduling of wood chips for in-field operation to reduce waiting time for the truck and the chippers in Australia. Talbot and Suadicani (2005) simulated two in-field chipping and extraction systems in spruce thinning. They illustrate how interference between a chip harvester and a bin forwarder affect productivity. Anderson et al., (2012) evaluated productivity and costs for two forest biomass production systems, considering difficult access roads for large trucks. Although these studies considered different approaches for analyzing waiting times in in-field biomass processing operations, little emphasis has been given to measuring the impacts of road characteristics, turn-around and turn-out availability on grinder productivity and economics. Additionally traditional machine cost estimations do not assign a cost to the waiting time.

Considering that most of the forested productive areas in the US PNW and many parts of the world are located on steep lands, and that grinder utilization, under this conditions is a function of truck availability in relation to road accessibility, the contribution of this study is to quantify the economic effect of truck-machine interference and improve the cost estimation and decision making process at the operational level. The cost of grinder waiting times due to truck-machine interference must be estimated to accurately reflect the overall cost of the operation.

We expect that accounting for the economic impacts of truck-machine interference will improve the accuracy in traditional cost estimation that are typically based only in the average utilization rate of machinery cost not taking into account the dynamics of waiting times due to truck-machine interference caused by truck accessibility to the grinding site.

The long term goal is to improve the efficiency of the forest biomass supply chain from forest residues to energy. The main objective of this study was to estimate the economic effect of truck-machine interference in forest biomass processing and transport operations on steep terrain using stationary grinders. Our specific objectives were: (i) determine the effect of road characteristics, number of trucks and truck configuration on grinder utilization rates; and (ii) estimate the optimal number of trucks that minimize processing and transportation costs.

To understand and quantify the impact of truck-machine interference and road characteristics, we implemented three simulations enclosed in a model. The model is based on different cases that represent the most common situations that a manager can face in operations on steep terrain. The productive system was modeled in Java programming language and simulates the truck–grinder interference based on the number of trucks, arrival schedule and road characteristics. It takes into account the spatial location of the processing site in relation to turn-around location and internal forest network. An economic model was developed to estimate the waiting cost for grinders and trucks.

Actual operations for each of the cases were compared to model outputs. The model used the actual conditions of the processing site as inputs in order to propose operational strategies to improve economics. Although the model was developed and evaluated for specific selected grinders and transportation options, it can be used for other stationary comminution equipment and transport configuration by adjusting the processing time, machine costs, truck capacity and road characteristics. The model will be available as part of a decision support system that is being developed and will be presented in future research.

3.3 Materials and methods

3.3.1 Forest residues processing and transportation

The field processing of forest residues involves the transport of the grinder to a suitable location close enough to the residue piles to facilitate machine feeding, usually by a hydraulic knuckle boom loader on a tracked carrier ("excavator"), and with access for chip trailers. A turn-around has to be available for the trucks close to the grinding location. Residues are usually piled during or after logging operations. In some operations small end-dumping off-highway trucks are used to transport unprocessed residues from difficult access locations to a centralized landing. Depending on the distance, excavators can be used to move the material to locations reachable by the grinder (Figure 3.1).

Available grinders differ by engine power and rotor sizes. In general, large grinders have an engine greater than 735 kW. Two categories of grinders have been commonly used in the US to process forest residues: tub and horizontal grinders. Tub grinders consist of a large tub where residues are deposited. Usually, they have a mechanical tub rotation system to prevent plugging and facilitate the feeding until residues reach the cutting rotor aided by gravity. Horizontal grinders have a mechanical horizontal feeding system aided by a feed conveyor. The mechanical feed system increases productivity but horizontal grinders are more limited by the size and shape of the residues than tub grinders. In both types of grinders, processed material is removed from the comminution site and loaded either into the trailer or dumped on the ground using a discharge conveyor.

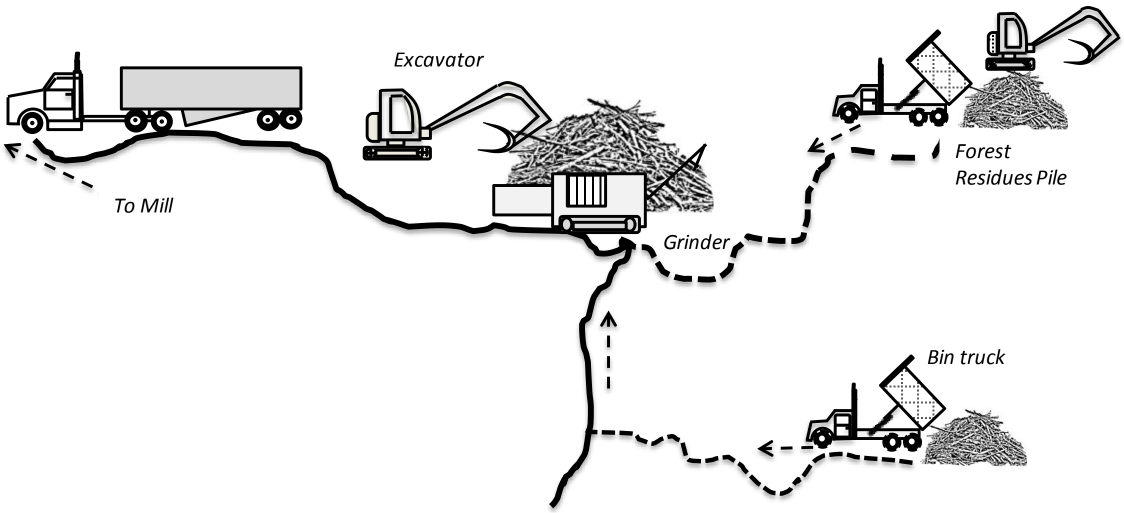

Figure 3.1 Diagram of forest residue processing and transport using a stationary grinder.

Transportation of processed forest residues is made by a chip trailers pulled by a 6 x 4 truck tractor. Typical trucks are tri-axle with traction in the two rear axles. Some trucks can contain an additional non-powered drop axle to increase legal weight capacity while others have power to all axles (6x6 all-wheel drive) in order to improve traction on steep roads. Haul capacity is usually limited by the volume of the trailer and maximum allowable weight based on road regulations. A typical 14.6 m long trailer can have a capacity up to 24.5 tonnes. Most chip trailers are made with light materials such as aluminum and are open in the top and contain an underneath extension known as a drop center to increase capacity. Non-conventional trailers include stinger-steered, and rear steer axles. Rear steer axle trailers allow large chip vans (trailer length of 14.6 m) to operate on narrow roads and tight curves, however these trailers are more expensive than standard trailers and are not yet common.

3.3.2 Model description

The simulation model simulated in-field processing of forest biomass using stationary grinding and transportation from the forest to a bioenergy facility. The model was designed and implemented in JAVA platform using a package for process-based discrete-event simulation developed by Helsgaun (2000). The model is based on deterministic inputs.

Different conditions based on road accessibility were modeled by designing three cases that were implemented to isolate and understand the effect of truck-machine interference in steep terrain on grinding and transport productivity and economics. In each case we analyzed the effect of road access as the limiting factor to increase grinding productivity. The effect of number of trucks as limiting factor was also analyzed.

Inputs for the model were grinder loading time, trailer capacity, number of trucks, inter-arrival time between the trucks, average truck speed (paved, gravel and dirt), turning-around time, positioning time, backing-up time (if needed), time to put the tarp over the load usually after the trucks leaves the local area, and unloading time at the bioenergy facility. Additionally the model needed the grinder spatial location in relation to the road access for each of the design cases.

3.3.3 Case I: Stationary grinder truck-machine interference with truck turn-outs

This case illustrates the situation when the processing site is located between a truck turn-out and a truck turn around location (Figure 3.2). Single-track forest roads allow the access of only one truck at a time. At the processing site the space is reduced forcing an entering truck to stay in the road while is being loaded. In this situation, when a truck arrives, it must check first if there is a truck at the processing site. If no truck is at the processing site the truck can drive up to the grinder location. However, if a truck is being loaded, the arriving truck must wait in a turn-out (typically the entrance of the harvest unit, an intersection or a wide spot in the road) until the first truck is loaded and passes the turn-out point.

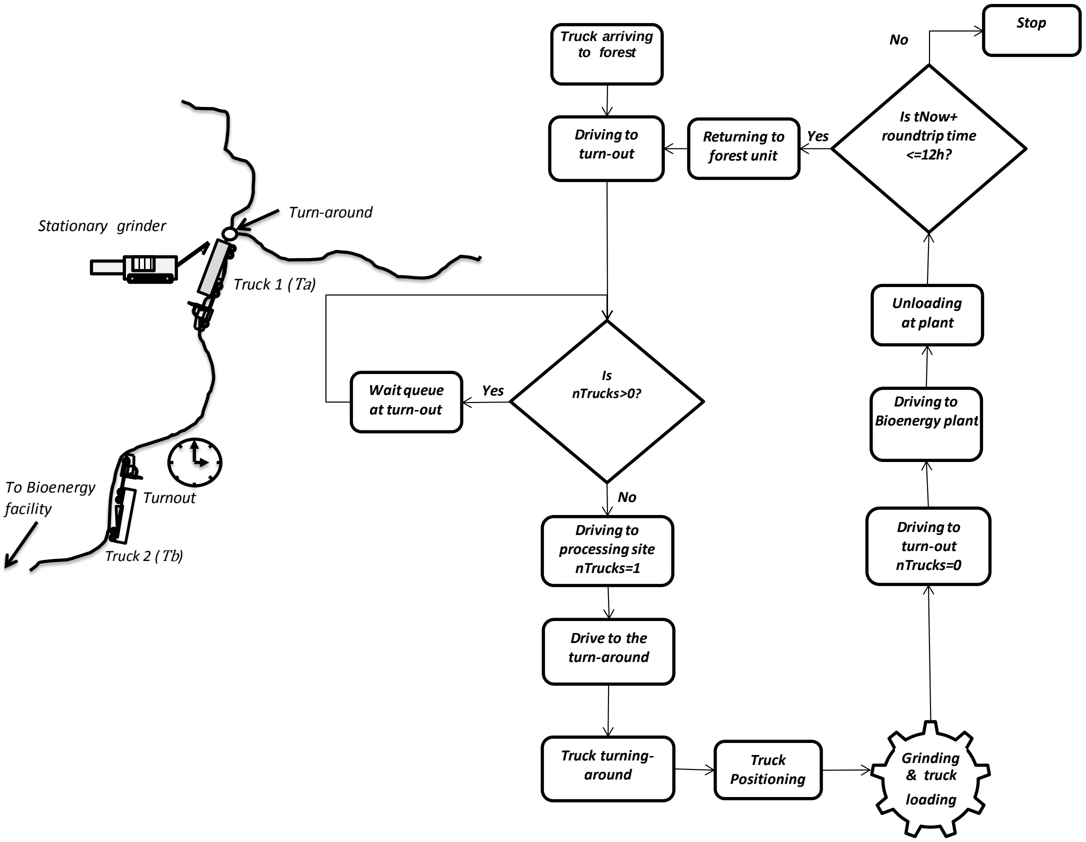

Figure 3.2 Case I model, in-road loading and turn-around located after processing site

The truck turn-around is located beyond the processing point. For this case, the waiting time of a truck arriving to the grinding site while another truck is being loaded is a function of the loading time (based on grinder hourly productivity), the time the loaded truck spends driving to the turn-out and the time between the truck arrivals for the first arrival of the day (Eq. 3.1) . Eq. 3.2 states that truck inter-arrival times must not be greater than the processing time plus the time the loaded truck spent driving between the grinder and the turnout location. This constraint allowed us to isolate the effect of road access as the limiting factor of grinding productivity. It provides an estimate of the highest grinder utilization rate possible (upper limit) considering road access availability. The truck inter-arrival time constraint only applies to the first arrival of the shift. Subsequent truck arrivals depend on the time consumed as a function of the round-trip distance, travel time on the road system, unloading time at the bioenergy facility, working shift duration and truck arrival queuing time (if any). These additional factors may reduce grinder utilization below the upper limit, but are beyond the scope of this study.

Grinder waiting time (Eq. 3.3) is dependent upon: (i) the time the loaded truck is traveling from the grinder location to the turn-out (where the empty truck is waiting); (ii) the time that the arriving empty truck spends traveling from the turn-out to the turn- around; (iii) the time that the empty truck spends turning around; (iv) the time the empty truck spends driving from the turn-around to the grinder location; and (v) the time the empty truck spends positioning at the grinder location.

$$W_t = P_t + Ta_{gn} - A_t \qquad (3.1)$$

$$A_t \leq P_t + Ta_{gn} \qquad (3.2)$$

$$G_t = Ta_{gn} + Tb_{na} + Tb_a + Tb_{ag} + Tb_g \qquad (3.3)$$

where

W_t	arriving empty truck waiting time while another truck is being loaded, (h)
P_t	processing time for a truck load, (h)
Ta_{gn}	the time the loaded truck is traveling from the grinder location, *g*, to the turn-out, *n*, (h)
A_t	Truck inter-arrival time based on the number of trucks at the beginning of the shift, (h)
G_t	grinder waiting time, (h)
Tb_{na}	time that the empty truck spends travelling from turn-out, *n*, to the turn-around, *a*, (h)
Tb_a	time that the empty truck spends turning-around on turn-around, *a*, (h)
Tb_{ag}	time that the empty truck spends travelling from the turn-around, *n*, to the grinder , *g*, (h)
Tb_g	time that the empty truck spends positioning at grinder location , *g*, (h)

3.3.4 Case II: Stationary grinder truck-machine interference with turn-around located before grinder processing site

Case II models a situation where the turn-around is located near the processing site, but off the road so that if a truck is being loaded, a second truck entering to the processing site can stay in the turn-around until the loaded truck passes the point where the turn-around is located (Figure 3.3). We assumed that the turn-around has enough space for one truck to stay out of the road. After the first truck is loaded, the second truck must back up to the grinder location.

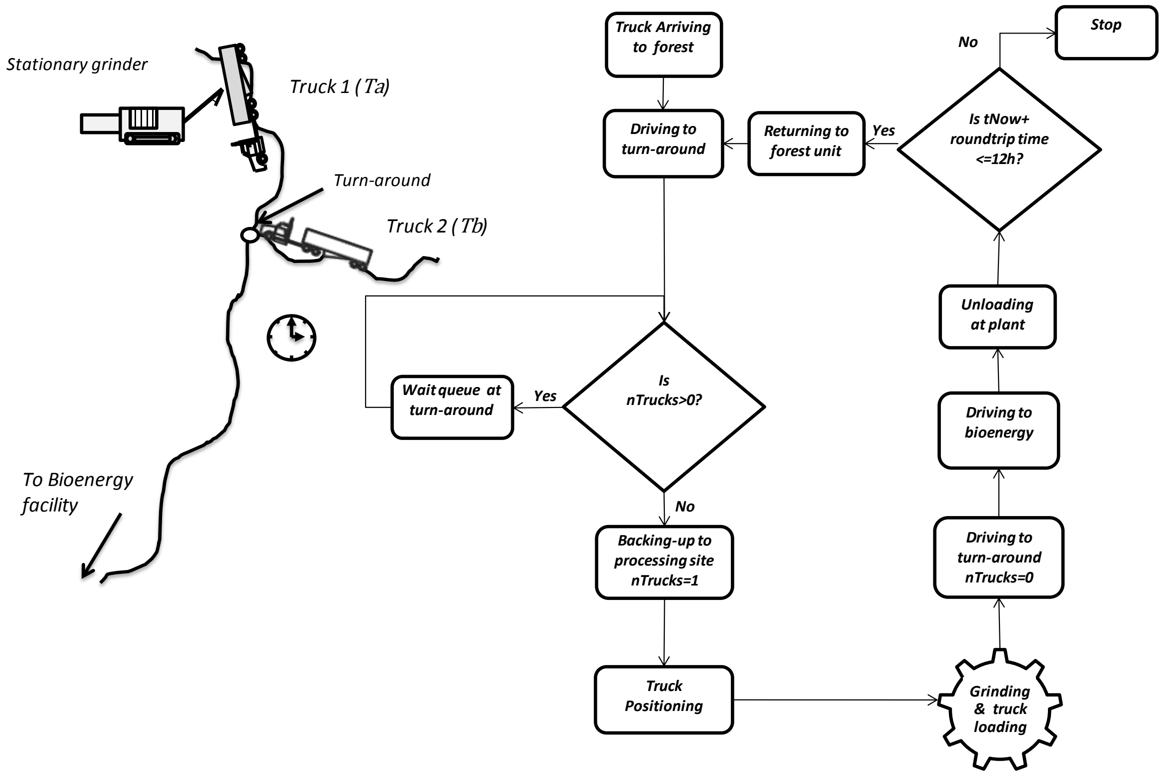

Figure 3.3 Case II, truck-grinder interference, turn-around located before processing site.

Truck waiting time for an incoming truck is a function of the processing time, the time spent by the loaded truck to drive down from the grinder to the turn-around location and the truck inter-arrival time Eq. 3.4. Truck inter-arrival times must be less or equal than the processing time plus the time the loaded truck spends driving to the turn-around (where the empty truck is waiting) Eq. 3.5.

Grinder waiting time is dependent on the time the loaded truck spent traveling from the grinder location to the turn-around, plus the time the empty truck is backing up in direction to the grinder, plus the time for positioning (Eq. 3.6).

$$W_t = P_t + Ta_{ga} - A_t \qquad (3.4)$$

$$A_t \leq P_t + Ta_{ga} \qquad (3.5)$$

$$G_t = Ta_{ga} + Tb_{bg} + Tb_g \qquad (3.6)$$

where

Tb_{bg} time that the empty truck spends backing up to the grinder , *g*, (h)

Ta_{ga} time that a loaded truck spends travelling from the grinder location , *g*, to the turn-around *a* (h)

3.3.5 Case III: Stationary grinder truck-machine interference with off-road truck-loading space

Case III applies to a loop road that illustrates the ideal situation to avoid truck-machine interference. In a one way loop road on steep terrain, no truck turn-around is needed because the uphill and downhill traffic does not transit over the same road (Figure 3.4).

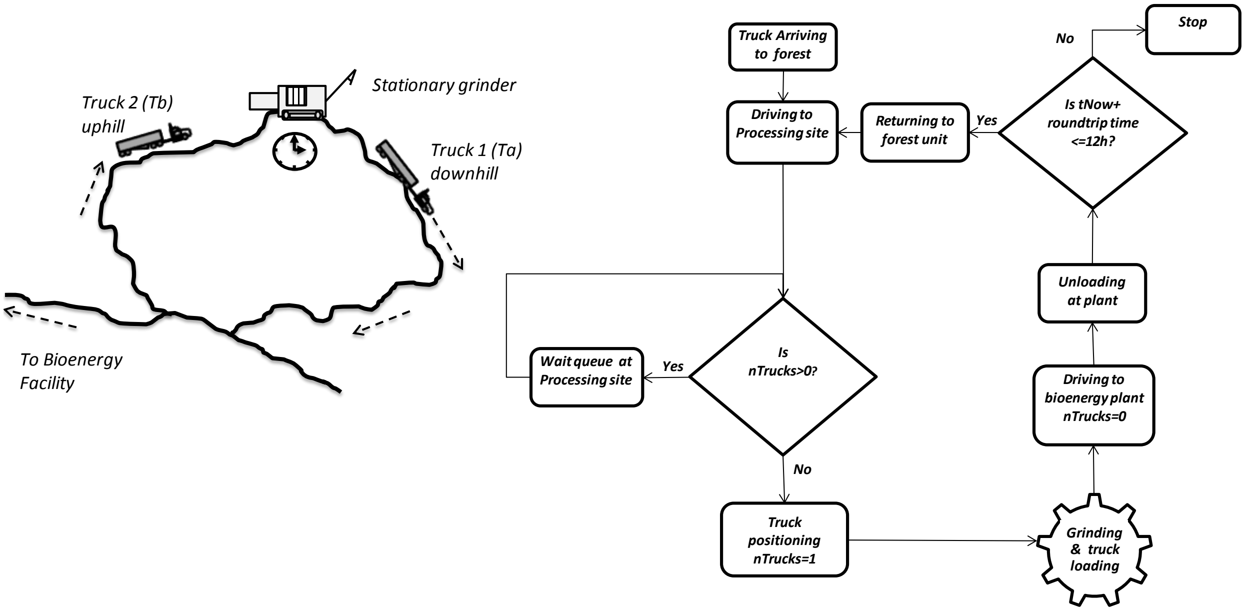

Figure 3.4 Case III, truck-grinder interference, loop road.

