Multi-Stem Mechanized Harvesting Operation Analysis – Application of Arena 9 Discrete-event Simulation Software in Zululand, South Africa

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Abstract

Time studies were carried out on a stump-to-mill multi-stem *Eucalyptus* harvesting and transport operation in Zululand, South Africa in 2007. A simulation model (System 1) of this system was subsequently built using a commercial simulation software package (Arena 9) and data from the time studies incorporated into the model. Following this, two hypothetical stump-to-mill multi-stem models (Systems 2 and 3) were built using Arena 9 and parameterized input data. All models were found to adequately represent reality. Simulated harvesting system balance was improved through normalization of machine utilization in Systems 2 and 3. Production improvements were predicted with simulated timber production per month increasing by 31.1% and 30.8%, from System 1 with three trucks, to System 2 with four trucks, and System 3 with four trucks, respectively. Cost reduction was predicted, with the cost per unit of timber decreasing by 12.5% and 4.1%, from System 1 with three trucks, to System 2 with four trucks and System 3 with four trucks, respectively. Beneficial operational techniques were also confirmed using the simulation models. In the studied conditions delimbing and debarking of full trees into tree lengths at roadside with delimber-debarkers before cross-cutting and loading with a slasher was predicted to be \$0.65/m^3 cheaper than delimbing, debarking, and cross-cutting full trees into pulpwood with processors at the landing and then loading with a loader. Usability of Arena 9 in modeling forest harvesting operations was concluded as acceptable, but required detailed background logic inclusion.

Keywords: Multi-stem, mechanized, South Africa, Discrete-event, Arena 9, simulation, modeling, Zululand.

Introduction

Mechanization of South African (SA) timber harvesting operations has been a steady, albeit slow process over the past 10 years. Recently, though, there has been an acceleration in the establishment of mechanized systems within the industry. Although the volume of timber harvested by mechanical equipment in the country is increasing, there are few (if any) national benchmarks and proven best operating practices on which these systems can be based. As a result, inefficiencies and unnecessary variation within and between operations are common. This problem resulted in the demand for studies in system comparison and improvement, which would hopefully lead to identification of improved operating practices and systems in SA forest harvesting operations. One relatively recent mechanized application in the country is the multi-stem system, employed in SA pulpwood operations, which is the focus of this study.

The question addressed in this study is one of mechanized harvesting system representation and improvement through the application of simulation techniques. Simulation modeling facilitates detailed manipulation and testing of operating practices and system combinations on a trial-and-error basis within the safety of a computer program. It therefore has no bearing on the real world system until the final improved simulated system is decided upon and implemented. This ensures, as far as is possible, that any changes made to the real

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system will be beneficial. In this study, a simulation model of a multi-stem mechanized harvesting and transport operation working in seven-year-old *Eucalyptus grandis X camaldulensis* pulpwood was constructed using Arena 9 commercial simulation software. Based on detailed time study data for the original system, two further simulation models representing hypothetical multi-stem systems were constructed. Using the simulation models and their outputs, the following objectives were addressed:

1. Determine whether or not Arena 9 commercial simulation software can be used to adequately model forest harvesting operations by gauging potential system balance, production, and/or cost improvement/s achievable through application of simulation-based operational adjustments.
2. Define beneficial equipment operation and application practices for multi-stem systems.
3. Through construction and use of Arena 9 in producing forest harvesting operation models, evaluate the software's usability in terms of its applicability to and ease of use in such models, as well as its ability to meet forestry-based user requirements.

Location, Materials, and Methods

Research Site

The research site is situated two km east of Kwambonabi town at the co-ordinates 28˚ 36' 05.58" S, 32˚ 06' 24.74" E and at an altitude of 80 m above mean sea level. Terrain classification for the harvesting site can be defined as 222.1.1 according to the National Terrain Classification System for Forestry (Erasmus, 1994). All compartments in the study area have a transport road along the western boundary and distance to the back of the compartment of 850 m. The secondary transport distance from roadside to the mill is 40 km.

Research System

This study focused on modeling a real world multi-stem forest harvesting operation (System 1) and two hypothetical multi-stem operations (Systems 2 and 3). All system models were created using Arena 9 commercial simulation software. The real world system represented by System 1 produced an average of 475.2 m^3 of pulpwood delivered to the mill per 11 h daytime shift during the period of study. System 1 comprised the following equipment (see Appendix 1 for matrix):

- 1 Tigercat 720D drive-to-tree wheeled feller buncher with continuous disc saw.
- 1 Tigercat 630C grapple skidder with dual arch and bunching grapple.
- 1 Volvo EC 210BLC excavator with Maskiner SP650 delimber-debarker head.
- 1 Volvo EC 210BLC excavator with Maskiner SP551 delimber-debarker head.
- 1 Hitachi Zaxis 200 excavator with Maskiner SP650 delimber-debarker head.
- 1 Volvo EC 210BLC excavator with Tigercat slasher deck.
- 3 Volvo FM400 6x4 rigid trucks with drawbar trailers.

