Economic Impact of Truck–Machine Interference in Forest Biomass Recovery Operations on Steep Terrain

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Abstract

In forest biomass recovery operations from harvest residues, processing equipment can work most productively if they can work without interference or waiting on trucks. 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 grinder is waiting for trucks or vice versa. We analyzed how the number of available trucks and road characteristics affect grinder utilization and 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 turnaround, turnouts, truck turning-around time, truck positioning time, and distance traveled on each road surface have a significant effect in forest residues processing and transport economics at the operational level. After the optimization was performed, the grinder utilization rate on a harvest unit with highly constrained road access reached 60 percent using six trucks. Waiting cost represented 15.15 percent of total grinding cost. On the medium constrained road access harvest unit, maximum grinder utilization reached 77 percent using five trucks. A loop road case resulted in a grinder utilization rate of 81 percent using five trucks.

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 few 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 (Hakkila 1989). The US Department of Energy (2011) estimates that approximately 40 million metric tonnes of forest residues is available following timber harvesting each year in the United States.

Forest residues in the US Pacific Northwest (PNW) are typically comminuted during field operations following timber harvesting using 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 et al. 2011). Grinders are expensive machines with engines producing between 500 and 1,000 horsepower that result in high purchase and running costs. Track-mounted grinders have limited mobility to facilitate the placement of the machinery at a processing site. Road accessibility and low driving speeds of the tracked carrier limit machine mobilization within a

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forest unit. Chippers are also available to process the material. The choice of chipping versus grinding depends on operating conditions and product end use. The ability to operate in the presence of contamination (dirt and rocks), and the high throughput when product specifications permit larger nonuniform pieces, favor grinders (Ryans 2009).

Processed material is usually discharged directly into open-top chip 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. The use of set-out trailers is not a feasible alternative because a truck must be present when loading to move the trailer forward to distribute the load.

Forested steep lands create additional problems related to road accessibility. Available truck turnaround spaces are usually reduced in number and limited in space. Distance between the processing location and available truck turnaround 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 turnout or turnaround space that must be located as close as possible to the grinding site. Availability and location of truck turnout and turnaround spaces are important factors to consider when planning biomass recovery operations on steep terrain (TSS Consultants 2012)

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. In places where chip vans cannot access the residue location, short trucks, such as bin, roll-off, or hook-lift trucks, can be used to move the unprocessed material to a centralized location with better access to large trucks. The cost of short trucks is very sensitive to changes in hauling distance; therefore, a cost–benefit analysis must be carried out to evaluate each operation (Han et al. 2010). Additionally, forest residue type and material size have significant effect on productivity of short trucks when transporting loose residues (Harrill 2010).

Spinelli and Visser (2009) used literature related to in-field wood chipping operations to analyze and estimate delays of different machines and different operating conditions. They found an average chipper utilization rate of 73.8 percent. 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. Although organizational-type delays exist in grinding operations on steep terrain, it is also necessary to analyze the effect of road accessibility in machine utilization. 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 such as turnaround and turnout availability on grinder productivity and economics. Additionally, traditional machine cost estimations based on the average delay costs can be inaccurate if machine utilization is constantly affected by road access and equipment balancing.

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 these 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 estimations that are typically based only on the average utilization rate of machinery cost.

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 (road grade ranging from 8% to 20%) using stationary grinders. The term stationary refers to the limited mobility of the machine within the forest unit compared with other processing alternatives, such as mobile chippers. Our specific objectives were to (1) determine the effect of road characteristics, number of trucks, and truck configuration on grinder utilization rates and (2) 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 visited 21 different biomass recovery operations in Oregon and Washington that allowed us to develop different cases that represent the most common situations that a manager can face in operations on steep terrain. The different cases were based on the spatial location of the residue pile in relation to the available truck turnarounds and turnouts. The productive system was modeled through simulation. The model was developed in the 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 turnaround location and internal forest network. An economic model was developed to estimate the waiting cost for grinders and trucks, taking into account fixed and variables costs.

Actual operations for each of the cases were compared with 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.

Materials and Methods

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 loaders'') and with access for chip trailers. A turnaround 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, excavator loaders can be used to move the material to locations reachable by the grinder.

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 United States 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, and they may require more maintenance than tub grinders (RE Consulting and Innovative Natural Resource Solutions LLC 2007). In both types of grinders, processed material is removed from the comminution site and either loaded into the trailer or dumped on the ground using a discharge conveyor.

Transportation of processed forest residues is made by chip trailers pulled by a 6 by 4 truck tractor. Typical trucks are triaxle with traction in the two rear axles. Some trucks can contain an additional nonpowered drop axle to increase legal weight capacity, while others have power to all axles (6 by 6 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. Nonconventional 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.

Model description

The 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 the 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 on 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 a limiting factor was also analyzed.

Inputs for the model were grinder loading time, trailer capacity, number of trucks, interarrival 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 leave 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.

Case I: Stationary grinder truck–machine interference with truck turnouts

Case I illustrates the situation when the processing site is located between a truck turnout and a truck turnaround location (Fig. 1). 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 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 turnout (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 turnout point.