The waiting time for a second truck arriving to the unit while the first truck is being loaded is only dependent on the loading time (Eq. 3.7). Inequality 3.8 ensures that a truck will be available for the grinder after a truck is being loaded. Waiting time of the grinder is dependent on the positioning time of the arriving truck (Eq. 3.9).

$$W_t = P_t - A_t \tag{3.7}$$

$$A_t \leq P_t \tag{3.8}$$

$$G_t = Tb_g \tag{3.9}$$

This case also applies to situations where no truck-machine interference exists. Off-road truck loading is a typical example where trucks are able to reach the processing site and form a queue. However these situations are not common on steep terrain road systems, but were added to have a full spectrum of potential scenarios.

3.3.6 Economic model

We developed an economic model to estimate the costs of processing and transporting forest biomass from residues using two sizes of stationary grinders and three truck-trailer configurations. The processing equipment and transportation options were selected from actual field operations in Washington and Oregon, USA. We modeled the economics of a Peterson 4710B (522 kW) and a Peterson 5710C (783 kW), both track-mounted and horizontal grinders. Transportation configurations modeled were two types of 6x4 truck-trailer combinations and one 6x6 truck-trailer combination. One 6x4 truck was equipped with a 7.62 m long trailer with a capacity of 13.6 tonnes. The other truck was equipped with a 13.72 m long trailer with a capacity of 21.7 tonnes. The all-wheel drive truck (6x6) was equipped with a hydraulic rear-steer axle 14.6 m long trailer with a capacity of 24.5 tonnes.

We estimated the hourly costs for situations when the grinder or truck were either operating or waiting. Operating costs for processing and transportation were calculated based on fixed cost, variable costs and profit and risk.

Fixed costs (Eq. 3.10) for processing and transportation were calculated based on: (i) purchased price (table 3.1); (ii) machine life (5 years, 7500 productive machine hours for the grinders and 8 years or 1.2 million km for trucks); (iii) annual depreciation (calculated using straight line depreciation method based on 20% of salvage value); (iv) interest cost (10% of average yearly investment); (v) insurance and road usage permits (10% of average yearly investment for trucks and 5% for the grinders). We assumed a total of 1500 productive machine hours per year for the grinders and 2000 productive hours for the trucks. All equipment was assumed to be purchased new.

The hourly variable cost for processing (Eq. 3.11) consisted of: (i) labor ($45,000/year) and benefits (35% of annual salary); (ii) fuel, (102 lt/h for the 4710B and 113 lt/h for the 5710C); (iii) lubricants (36% of fuel cost); (iv) grinder bits (22 bits with a size of 7 x 12.7 cm for the 4710B grinder with an average expected life of 58 h; and 20 bits with a size of 7.6 x 16.5 cm, for the 5710C with an average expected life of 48 h); and (v) general repair and maintenance (50% of annual depreciation cost). Grinder loading was by a hydraulic knuckle boom loader on a tracked carrier.

Supporting equipment consisted of one water truck and one service-operator truck. Overhead cost includes, supervision, communication equipment and office support.

The transportation hourly variable cost (Eq. 3.12) consisted of: labor ($37,770/year) and benefits (35% of annual salary); fuel cost, based on the travel speed (average truck speed loaded or unloaded was set to 70 km/h on paved roads; 15 km/h on gravel roads; and 10 km/h on dirt roads) and tractor-trailer weight (loaded and unloaded) on different road surfaces (paved, gravel, dirt). We calculated the power necessary to overcome rolling and air resistance forces. We assumed that rolling resistance increased on gravel and dirt surfaces (coefficient of 0.013 in paved; 0.020 in gravel and 0.021 in dirt). We assumed an air density of 1.22 kg/m^3 and a drag coefficient of 0.8 for air resistance force calculations. Average frontal area of the truck was assumed to be 9.29 m^2. Tire cost was calculated assuming a tire life of 96,000 km. Lubricants were calculated as a percentage of fuel costs (36%). Repair and maintenance were calculated as a percentage of depreciation annual cost (70%). Overhead cost was calculated based on one dispatcher, communications and office consumables.

$$F_m = (d_m + i_m + t_m) / H_y \qquad (3.10)$$

$$V_g = f_g + l_g + b_g + k_g + r_g + x_g + k_g + s_g + o_g \qquad (3.11)$$

$$V_t = f_{ijr}^t + l_t + w_t + b_t + r_t + o_t \qquad (3.12)$$

where

F_m hourly fixed cost of machine m, ($/h),

d_m	annual depreciation cost of machine m, ($),
i_m	annual interest (finance) cost of machine m, ($),
t_m	annual insurance and taxes cost for grinder m, ($),
H_y	annual productive machine hours, (h),
V_g	hourly total variable cost of grinder type g, ($/h),
f_g	hourly fuel cost of grinder type g, ($/h),
l_g	hourly labor cost of grinder type g, ($/h),
b_g	hourly lubricants cost of grinder type g, ($/h),
x_g	hourly cost of loader for grinder type g, ($/h),
k_g	hourly bits, cost of grinder type g, ($/h),
r_g	hourly repair and maintenance cost of grinder type g, ($/h),
s_g	hourly supportive equipment cost of grinder type g, ($/h),
o_g	hourly overhead cost of grinder type g, ($/h),
V_t	hourly total variable cost of truck type t, ($/h),
f_{ijr}^{t}	hourly fuel cost of truck type t traveling from *i* to *j* on surface road *r*, ($/h),
l_t	hourly labor cost for truck type t, ($/h)
w_t	hourly tire cost for truck type t, ($/h)

b_t	hourly lubricants cost for truck type t, ($/h)
r_t	hourly repair and maintenance cost for truck type t, ($/h)
o_t	hourly overhead cost for truck type t, ($/h)

Additionally, we added a profit and risk cost for the grinder and trucks, that was calculated as a percentage (10%) of total fixed and variable cost.

Waiting costs for transportation and processing were calculated based on the waiting time caused by truck-machine interference. We assumed that no fixed cost existed when a truck or grinder was not operating, i.e., machine productive life was not being shortened when the machine is not operating. Total hourly waiting cost was limited to labor, supporting equipment, and overhead costs. Profit and risk cost (when the truck or machine is operating) was also included in the waiting cost estimation, to account for the opportunity cost of loss of productivity while waiting. Eq. 3.13 for grinders and Eq. 3.14 for trucks show the estimation of waiting costs.

$$Wc_g = l_g + s_g + o_g + pr_g \tag{3.13}$$

$$Wc_t = l_t + o_t + pr_t \tag{3.14}$$

where

Wc_g	hourly waiting cost for grinder type g, ($/h)
Wc_t	hourly waiting cost for truck type t, ($/h)
pr_g	hourly profit and risk for grinder type g, ($/h)

pr_t hourly profit and risk for truck type t, ($/h)

Operating and waiting cost for the selected equipment are shown on Table 3.1 for processing options and Table 3.2 for transportation.

Table 3.1 Operating and waiting costs for processing machinery.

Cost category	Operating cost		Waiting cost	
	Grinder 4710 B	Grinder 5710 C	Grinder 4710 B	Grinder 5710 C
Fixed costs				
Purchase price ($)	515,000	700,000		
Depreciation, ($/h)	54.93	74.67	-	-
Interest , ($/h)	23.35	31.73	-	-
Insurance and taxes, ($/h)	17.17	23.33	-	-
Annual productive machine hours, (h)	1,500	1,500	-	-
Hourly fixed machine cost, ($/h)	95.45	129.73	-	-
Variable costs				
Labor, ($/h)	33.75	33.75	33.75	33.75
Bits, grates and anvil cost, ($/h)	18.68	21.88	-	-
Repair and maintenance, ($/h)	27.47	37.33	-	-
Grinder Fuel Cost, ($/h)	108.00	120.00	-	-
Lubricants cost, ($/h)	38.88	43.20	-	-
Loader cost, ($/h)	102.89	102.89	-	-
Supporting equipment, ($/h)	14.80	14.80	14.80	14.80
Overhead cost, ($/h)	21.08	21.08	21.08	21.08
Hourly variable costs, ($/h)	365.54	394.94	69.63	69.63
Profit and risk 10%, ($/h)	46.10	52.47	46.10	52.47
Total hourly cost, ($/h)	507.09	577.14	115.73	122.10

Given that the hourly transportation fuel cost changes with the traveled distance in each road surface, we assumed an average transportation cost for a round-trip distance of 120 km (100 km on paved, 16 on gravel and 4 on dirt roads) for illustration purposes in Table 3.2.

Table 3.2 Operating and waiting costs for transportation options. Standard trailers were pulled by 6x4 truck tractors, the rear steer-axle was pulled by a 6x6 truck tractor.

Category	Operational cost by trailer type			Waiting cost by trailer type		
	Standard 7.62 m	Standard 13.7 m	Rear steer-axle 14.63 m	Standard 7.62 m	Standard 13.7 m	Rear steer-axle 14.63 m
Fixed costs						
Purchase price tractor-trailer, ($)	100,000	180,000	300,000			
Depreciation, ($/h)	4.64	8.24	14.70		-	-
Interest ($/h)	3.23	5.81	9.74		-	-
Insurance and taxes ($/h)	3.23	5.81	9.74		-	-
Annual productive machine hours (h)	2,000	2,000	2,000		-	-
Hourly fixed cost ($/h)	11.10	19.86	34.17		-	-
Variable costs						
Labor, ($/h)	23.18	23.18	27.61	23.18	23.18	27.61
Tire cost, ($/h)	6.41	6.41	9.50		-	-
Repair and Maintenance, ($/h)	3.25	5.77	11.76		-	-
Fuel & Lubricants, ($/h)	23.87	29.08	32.83		-	-
Overhead cost, ($/h)	6.70	6.70	6.70	6.70	6.70	6.70
Hourly Variable cost ($/h)	63.40	71.14	88.40	29.88	29.88	34.31
Profit and Risk 10% ($/h)	7.45	9.10	12.26	7.45	9.10	12.26
Total Hourly Cost ($/h)	81.96	100.10	134.83	37.33	38.98	46.57

3.3.7 Model applications

We compared model outcomes to actual recovery operations in western Oregon and Washington, USA, for each of the proposed cases. The model was then used to minimize the cost of the operation and improve productivity by reducing truck-grinder interference. We used the same actual operational parameters in each operation, as model inputs. Grinder utilization and economics were evaluated and optimized as a function of the number of trucks required to minimize processing and transportation cost of the operation. After the optimization, we evaluated the effect of road accessibility in grinder utilization as the limiting factor for each case.

For case I, the analysis was performed in a harvest unit located about 78 km west of the city of Port Angeles in northern Washington, United States (48°14’43”N, 124°12’ 41’’W). Forest residues were processed in the field and transported to a bioenergy facility. The unit was characterized by steep, single passage roads (Figure 3.5). Paved highway distance from the bioenergy facility to the entrance of the unit was 65 km. The distance from the entrance of the unit to the processing site (stationary grinder location) was 13.65 km (12.65 km of gravel road and 1 km of dirt road). Maximum road grade in the internal forest road was an adverse grade of 16% for the unloaded truck. Distance from the turn-out (truck waiting point) to the turn-around site was 1.05 km. Distance from the grinder to the turn-around was 50 m.

A Peterson 5710C was used to process the residues. The shift duration was ten scheduled machine hours. This included 9.25 productive machine hours and 45 minutes of daily scheduled downtime. Thirty minutes were allocated for cleaning and maintenance and 15 minutes for engine warm-up. Two 6x6 trucks, each equipped with a rear-steer axle 14.6 m long (24.5 t of capacity) trailer, were used to transport the processed residues. Based on the time field test, we calculated an average truck loading time of 27.61 minutes (53.24 t/productive machine hour) in the study unit. Truck turn-around time and truck positioning at the processing site were each fixed at 5 minutes. Unloading time at the mill was estimated to be 30 minutes per truck.

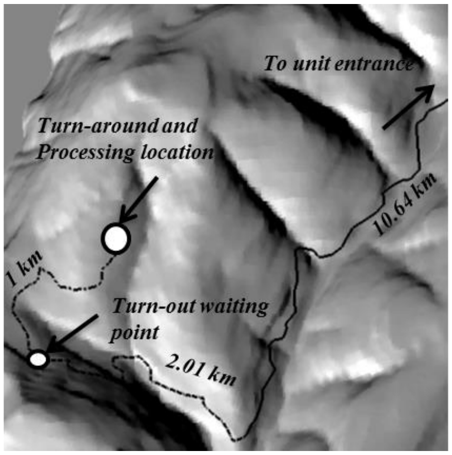

Figure 3.5 Road access and processing location for study site Case I.

Case II was analyzed and modeled in a harvest unit located 19.2 km south of the city of Cottage Grove, Oregon, United States, (43°39’56”N, 122°57’15’’W). Distance on paved road from the entrance of the unit to the bioenergy facility was 60.5 km. Distance on gravel road from the entrance of the unit to the turn-around was 5.8 km. Turn-around to grinder location distance was 60 m. Maximum road grade found in the gravel road network was and adverse grade of 8% for the unloaded truck (Figure 3.6).

A Peterson 4710 B (522 kW) was used to process the residues. Three trucks, each equipped with a 13.72 m long trailer with a capacity of 21.7 tonnes, were used to transport biomass the material to a co-generation plant for electricity production. Average in-field loading time was 22.38 minutes. We used the same values estimated in Case I for the time the trucks spent turning-around, positioning and unloading at the mill. Truck backing speed was 3 km/h.

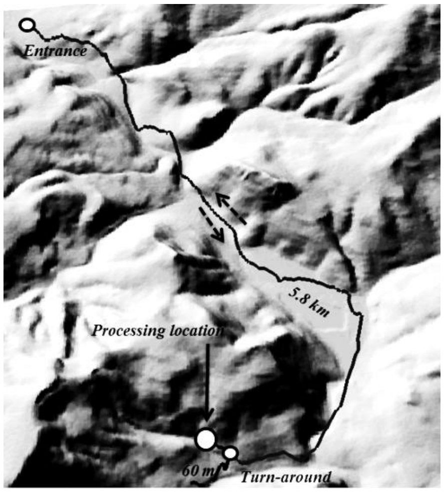

Figure 3.6 Road access and processing location study site Case II.

Case III was evaluated in a forest operation located 6 km from the city of Rockaway, Oregon, United States (45°34’51”N, 123°54’ 36’’W). Processed material in this unit was transported using two short trucks (7.62 m long and a capacity of 14.5 tonnes) to a transfer yard where the product was dumped and loaded into long trucks

(16.15 m long with a capacity of 27 tonnes). Since our study is focused on the truck-grinder interference, we analyzed cost of processing and transport until the material was dumped in the transfer yard. The processing site was located at the top of the harvest unit. Uphill gravel road distance from the entrance of the unit to the grinder location was 6.72 km. Downhill gravel road distance from the grinder to the exit of the unit was 6 km. A maximum road grade of 12% was found on the uphill gravel road. Distance on paved road from the exit to the transfer yard was 8.48 km (Figure 3.7). A Peterson 4710B was used to process the material. Estimated grinder processing time per truck was 18.65 minutes (46 t/productive machine hour).

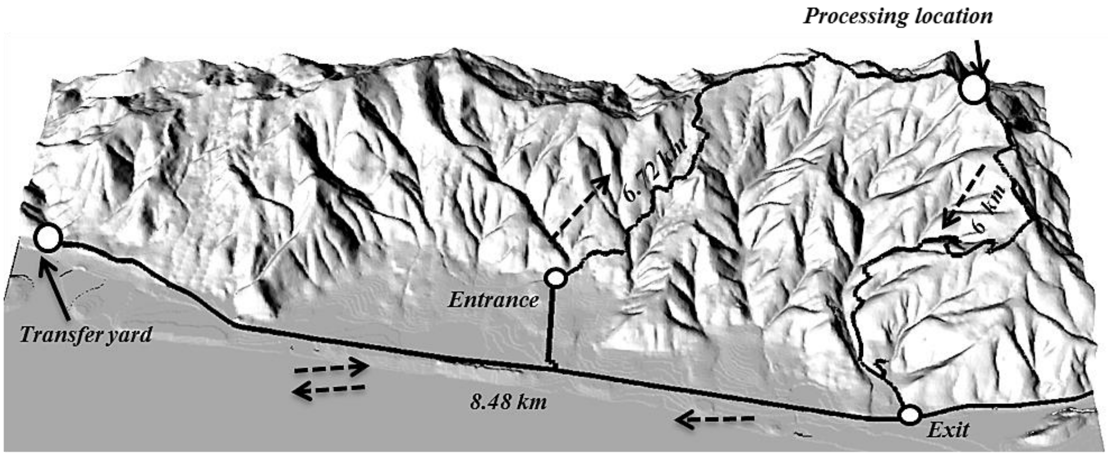

Figure 3.7 Road access and processing location for the study site Case III.

3.4 Results and discussion

3.4.1 Case I

In this case, after a truck is loaded, the grinder must wait for the next truck to arrive. While empty trucks are available, grinder waiting time is dependent on the road characteristics. We calculated the time elements necessary to estimate grinder waiting time (Table 3.3). Grinder waiting time was calculated using Eq. 3.3. The grinder had to wait 22.9 minutes per load due to the effect of the distance between the turn-out and the grinder location. Adding the grinder waiting time to the actual loading time (27.61 min), gives an estimated total cycle time of 50.5 minutes including the grinder waiting time between truck arrivals (if trucks are available).

Table 3.3 Time elements to estimate grinder waiting time in Case I.

Truck type	From	To	Distance (km)	Time spent (min)
Truck out, (Ta_{gn})	Grinder	Turn-out	1.00	6.00
Truck in, (Tb_{na})	Turn-out	Turn-around	1.05	6.30
Truck in, (Tb_{a})	Turning-around	-	-	5.00
Truck in (Tb_{ag})	Turn-around	Grinder	0.05	0.60
Truck in, (Tb_{g})	Positioning	-	-	5.00
Grinder waiting time				22.90

The actual operation used two trucks to transport the processed forest biomass. The results shows that the grinder was utilized only 20% (4 loads per day of 24.5 tonnes each) of the potential productive time. We calculated the total costs per bone dry metric tonne (BDMt) of processed residues, assuming average moisture content of 30% wet basis (Briggs, 1994). Processing (grinding) cost accounting for waiting time was estimated at $31.01/BDMt. Grinder waiting cost accounted for 46% ($14.01/BDMt) of the total processing cost. Transportation cost was $26.42/BDMt.

The effect of number of trucks on the utilization rate was analyzed by modeling different scenarios varying the number of trucks from one to ten. We assumed that trucks worked a minimum 8 hours and a maximum of 12 hours. Truck first inter-arrival time was assumed to be equal to the processing time plus the time the loaded truck traveled from the grinder location to the turn-out. This guaranteed that grinder and truck arrival waiting time were minimized (in the case of the grinder it only applied if empty trucks were available).

Adding more trucks, could minimize grinder waiting time but road characteristics need to be considered. Maximum grinder utilization rate was 60% (12 loads per day), using 6 trucks (Figure 3.8). Adding more than 6 trucks did not increase the grinder utilization because the system became limited by road access. Adding more trucks might also lead to more congestion at truck arrival, increasing the round-trip time. Some trucks were not fully utilized because they are not be able to achieve the minimum working hours. Total cost decreased 38% due to an increase in the grinder utilization from 10% (one truck) to 60% (6 trucks).

