CIRRELT

Centre interuniversitaire de recherche sur les réseaux d'entreprise, la logistique et le transport

Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation

Discrete Event Simulation to Improve Log Yard Operations

Daniel Beaudoin
Luc LeBel
Mohamed Amine Soussi

March 2013

CIRRELT-2013-16

Bureaux de Montréal :
Université de Montréal
C.P. 6128, succ. Centre-ville
Montréal (Québec)
Canada H3C 3J7
Téléphone : 514 343-7575
Télécopie : 514 343-7121

Bureaux de Québec :
Université Laval
2325, de la Terrasse, bureau 2642
Québec (Québec)
Canada G1V 0A6
Téléphone : 418 656-2073
Télécopie : 418 656-2624

www.cirrelt.ca

Discrete Event Simulation to Improve Log Yard Operations

Daniel Beaudoin[1], Luc LeBel[1,2,*], Mohamed Amine Soussi[2,3,†]

[1] Département des Sciences du bois et de la forêt, Pavillon Abitibi-Price, 2405, rue de la Terrasse, Université Laval, Québec, G1V 0A6

[2] Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRELT)

[3] Département d'opérations et systèmes de décision, 2325, de la Terrasse, Université Laval, Québec, Canada G1V 0A6

Abstract. Due to seasonal considerations, sawmills build up large inventories in their log yard to ensure continuous operation. Our industrial partner services up to 140 log trucks per day, which translates to yard congestion and long truck wait times. This project looks at the impact of different loader-to-truck allocation strategies on truck cycle time and loaders driving distance, using a discrete event simulation model. It was found that by changing the current loader-to-truck allocation strategy, average truck cycle time and loaders driving distance can be significantly reduced by 14.6% and 18.4% respectively.

Keywords: Log yard, simulation, wood inventory, wood procurement.

Acknowledgements. The authors would like to acknowledge the support received from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Produits Forestiers D.G., and the Programme de recherche sur les entrepreneurs forestiers de récolte et de transport (PREfoRT) industrial partners.

† This research was carried out while Mohamed Amine Soussi was doing his MBA at Department of Operations and Decision Systems, Université Laval.

* Corresponding author: Luc.LeBel@cirrelt.ca

Dépôt légal – Bibliothèque et Archives nationales du Québec
Bibliothèque et Archives Canada, 2013

INTRODUCTION

Les Produits Forestiers DG owns and operates the largest private softwood lumber mill in Quebec, Canada. It is located in the municipality of Saint-Aurélie, close to the border with Maine. The mill has an annual volume consumption of 600 000 m^3. The mill does not have a timber license on public land. Therefore, 100% of its wood supply is purchased from private landowners in the Province of Quebec and from the northeastern United-States, mainly the states of Maine, Vermont and New York.

High levels of raw material inventory are common in the softwood lumber industry. It is mainly due to seasonal factors resulting in harvesting and transportation curtailment or shutdown for variable periods of time. Thus inventory is built up in the log yard to prevent disruption in mill production.

Different truck-trailer configurations deliver wood to the yard. The company owns and operates three different mobile loaders with different capabilities. Some trailer-loader combinations are less productive, or outright impossible. Loaders are also used for other yard activities such as spreading truck loads, repositioning wood piles to ensure stock rotation, log retrieval and delivery to mill entrances, and loading logs onto mill feeding decks. The highest priority for loader operators is to ensure continuous mill operation, followed by unloading in-coming trucks.

Truck drivers and contractors appreciate delivering wood to *DG*'s yard because of relatively short cycle time on the yard, which represents a competitive advantage when negotiating rates with transportation contractors. According to *DG*'s yard manager, average truck cycle time worsens in the busiest period of the year, mainly when log inventory must be built up in anticipation of harvesting and transportation shut down. In that period of the year, up to 140 logging trucks must be serviced daily, and flow of incoming trucks congests the yard and slows operations. For economic reasons, replacing or increasing the fleet of loaders was not an option.

The main objective of this project was to investigate the impact of different loader-to-truck allocation strategies, for unloading operations. Two metrics were used: average truck cycle time on the yard and total travelled distance of loaders.

The remainder of this paper is organized as follows: a literature review is presented in the next section, followed by a description of the simulation model. Then, the scenarios to be analyzed are described. Finally, results from the analysis are presented followed by a brief discussion.

LITERATURE

Simulation has been used extensively to investigate issues related to the design and operation of production systems in forestry. As highlighted by Myers and Richards (2003), previous research in forest operations has used simulation models to analyze single machine (Chiorescu and Gronlund 2001, Arriagada et al. 2008), interactions between machines in logging systems (Hartsough et al. 2001, Wang et al. 2005,) and also between logging phases (Asikainen 2001, Myers and Richards 2003, Pan 2008, Hogg et al. 2010). Simulation has also been applied to sawmilling to analyze a broad range of issues such as change in log supply characteristics (Aune

1973, Widenbeck and Araman 1995, Salichon 2005), bottleneck analysis (Dogan et al. 1997, Baesler et al. 2002), machine replacement (Dogan et al. 1997), and system design (Lin et al. 1995, Reeb 2003).

The log yard is located at the interface of forest operations and mill processing. In both research areas (i.e. forest operations and sawmilling), the log yard is usually indirectly accounted for through log inventory models. For example, LeBel and Carruth (1997) developed a simulation model to investigate the impact of uncertain parameters pertaining to forest operations on wood yard inventory. Mendoza et al. (1991) developed a combined log inventory and process simulation model for the planning and control of sawmill operations. The process simulation was designed to estimate various sawmill performance parameters while the log inventory model was designed to monitor and update the status of the logs in the log yard.

Performance implications of log yard layout, processes and operating rules have received little attention in the literature. Gerstkemper (1982) developed a simulation model of a log landing used in helicopter logging operations. The simulation model was used to identify minimum turn times that could be handled by a number of different landing configurations. McNeel and Nelson (1991) developed a simulation model to analyze operating and financial characteristics of a small-capacity sort yard. Sedney (1992) developed a simulation model to determine general operational feasibility of the sort yard under various timber and market conditions and sort yard configurations.

From these research papers we perceive a gap in the application of operations research techniques for providing operating rules of standard sawmill log yards. Considering its strategic role with the wood supply chain, it appears useful to improve our knowledge of log yard operation rules and methods to manage them effectively.

THE SIMULATION MODEL

Log yard operations were modeled as a discrete event simulation. The simulation model was used to generate statistics on truck cycle time in the yard, and travelled distances for all loaders. The log yard simulation model was developed using AnyLogic (XJ Technologies). Figure 1 illustrates the layout of *DG*'s log yard.