The truck turnaround 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 turnout, and the time between the truck arrivals for the first arrival of the day (Eq. 1). Equation 2 states that truck interarrival times must not be greater than the processing time plus the time the loaded truck spends 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 interarrival time constraint applies only 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) is dependent on (1) the time the loaded truck is traveling from the grinder location to the turnout (where the empty truck is waiting), (2) the time that the arriving empty truck spends traveling from the turnout to the turnaround, (3) the time that the empty truck spends

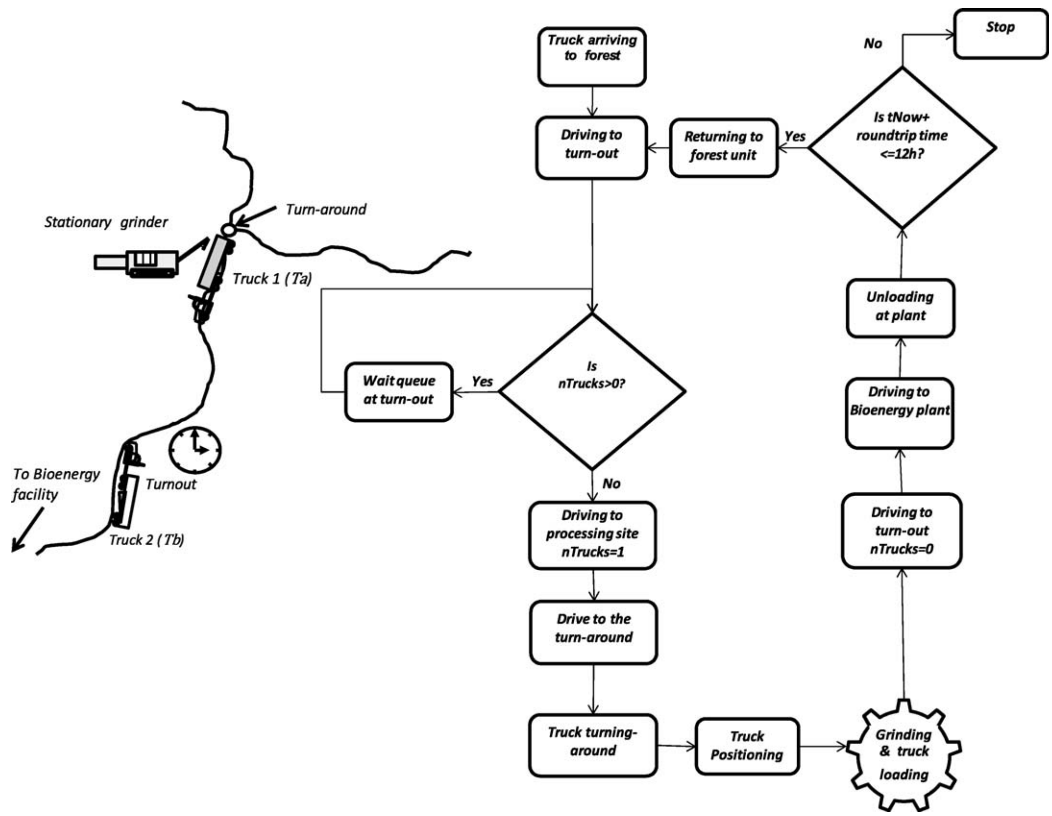

Figure 1.—Case I model, in-road loading and turnaround located after processing site.

turning around, (4) the time the empty truck spends driving from the turnaround to the grinder location, and (5) the time the empty truck spends positioning at the grinder location:

$$W_t = P_t + Ta_{gn} - A_t \tag{1}$$

$$A_t \leq P_t + Ta_{gn} \tag{2}$$

$$G_t = Ta_{gn} + Tb_{na} + Tb_a + Tb_{ag} + Tb_g \tag{3}$$

where

- $W_t =$ arriving empty truck waiting time while another truck is being loaded (h);
- $P_t =$ processing time for a truckload (h);
- $Ta_{gn} =$ the time the loaded truck is traveling from the grinder location, *g,* to the turnout, *n* (h);
- $A_t =$ truck interarrival 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 traveling from turnout, *n,* to the turnaround, *a* (h);
- $Tb_a =$ time that the empty truck spends turning around at turnaround, *a* (h);
- $Tb_{ag} =$ time that the empty truck spends traveling from the turnaround, *a,* to the grinder, *g* (h); and
- $Tb_g =$ time that the empty truck spends positioning at the grinder location, *g* (h).

Case II: Stationary grinder truck–machine interference with turnaround located before grinder processing site

Case II models a situation where the turnaround 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 turnaround until the loaded truck passes the point where the turnaround is located (Fig. 2). We assumed that the turnaround 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.

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 turnaround location, and the truck interarrival time Eq. 4. Truck interarrival times must be less than or equal to the processing time plus the time the loaded truck spends driving to the turnaround (where the empty truck is waiting; Eq. 5).