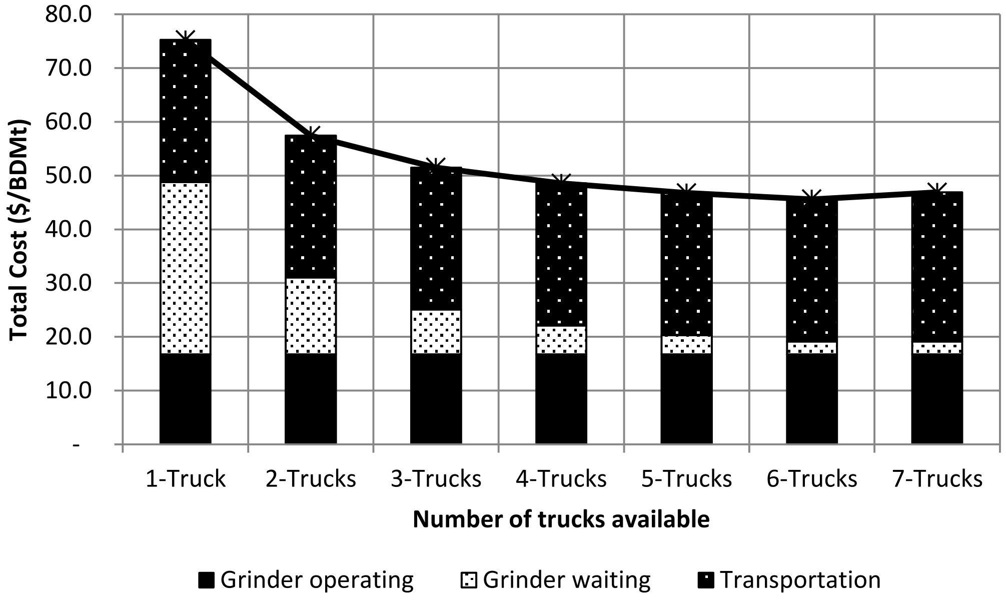

Figure 3.8 Total cost of forest biomass processing and transport for study site Case I. Cost are expressed in US dollars per bone dry metric tonne.

Distance from the turn-out to the processing site greatly affected grinder utilization, accounting for 54% of the total waiting time per cycle due to road accessibility. The economic effect of changing distance between the turn-out to the processing site was analyzed. We made a sensitivity analysis varying the turn-out-processing site distance from 0.5 km to 10 km, the distance to the bioenergy facility was keep constant. Six trucks were used in the model in order to isolate the effect of road accessibility as the limiting factor. All other inputs remained the same. The cost increased by $33.2/BDMt when the turn-out to grinder distance is increased from

0.5 km to 10 km (Figure 3.9). This difference in cost can be used to assess the potential benefits of building a truck turn-out closer to the grinding site or increasing the grinding site area to allow off-road truck loading.

Figure 3.9 Sensitivity of total cost to changes in truck turn-out-grinder distance, study site Case I.

3.4.2 Case II

For the actual operational conditions in Case II (5 trucks, 10 loads of 21.7 tonnes each per day), the grinding utilization rate was 60%. Processing cost was estimated as $19.14/BDMt and transportation was $26.46/BDMt. Results for the operation indicated that seven trucks minimized total processing and transportation costs (19 loads of 21.7 tonnes each per day). Maximum grinder utilization was estimated to be 77%. Although adding one more truck increased grinder utilization rate (81%), the extra truck was not fully utilized and the queuing time at arrival was higher (Figure 3.10). This increased the overall transportation cost and minimizing the net gain. Grinder waiting time due to road accessibility was 6.56 min per cycle (Table 3.4).

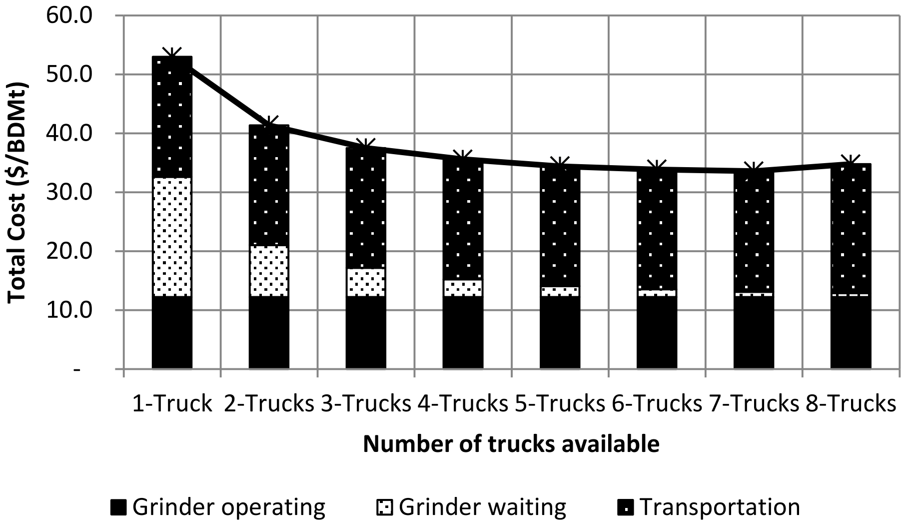

Figure 3.10 Total cost of forest biomass processing and transport for study site Case II

In Case II, after the number of optimal trucks was reached, the system became limited by the time that the in-coming truck spent backing up and the time the loaded truck spent traveling from the grinder to the turn-around location. Truck backup time depended upon the distance from the turn-around to the grinder location, and the average backup speed (3 km/h).

Table 3.4 Time elements to estimate grinder waiting time in Case II.

Truck type	From	To	Distance (km)	Time spent (min)
Truck out, (Ta_{ga})	Grinder	Turn-around	0.06	0.36
Truck in, (Tb_{bg})	Turn-around	Grinder	0.06	1.20
Truck in, (Tb_{g})	Positioning	-	-	5.00
Grinder waiting time				6.56

To illustrate the effect of the backup distance we made a sensitivity analysis changing the backup distance from 50 to 500 m. Based on the results, costs increased by \$3.7/BDMt when changing the distance from the turn-around to the grinder increased from 50 to 500 m (Figure 3.11)

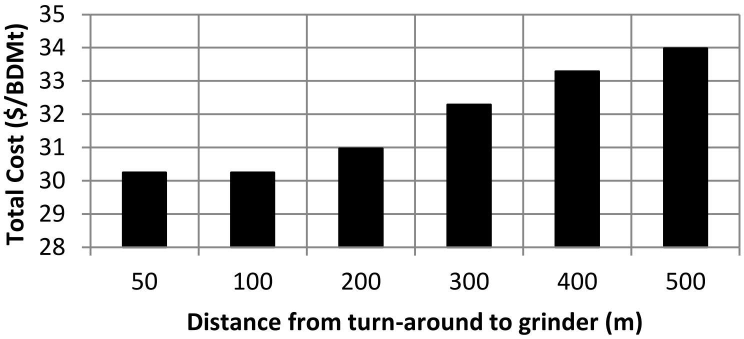

Figure 3.11 Cost sensitivity to changes in turn-around to grinder distance study Case II.

3.4.3 *Case III*

Actual grinder utilization rate using two trucks was 40%, with a processing cost of \$20.73/BDMt and a transportation cost of \$21.76/BDMt. The most cost-effective number of trucks for this unit was four (24 loads of 14.5 tonnes each). The maximum grinder utilization rate was 74%. Adding one more truck increased utilization rate to 81%, but the increased truck queuing time and the underutilization of some units raised the transportation costs, causing an overall increase in the total costs (Figure 3.12).

If truck positioning was the only factor limiting grinder utilization, we estimated that the grinder could be utilized at a maximum of 84%. The rest of the time the grinder has to wait for the truck to be positioned. We used a value of 5 minutes for positioning, but this value could vary according to the experience of the driver and the maneuver difficulty in relation to the road and grinder position. In any case this can have a significant effect on grinder productivity as the number of loads per day increases.

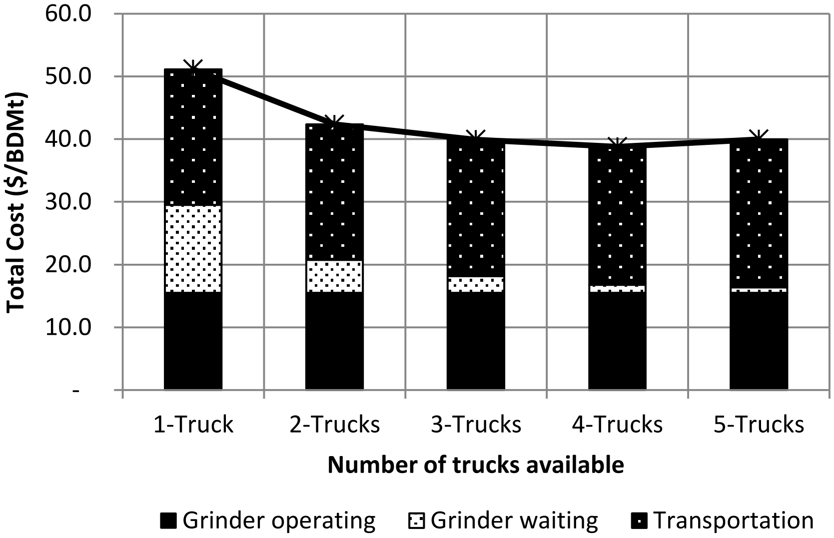

Figure 3.12 Total cost of forest biomass processing and transport for study site Case III

3.4.4 *Summary of results*

Results from the three grinding sites show how truck-machine interferences affect the economics of processing and transport. Waiting cost for processing and transportation were estimated using labor, supporting equipment, overhead and profit and risk (when operating) costs. Grinder utilization rate was dependent on the number of available trucks and road accessibility conditions. As optimal truck number for each unit was reached, the system became limited by the road access characteristics expressed in each of the three cases (Figure 3.13). The maximum grinder utilization rate reached 81% for Cases II and III. However, maximum utilization rate did not necessarily indicate that the minimum cost of processing and transportation was achieved.

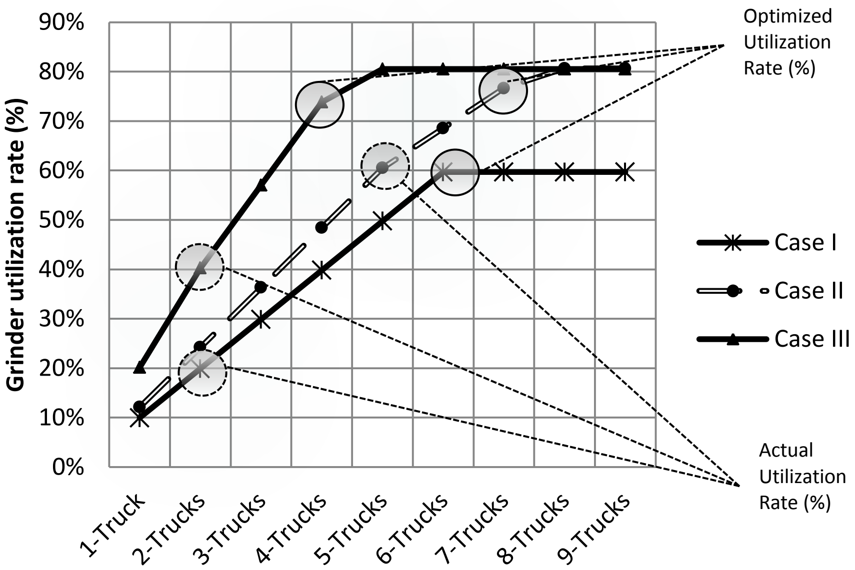

Figure 3.13 Effect of number of trucks in grinder utilization rate for the three study sites.

The site analyzed for Case I represented the most constrained situation in terms of truck accessibility. With the optimal number of trucks (6), waiting costs represented 13% of total grinding costs. For Case II results from the model indicated that optimal number of trucks was seven. Grinder waiting cost accounted for 7% of total grinding costs. In Case III, although a maximum grinder utilization of 81% was found using five trucks, the increase in transportation cost caused by truck queuing time and truck underutilization, impacted the gain resulting in an optimal number of 4 trucks (74% of utilization rate).

Under actual operational conditions at the three field sites the number of trucks was the limiting factor. Specific reasons were given by each of the managers to explain the lack of trucks. In Case I, only two trucks were assigned to the unit because the local bioenergy facility accepted a specific quota of biomass per day. In Case II only five trucks were used because the local trucking companies were unable to provide more than five trucks. In Case III the contractor only owned two trucks that were designated to the operation.

A summary of the optimized number of trucks and potential economic savings are shown on table 3.5. Although Case III was least constrained in terms of road access characteristics, it was still affected by waiting time caused by the truck positioning. Case II reported the minimum cost savings of the three cases since the number of trucks used in the actual operation (5) was close to the optimal (7) predicted by the model.

Table 3.5 Summary of results for the three cases.

Category	**Case I**	**Case II**	**Case III**
Assumed moisture content (%)	30	30	30
Grinder Productivity BDMt/productive machine hour	37.3	45.04	36.09
Actual number of trucks	2	5	2
Optimized number of trucks	6	7	4
Actual grinding cost ($/BDMt)	31.01	14.26	20.73
Optimized grinding ($/BDMt)	19.14	13.28	16.74
Actual grinder waiting costs as percentage of grinding cost	46	13	25
Optimized grinder waiting costs as percentage of grinding cost	13	7	5
Actual transportation cost ($/BDMt)	26.42	20.36	21.61
Optimal transportation ($/BDMt)	26.46	20.48	22.02
Savings from optimized solution ($/BDMt)	11.83	0.86	3.58
Saving in as a percentage of total (%)	20.60	2.50	8.46

3.5 Conclusions

We developed three simulation models and analyzed three actual in-field grinding sites that illustrated the economic effect of truck-machine interaction on biomass processing and transport operations. A considerable amount of the variability in forest residue processing costs was explained by understanding truck-grinder interactions. Truck-grinder interference affected grinder productivity in two ways. One is produced by the lack of trucks to keep the grinder producing. The other occurs when road accessibility characteristics limit the amount of truck that can reach the processing site at the same time. The model provides to the analyst a method to estimate the potential waiting times for the grinder and produce an accurate utilization rate at the operational level. In addition, the model allows the analyst to simulate different scenarios and analyze the sensitivity of a specific site to particular factors as number of trucks, truck size, grinder productivity, and road characteristics.

The model can also be used by contractors to assess the potential economic losses of operating in difficult access areas. Based on the results of the model, operating at a site with the characteristics expressed in Case I would cost more compared to sites that have the characteristics of Cases II and III. If the number of trucks is not the limiting factor, Cases II and III must be preferred to avoid significant productivity reductions.

In our model we assumed that the forest residue piles were made before the grinding operations. However, if piling and processing activities are performed at the same time, the time spent waiting by the grinding operation can be beneficial, if the waiting time is large enough to allow the loader to work on piling. Future analysis will be needed to analyze the potential economic trade-offs of the waiting times to pile the material.

The model is designed to be applied at the forest residue pile level. In a typical unit with different piles of residues, the model can be used to evaluate grinder utilization rates at each residue pile and also to estimate the economic feasibility of processing some piles with difficult road access. All forest residue piles do not need to be processed and transported. Currently only a small fraction of residues are utilized while most are burned. Given the limited value of forest residues, careful cost management is needed to create successful businesses. Future research will incorporate this model into a complete decision support system that will optimize forest biomass processing and transport at the harvest unit level.

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CHAPTER 4

ECONOMIC OPTIMIZATION OF FOREST BIOMASS PROCESSING AND TRANSPORT

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4.1 Abstract

A model based on mixed integer programming (MIP), Geographic Information Systems (GIS), simulation and forest operation analysis is presented to economically optimize the processing and transportation of forest biomass from residues for energy purposes. The model is incorporated in a computerized decision support system Reside Network Optimization (RENO) and estimates the optimal mix of methods and equipment for conducting forest biomass recovery operations given a residue assortment, road and landing access and product deliverables. The problem to be solved is classified as a special case of multi-commodities, multi-facilities problem. The solution procedure represents the problem as a network and properly defines the possible arcs, nodes and their cost. At each point of comminution, different types of equipment can be used depending on the site characteristics and spatial location of the residues. Similarly not all tractor-trailer configurations can reach all forest residue locations. Some processing operations are closely coupled to transportation and others are not. The decision in this problem is what volume of residue type *x*, at each forest location, *w*, will be processed in location *z*, by equipment type *m* and transported by a truck type *t* in order to minimize total processing and transportation costs subject to road accessibility, centralized yard availability, truck turn-arounds, truck turn-outs. Costs in the network are calculated with the support of a simulation model to account for truck-machine interactions. The model is designed to give support to forestry managers, landowners and contractors at the operational level.

Keywords: Mixed Integer Programming, forest biomass, economics, optimization.

4.2 Introduction

In the last decade, considerable interest has been dedicated to the exploration of alternative sources of energy to decrease the dependency on fossil fuels. Energy production from forest residues represents a technically a feasible option for liquid fuels and electricity production. In the United States it is estimated that nearly 40 million dry metric tons of logging residues are produced annually (US Department of Energy 2011). The Northwest Advanced Renewables Alliance (NARA) is a group of public universities, government laboratories and private industry formed to develop a jet fuel supply chain from forest residues (NARA 2011). The NARA project is focused on jet fuel as aircraft cannot fly using other sources of renewable energy such as electric batteries, nuclear energy, or solar cells (US Department of Agriculture 2012).

Forest residues consist of a mixture of pieces of varying diameters and length that do not meet the specifications of timber or pulp markets. Historically, logging residues have been piled and burned in order to prepare harvested areas for replanting. New smoke control regulations as well as risk of fires have increased the interest in residue handling techniques that can produce revenue rather than cost. Forest residues have no competing uses, and require the use of expensive equipment to process the material and transport it to a bioenergy facility. Cost efficiency in processing and transportation is a key factor to ensure the economic sustainability of this emerging supply chain.

For energy purposes, logging residues need to be mechanically reduced in particle size using a chipper or a grinder (Staudhammer et al. 2011). Forest residues can be processed at the forest, at a centralized yard or at the bioenergy facility. If the forest residues are processed in the bioenergy facility, the loose material must be packaged and transported to the facility. If the material is processed in the forest, grinder or chippers must be placed close to the residues to mechanically reduce the material in size, and trucks have to be available to transport the processed material. Bulk density and moisture content are among the most important variables that have an effect on the processing and transport of the forest residues (Hakkila 2003).

Different systems are available for forest residues processing and transport. Comminution options include mobile and stationary grinders and chippers. Truck options include hook-lift trucks, dump trucks; trucks with trailers (conventional 5th wheel, sliding axle trailers, steerable trailers, stinger-steered trailers, double trailers, live-floor or end dump). Processing and transport operations can be either tightly or loosely coupled. Tightly coupled operations may require elements of equipment scheduling to account for equipment interactions. Among all the feasible options, the forest manager or landowner has to decide which system is most cost effective given road and landing access, material physical properties, pile location, available truck turn-around locations, machine availability, machine performance and product deliverables.

Most of the current literature related to this problem is focused in the optimization of a biomass supply chain at a strategic or tactical level. Van Belle et al.

(2003), presented strategies for supplying coal-fired power plants with forest residues based on three levels of procurement and social and environmental factors. The authors tested different biomass processing systems for each procurement level. Flisberg et al. (2012) developed a decision support system for forest fuel logistics for heating plants in Sweden. The linear programming model considered the use of different processing and transportation technologies. Economic savings were reported at tactical level. Mobini et al. (2011) used discrete-event simulation to investigate the logistics of supplying a power plant with forest biomass. They estimated potential delivered volume and cost to the gate of the plant including the potential carbon emission produced in the process. Roser et al. (2006) developed a decision support system for analyzing forest harvesting and residue recovery options for energy production. Their research described the use of harvesting residues for energy production and potential soil nutrient depletion. Frombo et al. (2009) developed an environmental decision support system to find the optimal plant size, location and technology for power production from woody biomass. A non-linear mixed integer programming model was used as the solution approach. Authors applied the model to a strategic optimization problem in Italy. Although these studies provide support to forest biomass recovery operations, they do not consider factors at the operational level such as road characteristics, pile location, and truck-machine interactions that can have a great impact on the economics of the operation. These factors must be addressed at a detailed level in order to provide effective methods to reduce costs, increase profitability of the operation and ensure viability of the supply chain in the long term.