Logging trucks enter the yard by two entrances labelled (1) and (2) in Figure 1. These two entrances in the yard are respectively referred to as *paved road* and *dirt road*. Trucks entering the yard from (1) use public highways, whereas Trucks entering the yard from (2) use private forestry roads. Upon arrival and when departing, all trucks go over the scale (3). The weight difference corresponds to the transported tonnage. Sample trucks are selected randomly for scaling. Their load is spread in a designated area (4) and every log is measured. Data collected are used to establish mass-to-volume conversion factors. These factors serve to evaluate the volume of wood delivered to the mill and pay suppliers. Some of the suppliers prefer to be paid based on real delivered volume. For those, complete truck loads are unloaded at (4). Every log is then measured. All deliveries can be stocked either in (5) or (6) to be retrieved at a later time. (5) is a zone dedicated for the stocking of tree length wood, while (6) is dedicated to the stocking of shortwood. Finally, (7) and (8) are the two entrances of the mill for further wood processing. (8)

is used to supply the mill with tree length wood (stems), while (7) is dedicated to shortwood (logs). The two mill entrances are respectively referred to as the *wave* and the *slasher*.

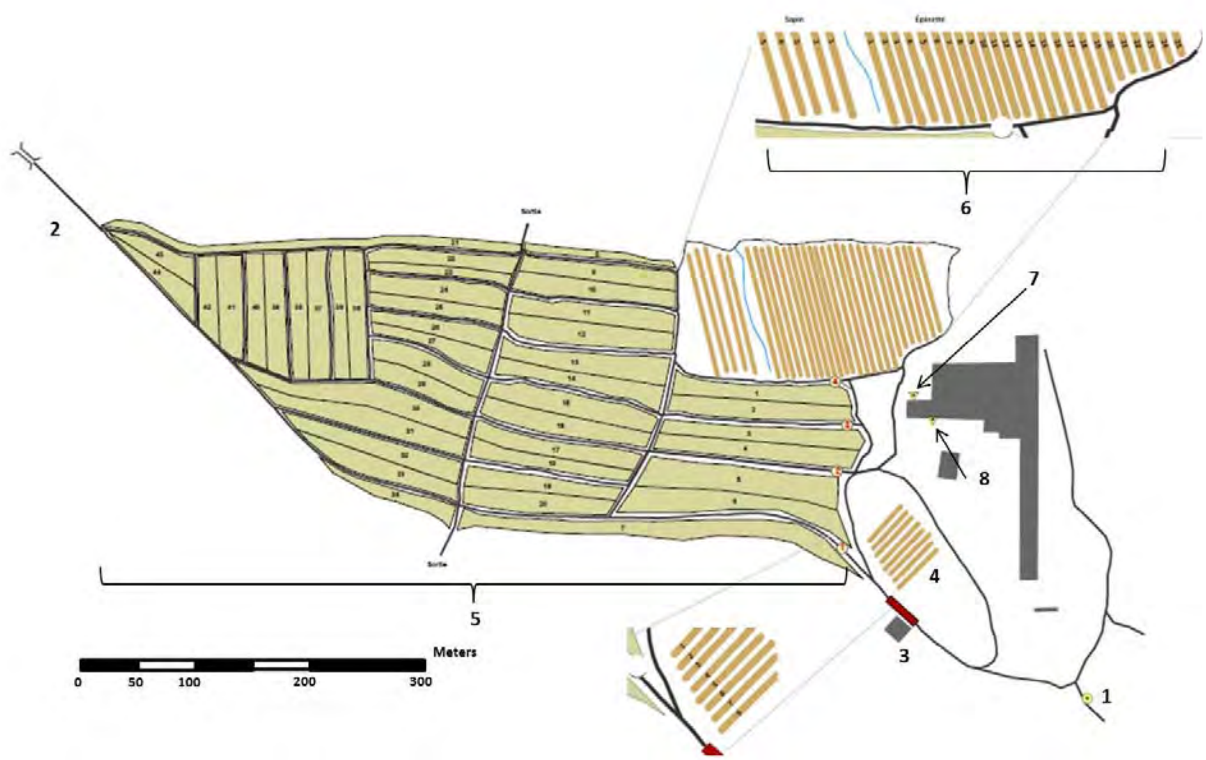

Figure 1 Log yard layout at *Les Produits Forestiers DG.*

Input Data

Preliminary Data

Preliminary data is required to gain an understanding of log yard setup and operation. Data include yard layout, material flow information and yard operating rules.

Log Yard Layout

The yard layout was obtained by collecting data on the yard with a GPS unit. Collected data were used to produce the log yard layout map (Figure 1). A scaled map of the yard layout is important to spatially position important features, and to provide the basic layout of a simulation model. The layout identifies location of roads, scale, stocking zones and areas within zones (44 areas in (5) and 30 areas in (6)), mill entrances, and entering points onto the yard.

Material Flow and Yard Operating Logic

Material flow information and yard operating rules were gathered through observations and meetings with the log yard manager, scalers, and loader operators. Use of multiple sources contributed to data completeness and accuracy.

Logging trucks delivering wood to the yard use four different types of trailers: tree-length trailers, shortwood trailers, multi-purpose trailers and flatbed trailers. The company owns and operates three different mobile loaders on the yard, referred to by their brand names: Tanguay, Liebherr, and Volvo. Not every loader can unload every trailer. Table 1 specifies possible loader-to-trailer assignments.

Table 1 Loader-to-trailer assignments.

Loader	Trailer type			
	Tree-length	Shortwood	Multi-purpose	Flatbed
Tanguay	√	√		
Liebherr	√	√	√	
Volvo		√		√

Figure 2 represents the flow diagram for logging trucks from arrival to departure from the yard.