Grinder waiting time is dependent on the time the loaded truck spent traveling from the grinder location to the turnaround plus the time the empty truck is backing up in direction to the grinder plus the time for positioning (Eq. 6):

$$W_t = P_t + Ta_{ga} - A_t \tag{4}$$

$$A_t \leq P_t + Ta_{ga} \tag{5}$$

$$G_t = Ta_{ga} + Tb_{bg} + Tb_g \tag{6}$$

where

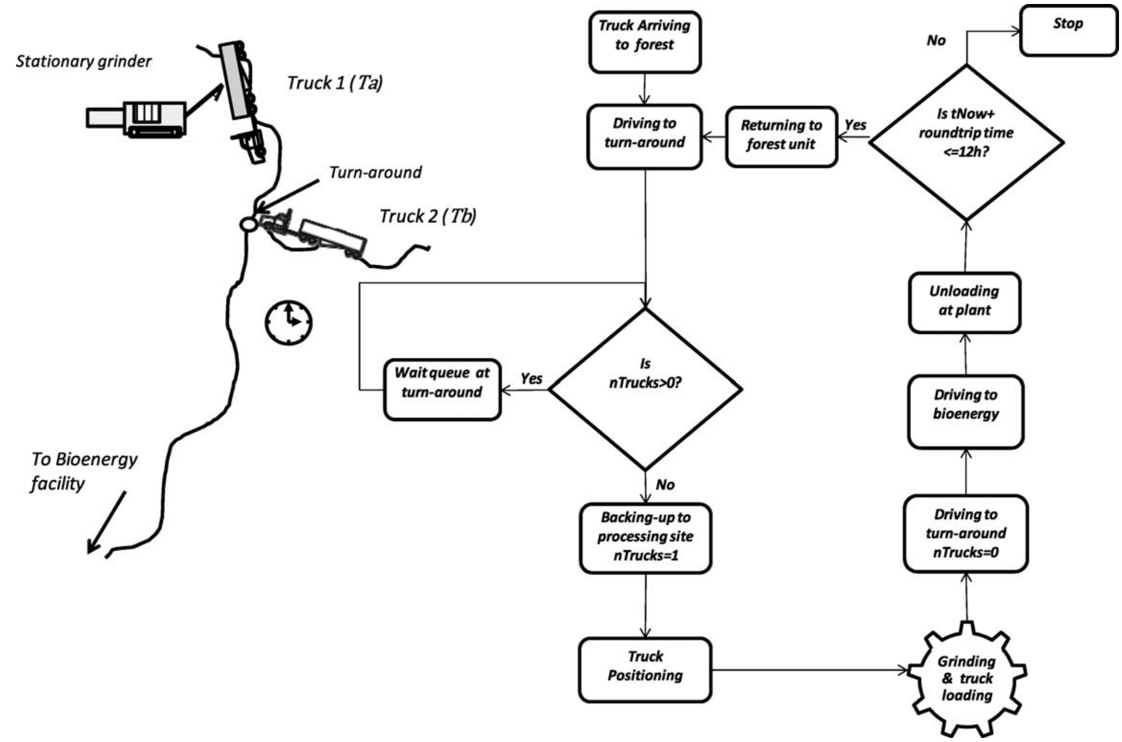

Figure 2.—Case II, truck–grinder interference, turnaround located before processing site.

Tb_{ga} = time that a loaded truck spends traveling from the grinder location, *g,* to the turnaround, *a* (h), and

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

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 turnaround is needed because the uphill and downhill traffic does not transit over the same road (Fig. 3).

The waiting time for a second truck arriving to the unit while the first truck is being loaded is dependent only on the loading time (Eq. 7). Inequality 8 ensures that a truck will be available for the grinder after a truck has been loaded. Waiting time of the grinder is dependent on the positioning time of the arriving truck (Eq. 9):

$$W_t = P_t - A_t \tag{7}$$

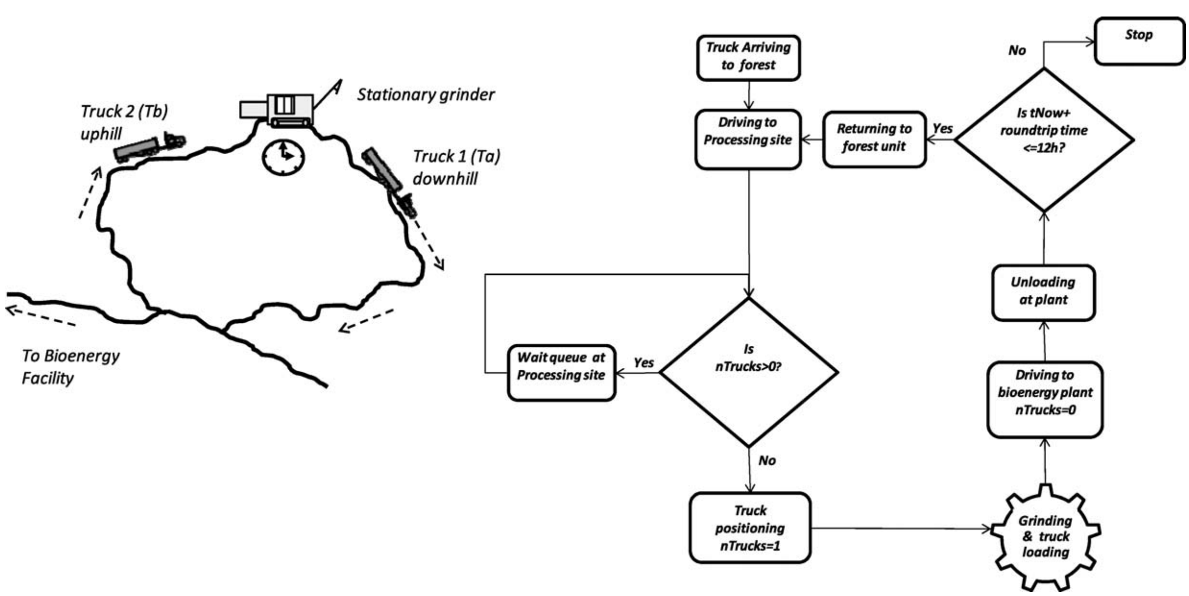

Figure 3.—Case III, truck–grinder interference, loop road.

$$A_t \leq P_t \tag{8}$$

$$G_t = Tb_g \tag{9}$$

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 provide a full spectrum of potential scenarios.