The main goal of this research is to provide economical and operational decision support to forest managers and landowners for the renewable energy supply chain from forest residues. The general objective of this paper is propose a new methodology that combines simulation, mixed integer programming (MIP) and geographic information systems (GIS) to optimize forest biomass processing and transport economics at the operational level. Specific objectives are: (i) to develop a solution procedure for the economic optimization of forest biomass processing and transport; (ii) to provide accurate estimates of cost effective processing and transportation options given specific operational factors such as pile location, road grade, road standard, turn-around location, truck-machine interference, forest road distances and available technology; and (iii) to develop a computerized decision support system with a graphical user interface to enable analysts to optimize their operation.

The scope of this paper primarily relates to difficult access sites characterized by steep roads and mountainous landscape, although is also applicable to other areas with less restricted road accessibility.

4.3 Problem Description

Different systems for processing and transport are available for forest managers and land owners in the United States. Comminution options include stationary horizontal grinders (electric or diesel), tub grinders, and forwarder-mounted mobile chippers. Short distance in-forest transportation options for unprocessed residues comprise small trucks such as hook-lift trucks, bin trucks and dump trucks. Long distance transportation options include chip vans with different types of tractor-trailer configurations. Trailers vary in length from 9.75 m to 16.15 m. An extension in the bottom center of the trailer (drop-center) increase the capacity of hauling the chips but decreases the ability of the truck to cross vertical curves. Different processing and transportation systems include: (i) stationary grinder at centralized landing with bin, dump or hook-lift trucks; (ii) stationary grinder processing at each pile location; (iii) mobile chipper processing at each pile and loading set-out trailers; (iv) stationary grinder at centralized processing yard with direct discharge into piles; and (v) bundling in forest and grinding or chipping at the bioenergy plant.

4.3.1 System 1: Stationary grinder at centralized landing with short trucks

This system is suitable for sites with difficult access for chip vans. Minimum equipment required is one stationary grinder, two excavators (one to load the grinder and the other to load the hook-lift truck), one hook-lift truck or bin truck, and one chip van. Logging residues are extracted and pre-piled along the road near to the harvest unit. Then, with an excavator, the slash is loaded into small containers (30-40 cubic meters), located along the road or directly to containers on the hook-lift trucks. The containers are trucked to the centralized landing by hook-lift trucks where the residue is processed using a stationary grinder. Finally, the product is conveyor fed or blown into chip vans and transported to the bioenergy plant. A centralized landing represents a location within the forest unit that can be used as processed center, but access is limited to internal forest road characteristics.

Figure 4.1a displays the different stages of this system. The solid black line represents the forest road network that provides good access to the chip van, while the dotted black line represents difficult road conditions only accessible by small trucks. A centralized landing must be located in a strategic location that minimizes the distance between the forest residue piles and provides easy access for trucks pulling chip vans to turn-around and to be loaded.

This system reduces the moving cost performed by a lowboy or “walking” the grinder or chipper between comminution points. Disadvantages are: (a) the bin or hook and lift truck cost, due to its small capacity is highly sensitive to increases in travel distance (between the piles and the centralized yard); (b) hook-lift trucks are usually limited by volume rather than weight due to the heterogeneity and low bulk density of the raw material; (c) determining the optimal location of the centralized landing is a difficult task that involves many choices; (d) few planning tools are available to help forest managers of landowners make these choices; and (e) the necessary area to pile all the residues for the centralized landing may not be available within the unit.

4.3.2 System 2: Stationary grinder with processing at each pile

This system also works around the stationary chipper but no hook-lift trucks or excavators are used to move the material closer because no centralized landing is established. Instead, a stationary grinder moves itself between each pile and processes the material in situ. The use of this system is dependent upon the amount of raw material in each pile. Minimum equipment required for this system is one stationary grinder, one excavator, one lowboy truck available for moving, and one chip van. The different stages of this system can be observed on figure 4.1b.

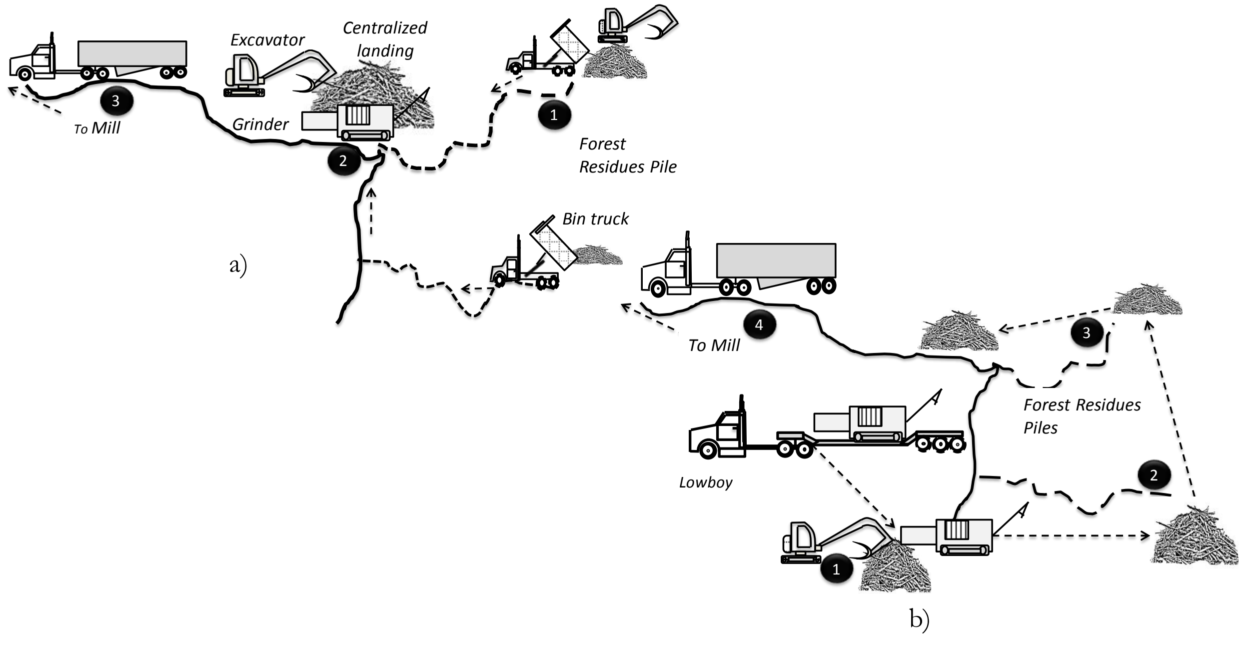

Figure 4.1 System 1 and 2 for processing and transport of forest biomass. a) System 1, stationary grinder at centralized landing and small trucks supplying forest residues. b) System 2, stationary grinder processing the material at each pile. The numbers in the black circles indicate the stages of the process for the system.

Advantages of this system are that it reduces the cost of the operation by eliminating the use of small trucks or an additional excavator. Disadvantages are: (a) a decrease in the overall productivity caused by the machine mobilization time which increases as a function of the distance between piles; and (b) the grinder may not be able to be placed at some piles located in zones with difficult access thus losing potential supply sources.

4.3.3 System 3: Mobile chipper with set-out trailers

In system 3, comminution of residues is carried out with a mobile chipper that moves between the piles to process the material and fill an attached bin. Then, the processed material in the chipper bin is dumped directly into trailers (Figure 4.2). Once the trailers are full (limited by volume or weight) of chips, a highway truck can take them to the bioenergy plant. Minimum equipment required for this system is, one mobile chipper, two trailers and one truck to haul the material to the plant. Advantages of this system are the ability of the mobile chipper to reach different pile locations and the reduced truck dependence produced by the partial decoupling of the comminution process from the transportation. Also the mobile chipper can access piles that are not at road side. Disadvantages of this system are: (a) the residue must be cleaner in relation to the stationary grinders in order to avoid rapid dulling of the chipper knives; (b) the chipper has lower productivity compared to stationary grinders due to a smaller power plant; (c) mobile chipping require the use of higher fixed cost and specialized machinery; (d) part of the time the chipper is not working because of moving between the pile and trailer.

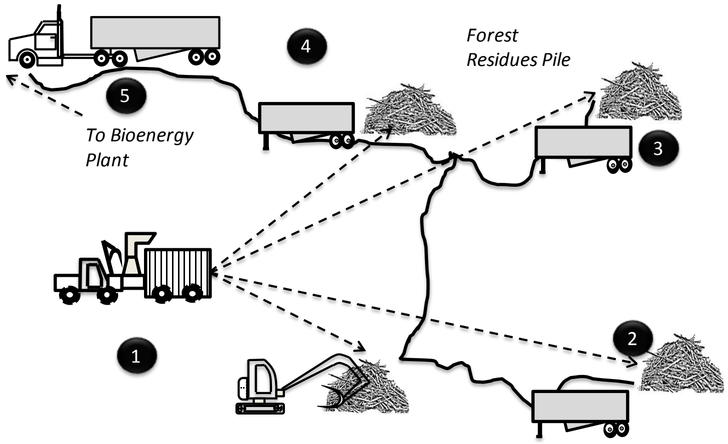

Figure 4.2 System 3, mobile chipper, processing the material at each pile and loading trailers.

4.3.4 System 4: Stationary grinder at centralized yard

This system utilizes a centralized yard than can be located at an easily accessible s place between the forest unit and the bioenergy facility. In differs from all other systems as the stationary grinder is not loading the processed material directly into trailers. Instead, the material is discharged directly into piles. The piled material is then loaded into the truck by a front-end loader. The minimum equipment required for this system consists of one stationary grinder, one bin truck to move the forest residues from the forest to the centralized yard, one front loader, and one chip truck for long distance transportation to the bioenergy facility (Fig. 3).

Advantages of this system are that the processing of the residue is totally decoupled from the long distance transportation, the grinder utilization rate is maximized and truck machine interactions are reduced. Larger trucks can access the area minimizing transportation cost by increasing transported volume per trip and a front-end loader can often load a truck more quickly than a grinder. However, the system is still dependent upon the transport of loose residues from the forest. Operating costs may rise due to the addition of a front-end loader and land rent charges, or legal permits associated with the centralized yard.

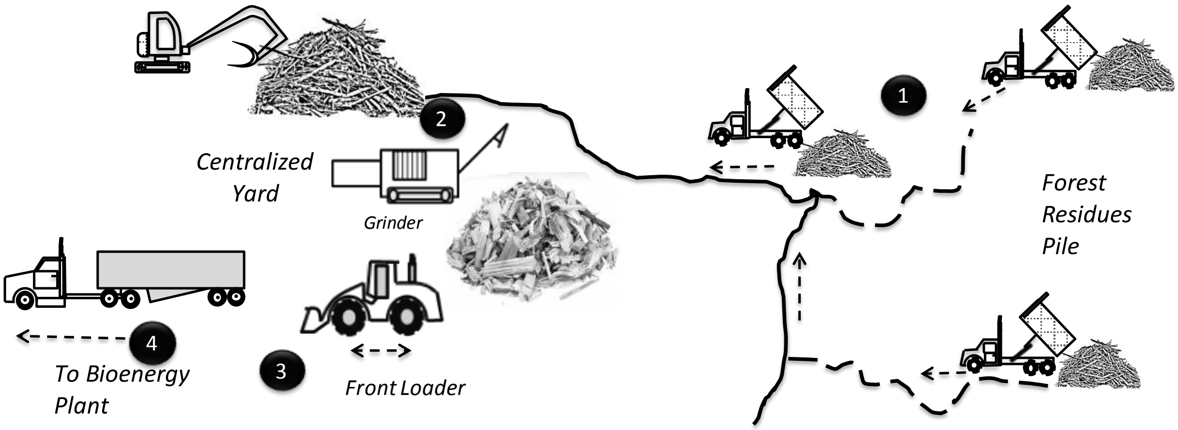

Figure 4.3 System 4, processing at centralized yard out of the forest unit. The numbers in the black circles indicate the stages of the process for the system.

4.3.5 System 5: Bundler in forest and processing at bioenergy plant

System 5, involves chipping or grinding at the end use facility, which normally can be implemented more economically, especially if the grinder is powered by electricity instead of diesel. As an alternative to long distance transport of loose residue material in short trucks, the transport of forest residues can be improved by the use of bundlers to package the material before long distance transportation. A bundler needs to be located in a strategic location within the unit to produce the bundles.

The minimum equipment required for this system is one bundler, one bin truck or excavator, one log truck adapted for the transport of bundles and one electric grinder (Fig. 4). An advantage of this system is that it potentially reduces the processing cost by using electric motors instead of diesel engines, however the savings has to compensate for the cost of bundling and transport the packaged material to the bioenergy plant. In general the main constraint to the implementation of this system is the bundling cost. The bundling process requires one additional machine and therefore one step more in the forest biomass supply chain. Also a bundler is a specialized machine with high fixed cost and can require a skilled operator.

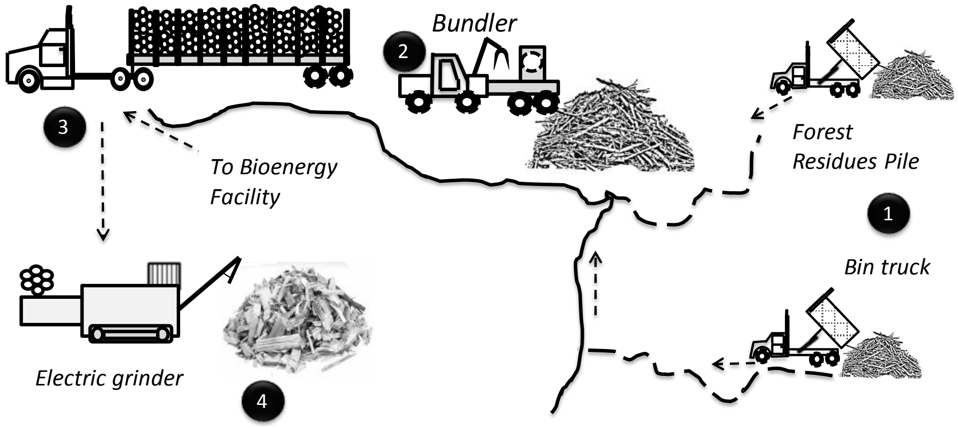

Figure 4.4 System 5, producing bundles of residues at centralized landing and processing at bioenergy facility. The numbers in the black circles indicate the stages of the process for the system.

4.3.6 Truck-machine Interactions

Truck machine interactions occur when the operational circumstances and road access limit productivity. We identified two general cases of truck-machine interactions that primarily affect forest harvest residue recovery operations in steep terrain. These interactions mainly occur with stationary equipment. With mobile equipment these interactions are minimized with the use of setout trailers that partially decouple the chipping from the transport. Case I occurs when access to the pile is restricted to single lane roads and the comminution site is limited in space allowing only in-road loading and the turn-around is located on the other side of the processing location. If an incoming truck needs to reach the comminution site but another truck is being loaded, the in-coming truck must wait at a turn-out (e.g. wide spot in the road, an intersection or a turn-around) until the loaded truck passes the point where the in-coming truck is waiting. In Case II, the turn-around for the comminution site is located before the processing location and the in-coming truck can reach the turn-around and wait for the other truck to be loaded. After the loading process is finished, the incoming truck has to wait for the loaded truck to pass the turn-around and then the waiting truck can back up to the grinding site. This causes an obstruction depending on the back-up distance but its impact in grinder productivity is not as high as in Case I.

4.4 Model Description

We formulated the problem as a network and solved it using mixed integer programming and simulation. The network problem can be classified as a special case of the multi-commodity, multiple-facilities problem. Forest residues exist at a number of predefined locations (nodes) along existing roads (arcs). At each predefined location, a defined quantity of forest residues could be transformed into chippable or non-chippable (grindable) material and either processed at roadside, bundled, or carried to a number of predefined trans-shipment points. At a trans-shipment point, residues can be upgraded (comminuted) and loaded for longer distance transport to plant facilities. Trans-shipment points can usually be accessed by larger capacity highway trucks. The model assumes that residues are located at road-side. The cost of forwarding residues to road-side can be included in the model, but the scope of this study is focused on processing and transportation.

Economic optimization of forest residues processing and transport refers to identifying the most cost effective alternative under the limitations of the machinery, trucks, material and site. In order to find the best alternative, the model needs to combine cost and productivity information, user inputs, mathematical optimization and simulation. The model, called Residue Evaluation and Network Optimization (RENO), was incorporated in a computer program developed using the Java platform. RENO is able to read spatial vector data and generate the matrix for the mathematical optimization model. User inputs are: (i) a geospatial vector file with information about the location of the piles, truck turn-arounds, and potential centralized landings within a forest unit; (ii) a geospatial vector file of the internal road system; (iii) forest road grade and standard, (iv) unprocessed material transportation options; (v) comminution options, (vi) long distance transportation options; (vii) mixture of species and average moisture content; (viii) stumpage cost; (ix)highway distance, (x) price. Outputs from the model are: (a) cost of processing and transport of each pile; (b) net revenue; (c) selected comminution technology, (d) selected transportation technology or technology combination for each pile, (e) potential machine utilization rates at each processing location; and (f)sensitivity analysis for the main variables affecting cost such as changes in moisture content, changes in road distance from the entrance to the unit to the bioenergy facility or changes in machine productivity.

A preprocessing of the vector data is needed to enable the program to read the spatial location of residue piles and road features in relation to the forest road network. A network layer is created by splitting the forest road at each pile, turn-around, turn-out and junction location (figure 4.5). The road segmentation at each point allows the program to create and adjacency list of the road network to calculate transportation distances between residue piles and other road features. RENO calculates the distance between points in the road network using the shortest path Floyd-Warshall algorithm (Floyd, 1962; Warshall, 1962). The preprocessing process was made on ArcGIS 10 (ESRI, 2012)

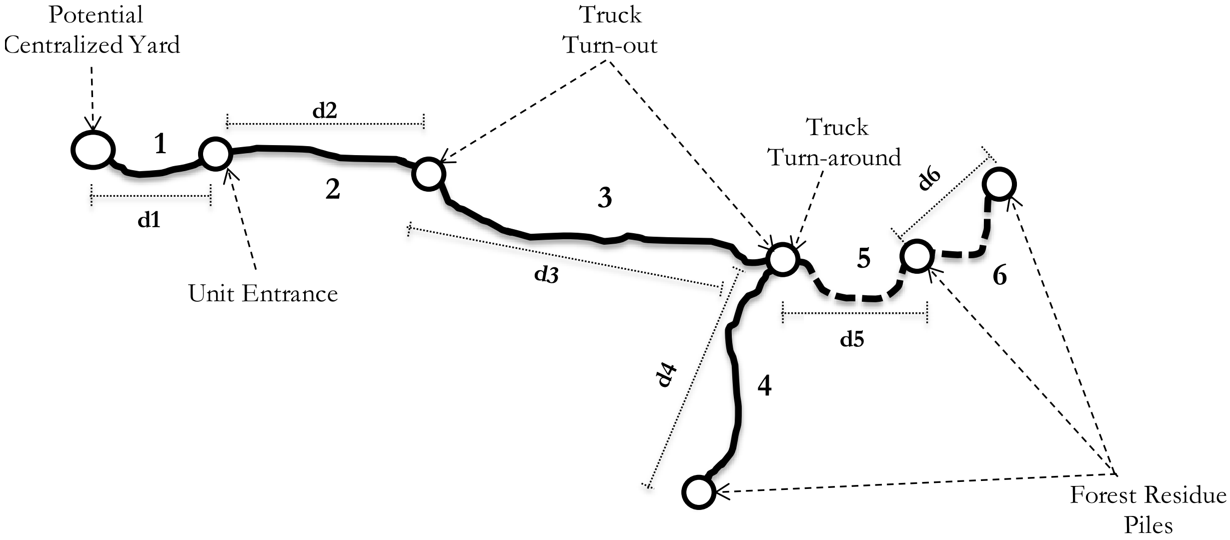

Figure 4.5 Vector data preprocessing, indicating the forest road segmentation at each feature location (forest residue pile, truck turn-around, truck turn-out, unit entrance and potential centralized yard.