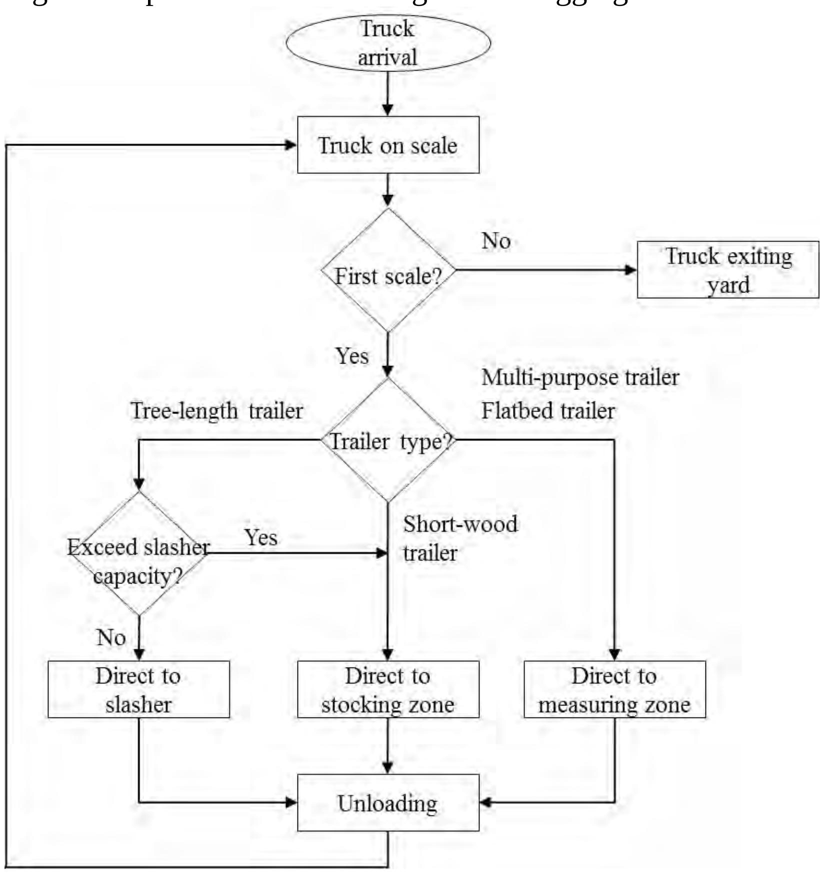

Figure 2 Flow diagram of logging trucks.

All logging trucks delivering wood to the yard must drive over the scale twice in order to estimate the delivered volume. Upon arrival, instructions given to truck drivers depend on trailer type, as depicted in the flow diagram of logging trucks (Figure 2). Tree-length trailers are unloaded directly at the slasher if the total load of the trailer can be unloaded without exceeding the slasher's stocking capacity. Otherwise the truck is directed to the tree-length stocking zone for unloading. The shortwood trailers are always directed toward the shortwood stocking zone, while the flatbed and multi-purpose trailers are always directed toward the measuring zone for unloading.

As logging trucks are directed toward the unloading areas, a loader must be assigned to each truck for unloading. In addition to unloading trucks, loaders are used to deliver and stack wood on log decks at mill entrances. Figure 3 presents the flow diagrams for the Tanguay and Liebherr loaders, while Figure 4 presents the flow diagram for the Volvo loader.

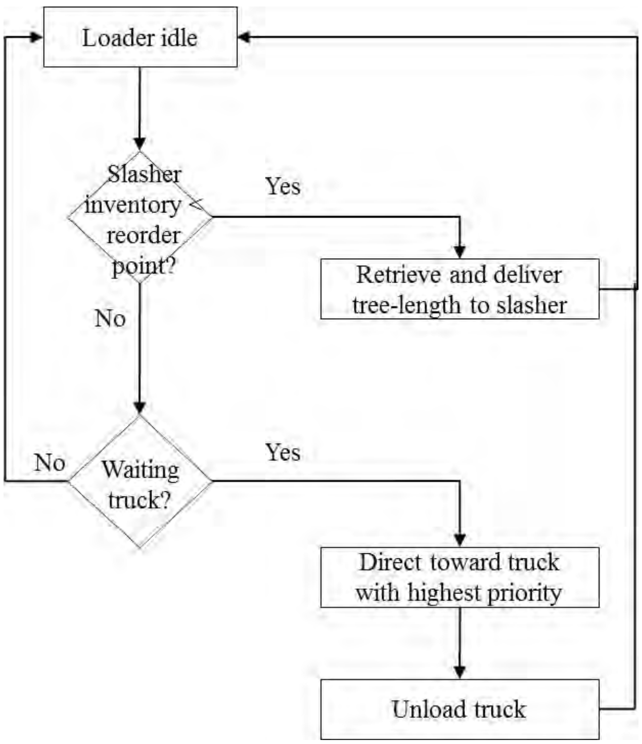

Figure 3 Flow diagram for the Tanguay and Liebherr loaders.

The Tanguay and the Liebherr loaders have similar capabilities and are used for the same tasks. The priority is to ensure the mill does not run out of wood. So, when inventory at the slasher reaches the set reorder point, it triggers the retrieve and deliver operation for tree- length wood. These two loaders also ensure unloading operations (Table 1). They both unload tree-length and shortwood trailers. The Liebherr is the only loader used to unload multi-purpose trailers because it has a rising cab, allowing the operator to see inside the enclosed trailer.

As for the two other loaders, the priority for the Volvo is to ensure that the mill does not run out of wood. So, when inventory at the wave reaches the set reorder point, it triggers the retrieve and deliver operation for shortwood. This loader also ensures unloading operations of shortwood and flatbed trailers (Table 1).

For all loaders, the current yard operating rules stipulate that priority ranking for unloading of logging trucks is based on first-in – first-out (FIFO) queue processing.

Model Realization Data

Model realization data is required to drive the computer simulation. It elaborates on the preliminary data collected, by providing specific information relating to the processes. The model realization data collected consists of: inter-arrival time of trucks, transported weight, unloading time of trucks, loading and unloading times of trailer used in retrieval operations, sawmill inventory reorder points, feeding and consumption, and equipment travelling speeds and distances. Time was modeled in minutes, distance in meters, and wood quantity in tons.

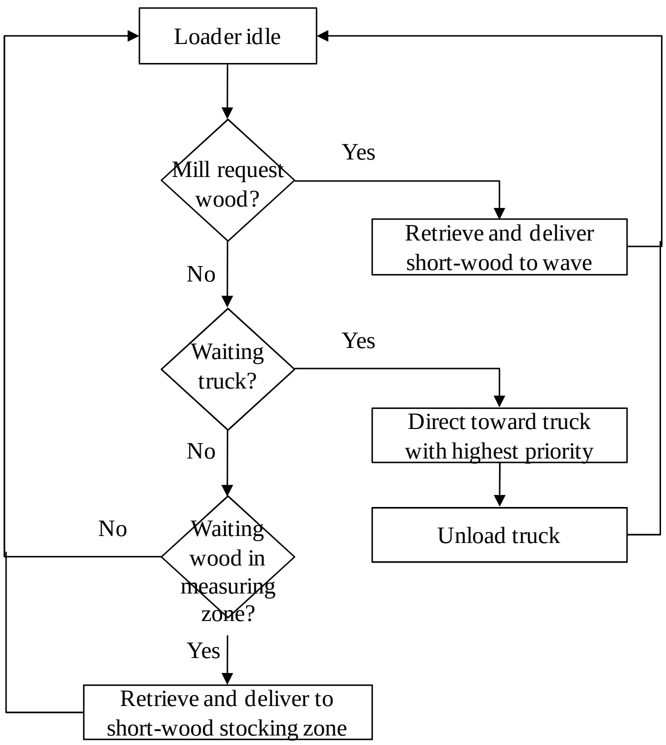

Figure 4 Flow diagram for the Volvo loader.

Inter-arrival Time of Trucks

A distinction is made between trucks delivering wood to the yard from the paved or dirt roads. Through analysis of transportation slips from first week of February 2010, 481 trucks were serviced in the yard over the reference period. From these, 157 entered the yard from the paved road and 324 from the dirt road. Inter-arrival time for trucks entering from the paved road was modeled using a gamma distribution with a shape parameter $\alpha = 0.83$ and a scale parameter $\beta = 29.36$ (Goodness of fit: Critical $\chi^2 = 14.07$, $\alpha = 0.05$, actual $\chi^2 = 2.78$).