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. We modeled the economics of a Peterson 4710B (522 kW) and a Peterson 5710C (783 kW), both track-mounted horizontal grinders. Transportation configurations modeled were two types of 6 by 4 truck–trailer combinations and one 6 by 6 truck–trailer combination. One 6 by 4 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 (6 by 6) 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 was either running or waiting. Running costs for processing and transportation were calculated on the basis of fixed cost, variable costs, and profit and risk.

Fixed costs (Eq. 10) for processing and transportation were calculated on the basis of (1) purchased price, (2) machine life (5 y, 7,500 productive machine hours for the grinders and 8 y or 1.2 million km for trucks), (3) annual depreciation (calculated using straight-line depreciation method based on 20% of salvage value), (4) interest cost (10% of average yearly investment), and (5) insurance and road usage permits (10% of average yearly investment for trucks and 5% for the grinders). We assumed a total of 1,500 productive machine hours per year for the grinders and 2,000 productive hours for the trucks. All equipment was assumed to be purchased new. Assumptions were adapted from Brinker et al. (2002).

The hourly variable cost for processing (Eq. 11) consisted of (1) labor ($45,000/y) and benefits (35% of annual salary), (2) fuel (102 liters/h for the 4710B and 113 liters/h for the 5710C), (3) lubricants (36% of fuel cost), (4) grinder bits (22 bits with a size of 7 by 12.7 cm for the 4710B grinder with an average expected life of 58 h and 20 bits with a size of 7.6 by 16.5 cm for the 5710C with an average expected life of 48 h), and (5) 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. 12) consisted of labor ($37,770/y) and benefits (35% of annual salary) and 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, and 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 on paved, 0.020 on gravel, and 0.021 on dirt roads). 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 following Food and Agriculture Organization of the United Nations (1992) rates (10%). Repair and maintenance were calculated as a percentage of depreciation annual cost (70%). Overhead cost was calculated on the basis of one dispatcher, communications, and office consumables. A similar costing approach has been reported by Lautala et al. (2011), where costs were classified as administrative expenses:

$$F_m = (d_m + i_m + t_m)/H_y \tag{10}$$

$$V_g = f_g + l_g + b_g + k_g + r_g + x_g + k_g + s_g + o_g \tag{11}$$

$$V_t = f^t_{ijr} + l_t + w_t + b_t + r_t + o_t \tag{12}$$

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^t_{ijr} = 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 ($/h); and
o_t = hourly overhead cost for truck type, t ($/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 on the basis of the waiting time caused by truck–machine interference. In calculating waiting costs when a truck or grinder was not running, we assumed that the only fixed cost components were interest, insurance, and taxes;

Table 1.—Running and waiting costs for processing machinery.

Cost category	Running cost: Grinder 4710 B	Running cost: Grinder 5710 C	Waiting cost: Grinder 4710 B	Waiting cost: Grinder 5710 C
Fixed costs				
Purchase price ($)	515,000	700,000	—	—
Annual depreciation ($/h)	54.93	74.67	—	—
Annual interest ($/h)	23.35	31.73	17.51	23.80
Annual insurance and taxes ($/h)	17.17	23.33	12.88	17.50
Annual productive machine hours (h)	1,500	1,500	—	—
Hourly fixed machine cost ($/h)	95.45	129.73	30.39	41.30
Variable costs ($/h)				
Labor	33.75	33.75	33.75	33.75
Bits grates and anvil cost	18.68	21.88	—	—
Repair and maintenance	27.47	37.33	—	—
Fuel cost	108.00	120.00	—	—
Lubricants cost	38.88	43.20	—	—
Loader cost	102.89	102.89	—	—
Supportive equipment	14.80	14.80	14.80	14.80
Overhead cost	21.08	21.08	21.08	21.08
Hourly variable costs	365.54	394.94	69.63	69.63
Profit and risk, 10% ($/h)	46.10	52.47	46.10	52.47
Total cost ($/h)	507.09	577.14	176.50	204.70

that is, machine productive life was not being shortened when the machine was not running. Depreciation cost due to truck and machine obsolescence was not considered in the waiting cost. Total hourly waiting cost was limited to labor, supporting equipment, and overhead costs. Profit and risk cost (when the truck or machine is running) was also included in the waiting cost estimation to account for the opportunity cost of loss of productivity while waiting. Equation 13 for grinders and Equation 14 for trucks show the estimation of waiting costs:

$$Wc_g = l_g + s_g + o_g + pr_g + ((i_m + t_m)/H_y) \tag{13}$$

$$Wc_t = l_t + o_t + pr_t + ((i_t + t_t)/H_y) \tag{14}$$

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

Running and waiting cost for the selected equipment are shown on Table 1 for processing options and Table 2 for transportation. Given that the hourly transportation fuel cost changes with the traveled distance on each road surface, we