RENO creates routes based on the preprocessed spatial data and user inputs. A hypothetical network with two residue piles is presented on Figure 4.6 to explain how RENO constructs a network. Each pile (node 1 or 2) is candidate to be a centralized landing if it is large enough to allow a normal flux of processing and transport of raw material. Additionally, potential centralized yards (node 3) can be included within the spatial data. A fixed cost associated to each pile or potential centralized landing is charged to account for the mobilization cost of the machinery to the site and to each candidate processing location. Variable processing cost of the residues is not accounted for in these arcs because comminution costs are dependent upon the type and number of available trucks. Traffic between piles or processing locations is only allowed using short distance transportation trucks, specifically on arcs *c, d, e, and f.* For each pile a node representing the truck turn-around is created (nodes with turn-around symbol). These nodes provide additional arcs (*g, h, k,* and *l*) that allow the program to represent the variable transportation cost of chip-vans in the internal forest road and also to track the cost from each pile. Additionally these arcs allow the analyst to include the fixed cost related to road improvements such as creating turn-arounds. Each turn-around is connected with several nodes (T1 and T2) indicating the transportation options selected by the user. Each transportation option is linked to a node (I-1 and I-2) that is used to represent the comminution cost which is a function of the type, number of trucks and truck machine interactions (arcs *m, n, o, p, q* and *r*). The cost assigned to each arc is calculated by a simulation model that estimates the machine (grinder or chipper) potential utilization rate based on the road configuration inputs and number of trucks. The program first analyses the road characteristics for the source pile under analysis and then locates an adjacent and feasible truck turn-around and turn-outs and calculates internal distances between them. After this process, the program simulates a ten hour shift using the type and number of trucks specified by the user to estimate the productive and standing time. Finally each I-node is connected to the final destination (bioenergy facility). The simulation allows the program to account for the effect of truck-machine interactions on productivity. Each arc (s, *t, u, v, w,* and *x)* is used to estimate the transportation cost from the entrance of the unit to the bioenergy plant. This is usually the paved highway distance and does not include the internal road distances within the forest unit.

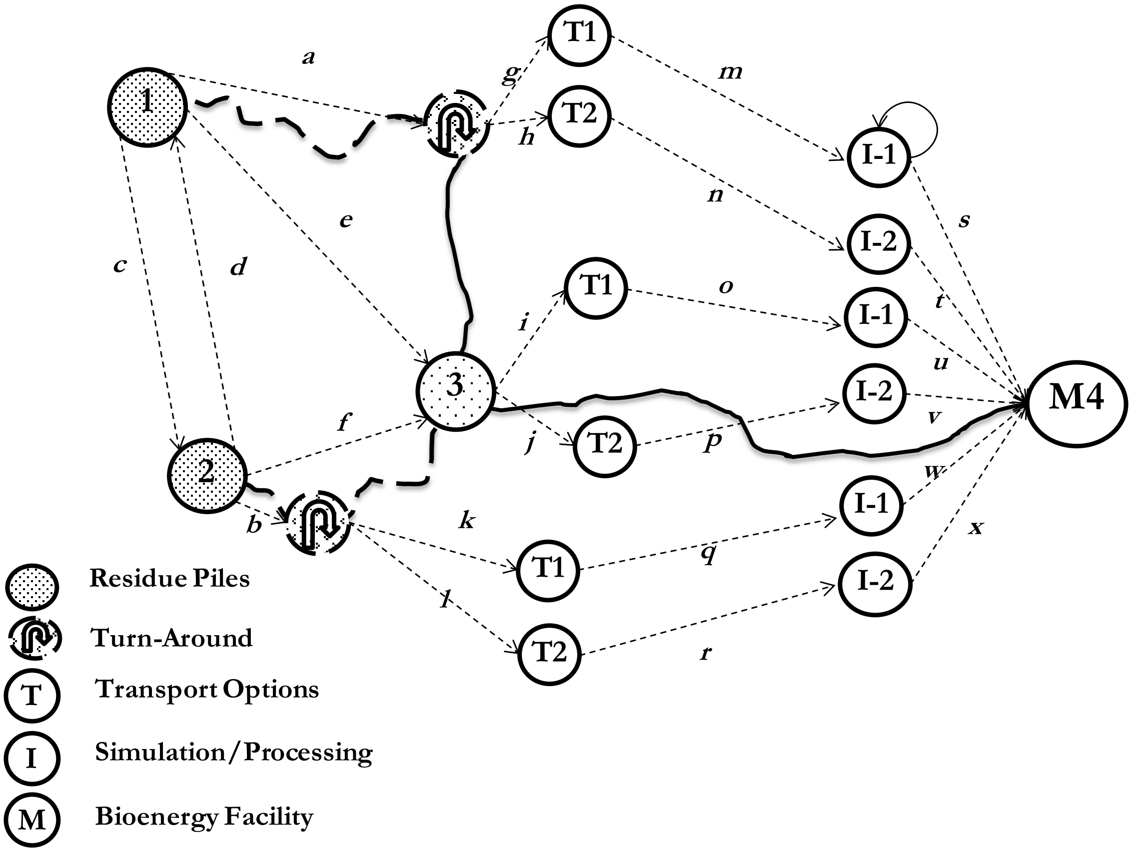

Figure 4.6 RENO routes that form the network in a typical road system with two residue piles.

Hourly productivity and costs (operating and standing) from each processing option were estimated from time and motion studies in different field conditions in Oregon and Washington, USA. Additionally, equipment suppliers, contractors, land owners and forest managers were consulted about their accounting systems used in forest biomass recovery operations to compare calculation schemes and improve accuracy of the cost estimations. In this study we accounted for the standing cost for grinders and trucks, due to truck-machine interactions. This is calculated using a simulation model. This special feature improved the traditional costing systems since the effect of truck-machine interactions is accounted for at the pile level. Standing cost for processing and transportation options were estimated based on labor, supporting equipment, overhead, and opportunity costs. To estimate the opportunity cost, we used the hourly profit and risk allowance calculated when the machine is operating.

4.5 Mathematical Formulation

The challenges in this problem are to properly define the possible arcs in the network, and their costs. At each point of comminution, equipment of different sizes can be used, with different mobilization costs and production costs. Similarly not all trailers types can reach all forest residue locations. Some operations are closely coupled (e.g. stationary grinders) and others are not (e.g. mobile chippers). The question to be solved is what volume of residue type, ***r***, at each forest location, ***i***, will be processed in location, ***j,*** into product type, ***p***, by equipment type, ***m***, and transported by truck type, ***n*** for primary transport, and truck type, ***t,*** for secondary transport to a plant, ***k,*** to minimize total cost or maximize net revenue subject to demand, road accessibility, centralized yard availability, and truck turn-around.

The processing operations for modeling purposes can be divided in stationary and mobile machines. In the case of stationary grinders, each pile is a candidate to be a centralized landing if it is large enough to allow a normal flux of processing and transport of raw material. Also the road network must permit the chip vans to reach the centralized landing. Mobilization cost of a stationary grinder is a function of the number of forest residue piles minus one. A centralized yard is defined in this study as a location outside the unit with good access for high capacity trucks and with enough space to allow tricks to turn-around.

The model represents the economic optimization of processing and transport as a capacitated network problem B=(V,L), where V are the nodes (piles, processing locations, turn-arounds, centralized landings, centralized yards, bioenergy plants) and L represents the directed links. The cost estimation and mixed-integer formulation of the problem is presented below:

4.5.1 Sets and Parameters

R	set of forest residue type (sorted, unsorted)
I	set of residue pile locations
J	set of residue processing locations
K	set of plants
M	set of processing equipment system
N	set of trucks to transport unprocessed material (bin trucks, dump trucks, hook-lift trucks)
T	set of trucks for long distance transportation
P	set of products (bundles, chips or grindings)

For cost estimation purposes we add the following sets to the model:

G	set of road standards (dirt, gravel, paved)
H	set of truck states while travelling (loaded, unloaded)

4.5.2 Processing

ao^{m}	hourly operating cost of processing using machine *m*, (\$/h)
aw^{m}	hourly standing cost of processing using machine *m*, (\$/h)
ap_{r}^{m}	hourly average productivity of machine m in forest residue type *r*, (green t/h)
awt_{j}^{m}	standing time of machine *m* in processing location *j, (*h)
q_{j}^{r}	amount of residues type *r* in processing location *j*, (green t)

Processing time, as a function of the average productivity of machine m is:

$$apt_{j}^{m} = \frac{q_{j}^{r}}{ap_{r}^{m}} \qquad (4.1)$$

Processing cost of machine *m* in location *j* (\$/green t), c_{j}^{mp} can be expressed as:

$$c_{j}^{mp} = \frac{aw^{m} awt_{j}^{m} + ao^{m} apt_{j}^{m}}{q_{j}^{r}} \qquad (4.2)$$

4.5.3 Transportation

ui_{j}^{t}	hourly idle transportation cost of truck type *t*, in processing location *j*, (\$/h)
uw_{gh}^{t}	hourly productive transportation cost of truck type *t* in road surface *g* in state *h* (\$/h)

ul^{tp}	capacity of truck *t* with product type *p*, (green t)
d_{jk}	distance from processing site *j* to plant *k*
q_j^p	amount of product type p processed in location *j*, (green t)
uv_{gh}^t	average speed of truck t in road surface *g* in state *h*
uit_j^t	average idle time of truck t at processing unit j (h)
uit_k^t	average idle time of truck t at plant k (h)

Round-trip travel time, urt_{jk}^t in hours is:

$$urt_{jk}^t = \sum_{g \in G} \frac{d_{jk}^g}{uv_h^{tg}} \tag{4.3}$$

Truck Productivity up_{jk}^{tp} in green t/ h is:

$$up_{jk}^{tp} = \frac{ul^{tp}}{urt_{jk}^t} \tag{4.4}$$

Truck Productive time upt_{jk}^t as a function of truck productivity

$$upt_{jk}^{tp} = \frac{q_j^p}{up_{jk}^{tp}} \tag{4.5}$$

Transportation cost from c_{jk}^{tp} in \$/green t is equal to:

$$c_{jk}^{tp} = \frac{uw_{gh}^{t} upt_{jk}^{tp} + ui_{j}^{t}\left(uit_{j}^{t} + uit_{k}^{t}\right)}{q_{j}^{p}} \qquad (4.6)$$

Equations 4.3 to 4.6 were adjusted to calculate the first stage transport costs c_{ij}^{nr}. Fixed cost cf_{ij}^{np} and cf_{jk}^{tp} are cost related to improvements in road standard to allow access to specific types of trucks if needed.

4.5.4 *Fixed Costs*

cm_{jk}^{tp} fixed cost of transporting processed forest residues type *p* using truck *t* on link *jk*

cm_{ij}^{np} fixed cost of transporting unprocessed forest residues type *p* using truck *n* on link *ij*

4.5.5 *Decision Variables*

w_{ij}^{nr} flow (green t) of unprocessed residues *r* (sorted or unsorted), delivered using truck type n, from pile *i*, to processing site *j*

x_{jk}^{tp} flow (green t) product type *p* (chips or grindings), transported using truck *t* from processing site *j* to plant *k*

$$f_{ij}^{n} \qquad \begin{cases} 1 \ \textit{first stage transport type n are used on link ij} \\ 0 \ \textit{first stage transport type n not used on link ij} \end{cases}$$

$$y_{jk}^{t} \qquad \begin{cases} 1 \ \textit{truck type t is used on link jk} \\ 0 \ \textit{truck type t is not used on link jk} \end{cases}$$

4.5.6 Objective Function

The objective is to minimize the total cost of processing and transport forest biomass from residues Eq. 7:

$$Min \sum_{jk\in J}\sum_{p\in P}\sum_{t\in T}\left(c_{j}^{mp} + c_{jk}^{tp}\right) x_{jk}^{tp} + cm_{jk}^{tp} y_{jk}^{t} + \sum_{ij\in J}\sum_{n\in N}\sum_{r\in R} c_{ij}^{nr} w_{ij}^{nr} + \sum_{m\in M}\sum_{p\in P}\sum_{z\in Z} cm_{ij}^{np} f_{ij}^{n} \qquad (4.7)$$

4.5.7 Restrictions

Equation (8) states that the amount of transported residue (green tonnes) has to be equal to the sum of the available tonnage in each pile Q_i^r:

$$\sum_{j\epsilon J} w_{ij}^{nr} = Q_i^r \qquad \forall_i \in I, \forall_r \in R \qquad (4.8)$$

Conservation of flow at each node Eq. 9:

$$\sum_{k\epsilon K}\sum_{t\epsilon T} x_{jk}^{tp} - \sum_{n\in N}\sum_{i\epsilon I} w_{ij}^{nr} = 0 \qquad \forall_j \in J, \forall_r \in R, \forall_p \in P \qquad (4.9)$$

Equation 10 represents the arc triggers to allow first stage transportation over links *ij:*

$$\sum_{n\in N}\sum_{r\in R} M\, f_{ij}^{n} \geq w_{ij}^{nr} \qquad \forall_i \in I, \forall_j \in J \qquad (4.10)$$

Equation 11 represents the arc triggers to allow second stage transportation over links *jk:*

$$\sum_{p\in P}\sum_{t\in T} M\ y_{jk}^{t} \geq x_{jk}^{tp} \quad \forall_{i} \in I, \forall_{j} \in J \tag{4.11}$$

Binary variables associated to the arc triggers for all transportation options Eq.12:

$$f_{ij}^{n}, y_{jk}^{t} = \{0,1\} \qquad \forall (i,j) \in L, \forall (j,k) \in L, \forall_{n} \in N, \forall_{t} \in T \tag{4.12}$$

Non-negativity constraint for continuous decision variables to guarantee that all the flows have to be equal or greater than zero, Eq. 13:

$$w_{ij}^{nr}, x_{jk}^{tp} \geq 0 \qquad \forall (i,j) \in L, \forall (j,k) \in L, \forall_{n} \in N, \forall_{p} \in P, \forall_{t} \in T \tag{4.13}$$

4.6 Application and results

We applied and compared the model results to actual operations in the western Oregon and Washington, USA. We concentrated our analysis in one of the units that contains all necessary features in relation to road access and pile location that allowed us to explore all model utilities and analyze the results. The analysis was performed in a harvest unit located about 27 km east of the city of Sutherlin in southwest Oregon, United States (43°25’34”N, 123°3’37"W). The forest residue piles contained mixed residues composed of western-hemlock (*Tsuga heterophylla)* and Douglas-fir (*Pseudotsuga menziesii)* branches, tops and parts not meeting the utilization standards for timber or pulp products. The diameter of the pieces ranged from 10 to 20 cm and the length ranged from 2 to 4 m. Average moisture content of the material based on 34 samples was 30% estimated by the wet basis method (Briggs 1994). A total of 1034 green metric tonnes (GMt) were identified in fourteen forest residue piles.

Forest residues were processed in the field and transported to a bioenergy facility located 62 km from the entrance of the forest unit. The forest road system within the unit was characterized by steep roads with a maximum road grade of 10%. Available forest residue piles, truck turn-around, truck turn-outs, potential centralized yards and potential places to hook and unhook double trailers were located using a GPS receiver Trimble GeoXH (Figure 4.7). The road system was mapped with the aid of a road geospatial vector file obtained from the Oregon Geospatial Enterprise Office, GEO (2012). Forest roads that were not represented in the vector file were mapped using a Visiontac® receiver. The internal road network and locations were processed using ArcMap 10 (ESRI 2012).

Available equipment (table 1) to process the material was: (i) one Peterson stationary horizontal grinder 5710C (783 kW); (ii) one Peterson horizontal grinder 4710B (522kW); (iii) one Diamond Z tub grinder (745kW); and (iv) one mobile chipper Bruks 805.2 (331 kW), mounted on a Valmet Forwarder 890.3.

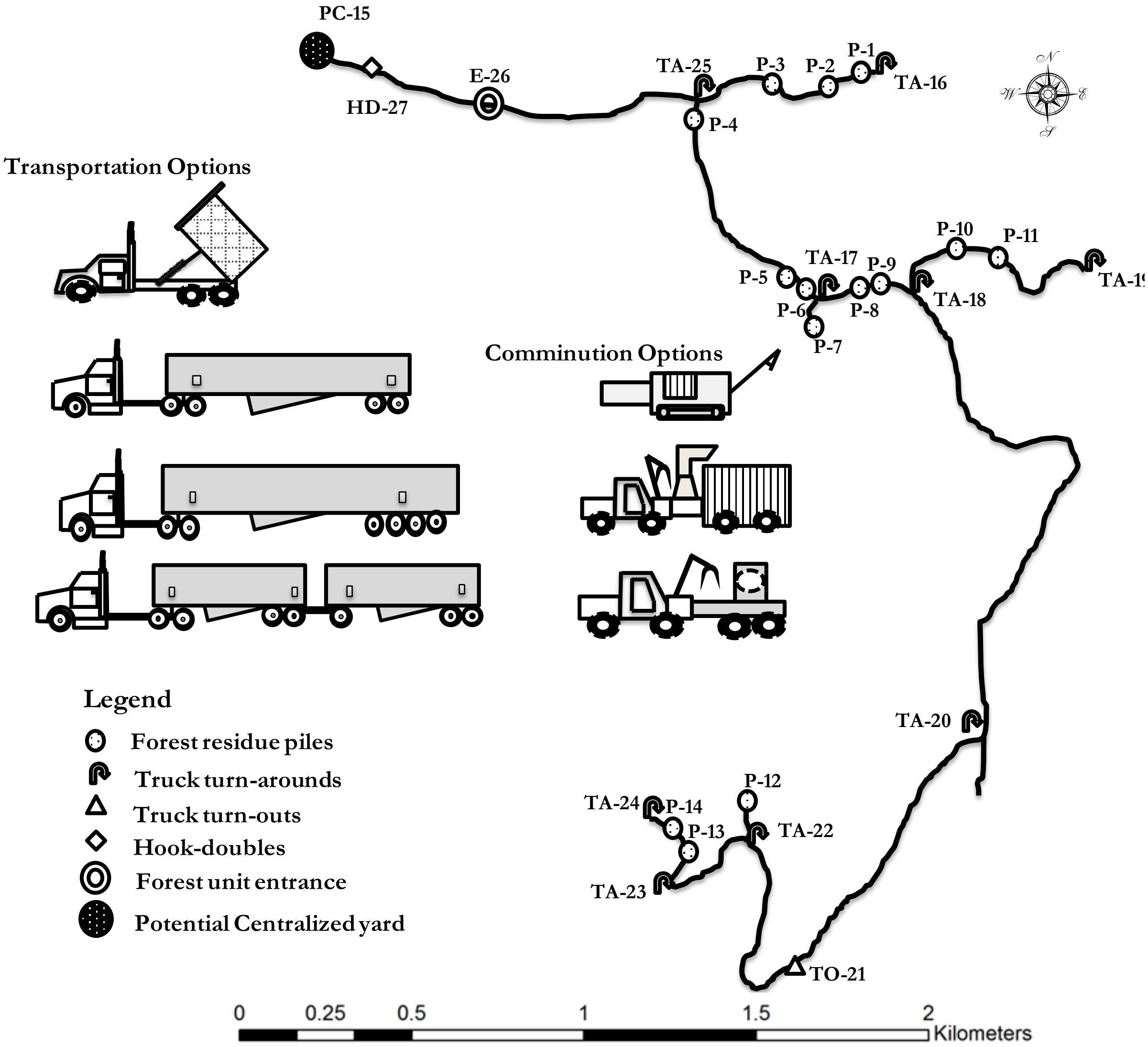

Figure 4.7 Available processing and transportation options and spatial location of forest residue piles (P), truck turn-arounds (TA), truck turn-outs (TO), potential centralized landings and double trailers set-up places (HD).

Table 4.1 Cost and productivity for available processing options.