Since no satisfactory fit was found for inter-arrival times from the dirt road, they were modeled as an empirical distribution. Figure 5 illustrates the cumulative frequency distribution used to model inter-arrival time of trucks entering the yard from the dirt road.

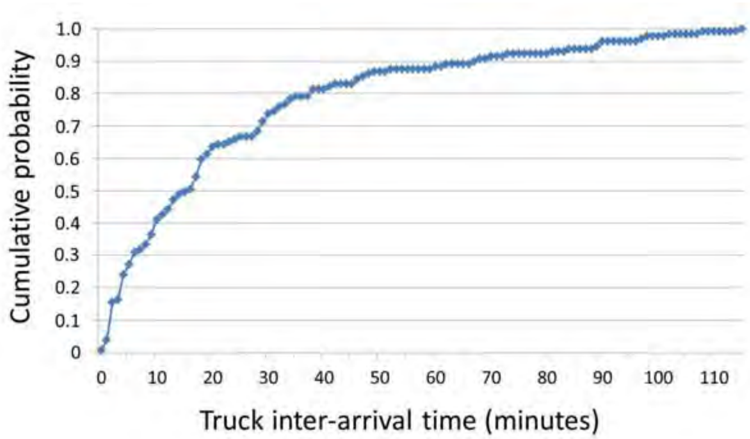

Figure 5 Inter-arrival time probability distribution from the dirt road.

Transported Weight

The weight transported by a logging truck depends on two factors: the entering point onto the log yard (wood origin: paved or dirt road), and the type of trailer hauled by the truck. Flatbed and multi-purpose trailers only arrive from the paved road. Tree-length and shortwood trailers both arrive from paved and dirt roads. Trailers used on the paved road (public road network) are subjected to weight and dimension restrictions, while trailers used on dirt road (here private forestry roads) are not subject to such restrictions, and therefore carry heavier loads. We make a distinction between standard tree-length trailer and off-road tree-length trailer, and similarly between standard shortwood trailer and off-road shortwood trailer. For the 157 trucks entering the yard from the paved road, 59% were standard tree-length trailers, 30% were standard shortwood trailers, and 11% were flatbed trailers. Multi-purpose trailers represent less than 1% of total trucks delivering wood to the yard annually. No multi-purpose trailer was recorded over the reference period. For the 324 trucks entering the yard from the dirt road, 62% were off-road tree-length trailers, and 38% were off-road shortwood trailers. The probability that a given trailer type is hauled by the arriving logging truck was modeled as the percentage of occurrence over the reference period.

Once the type of trailer hauled by the logging truck is identified, a transported tonnage must be generated for that trip. For trucks entering the yard from the *paved* road, transported weight of standard tree-length trailers was modeled using a Burr distribution with shape factors of $\kappa = 4.16$, and of $\alpha = 13.12$, and a scale parameter of $\beta = 42.99$ (Goodness of fit: Critical $\chi^2 = 12.59$, $\alpha = 0.05$, actual $\chi^2 = 4.02$). Transported weight of standard shortwood and flatbed trailers are represented by empirical distributions. Their respective cumulative frequency distributions are presented in Figures 6 a) and b).

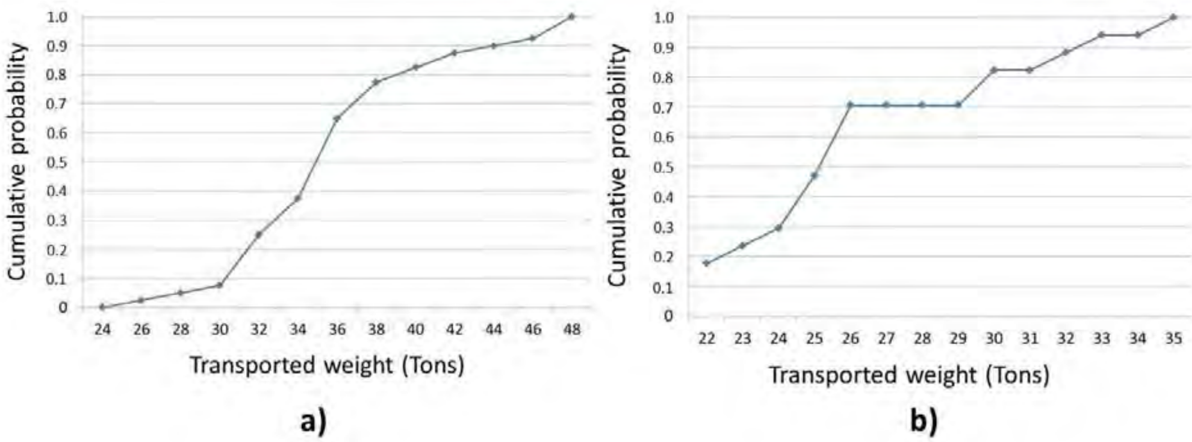

Figure 6 Transported weight probability distribution for standard trailers for a) shortwood and b) flatbed.

Transported weight for trucks entering from the dirt road was sampled from cumulative frequency distributions of Figures 7 for the off-road tree-length and the off-road shortwood trailers.

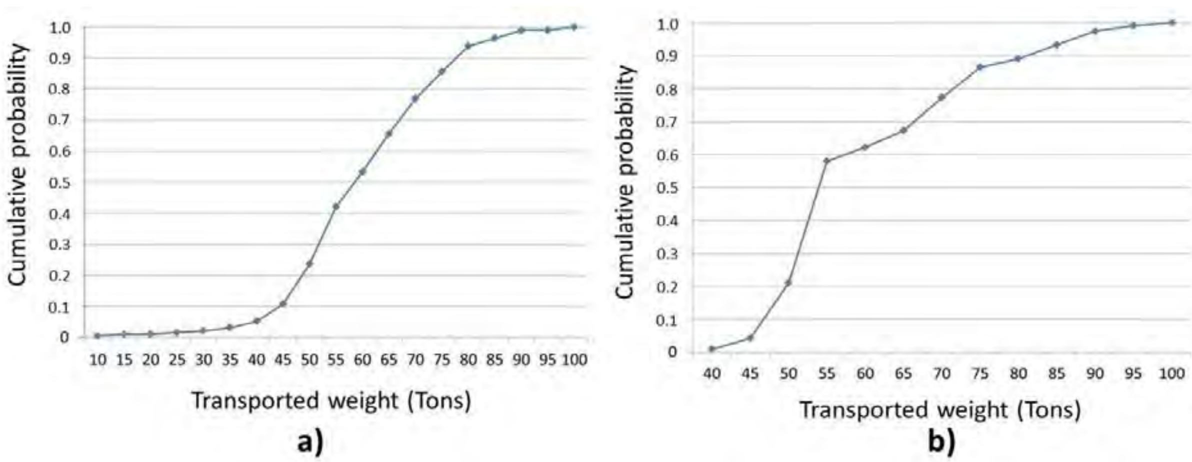

Figure 7 Transported weight probability distribution for off-road trailers for a) tree-length and b) shortwood respectively.