Table 2.—Running and waiting costs for transportation options.[a]

Cost	Running cost: Standard 7.62	Running cost: Standard 13.7 m	Running cost: Rear-steer axle 14.63 m	Waiting cost: Standard 7.62	Waiting cost: Standard 13.7 m	Waiting cost: Rear-steer axle 14.63 m
Fixed costs						
Purchase price tractor–trailer ($)	100,000	180,000	300,000	—	—	—
Annual depreciation ($/h)	4.64	8.24	14.70	—	—	—
Annual interest ($/h)	3.23	5.81	9.74	2.94	5.28	8.85
Annual insurance and taxes ($/h)	3.23	5.81	9.74	2.94	5.28	8.85
Annual productive machine hours (h)	2,000	2,000	2,000	—	—	—
Hourly fixed cost ($/h)	11.10	19.86	34.17	5.88	10.57	17.70
Variable costs ($/h)						
Labor	23.18	23.18	27.61	23.18	23.18	27.61
Tire cost	6.41	6.41	9.50	—	—	—
Repair and maintenance	3.25	5.77	11.76	—	—	—
Fuel and lubricants	19.30	19.30	26.55	—	—	—
Overhead cost	6.70	6.70	6.70	6.70	6.70	6.70
Hourly variable cost	58.84	61.36	82.13	29.88	29.88	34.31
Profit and risk, 10% ($/h)	6.99	8.12	11.63	6.99	8.12	11.63
Total hourly cost ($/h)	76.94	89.35	127.93	42.75	48.57	63.64

[a] Standard trailers were pulled by 6 by 4 truck tractors, and the rear-steer axle was pulled by a 6 by 6 truck tractor.

Table 3.—Average grinder productivity in each of the analyzed units.

Unit	Case	Grinder type	n	Loading time (h)	Load size (t)	Productivity (green t/h)
1	I	5710C (783 kW)	18	0.46	24.49	53.23
2	II	4710B (522 kW)	22	0.37	21.77	58.36
3	III	4710B (522 kW)	16	0.31	14.51	46.67

assumed an average transportation cost for a round-trip distance of 120 km (100 km on paved, 16 km on gravel, and 4 km on dirt roads) for illustration purposes in Table 2.

Model applications

We compared model outcomes to actual recovery operations in western Oregon and Washington 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. Productivity data were collected from time and motion studies performed in each of the analyzed units. Average productivity for the analyzed equipment in each of the harvest units is summarized in Table 3. Grinder utilization and economics were evaluated and optimized as a function of the number of trucks required to minimize processing and transportation costs 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 (48°14′43″N, 124°12′41″W). Forest residues were processed in the field and transported to a bioenergy facility. Residues consisted mainly of Douglas-fir (*Pseudotsuga menziesii*) with an average moisture content of 41.3 percent. The unit was characterized by steep, single-passage roads (Fig. 4). 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 percent for the unloaded truck. Distance from the turnout (truck

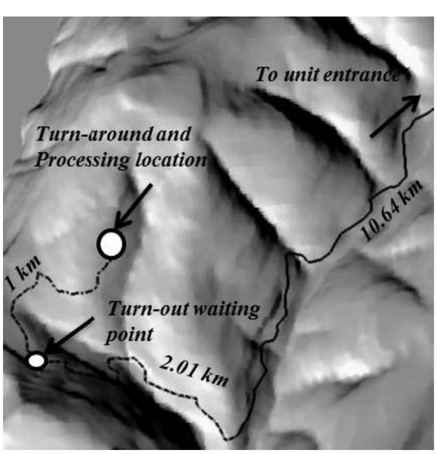

Figure 4.—Road access and processing location for study site Case I.

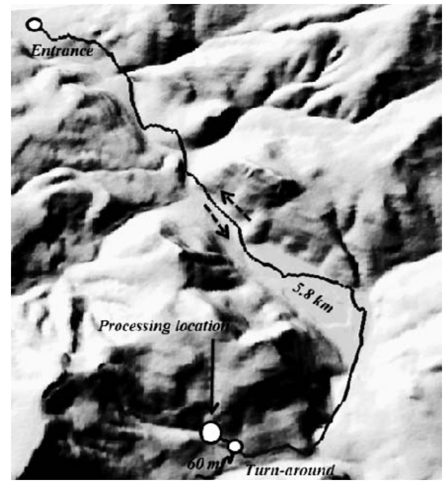

Figure 5.—Road access and processing location for study site Case II.

waiting point) to the turnaround site was 1.05 km. Distance from the grinder to the turnaround was 50 m.

A Peterson 5710C horizontal grinder was used to process the residues. The shift duration was 10 scheduled machine hours. This included 9.25 hours available to operate and 45 minutes of daily scheduled downtime. Thirty minutes were allocated for cleaning and maintenance and 15 minutes for engine warm-up. Two 6 by 6 trucks, each equipped with a rear-steer-axle 14.6-m-long (24.5-t-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 (53.23 t per productive hour) in the study unit. Truck turnaround 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.