Cost category	Operating cost			
	Grinder 4710 B	Grinder 5710 C	Tub Grinder 1000	Mobile Chipper
Hourly fixed machine cost, ($/h)	95.45	129.73	74.13	139.00
Variable costs				
Labor, ($/h)	33.75	33.75	33.75	37.50
Knives or Bits ($/h)	18.68	21.88	16.85	16.00
Repair and Maintenance, ($/h)	27.47	37.33	21.33	56.00
Fuel and Lubricants Cost, ($/h)	141.09	156.76	156.76	62.67
Loader cost, ($/h)	102.89	102.89	102.89	-
Support equipment, ($/h)	14.80	14.80	14.80	14.80
Overhead cost, ($/h)	21.08	21.08	21.08	21.08
Hourly Variable costs, ($/h)	359.75	388.50	367.47	208.06
Profit and Risk 10%, ($/h)	45.52	51.82	44.16	34.71
Total Cost, ($/h)	500.72	570.06	485.76	381.76
Hourly productivity (GMt/PMH)	45.30	54.40	29.20	12.00
Cost per green tonne ($/GMt)	11.05	10.48	16.64	31.81

Transportation options (table 2) were: (a) two 6x4 trucks, each equipped with a 9.75 m long drop center trailer with a capacity of 15.5 tonnes; (b) two 6x6 trucks, each equipped with an hydraulic rear-steer axle 14.6 m long trailer with a capacity of 24.5 tonnes; and (c) two 6x4 trucks, each equipped with a 16.15 m long drop center trailer. Additionally it was possible to couple two 9.75 m long trailers to one truck tractor to increase hauling capacity to 27 tonnes (double trailer configuration). Two hook- lift trucks each with a capacity of 4.9 tonnes were available, in the case that unprocessed forest residues need to be moved between the piles to establish a centralized landing or yard. If hook- lift trucks are used, an additional loader is needed at the source points to load trucks. Each hook-lift truck was available to rent at a rate of $70 per hour (operating or standing) including the cost of the bin.

Since transportation costs vary according to the round-trip travel distance and speed, we estimated, for illustration purposes, average transportation costs for a 50 km paved highway distance, an 8 km gravel forest road and a 2 km dirt road an average speed of 70, 15, and 10 km/h respectively (table 2).

Forest residue piles were located road-side. Each pile was considered eligible to be a centralized landing and therefore hook-lift trucks can be used to transport the material among the residue pile locations if needed. Forest residues pile 3 had an associated fixed cost of $800 that represents the cost to clean the area to place the stationary equipment (assuming six productive machine hours of knuckle boom excavator with a cost of $136.64/PMH). When processing with the mobile chipper this cost was assumed to be zero. In relation to the transportation, the access to the piles within the forest unit was limited to 9.75 m long trailers and rear-steer axle 14.63 m long trailers due to the reduced space in the turn-outs and turn-arounds and potential off-tracking around the small radius curves from the entrance of the unit to the pile locations. If the 16.15 m long trailer is selected to directly access the piles, then a road improvement will be necessary in relation the horizontal and vertical road geometry (e.g. fill ditches, remove or reverse road cross slope, and roadway widening).

Table 4.2 Average hourly transportation costs for an average round-trip distance of 100 km on paved roads, 16 km on a gravel road, and 4 km on a dirt road.

Cost	Operational cost			
	Standard 9.75	Standard 16.15 m	Rear steer-axle 14.63 m	Doubles 9.75-9.75 m
Fixed costs				
Purchase price tactor-trailer, ($)	160,000	200,000	300,000	195,000
Annual Depreciation, ($/h)	7.44	9.04	14.70	8.84
Annual Interest ($/h)	5.17	6.45	9.74	6.29
Annual insurance and taxes ($/h)	5.17	6.45	9.74	6.29
Annual productive machine hours (h)	2,000	2,000	2,000	2,000
Hourly fixed cost ($/h)	17.78	21.94	34.17	21.42
Variable costs				
Labor, ($/h)	23.18	23.18	27.61	23.18
Tire cost, ($/h)	6.41	9.98	9.50	10.69
Repair and Maintenance, ($/h)	5.21	6.33	11.76	6.19
Fuel & Lubricants, ($/h)	20.35	25.78	25.52	28.50
Overhead cost, ($/h)	6.70	6.70	6.70	6.70
Hourly Variable cost ($/h)	61.85	71.96	81.09	75.26
Profit and Risk 10% ($/h)	7.96	9.39	11.53	9.67
Total Hourly Cost ($/h)	87.60	103.30	126.79	106.35
Truck Capacity	15.5	25.4	22.7	27.5

A potential centralized yard was identified outside the forest unit and located at 0.5 km from the entrance. This location had the potential to provide good access for the 16.15 m long trailer option and was directly connected to the paved highway. Double trailers (9.75-9.75 m) were available to transport the material, but to access the forest unit the trailers would need to be decoupled due to narrow road width that would not allow for off-tracking.

The questions from an analyst's perspective are: (i) Which pile locations can be used as centralized landings?; (ii) Should a centralized yard be established; (iii) What type of processing option is the most cost effective under the problem circumstances; (iv) What type of truck configuration is the most cost effective for each pile?; and (v) What is the maximum investment that can be justified in road improvements to provide access to the larger trucks (e.g. 16.15 m long trailers).

Inputs for RENO were two vector files, one with the road network and a second containing the locations and estimated volume in each pile. Available processing and transportation options were selected and the distance to the mill was set to 62 km. The number of truck in each available configuration was also specified (2 sets of double 9.75 m long trailers, 5-single 9.75 m long trailers and 2-rear-steer axle 14. 63 m long trailers).

The first step in the optimization was estimation of the distance from each pile to the entrance of the unit, the location of the closest and feasible turn-around and turn-out, and the type of truck-machine interference that can occur (Table 3). Once the distances were computed the program proceeded to calculate the transportation costs of each selected option in the internal network. Truck standing cost while being loaded and during the hook and unhook process for the double trailer configuration were also calculated.

Table 4.3 Residue piles spatial location in relation the available and feasible truck turn-arounds and turn-outs and truck interaction case.

Residue Pile	Volume (BDMt)	Turn-around	TA distance (km)	Entrance (km)	Hook (km)	Turn-out ID	TO Distance (km)	Truck-Machine Interaction case
P-1	64	TA-16	0.02	1.17	1.56	TO-25	0.58	1
P-2	48	TA-16	0.13	1.07	1.46	TO-25	0.48	1
P-3	57	TA-16	0.34	0.85	1.25	TO-25	0.26	1
P-4	32	TA-25	0.02	0.61	1.01	TO-25	0.02	2
P-5	32	TA-17	0.10	1.23	1.62	TO-25	0.64	1
P-6	48	TA-17	0.04	1.29	1.68	TO-25	0.70	1
P-7	38	TA-17	0.06	1.39	1.78	TO-17	0.06	2
P-8	32	TA-18	0.12	1.48	1.87	TO-17	0.15	1
P-9	29	TA-18	0.08	1.52	1.91	TO-17	0.19	1
P-10	76	TA-19	0.46	1.79	2.18	TO-18	0.19	1
P-11	48	TA-19	0.33	1.92	2.31	TO-18	0.32	1
P-12	64	TA-22	0.08	4.83	5.23	TO-22	0.08	2
P-13	64	TA-24	0.19	5.13	5.52	TO-23	0.09	1
P-14	95	TA-24	0.06	5.26	5.65	TO-23	0.23	1
PC-15	0	TA-25	0.00	0.52	0.00	TO-21	0.00	0

The program only assigned the 16.15 m long trailer to the potential centralized yard, because the access for this large trailer was not feasible beyond the centralized yard. The next step was calculation of the processing cost based on the type of truck-trailer configuration and the number of available trucks for configuration. The program simulated a ten hour shift of forest biomass processing and transportation based on the estimated machine and truck productivity for all the selected options. After the simulation was finished, machine utilization rate and total processing costs for each pile were computed. Finally the round-trip transportation costs from the entrance of the unit to the mill for each configuration were calculated.

The program constructed a network for each of the processing machine types since only one type of machinery can be used at each site. Results showed that the most cost effective processing option for the analyzed unit is the use of the large horizontal grinder (745 kW). A total cost of $53.25/BDMt is expected using this machinery. This option is followed by the small horizontal grinder (522 kW) with a cost of $54.57/BDMt. The most expensive option was the mobile chipper. The use of the mobile chipper minimize the truck standing time since the operation is partially decoupled, however the low productivity of the chipper compared to the stationary grinders had a greater effect on the processing cost. The cost of the tub grinder is mainly affected by its low productivity (20.4 BDMt/PMH). The tub grinder is best suited for stumps.

We compared the actual operation to the model results. The actual operation used a mobile chipper to process the residues. Two 6x4 trucks equipped with two 9.75 m long trailers were used to transport the chips to the bioenergy facility. We applied our costing system accounting for standing cost (trucks and chipper). The estimated operational cost with the mobile chipper and double trailers was $67.98/BDMt. Our optimized solution was $53.22/BDMt, a reduction in cost of 22 percent. However the optimized solution is valid only if chips and grindings are considered equivalent products. In actual markets both products are considered equivalent for power generation although chips are more homogeneous in particle size suggesting that they may have a better price in some markets. Low productivity of the mobile chipper is the most impacting factor. Ghaffariyan et al. (2012) reported a productivity of 43.88 GMt/PMH for the same machine in chipping operations in Australia. However, the size of the processed material (small logs 40-15 cm in diameter and 6 m length) suggest that residues were of different quality (cleaner and larger) compared to the forest residue piles commonly found in Oregon and Washington.

An Ant Colony heuristic (Dorigo 1996) was incorporated into the model to provide a lower bound solution to the MIP for the branch and bound algorithm. This was made to help to reduce solution times as size of the problem increases. The Ant Colony heuristic solution is also used to provide an alternative solver if the analyst does not have access to a MIP solver. The Ant Colony solution for the analyzed unit provided values near to the MIP optimal. On average the Ant Colony heuristic provided values that were 99% of the objective function value of the optimal solution (Figure 4.8).

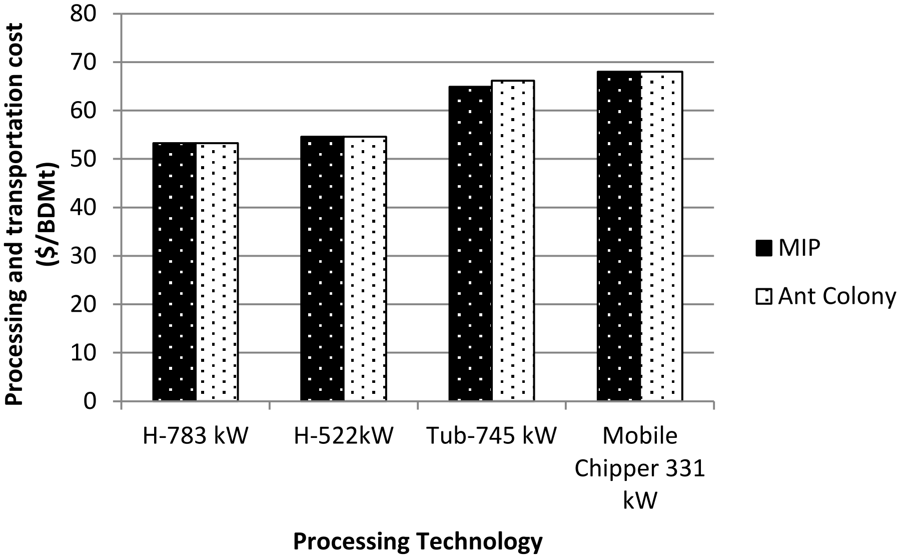

Figure 4.8 Processing and transportation cost as a function of the comminution equipment used in the operation.

The solution shows a mixture of transportation options depending of the pile location and access (Figure 4.9). In pile 3, 5, the unprocessed residues had to be transported to an adjacent pile using hook-lift trucks. In pile 3, the use of small trucks to move the material to pile 4 compensates for the higher fixed cost of processing the material in pile 3 ($810). However the overall cost of process and transport the material at that pile is higher compared to adjacent piles. At piles 1, 2, 4, 5, 6, 7, 8, 9, 1

0, and 11 the residues are processed at each location and transported using the double trailer configuration. The double trailers configuration is cheaper because hauling capacity is increased by about 80%. For piles 12, 13 and 14 the material is comminuted in-situ and then transported using the rear axle steered trailer configuration.

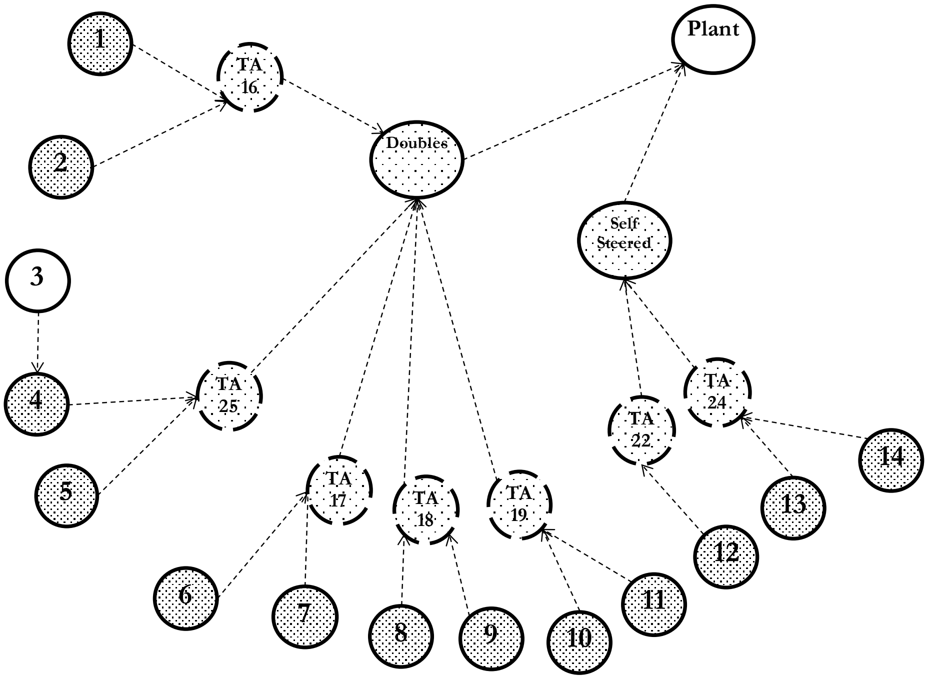

Figure 4.9 Representation of the optimal routes for each pile

For piles 12, 13 and 14, the rear steer axle trailer becomes a feasible and cost effective option due to the higher distance from the entrance of the unit. Longer distances from the entrance to the these piles (5.52 and 5.65 km respectively) compared to the rest of the piles Similarly with piles 13 and 14 the increase in cost of double trailers is mainly driven by truck machine interference (case I) and the longer distance from the entrance to the piles (5.12, 5.44 and 5.61 km respectively) compared to rest of the piles. The single 9.8 m long trailer appeared to be an expensive option under the operating conditions. None of the piles selected the use of this type of configuration to transport the material.

RENO reported the cost for each pile (Figure 4.10). This cost can be used to assess the economic feasibility of utilizing the pile as compared to leaving it. In general as piles are located farther from the unit entrance the overall cost of processing and transport increases due to the increase in transport cost inside the forest unit. However the type of truck interference also has an impact on the cost. Piles where Case II applies (4, 7 and 12) are cheaper to process and extract than their neighbors where Case I applies. Processing cost was also affected by road accessibility and distance. An increase in machine standing time is expected when processing material in piles with Case I truck –machine interference. Also as distance from the entrance of the unit to the pile increases, truck round-trip travel time increases affecting the number of truck that can return to pick up another load.

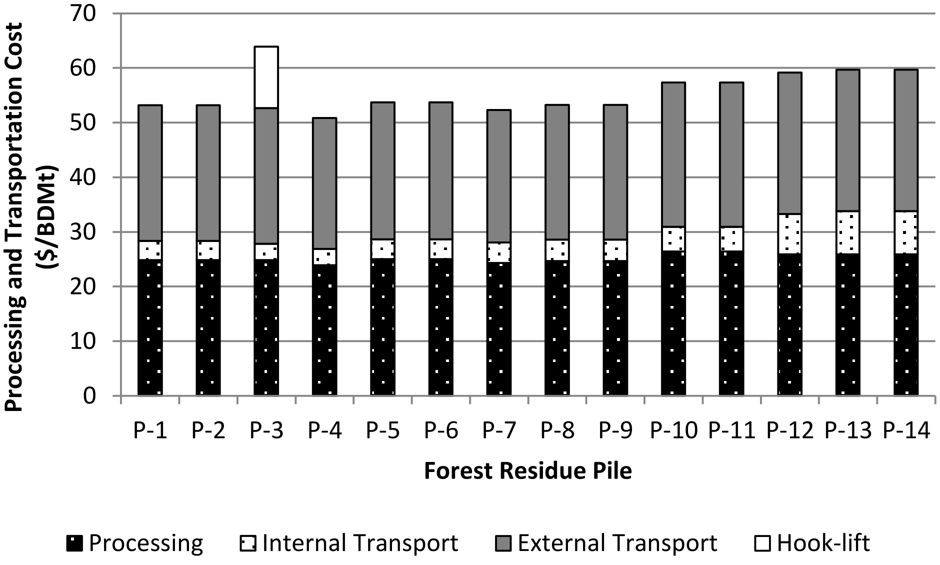

Figure 4.10 Processing and transportation cost for each pile

4.6.1 Machine utilization rate

Machine utilization rates were also calculated at each location, based on the results of the simulation model (Figure 4.11). Machine rates were calculated independent of the available volume at each pile, because each pile was considered a candidate for a centralized landing. Based on the number of available trucks, results showed an average utilization rate of 29% (for 2-double trailer trucks or 2-rear-steered trailer). Increasing the number of truck is beneficial because it reduces the grinder or chipper standing time but as number of truck increases the chances of having a truck queue may increase transportation cost and minimize the benefits of increasing the machine utilization rate. RENO modeled the optimal number of trucks necessary to maximize grinder utilization rate without increasing the overall cost of the operations due to truck standing cost. Utilization rate can be increased to 56% on average if four double trailer trucks are used on piles 1,2,5,6, 10 and 11; five double trailer trucks are used at pile locations 4, 8, 9, 13, and 14; and six trucks are used at pile locations 12 and 7. The change in the number of truck at each pile depends on the truck-machine interaction case, traveled distance on gravel roads and utilization of trucks.

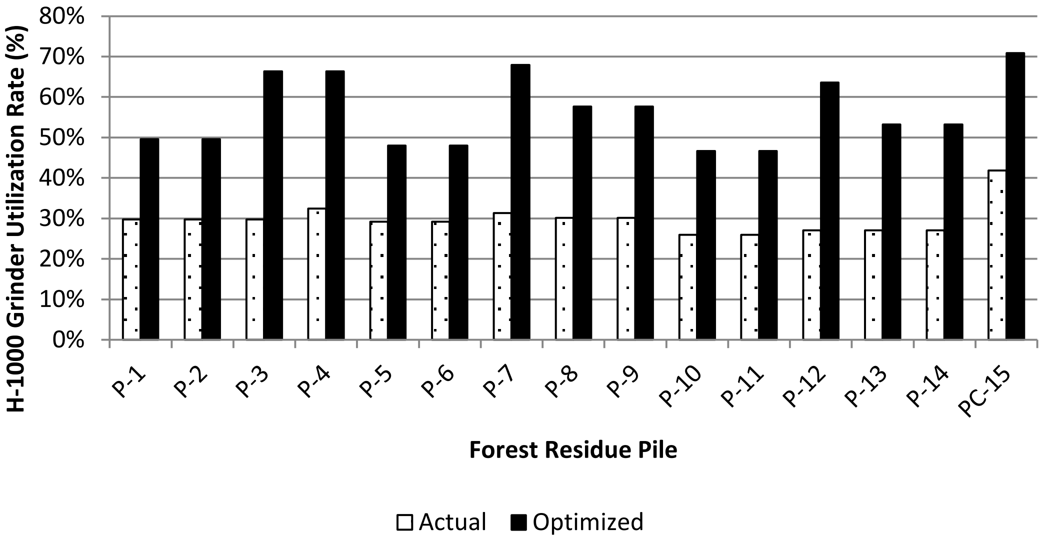

Figure 4.11 Actual grinder utilization rate with available number of trucks and optimal solution from the model.

The increase in grinder utilization rate decreased the cost by 12% ($46.50/BDMt). Increasing grinder utilization rate beyond this point is not feasible under this transport configurations but a road improvement may allow the use of larger single trailer trucks that have the potential to increase the overall machine utilization. However under the actual road conditions, a road modification may be required to allow larger trucks to access the piles.