Unloading Time of Logging Trucks

Unloading times of logging trucks were derived from time and motion studies conducted during the winter of 2011. Due to the limited number of data points, unloading times were assumed to be uniformly distributed. Table 2 identifies upper and lower bounds for the different loader-trailer type combinations. No distinction was made between the Tanguay and the Liebherr, as they have similar capabilities, and their respective data points ranged over the same durations.

Table 2 Unloading times of logging trucks (in minutes).

Loader	Trailer type				
	Tree-length		Shortwood		Flatbed
	Standard	Off-road	Standard	Off-road	
Tanguay/Liebherr	U[4;12]	U[14;18]	U[5;14]	U[13;18]	
Volvo			U[8;16]	U[14;20]	U[6;14]

Loading and Unloading Times of Trailer Used in Retrieval Operation

Eventually, wood stocked in the yard must be retrieved and fed to the mill. Retrieval and delivery is performed by loaders hitched with a custom-made trailer. Only the Tanguay and Liebherr use the trailer to retrieve wood. The same trailer is used regardless of the wood type (tree-length or shortwood). Loading and unloading times were gathered from time studies. For tree-length wood 33 and 31 data points were collected for the loading and unloading activities respectively, while for shortwood 28 and 23 data points were collected respectively for the same activities. Loading and unloading times in retrieval and delivery operations were modeled using the empirical distributions of Figure 8(a,b,c,d). Trailer capacity was estimated at 35 tons by the yard manager.

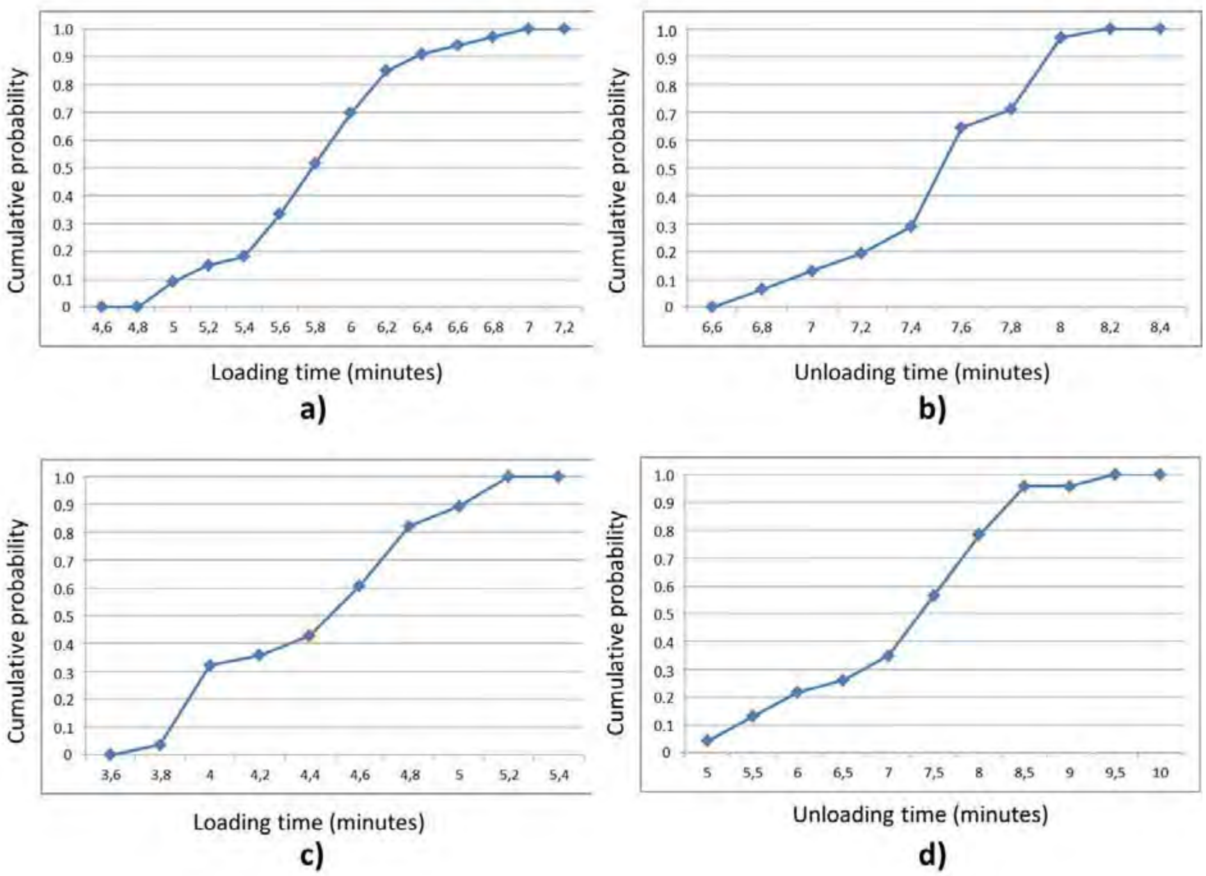

Figure 8 Loading and unloading time probability distributions for the retrieving and delivery operations. a) and b) for tree-length, and c) and d) for the shortwood respectively.

Sawmill Feeding, Consumption and Reorder Points

Wood enters the sawmill by two entrances. From historical data, the mill manager has evaluated that 65% of consumed wood is from the slasher, and remaining 35% is consumed through the wave. We modeled the mill consumption at the slasher and the wave as deterministic demand points. Wood consumption rate of the mill is 90 tons per hour, so demands at the slasher and the wave were fixed at 58.5 tons per hour and 31.5 tons per hour respectively. At both entrances, delivered wood is stacked on feeding decks. Inventory at feeding decks are monitored to ensure the mill does not run out of wood. When inventory at feeding decks drops below set reorder points, retrieval and delivery operations are triggered to replenish inventory. According to the mill manager, reorder points are set at 10 tons and 20 tons for the wave and the slasher respectively, and their stocking capacity was set at 100 tons and 300 tons respectively.

Equipment Travelling Speeds, Distances and Others

In order to account for travelling time in the yard, we used predefined speeds per equipment in conjunction with distances between specific points on the log yard layout map. Table 3 presents the travelling speeds used in the model. Stocking zones (5) and (6) (Figure 1) are subdivided in stocking areas (44 and 30 respectively) corresponding to the area that would be covered by a log or stem deck. Distances were evaluated based on the centroid of each stocking area.