Case II was analyzed and modeled in a harvest unit located 19.2 km south of the city of Cottage Grove, Oregon (43°39′56″N, 122°57′15″W). Residues consisted mainly of Douglas-fir with an average moisture content of 38.7 percent. 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 turnaround was 5.8 km. Turnaround to grinder location distance was 60 m. Maximum road grade found in the gravel road network was an adverse grade of 8 percent for the unloaded truck (Fig. 5).

A Peterson 4710B (522 kW) horizontal grinder 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 the biomass to a cogeneration 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.

Case III was evaluated in a forest operation located 6 km from the city of Rockaway, Oregon (45°34′51″N, 123°54′36″W). Residues consisted mainly of Sitka spruce (*Picea sitchensis*) and western hemlock (*Tsuga heterophylla*) with an average moisture content of 44.6 percent. Processed material in this unit was transported using two short trucks (7.62 m long with a capacity of 14.5 t) to a transfer yard where the product was dumped and loaded into long trucks (16.15 m long with a capacity of 27 t). Because

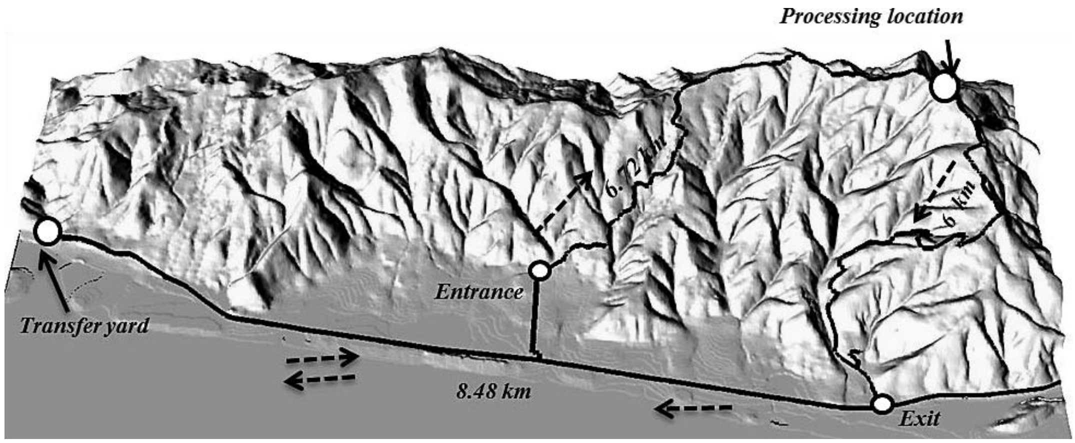

Figure 6.—Road access and processing location for study site Case III.

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 percent was found on the uphill gravel road. Distance on paved road from the exit to the transfer yard was 8.48 km (Fig. 6). A Peterson 4710B was used to process the material. Estimated grinder processing time per truck was 18.65 minutes (46.67 t per productive machine hour).

Results and Discussion

Case I

In Case I, 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 4). Grinder waiting time was calculated using Equation 3. The grinder had to wait 22.9 minutes per load due to the effect of the distance between the turnout 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).

The actual operation used two trucks to transport the processed forest biomass. The results show that the grinder was utilized only 20 percent (four loads per day of 24.5 t each) of the potential productive time. We calculated the total costs per bone dry metric tonne (BDMt) of processed residues based on the average moisture content wet basis. Processing (grinding) cost accounting for waiting time was estimated at \$48.48/BDMt. Grinder waiting cost accounted for 59 percent (\$28.5/BDMt) of the total processing cost. Transportation cost was \$31.19/BDMt.

The effect of number of trucks on the utilization rate was analyzed by modeling different scenarios varying the number of trucks from 1 to 10. We assumed that trucks worked a minimum of 8 hours and a maximum of 12 hours. Truck first interarrival time was assumed to be equal to the processing time plus the time the loaded truck traveled from the grinder location to the turnout. This guaranteed that grinder and truck arrival waiting time were minimized (in the case of the grinder, it applied only 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 percent (12 loads per d), using six trucks (Fig. 7). Adding more than six 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 were not able to achieve the minimum working hours. Total cost decreased 29.7 percent due to an increase in the grinder utilization from 10 percent (one truck) to 60 percent (six trucks).

Table 4.—Time elements to estimate grinder waiting time in Case I.

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

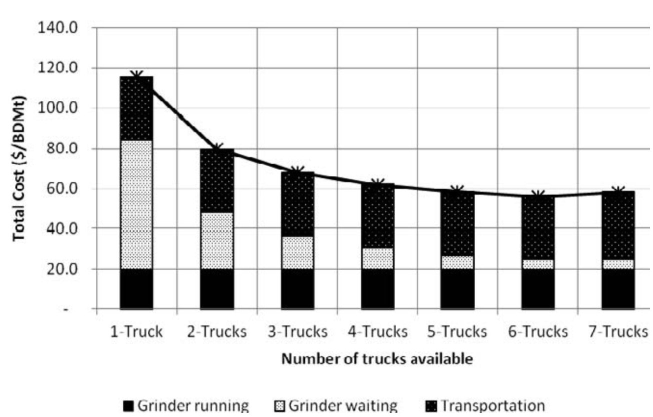

Figure 7.—Total cost of forest biomass processing and transport per bone dry metric tonne for study site Case I.