The cost of road modification to allow larger truck access depends on the particular characteristics of each unit, the trailer length and type of truck. The user can directly enter the road modification cost for each truck configuration in the graphical user interface, however if the analyst lacks an accurate cost estimation of these activities, RENO can calculate the marginal benefit of the feasible option and compare it to the desired configuration. For example, in the analyzed unit, if the analyst wants to analyze the access of a 16.15 m long trailer, first RENO calculates the overall cost in the unit of that truck assuming that no road modification is necessary and then compares it to the actual cost of operations using the transportation options that do not require road modification to access the unit. We compared the cost of transport the processed material using 4 trucks equipped with a 16.15 m long trailer with the actual solution that uses 2 double trailers and 4 single 9.75 m long trailers. By giving access to the 16.15 m long trailer, the actual cost is reduced $3,450 from $38,549 to $35,098, which represents a reduction of 9%. Any necessary road improvement must be equal or less than this value in order to become a feasible and cost effective option. The decrease in cost is relevant when using the 16.15 m long trailer because this type of trailers do not require a considerable amount of time to hook and unhook in the forest plus additional time to unload the processed material in the bioenergy facility.

4.6.2 Centralized yard

A potential centralized yard close to the main entrance but outside the unit was considered during the planning process. Based on the model results, processing at the centralized yard can increase grinder utilization rate up to 70% with direct loading into double trailers. Processing and transportation cost at the centralized landing was estimated in $36.98/BDMt, using 4 trucks each equipped with a 16.15 m long trailer. This cost is 30% lower than the cost reported in the optimal solution using a combination of double and rear-steered trailers ($53.25/BDMt), but not sufficient to compensate for the additional cost of using hook-lift trucks to transport the material from each pile to the centralized yard.

4.6.3 Sensitivity to the distance and Productivity

We performed a sensitivity analysis to analyze the effect of changes in the distance from the entrance to the bioenergy facility. We also analyzed the effect of changing the grinder H-1000 productivity since is the most economical option according to the optimal MIP solution. To analyze the effect of the distance (Figure 4.12) we run the model selecting only one transportation option (e.g. 2 double trailer trucks) and varying the distance from the entrance to the bioenergy facility from 20 to 200 km. Results show that the use of the double trailer configuration is the most cost effective option. As distance increases the other two options become more expensive limiting their use at those distances.

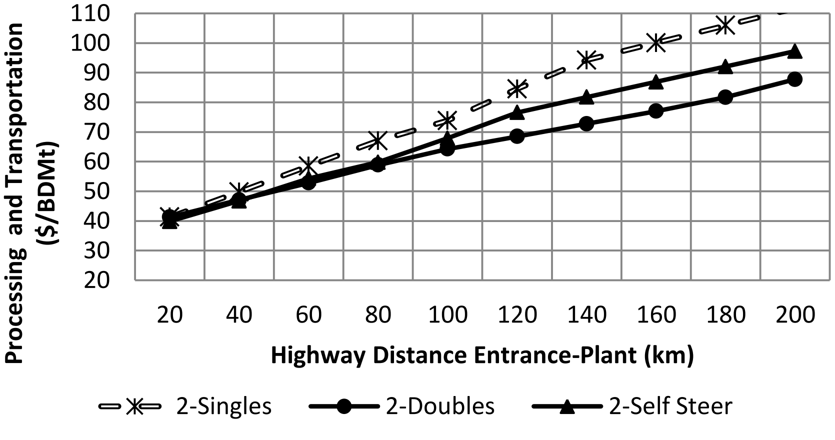

Figure 4.12 Effect of distance in total cost from the entrance to the bioenergy facility for each transportation option.

We also analyzed the effect of changing the paved highway distance of the system (2-double trucks 9.75-9.75 m long, 2 single trucks 9.75 m long and 2 self-steer 14.63 m long). An increase in the paved highway distance from the entrances to the bioenergy facility from 20 to 200 km causes an increment in cost of $59.59/BDMt (Figure 4.13). This increment is caused by the effect of distance in transportation cost and the potential increase in grinder standing time due to increase in truck inter-arrival time. The relation between distance and cost is not completely linear due to the fact that different transportation options are selected at each solution.

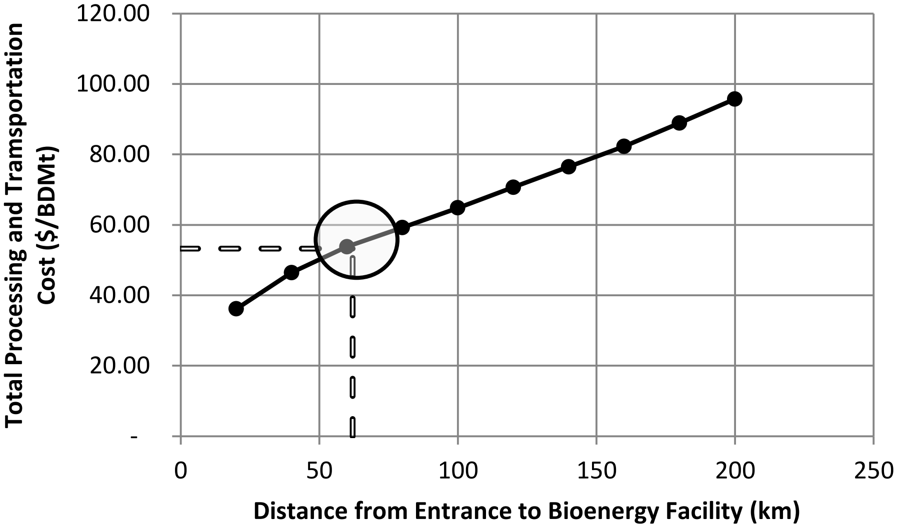

Figure 4.13 Effect of the distance in total cost from the entrance to the bioenergy facility.

The effect of changes in productivity for the horizontal grinder with the available truck options was also analyzed (Figure 4.14). An increase in productivity from 10 to 45 BDMt/ PMH may lead to a 58% decrease in cost.

4.6.4 Bundler Process

We compared model results with the utilization of a bundler for the analyzed unit. We incorporate this technology within the solution procedure by modifying the costs in the network. Bundling processing and cost were extracted from the USDA Forest Service Forest Residue Bundling Project (Rummer 2004). Based on this document, productivity was estimated at 4.6 BDMt/PMH and the hourly cost was $160/PMH. It was assumed that bundles were transported to a bioenergy facility using a straight-frame quad bunk logging trailer with a capacity of 17 tonnes. We assumed that bundles were processed at the bioenergy facility using a 740 kW electric grinder with an average productivity of 42 BDMt/PMH. Electricity cost (6 cents/kWh) was obtained from the U.S. Department of Energy (2013). Cost of processing and transport using a bundler was estimated in $63.80/BDMt. This cost is more expensive than the two horizontal grinders but cheaper than the tub and mobile chipper.

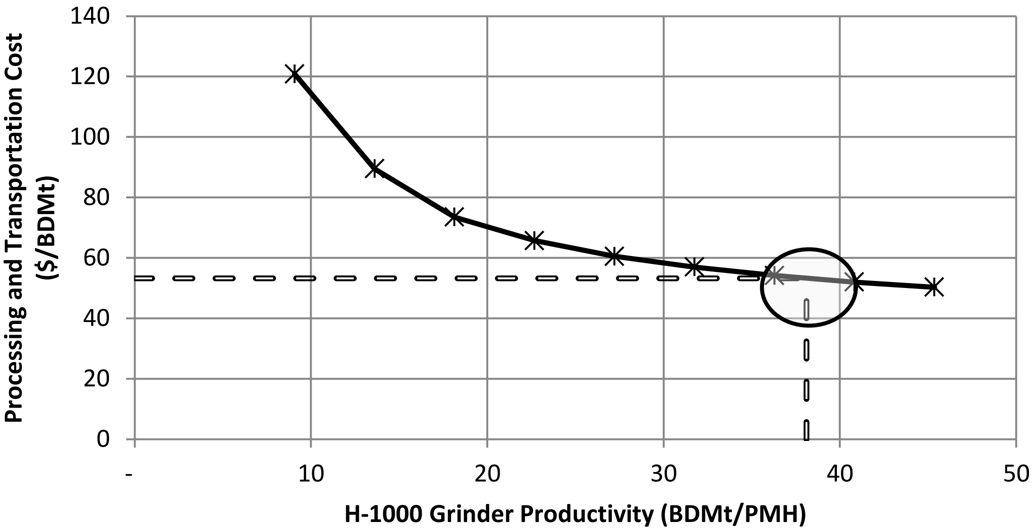

Figure 4.14 Effect of grinder productivity in total cost.

4.7 Conclusions

The model provides decision support to forest biomass recovery operations by developing different routes to optimize processing and transportation of forest biomass from residues at the operational level. The spatial component of the model allows the user to estimate internal distances and transportation cost in order to evaluate how different road characteristics and spatial location affect the cost. The developed network uses a mixed integer programming model that is aided by an Ant Colony heuristic to provide the lower bound for the branch and bound algorithm. Results demonstrate that the Ant Colony heuristic provides good results for the size of the study problem. For larger problems it is expected that the solution quality of the Ant Colony algorithm will decrease. Future research will be directed toward improvement of this algorithm. Our solution procedure is based on a route-network approach. By developing the routes we minimize the number of potential nodes which help to improve solution times. Simulation is an important feature in the model that allowed us to account for truck-machine interactions to develop reasonable utilization times based on road configuration and truck availability. The interface of RENO also allows creating the MIP matrix without direct interaction with the user. The manual development of a network is a time consuming activity in which the analyst can make errors that may be difficult to track as problem size increases.

From all different transportation options, the horizontal (740 kW) grinder resulted in the most cost effective processing option in the study problem. Instead of one dominant truck, different types were selected within the network. Hook- lift trucks are a feasible option when the fixed cost of operating at a particular site are high compared to adjacent locations. Also this option e can be used for small piles in order to minimize the grinder mobilization cost. Double trailer configuration are a cheaper option in this study but the time to hook and unhook the trailers as well as the time to unload at the mill must be analyzed carefully. The use of single (9.75 m long trailers) is a feasible option to access piles on steep terrain but the capacity of these smaller trailers is limited. They become available options at shorter distances (<55 km).

The model depends upon an accurate estimation of the available volume of residues to be processed. However, the dynamic of markets for wood products can change the type and amount of residue available. During the field part of this study, the market for pulpwood was high and available residue was usually comprised of branches and tops with diameters of less than 10 cm. In recent months the low prices for pulpwood in the US Pacific Northwest region have caused an increase in the piece size within the residue piles as pulpwood was not being utilized.

One of the strengths of the model is its flexibility to changes in productivity and cost. This flexibility allows the user to adapt to changes in markets of the woody biomass supply chain for energy purposes.

Identifying high cost piles can help forest manager and landowner to decide which piles need to be processed based on the profitability of the operation. In actual conditions the model is able to handle 4 different types of processing options, 6 standard drop center chip vans and 2 non-standard configurations (stinger steer and rear steer axle trailer), but it can be expanded to new options.

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CHAPTER 5 – GENERAL CONCLUSIONS

An efficient cost management strategies and planning process is required in order to ensure the long term success of a renewable energy supply chain from forest residues. I presented three papers in which I developed different models to analyze productivity and economics of forest biomass processing and transportation.

At the operational level, I analyzed the economics of processing and transportation. I evaluated two general types of processing equipment: stationary and mobile machines. Both types of machinery are commonly used in the United States and numerous operations were analyzed in Oregon and Washington to understand the operational details of the biomass recovery from residues. Different truck configurations were evaluated in terms of productivity, economics and accessibility. The study is focused on operations in steep terrain regions where road and terrain characteristics impose several operational constraints although it is also applicable in less constrained regions.

Forest road characteristics were evaluated to estimate their effect on productivity and economics. The economics of forest biomass collection can be greatly affected by forest road accessibility. Single passage forest roads can limit the number of trucks that can reach the processing site on time. The spatial location of the forest residue piles in relation to road features such as available truck turn-arounds and truck turn-outs can impact the truck inter-arrival rate affecting productivity. Those factors can increase the waiting time for processing machines (chippers or grinders).

This effect is increased when stationary grinders are used to process the residues due to the closely coupled operation where trucks have to be present at the processing site in order to maintain productivity of the stationary grinder. Forest roads characteristics must be analyzed in order to provide accurate cost estimation. Ignoring forest road features and spatial location of the forest residue piles within the unit can result in inaccurate cost estimations that can lead to inefficient operational practices.

Processing machine characteristics, transportation options and spatial location of the piles were analyzed and modeled as a system to understand the effect of truck-machine interactions on economics and productivity. The economic effect of these interactions was estimated based on three cases that were developed to understand in mathematical terms, the effect of road access, number of trucks, machine location in relation to the forest and highway network and type of processing and transportation technology.

A methodology to calculate the cost of waiting time for processing and transportation equipment was presented and evaluated for several forest operations. The cost of waiting time was estimated by adding the labor, supporting equipment, overhead costs and risk and profit (when machine or trucks are operating). This is a new approach, compared to typical machine rate calculations, to analyze closely coupled operations when the behavior of one machine can affect negatively or positively the productivity of the other. For example, the reduction of waiting time in stationary grinders can be achieved by increasing the number of trucks and reducing their inter-arrival time, however truck waiting time can be increased because several trucks arriving at relatively similar times may lead to more congestion and increasing truck queuing time. By valuing the economic effect of waiting time in trucks and processing machines I was able to balance the trade-offs and reduce the overall cost of the operation.

5.1 Economics of mobile chipping under uncertainty

In the first paper (chapter 2) I developed a stochastic simulation model that analyzes economics of mobile chipping. This involved the development of a framework to analyze and estimate the variability for each of the phases in the productive cycle. The system dynamics in the simulation model allowed me to account for the effect of truck machine interactions. I presented a new spatial-temporal approach to improve accuracy of data collection in field operations by using a combination of Geographic Information Systems (GIS) and tracking analysis to estimate machine path movements. The model was developed in Arena™ software and was fed with information from four different in-field operations in Oregon.

The model was applied to a forest operation in western Oregon. The model proved to be accurate in estimating productivity and economics of the operation and it demonstrated the applicability of simulation techniques to the mobile chipping problem. A cost distribution was developed in order to provide decision support to risk averse manager. Based on the economic model developed, accounting for truck machine interactions and uncertainty, cost varied from \$54 to \$68 per bone dry metric tonne, having a maximum probability of occurrence at a cost of $59/BDMt (35% of probability).

Varying the hauling distance from the entrance of the unit to the bioenergy facility has a negative impact in chipping cost by increasing the waiting time and consequently reducing productivity. Adding more trucks when distance increases appear a feasible option but transportation cost must be evaluated in order to balance benefits and costs. From all the transportation options selected, the double trailer configuration (9.75-9.75 m long) is the most cost effective option. As the forest road distance between the entrance and the location of the residue pile increases, the double trailers configuration starts to lose its competitive advantage due to the decrease in productivity caused by the increase in round-trip time. Two trucks carrying double trailers and two reserve trailers (9.75 m long each) in the field appears as the most cost efficient transportation option under the study conditions. The use of single trailers (9.75 m long) appeared to be cost effective only for distances equal to or less than 40 km.

Based on the simulation results operating the mobile chipper at a centralized landing and blowing the material directly into trailers can reduce comminution costs by about 15% as opposed to moving between the pile and the trailers. For this method to be cost effective, the maximum cost to transport the unprocessed residues varied from $5.40 to $15.53/BDMt.

5.2 Economics of truck-machine interaction in stationary equipment

In the second paper (chapter 3) the effect of truck-machine interactions between closely coupled equipment such as trucks and stationary grinders was analyzed. The effect of number of trucks and forest road accessibility on grinder utilization rate was estimated and compared to selected actual operations in Oregon and Washington. The necessary number of trucks for an operation is a function of the processing time, truck capacity, forest road distance, highway distance (paved distance from the entrance to the unit to the bioenergy facility), and daily maximum truck working time.

When the number of trucks is not the limiting factor, forest road characteristics must be analyzed to estimate their effect on truck productivity and economics in relation to the spatial location of the residue piles. The potential road limiting features were analyzed and grouped in three different cases.

Case I resulted in a situation where only one truck at a time could access the processing site due to road space limitations. An in-coming truck must wait at a turn-out or wide spot in the road until the loaded truck left the processing area and passed the road location where the unloaded truck was waiting. The economic impact in this case is a function of the driving time from the truck turn-out to the processing site, the truck turn-around time, the positioning time and the driving time from the processing site and the turn-around. The results from the model were compared to actual operations. In the study unit for Case I, the maximum achievable grinder utilization rate was 60% using six trucks. Using the actual number of trucks the grinder utilization could be expected to drop to 20%.

In case II, the forest road configuration allows a second truck to reach a turn-around and wait there until the grinder finishes the loading process of a first truck. After the loading process is accomplished, the first truck must pass the turn-around point to allow the second truck to back up to the processing site. Grinder waiting time is a function of the time the loaded truck drives from the processing location to the turn-around, the time the empty truck is backing up from the turn-around to the grinder location plus the positioning time. In the study unit for case II, maximum achievable utilization rate was 77% using seven trucks. Actual utilization rate was 60% using five trucks.

In case III, no truck interference is occurring since a loop road exists allowing an incoming truck to exit the unit using a different route. Grinder waiting time is only dependent upon the time the truck spent positioning. Maximum grinder utilization was 74%. Although adding one more truck increases the utilization rate, the increasing truck queuing time and the underutilization of some trucks outweigh the savings caused by the increase in utilization rate.

5.3 A solution procedure for the economic optimization of forest biomass processing and transportation

The final paper (chapter 4), comprised the design, development and implementation of a solution procedure to optimize the economics of forest biomass processing and transportation operations from forest harvest residues. The procedure involved combining Geographic Information Systems (GIS), a Mixed Integer Programming model, simulation, forest operations planning and network optimization to produce an efficient solution for processing and transportation technology. The model also uses the simulation model for each truck-machine case developed in chapter 3,

This model is incorporated in the computerized decision support system <u>Residue Evaluation and Network Optimization</u> (RENO) and was applied to forest biomass recovery operations in Oregon, USA. The model was able to estimate the processing and transportation cost at each pile and can be used to decide if is cost-effective to process all or a subset of piles within the unit.

The model allows to the analyst to select different available transportation and processing options and finds the most cost effective comminution machinery and truck configuration for each pile. Additionally, the model calculates the processing cost based on the number and capacity of available trucks to account for the economic effect of truck-machine interactions. Based on the spatial data the model identifies residue piles turn-around, turn-outs and potential centralized places to calculate internal distances that allow the transport cost estimation within the forest unit. Also the transportation cost outside the field unit on highway paved roads is estimated.

The solution for the study site suggests the use of a stationary grinder (745 kW) for processing the residues; the use of a double trailer configuration (9.75-9.75 m) in seven of the piles; the use of a single trailer configuration (9.75 m) in four piles and the use of hook-lift trucks in two of the piles to transport unprocessed residues to adjacent piles. This mix of transportation options is related to the residue pile location and road accessibility. Considering all piles, average utilization rate was 33% for two trucks hauling two double trailers and four trucks hauling single trailers. Utilization can be increased to 53% by doubling the number of double trailer trucks available.

The implementation of a centralized yard in the study area does not appear to be cost-effective. Although grinder utilization rate can increase up to 70% with direct loading into double trailers, the benefits do not compensate for the cost of using hook-lift trucks to concentrate the residues.

5.4 Future direction of biomass processing and transportation research at the operational level

The model developed provides the most cost effective processing machinery and transportation configuration for conducting forest biomass recovery operations. However the model is dependent on a series of inputs that need to be analyzed in future studies. The volume estimation method to determine the available residue at each pile is necessary. This model has to take into account different physical factors related to the logging method used in the operation, the physical properties and species mixture of the material and requirement in terms of piece size and type for sawtimber and pulpwood industries. Models for the moisture content estimation at the pile are required to improve estimation of the value of the material. New technologies to maximize the hauling capacity are also required.

From the mathematical optimization point of view, future research can be focused in the development of a truck scheduling model that uses the solution from RENO in order to generate optimal routes for each truck based on the available volume at each pile. This model can generate delivery schedules per day in order to optimize transportation and the overall cost of the operation.