Table 3 Travelling speeds of loaders and logging trucks used in the model.

	Speed (km/h)
Loader	
Tanguay	25
Liebherr	25
Volvo	40
Logging truck	35

Run Conditions

The simulation was first run to reproduce the way the log yard was currently being operated. At closing time, all trucks in the yard are serviced, and then loaders are parked for the night. Therefore, every morning starts with empty queues and no “work in progress”. As a result, the simulation does not require any initialization bias, as the beginning of each run will always start from an initial empty state.

The simulation run time was set to one 14-hour day (840 minutes). The actual log yard operates for 840 minutes, including break times. Only two loaders are affected by break times. The Tanguay and the Liebherr alternately break for 30 minutes over the lunch hour.

Model Verification and Validation

Model verification ensures the model is programmed correctly, algorithms have been implemented properly, and the model does not contain errors, oversights, or bugs. On-screen animation was useful to communicate with the yard manager and present processes, model specifications, and operating rules. The animation helped detect problems related to miscomprehension of yard operating rules and bugs in programming. The manager also admitted that the visualization of the operations provided by the on-screen animation helped improve confidence in simulation model results.

Validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study (Banks 2010). The most definitive test of simulation model validity is establishing that model output data closely resembles output data that would be observed from the actual system. To validate the model, we compared simulated average cycle time on the yard with historical data. The model was used 30 times to get an acceptable sample size. There was no significant difference in the average cycle time on the yard, for the model (M=32.52, SD=1.91) and historical data (M=32.41, SD=2.66); $t(29)=0.50$, $p = 0.91$. The box-plots of Figure 9 compare historical average cycle time on the yard with simulated times. The box-plots show minimum, median, maximum, and 1st and 3rd quartiles.

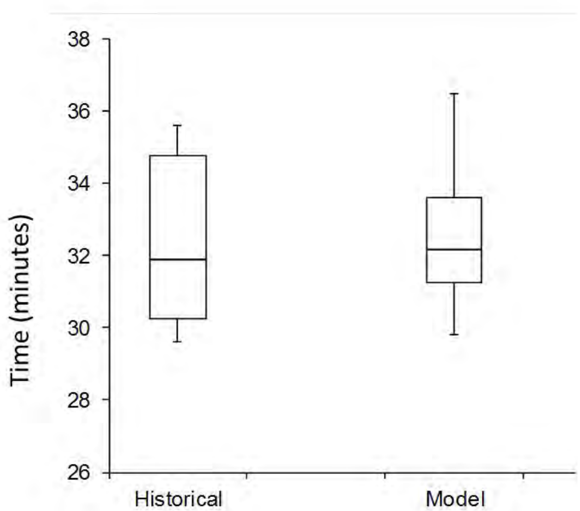

Figure 9 Modeled and historical truck average cycle time on the yard.

These results suggest that the model is an accurate representation of the system. No historical data were available for the distances driven by loaders.

SCENARIOS AND SENSITIVITY ANALYSIS

Loader-to-truck Allocation Strategies

As previously identified, the objective of this study is to evaluate the performance of different loader-to-truck allocation strategies on trucks average cycle time on the yard and driven distances by loaders.

The three allocation strategies consisted of the following:

1. "*First in – first out*" allocation strategy (S1): loaders move from queue to queue in order to service trucks in the order they entered the yard. This is the allocation strategy that was currently used by the yard manager. It is used as baseline data to compare to other two allocation strategies.
2. "*Empty the queue first*" allocation strategy (S2): a loader services all the trucks in a queue before moving to a different queue, regardless of the order in which trucks entered the yard. Once the queue is emptied, the loader moves to the queue containing the truck having the longest wait time and not being serviced.
3. "*Longest queue first*" allocation strategy (S3): when a loader is available, it is directed toward the longest queue. If two or more queues have the same length, the next queue to be serviced is selected randomly.

In order to evaluate the different allocation strategies, sensitivity analysis was performed on three parameters: mill consumption rate and travelling speeds of the Volvo and the Tanguay/Liebherr loaders. Table 4 presents the 12 scenarios investigated. The three allocation strategies have been tested as a one-day run for 30 replications under each scenario.

Table 4 Specifications of scenarios used in sensitivity analysis.

Scenario	Mill consumption (tons/h)	Loader speed (km/h)	
		Volvo	Tanguay & Liebherr
1	80	40	25
2	80	40	15
3	80	30	25
4	80	30	15
5	90	40	25
6	90	40	15
7	90	30	25
8	90	30	15
9	100	40	25
10	100	40	15
11	100	30	25
12	100	30	15

Results and discussion

The *first in – first out* loader-to-truck allocation strategy corresponds to current practice and is used as benchmark for the analysis. Figures 10 and 12 present the results from 30 simulations, for truck average cycle time on the yard and total travelled distances for loaders for every allocation strategies under each scenario. Confidence intervals were evaluated using a Student's t-distribution (α=0.05, dof=29).

Truck average cycle time

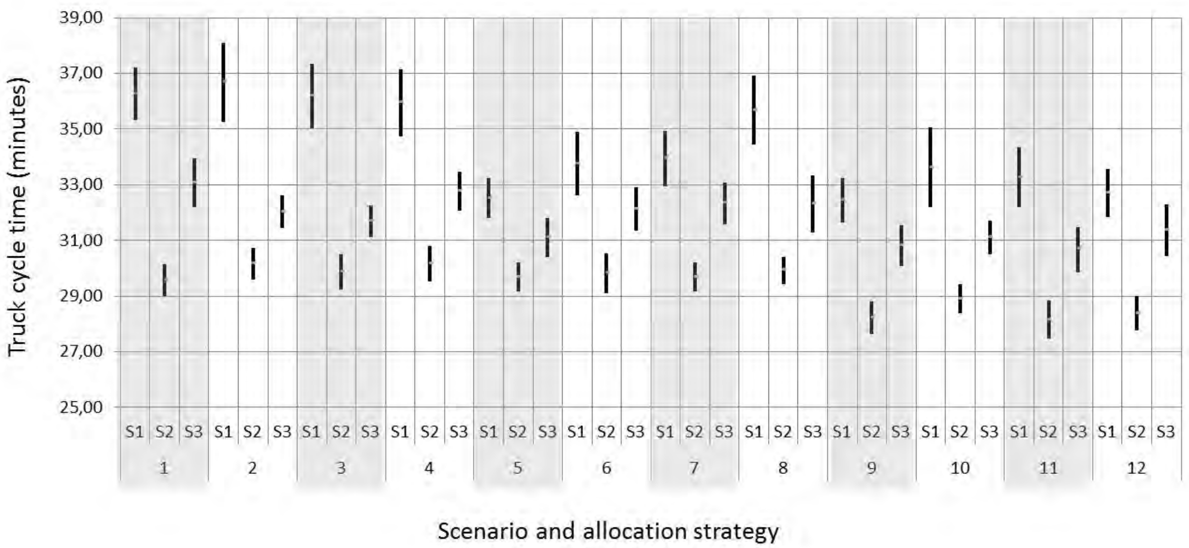

Figure 10 Simulated average truck cycle time on the yard for the loader-to-truck allocation strategies (95% confidence interval).