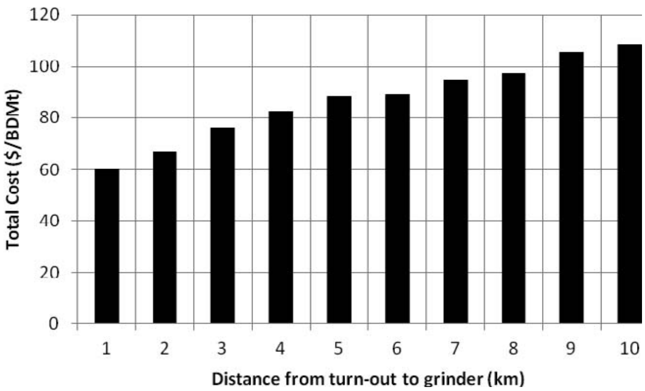

Figure 8.—Changes in total cost of forest biomass processing and transportation per bone dry metric tonne as a function of distance from truck turnout to grinder location using six trucks for study site Case I.

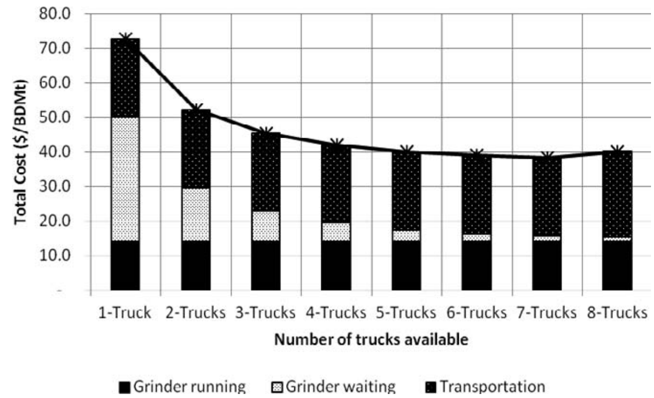

Figure 9.—Total cost of forest biomass processing and transportation per bone dry metric tonne for study site Case II.

Distance from the turnout to the processing site greatly affected grinder utilization, accounting for 54 percent of the total waiting time per cycle due to road accessibility. The economic effect of changing distance between the turnout to the processing site was analyzed. We made a sensitivity analysis varying the turnout–processing site distance from 0.5 to 10 km; the distance to the bioenergy facility was kept 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 $48.06/BDMt when the turnout to grinder distance was increased from 0.5 to 10 km (Fig. 8). This difference in cost can be used to assess the potential benefits of building a truck turnout closer to the grinding site or increasing the grinding site area to allow off-road truck loading.

Case II

For the actual operational conditions in Case II (five trucks, 10 loads of 21.7 t each per d), the grinding utilization rate was 60 percent. Processing cost was estimated as $17.39/BDMt, and transportation was $22.59/BDMt. Results for the operation indicated that seven trucks minimized total processing and transportation costs (19 loads of 21.7 t each per d). Maximum grinder utilization was estimated to be 77 percent. Although adding one more truck increased the grinder utilization rate (81%), the extra truck was not fully utilized, and the queuing time at arrival was higher (Fig. 9). This increased the overall transportation cost, minimizing the net gain (transportation cost increased from $22.77/BDMt with seven trucks to $24.78/BDMt with eight trucks). Grinder waiting time due to road accessibility was 6.56 minutes per cycle (Table 5).

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

Table 5.—Time elements to estimate grinder waiting time in Case II.

Truck type	From	To	Distance (km)	Time spent (min)
Truck out (Ta_{ga})	Grinder	Turnaround	0.06	0.36
Truck in (Tb_{bg})	Turnaround	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 $4.8/BDMt when changing the distance from the turnaround to the grinder increased from 50 to 500 m (Fig. 10)

Case III

In Case III, the actual grinder utilization rate using two trucks was 40 percent, with a processing cost of $29.68/BDMt and a transportation cost of $25.81/BDMt. The most cost-effective number of trucks for this unit was four (24 loads of 14.5 t each). The maximum grinder utilization rate was 74 percent. Adding one more truck increased the utilization rate to 81 percent, but the increased truck queuing time and the underutilization of some units raised the transportation costs, causing an overall increase in the total costs (Fig. 11).

If truck positioning was the only factor limiting grinder utilization, we estimated that the grinder could be utilized at a maximum of 84 percent. The rest of the time, the grinder has to wait for the truck to be positioned. We used a value of

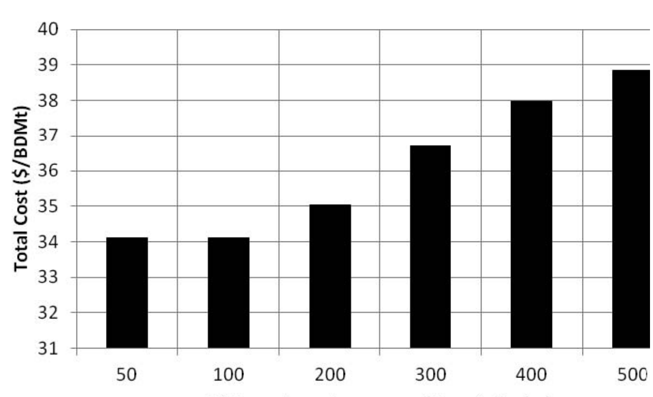

Figure 10.—Total cost of forest biomass processing and transportation per bone dry metric tonne as a function of changes in the turnaround to grinder distance for study site Case II.