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APPENDICES

Appendix A – Supplementary formulas for hourly cost calculations

Fixed cost equations

$$S_m = P_m * rv_m \qquad \text{(A1)}$$

$$AD_m = \frac{P_m - S_m}{n_m} \qquad \text{(A2)}$$

$$AYI_m = \frac{(P_m - S_m)(n_m + 1)}{2n_m} + S_m \qquad \text{(A3)}$$

$$in_m = ir_m * AYI_m \qquad \text{(A4)}$$

$$It_m = ix_m * AYI_m \qquad \text{(A5)}$$

$$Fx_m = \frac{AD_m + In_m + It_m}{H_m} \qquad \text{(A6)}$$

Variable cost equations

$$La_m = \frac{Lr_m(1 + Lb_m)}{wh_m} \qquad \text{(A7)}$$

$$Rc_m = \frac{AD_m * rr}{H_m} \qquad \text{(A8)}$$

$$Kc = \left(\frac{Kp * nk}{Kl} + \frac{Kr * nk}{Kt}\right) \qquad \text{(A9)}$$

$$Su_m = Cwt_m + Cst_m + Cot_m \qquad \text{(A10)}$$

$$Fc = (fi\,)Fp \qquad \text{(A11)}$$

$$Va_{ch} = La_m + Rc_m + Fc(1 + lfc) + Kc \qquad \text{(A12)}$$

$$R_t = \frac{W_t * cr(0.278 * V_t)}{1000}(9.8 m/s^2) \qquad \text{(A13)}$$

$$AR_t = \frac{\frac{\delta}{2} * dr * FA_t(0.278 * V_t)^3}{1000} \qquad \text{(A14)}$$

$$Pwr = (R_t + AR_t)/efi \qquad \text{(A15)}$$

$$fct = \frac{ct * Pwr}{wf} \qquad \text{(A16)}$$

$$Ti = \frac{\left(\frac{T_n * nt_m}{ml_n}\right)my}{H_{tr}} \qquad \text{(A17)}$$

$$Va_{rwz} = La_m + Rc_m + fct(1 + lfc)fc + Ti \qquad \text{(A18)}$$

where

S_m	salvage value of machine *m*,($).
P_m	purchase price,($)
rv_m	salvage value percent of the purchase price of machine m (%)
AD_m	annual depreciation for machine *m*, ($)
n_m	machine life of machine m,(Years)
AYI_m	average yearly investment,($)
in_m	interest cost of machine *m*, ($)
ir_m	interest rate of machine m, (%)
ix_m	insurance and road use, license and tax rate of machine m, (%)
It_m	insurance and tax or road use cost for machine m, ($)
H_m	Scheduled machine hours per year of machine m (h)
Fx_m	fixed costs of machine m, ($/h)

La_m	hourly labor cost of operator of machine m,($/h),
Lr_m	annual salary of operator of machine m,($/h)
Lb_m	benefit rate, percentage of annual salary of operator of machine m,($/h)
wh_m	scheduled labor hours per year of operator of machine m, (h)
Rc_m	repair and maintenance cost, of machine m, ($/h)
rr	repair and maintenance percentage of depreciation, (%)
Kc	knife cost,($/h)
Kp	price of new chipper knife,($/knife)
Kr	cost or knife re-sharpening,($/knife)
nk	number of knives
Kl	Expected knife life,(h)
Kt	time between knife re-sharpening,(h)
Su_m	cost of supporting equipment of machine m, ($/h)
Cwt_m	cost of water truck of machine m, ($/h)
Cst_m	cost of service truck of machine m, ($/h)
Cot_m	cost of operator's truck of machine m, ($/h)
Fc	fuel cost ($/h)
fi	liters per hour for chipper-forwarder
lfc	lubricants ratio as percentage of fuel cost, (%)
Fp	fuel price ($/lt)
Va_{ch}	variable chipping cost ($/h)
R_t	power of truck type t, necessary to overcome rolling resistance,(kW)
W_t	weight of truck type t, empty or loaded,(kg)
cr	rolling resistance coefficient based on road standard
V_t	average speed of truck loaded or unloaded,(km/h)
AR_t	power of truck type t, necessary to overcome air resistance,(kW)
FA_t	frontal area of truck type t,(m^2)
δ	air density,(kg/m^3)
dr	coefficient of drag
Pwr	power necessary to overcome rolling, and air resistance based on truck engine efficiency (kW)
efi	truck engine efficiency (%)
fct	hourly truck fuel consumption (lt/h)
ct	truck fuel consumption (kg/Kwh)

wf	weight of diesel (kg/lt)
Ti	hourly tyre cost,($/h)
T_n	tyre price,($/tyre) of type n (includes the cost of 2 retreads)
nt_m	number of tyres in truck type m
ml_n	tyre expected life (including retreads) (km)
my	driven kilometers per year (km)
H_{tr}	productive machine hours per year for trucks (h)
Va_{rwz}	variable transportation hourly cost based on road standard r, weight *w* and speed *z*, ($/h)

Appendix B – Assumptions for mobile chipping processing and transport

Table B. 1. Assumptions for Trucks and chipper fixed cost calculation

Cost	Transportation		Processing
	Single Trailer	Doubles Trailer	Mobile Chipper
Horse power (kW)	404	404	331
Trailers length (m)	9.75	9.75-9.75	
Purchase price truck/chipper ($)	130,000	130,000	750,000
Purchase price of the trailer ($)	30,000	65,000	
Machine life truck (km)	720,000	770,000	
Machine life trailer (km)	1,440,000	1,440,000	
Chipper life (h)	-	-	7500
Machine life (years)	8	8	5
Trailer life (years)	15	15	
Salvage value truck/chipper percent of purchase (%)	35	35	20
Salvage value trailer percent of the purchase price (%)	25	25	
Interest rate (%)	10	10	10
Insurance, Road use, license and tax rate (%)	10	10	4.5
Scheduled machine hours per year	2,200	2,200	2000
Total fixed cost ($/h)	16.26	19.20	116.75

Table B.2. Assumptions for chipping and transport variable cost calculation

	Transportation		Processing
Cost Item	Single Trailer	Double Trailer	Mobile Chipper
Labor Cost ($/year)	37,770	37,770	50,000
Benefits percentage of (%)	35	35	35
Working hours per year (h)	2,200	2,200	1,800
Repair and Maintenance percentage of depreciation (%)	70	70	70
New knives price ($/Knife)	-	-	500
Number of knives in the drum	-	-	2
Knife life (h)	-	-	500
Time between knife re-sharpening (h)	-	-	10
Knife sharpening cost ($/Knife)	-	-	60
New tyre cost	700	700	-
Retread truck tyre cost	300	300	-
Tyre life km/tyre (include retread)	192,000	192,000	-
Driven km per year	83,000	83,000	-
Number of tyres	18	30	-
Frontal area (m2)	9.29	9.29	-
Drag coefficient	0.80	1.00	-
Air density (kg/m3)	1.22	-	
Rolling resistance coefficient paved road	0.013	0.013	-
Rolling resistance coefficient gravel road	0.020	0.020	-
Rolling resistance coefficient dirt road	0.021	0.021	-
Fuel cost ($/lt)	1.06	1.06	1.06
Lubricants percentage of fuel cost (%)	10	10	36
Chipper-forwarder fuel consumption (lt/h)	-	-	45.4
Fuel weight (kg/lt)	0.85	0.85	-
Truck fuel consumption high throttle (kg/kWh)	0.24	0.24	-
Truck fuel consumption low throttle (kg/kWh)	0.30	0.30	-
Truck engine efficiency (%)	85	85	-

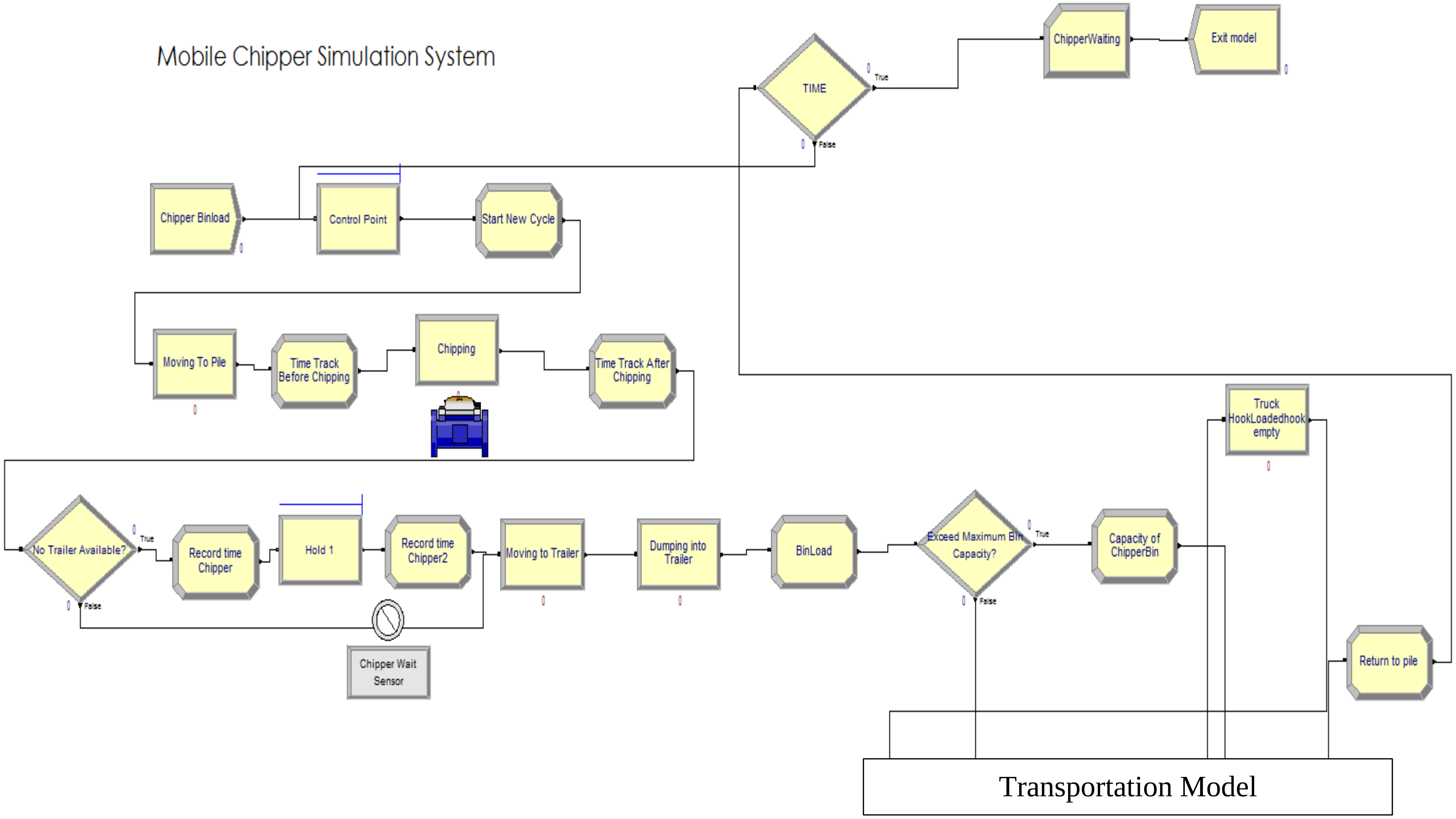
Appendix C – Linear programming model for truck maximum payload calculation

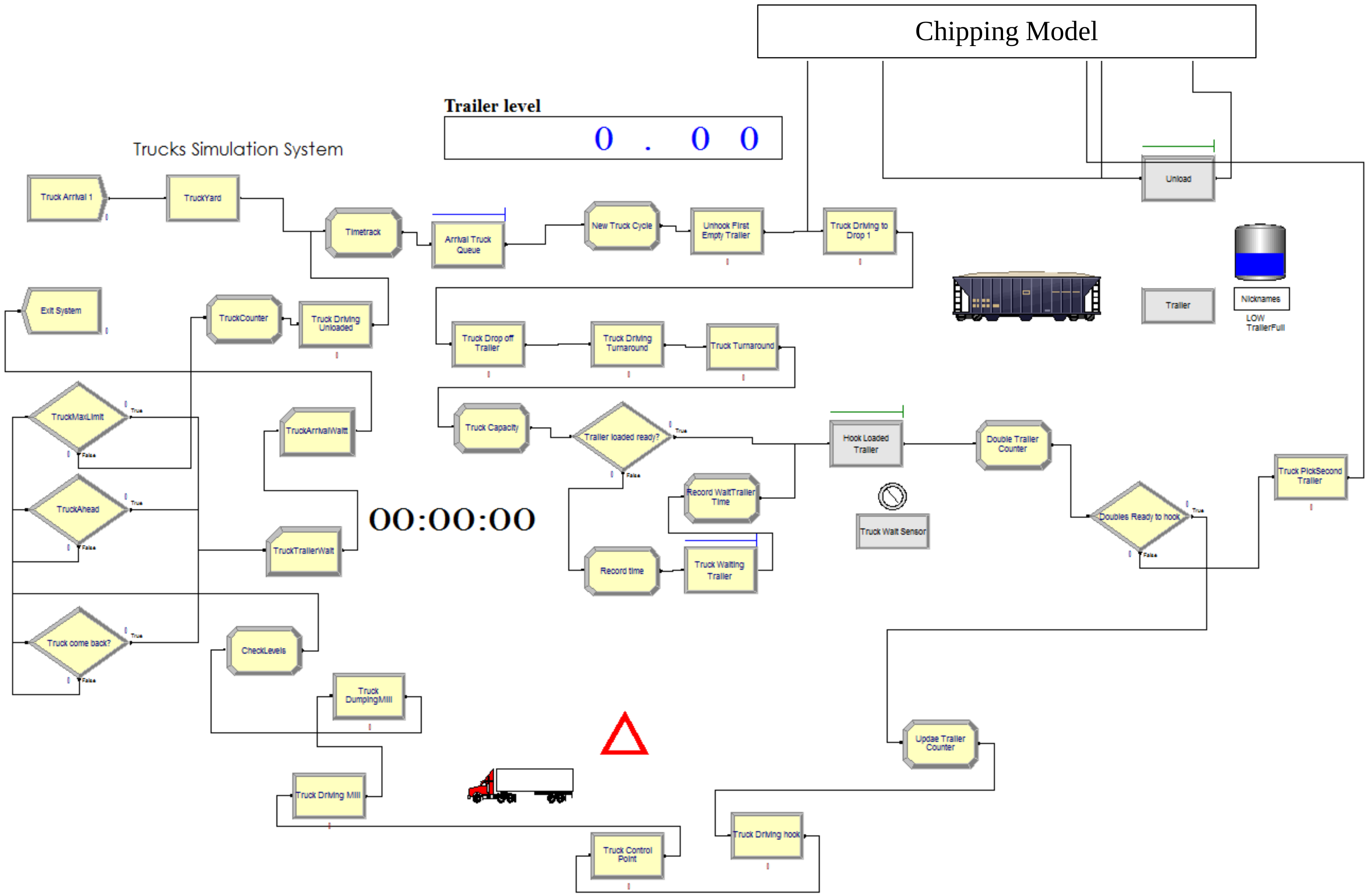
```
!Truck and trailer configuration WITH the lift axle Extended Maximum
allowable weight Oregon, 32 foot single drop center trailer;

Max=Z;
!Objective function Maximum allowable vehicle weight;
Z= w1+w2+w3+w4+w5;

!Maximum loading per axle;
w1<=12000;
w2<=20000;                    !Lift axle;
w3<=20000;
w4<=20000;
w5<=20000;


!Group limit according to the distance and number of axles;
w1+w2<=40000;
w1+w2+w3<=51000;
w1+w2+w3+w4<=68500;
w1+w2+w3+w4+w5<=75500;


w2+w3<=34000;
w2+w3+w4<=54500;
w2+w3+w4+w5<=61500;


w3+w4<=40000;
w3+w4+w5<=54500;


w4+w5<=34000;
```

```
!Truck and trailer configuration WITH the lift axle Extended Maximum
allowable weight Oregon, Self Steer Trailer 48' trailer;

Max=Z;
!Objective function Maximum allowable vehicle weight;
Z= w1+w2+w3+w4+w5+w6+w7;

!Maximum loading per axle;
w1<=12000;  !Front Axle;
w2<=8000;   !Drop Axle;
w3<=20000;  !Truck Driver 1;
w4<=20000;  !Truck Driver 2;
w5<=20000;  !Wide Tire Steer Trailer 1;
w6<=20000;  !Wide Tire Steer Trailer 2;
w7<=20000;  !Tri-axle double tires;

!Group limit according to the distance and number of axles;
w1+w2<=40000;
w1+w2+w3<=48500;
w1+w2+w3+w4<=56000;
w1+w2+w3+w4+w5<=80000;
w1+w2+w3+w4+w5+w6<=87500;
w1+w2+w3+w4+w5+w6+w7<=95000;

w2+w3<=34000;
w2+w3+w4<=43500;
w2+w3+w4+w5<=68000;
w2+w3+w4+w5+w6<=75500;
w2+w3+w4+w5+w6+w7<=84000;

w3+w4<=34000;
w3+w4+w5<=60000;
w3+w4+w5+w6<=68000;
w3+w4+w5+w6+w7<=75500;

w4+w5<=40000;
w4+w5+w6<=60000;
w4+w5+w6+w7<=68500;

w5+w6<=34000;
w5+w6+w7<=43500;

w6+w7<=34000;
```

```
!Truck and trailer configuration WITH the lift axle Extended Maximum
allowable weight Oregon 53 foot single drop center trailer Quad;

Max=Z;
!Objective function Maximum allowable vehicle weight;
Z= w1+w2+w3+w4+w5+w6+w7+w8;

!Maximum loading per axle;
w1<=12000;  !Front Axle;
w2<=8000;   !Drop Axle;
w3<=20000;  !Truck Driver 1;
w4<=20000;  !Truck Driver 2;
w5<=20000;  !Trailer Axle 1;
w6<=20000;  !Trailer Axle 2;
w7<=20000;  !Trailer Axle 3;
w8<=20000;  !Trailer Axle 4;

!Group limit according to the distance and number of axles;
w1+w2<=40000;
w1+w2+w3<=50000;
w1+w2+w3+w4<=58000;
w1+w2+w3+w4+w5<=80000;
w1+w2+w3+w4+w5+w6<=89500;
w1+w2+w3+w4+w5+w6+w7<=97500;
w1+w2+w3+w4+w5+w6+w7+w8<=105500;

w2+w3<=34000;
w2+w3+w4<=45500;
w2+w3+w4+w5<=70000;
w2+w3+w4+w5+w6<=77000;
w2+w3+w4+w5+w6+w7<=85000;
w2+w3+w4+w5+w6+w7+w8<=92000;

w3+w4<=34000;
w3+w4+w5<=60000;
w3+w4+w5+w6<=68000;
w3+w4+w5+w6+w7<=75500;
w3+w4+w5+w6+w7+w8<=84000;

w4+w5<=40000;
w4+w5+w6<=60000;
w4+w5+w6+w7<=72000;
w4+w5+w6+w7+w8<=79000;

w5+w6<=34000;
w5+w6+w7<=43500;
w5+w6+w7+w8<=52500;

w6+w7<=34000;
w6+w7+w8<=43500;

w7+w8<=34000
```

Appendix D – Simulation Model




Chipping Model
Trailer level
0 . 0 0
Trucks Simulation System
Truck Arrival 1
TruckYard
Timetrack
Arrival Truck Queue
New Truck Cycle
Unhook First Empty Trailer
Truck Driving to Drop 1
Unload
Trailer
Nicknames
LOW
TrailerFull
Exit System
TruckCounter
Truck Driving Unloaded
Truck Drop off Trailer
Truck Driving Turnaround
Truck Turnaround
TruckMaxLimit
True
False
TruckArrivalWait
Truck Capacity
Trailer loaded ready?
True
False
Hook Loaded Trailer
Double Trailer Counter
Truck PickSecond Trailer
TruckAhead
True
False
Record WaitTrailer Time
Truck Wait Sensor
Doubles Ready to hook
True
False
TruckTrailerWait
00:00:00
Record time
Truck Waiting Trailer
Truck come back?
True
False
CheckLevels
Truck DumpingMill
Updae Trailer Counter
Truck Driving Mill
Truck Driving hook
Truck Control Point