Empty the queue first allocation strategy (S2) shows significant lower average truck cycle time then the *first in – first out* strategy (S1) in all scenarios. Differences range from 2.84 minutes (8.2%) to 6.69 minutes (19.4%), and average 5.04 minutes (14.6%). The *longest queue first* strategy (S3) did not show significant differences in average truck cycle time when compared to the *first in – first out* strategy (S1) in 4 out of the 12 evaluated scenarios (scenarios 6, 7, 9 and 12). Average truck cycle time for the e*mpty the queue first* strategy (S2) also shows significant differences with the *longest queue first* strategy (S3) in all scenarios. Differences range from 1.43 minutes (4.5%) to 3.49 minutes (10.9%) and average 2.41 minutes (7.6%).

Average cycle time on the yard is an aggregated indicator providing no information on the variability among individual trucks. The box-plots of Figure 11 compare individual truck wait time on the yard under each loader-to-truck allocation strategy. The box-plots show minimum, median, maximum, and 1st and 3rd quartiles. Results indicate that alternative strategies (S2 and S3) result in higher variation in wait time for individual trucks compared to current strategy (S1). Identifying the sequence of trucks to be serviced based on the desire to empty a queue (S2) or on queue length (S3) results in some trucks waiting much longer than average (and some, less) than the current strategy (S1). This suggests that some trucks entering the yard are serviced before others waiting because they are directed towards a queue currently being served.

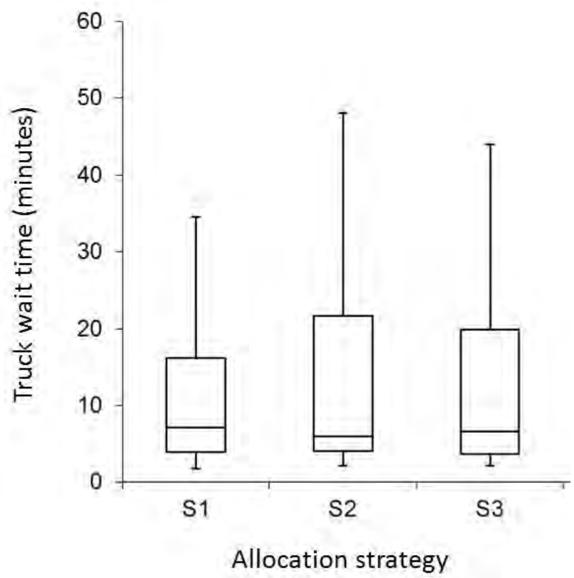

Figure 11 Individual wait time of individual trucks under each loader-to-truck allocation strategy.

The data collected through the simulation experiments did not allow differentiating results by trailer type. This would have allowed comparisons of individual truck wait time per trailer type among the allocation strategies. In other words, it would have been interesting to know if different allocation strategies penalize or favor certain trailer types.

Although the current *first in – first out* loader-to truck allocation strategy (S1) shows higher average truck cycle time on the yard, it is perceived by the truck driver as being fair. Truck cycle time on the yard has a direct impact on unit transportation rates negotiated between the mill and transportation providers. Long cycle times may limit number of trips a truck can fit into one work day. Typically, trucks negotiate different billing rates for activity in and out of the log yard. Transportation of logs from forest to mill is billed per unit production delivered (eg. \$/tonne, \$/load, \$/m^3), whereas time spent in the log yard is billed at an hourly rate (typically \$150/hour). Based on our simulation results, *empty the queue first* loader dispatching rule (2) represents estimated per-truck savings of \$12.50, relative to status quo. For the mill in this case study, we estimate annual reduction of in-yard truck waiting cost of approximately \$95 000. Any perception by truck owners that cycle time on the yard increases would have an impact on rate negotiation and could reduce or eliminate these potential gains.

Travelled distance of loaders

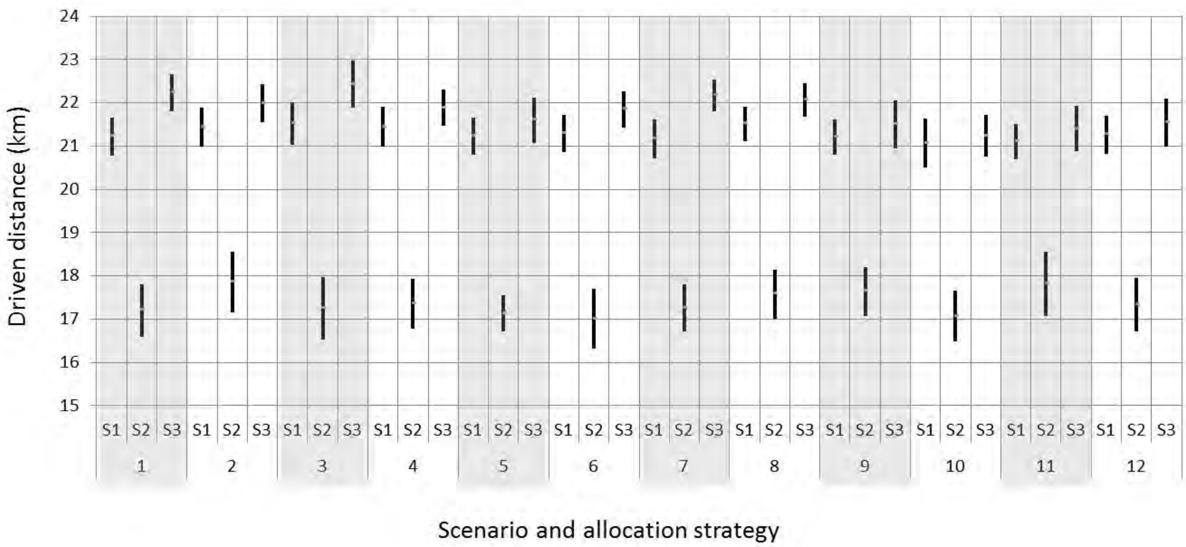

Figure 12 Simulated total average travelled distance for the loader-to-truck allocation strategies (95% confidence interval).

Empty the queue first allocation strategy (S2) shows significant lower average total travelled distance than the *first in – first out* strategy (S1) in all scenarios. Differences range from 3.29 km (15.4%) to 4.29 km (20.1%), and average 3.92 km (18.4%). The *longest queue first* strategy (S3) shows significant increase in average total travelled distance when compared to the *first in – first out* strategy (S1) in 2 out of the 12 evaluated scenarios (scenarios 1 and 7), and no statistical differences in the other 10 scenarios. The e*mpty the queue first* strategy (S2) also shows significantly lower average total travelled distance than the *longest queue first* strategy (S3) in all scenarios. Differences range from 3.59 km (16.4%) to 5.34 km (24.4%), and average 4.48 km (20.5%).