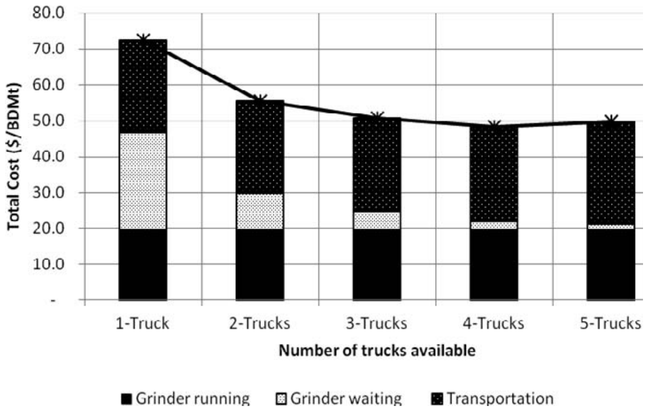

Figure 11.—Total cost of forest biomass processing and transportation per bone dry metric tonne as a function of the number of trucks for study site Case III.

Table 6.—Summary of results for the three cases.

Category	Case I	Case II	Case III
Moisture content (%)	41.30	38.70	44.60
Grinder productivity (BDMt/productive h)	31.25	35.77	25.86
Actual no. of trucks	2	5	2
Optimized no. of trucks	6	7	4
Actual processing cost ($/BDMt)	48.48	17.39	29.68
Optimized processing ($/BDMt)	24.75	15.68	21.99
Actual grinder waiting costs as percentage of grinding cost	58.81	18.53	34.06
Optimized grinder waiting costs as percentage of grinding cost	15.56	9.60	7.77
Actual transportation cost ($/BDMt)	31.19	22.59	25.81
Optimal transportation ($/BDMt)	31.26	22.77	26.35
Savings from optimized solution ($/BDMt)	23.67	1.54	7.14
Decrease in cost as a percentage of the total	29.70	3.85	12.88

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.

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 running) 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 (Fig. 12). The maximum grinder utilization rate reached 81 percent for Cases II and III. However, maximum utilization rate did not necessarily indicate that the minimum cost of processing and transportation was achieved.

The site analyzed for Case I represented the most constrained situation in terms of truck accessibility. With the optimal number of trucks (six), waiting costs represented 15.15 percent of total grinding costs. For Case II, results from the model indicated that the optimal number of trucks was seven. Grinder waiting cost accounted for 9.60 percent of total grinding costs. In Case III, although a maximum grinder utilization rate of 81 percent 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 four 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 owned only two trucks that were designated to the operation.

A summary of the optimized number of trucks and potential economic savings are shown in Table 6. 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

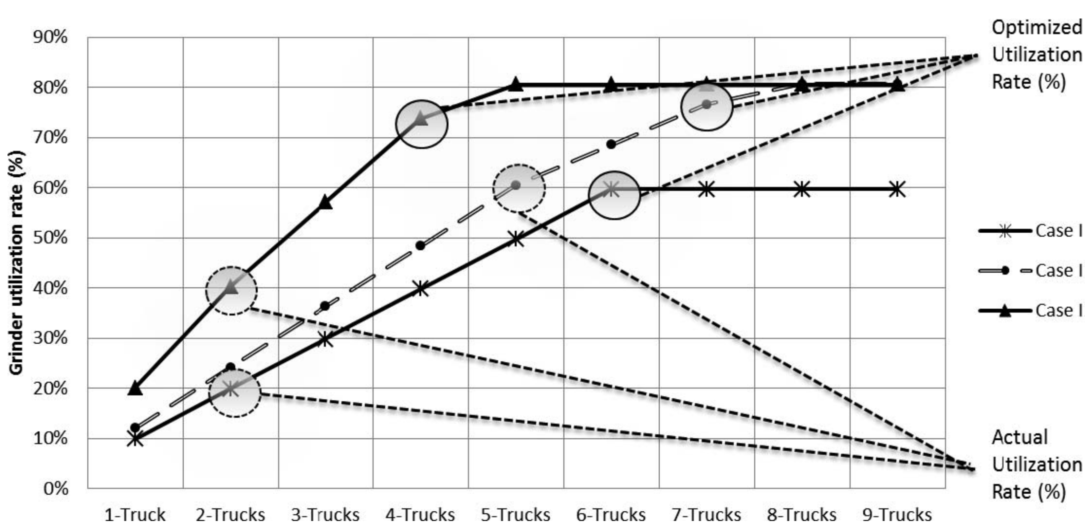

Figure 12.—Grinder utilization rate as a function of the number of trucks for the three study sites.

savings of the three cases because the number of trucks used in the actual operation (five) was close to the optimal (seven) predicted by the model.

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 number of trucks 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 to 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 such 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 with 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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