Analysis for individual loaders in the *empty the queue first* (S2) strategy reveals that reduction in total travelled distance is always attributable to the Tanguay and the Liebherr. Both loaders show significant reduction in travelled distances, while no statistical difference has been observed for the Volvo (95% confidence interval).

The two main tasks assigned to loaders are to supply the mill so that it does not run out of wood to process and to unload incoming logging trucks. The simulation model only accounted for the travelled distances of loaders to perform these tasks. Loaders are also used for other purposes in the yard such as pivoting logs, cleaning, etc. These other tasks have not been modeled and accounted for in the simulation. Although total travelled distances do not reflect the real distances driven daily by the loaders, it still provides valuable information to perform comparisons among loader-to-truck allocation strategies.

Reducing travelling distance by loaders can reduce operating costs related to this machine. In addition, it may simplify the loader operator task complexity and travelled-induced accident.

CONCLUSIONS

We have investigated the impact of different loader-to-truck allocation strategies on truck average cycle time on the yard and the total travelled distance of loaders. Toward this end, a discrete event simulation model of the log yard operations has been developed. Three different allocation strategies have been simulated, one of which corresponds to current practice and was used for benchmarking. Sensitivity analysis has been performed on mill consumption rate and travelling speeds of the loaders.

The results of the study found that the *empty the queue first* allocation strategy showed significant differences in both performance criteria compared to the current strategy (*first in – first out*). The *empty the queue first* allocation strategy shows a decrease in truck average cycle time on the yard of 5.04 minutes (14.6%) and an average decrease in total distance travelled by loaders of 3.92 km daily (18.4%). Meanwhile, results also indicate that truck wait time variability under the alternative strategies increases in comparison to current situation.

We recommend that further experiments be conducted before deciding on modifying the current loader-to-truck allocation strategy. Especially to validate that alternative strategies considered do not penalize certain trailer types. Furthermore, based on the results obtained, other strategies should be investigated. Per example, a strategy such as *empty the queue first* could be complemented with an upper limit on the wait time of individual trucks. Such a strategy could benefit from lower average truck cycle time while limiting the variability of individual truck wait time. Finally, all trucks queued at mill closing time must be unloaded, at overtime rates, before locking log yard gate for the night. Reduction of truck cycle time should indirectly reduce overtime paid to log yard personnel, as we expect reduced truck cycle time to induce shorter end-of-day queues. Our simulation experiments did not looked into this particular issue. Further experiments should investigate the possible impact of the different loader-to-truck allocation strategies on overtime paid to log yard personnel.

Research on log yards is sparse. This work focused primarily on one aspect of the design and operation problems of log yards. Further research on the subject should allow further knowledge and improvements in yard performance.

REFERENCES

Arriagada, R.A.; Cubbage, F.W.; Abt, K.L.; Huggett Jr, R.J. 2008. Estimating harvest cost for fuel treatments in the West. Forest Products Journal, 58(7/8): 24-30.

Asikainen, A. 2001. Simulation of logging and barge transport of wood from forests on islands. International Journal of Forest Engineering, 12(2): 43-50.

Aune, J.E. 1973. Application of simulation technique in the study of sawmill productivity. Master’s thesis. Vancouver, University of British Columbia.

Baesler, F.F.; Moraga, M.; Ramis, F.J. 2002 Productivity improvement in the wood industry using simulation with artificial intelligence. *In* Proceedings of the 2002 Winter Simulation Conference, 2: 1095-1098.

Banks, J. 2010. Discrete-event system simulation. 5th ed. Upper Saddle River; Montreal: Prentice Hall. 622p.

Chiorescu, S.; Gronlund, A. 2001. Assessing the role of the harvester within the forestry-wood chain. Forest Products Journal, 51(2): 77-84.

Dogan, C.A.; McClain, T.F.; Wicklund, S.A. 1997, Simulation modeling and analysis of a hardwood sawmill. Simulation Practice and Theory, 5: 387-403.

Gerstkemper, J.C. 1982. A simulation of the operation of a log landing for a heli-stas airship in old-growth timber. Master thesis, Oregon State University, Corvallis, Oregon.

Hartsough, B.R.; Zhang, X.; Fight, R.D. 2001. Harvesting cost model for small trees in natural stands in the interior northwest. Forest Products Journal, 51(4): 54-61.

Hogg, G.A.; Pulkki, R.E.; Ackerman, P.A. 2010. Multi-stem mechanized harvesting operation analysis – Application of Arena 9 discrete-event simulation software in Zululand, South Africa. International Journal of Forest Engineering, 21(2): 14-22.

Lebel, L.; Carruth, J.S. 1997. Simulation of woodyard inventory varitions using a stochastic model. Forest Products Journal, 47(3): 52-57.

Lin, W.; Kline, D.E.; Araman, P.A.; Wiedenbeck, J.K. 1995. Design and evaluation of log-to-dimension manufacturing systems using simulation. Forest Products Journal, 45(3): 37-44.

McNeel, J.F.; Nelson, J. 1991. Simulating sort yard operations for improved productivity and cost. Forest Products Journal, 41(3): 63-67.

Mendoza, G.A.; Meimban, R.J.; Araman, P.A.; Luppold, W.G. 1991. Combined log inventory and process simulation models for the planning and control of sawmill operations. *In* Proceedings of the 23rd CIRP International Seminar on Manufacturing Systems, June 6-7, 1991, Nancy, France. Pp.1-8.

Myers, J.; Richards, E.W. 2003. Supporting wood supply chain decisions with simulation for a mill in Northwestern BC. INFOR, 41(3): 213-234.

Pan, F.; Han, H.-S.; Johnson, L.R.; Elliot, W.J. 2008. Production and cost of harvesting, processing, and transporting small-diameter (<= 5 inches) trees for energy. Forest Products Journal, 58(5): 47-53.

Reeb, J.E. 2003. Simulating an extra grader in a sawmill. Forest Products Journal, 53(11/12): 81-84.

Salichon, M.C. 2005. Simulating changing diameter distributions in a softwood sawmill. Master thesis, Oregon State University, Corvallis, Oregon.

Sedney, D.G. 1992. Simulation of a log merchandising and sorting yard. Master thesis, University of Idaho, Moscow, Idaho.

Wang, J.; LeDoux, C.B.; Li, Y. 2005. Simulating cut-to-length harvesting operations in Appalachian hardwoods. International Journal of Forest Engineering, 16(2): 4-27.

Wiedenbeck, J.K.; Araman, P.A. 1995. Rough mill simulations reveal that productivity when processing short lumber can be high. Forest Products Journal, 45(1): 40-46.

LIST OF FIGURES

LIST OF TABLES