System Observation

A time study of all work phases and elements of the real world system was carried out over a total of 191.1 h. Equation [1] was used to calculate the number of observations required.

$$n = \left(\frac{40\sqrt{n' \sum x^2 - \left(\sum x\right)^2}}{\sum x} \right)^2 \qquad [1]$$

(extracted from Kanawaty, 1992).

Where:

n = Sample size required for a 95.45% level of confidence and a margin of error of 5% of the true mean.
n' = Number of observations in the preliminary study.
$\sum$ = Sum of values.
x = Observation value.

Skidder average speed was calculated using recorded extraction time and distance data for the machine when traveling loaded, unloaded, and with slash. These speed observations were plotted against the respective distances traveled. This allowed calibration of functions, which described speed trend lines for each travel state per specified distance.

Simulation

Once the time study data had been captured, simulation model construction was initiated in Arena 9. The software is made up of a combination of general purpose programming language, simulation language, and simulators, and offers interchangeable templates of different types of graphical simulation modeling and analysis modules (Kelton *et al.* 2003). Simulations constructed in this study were dynamic (consider time), stochastic (consider randomness of observations), and discrete-event (activity-oriented) models.

Steps in developing the simulation model were as follows:

1. Level of detail to be included in the construction of the model based on input data, model complexity, and result requirements were defined.
2. A simplified rough draft of how the flowchart model would be constructed was created.
3. A simplified simulation model was built off the flowchart model using Arena 9.
4. The simplified model was run several times, with iterative corrections and adjustments being made.
5. The simplified model was developed and extra detail included to produce a model that would imitate reality to the required level.

6. Animations were added to the model. These assisted in further model verification, as well as making the working model far easier to explain and present to external parties (Meimban et al. 1992).
7. Final verification and validation of the completed model were conducted to establish whether or not the model should be rejected. Once this step had been completed, the model was ready to be used for producing simulated observations, from which predictions could be drawn.

The model was set to run for a simulated period of 10 months (each month was a replication). Each month was made up of 26 working days, with one shift of 11 workplace h/day. The reason for only simulating one shift per day was that time study data from the real world operation were only collected during the day shift due to safety concerns. Thus, to promote model accuracy only real daytime data were included in the model. The warm-up (transient) period for the model comprised of one shift (i.e., 11 h). This warm-up phase was extremely short in relation to the length of time the model was run for. In reality, however, the system undergoes a brief warm-up phase when starting a new compartment, which had to be included in the simulation. Total running time for the model over the 10 replications was 2,860 workplace hours, from which the 11 h warm-up period was excluded, leaving a total of 2,849 h (170,940 min.) of observation time. Shifts and months were set to flow into one another, with the situation at the completion of one period being the situation at the start of the following period.

Verification and Validation

One should bear in mind that a model is an abstraction of reality. This means that even a perfect simulation model will not generate results that agree exactly with the real situation, but it should yield an adequate approximation of it (Rummukainen *et al.* 1995). Model verification and validation are two tools used in simulation studies to ensure as far as possible that this is the case. Model verification involves debugging of the simulation model until the analyst is confident that model logic contains no anomalies. Validation refers to determining whether the model and its outputs accurately represent the real world system (Asikainen, 1995).

In verification, the tools used were Arena 9's built-in error report function, entity counters, and animation functionality, as well as running the model for an extended simulated period of 11,440 h (686,400 min) to ensure no traceable runtime errors were manifested from the given data within this time frame.

Validation in this study was carried out using the system data used to build the model. This goes against recommendations by Reynolds *et al.* (1981), who claim that "Proper validation of a stochastic simulation model requires that the predictions of the model be compared with real world data that are independent of the data that were used in the construction of the model." Lack of additional data due to this being the first multi-stem system study in the country meant this was not an option. However, this was not a critical problem in this study, as the model was specific to the particular system in the conditions studied and was not extrapolated to represent alternative operations or operating conditions. Validation methods used in this study were as follows:

- Model output data were contrasted with the real world system's observed outputs per work element using frequency distributions and the Chi-square test with the null hypothesis being that the simulated frequency distributions did not differ from the real world frequency distributions.
- Modeled system outputs (i.e., pulpwood and trucks) were compared with corresponding outputs from the real world system. To generate sufficient modeled data, the model was run for 40 simulated months (each month was treated as one replication). Simulated truck loads/month ranged from 210 to 232 over this period, with the average being 224.2. Considering only day-shifts, System 1 in reality produced 222.3 truck loads of timber in a 26-day month. A two-tailed t-test of paired means was run to determine whether or not there was a significant difference between modeled and real world observations at a 95% confidence interval.
- Resource capacities and entity arrival rates were adjusted and outputs evaluated to ensure robustness of the model in terms of its logic and scope.
- Traditionally in simulation studies, part of the validation process involves validating the random number stream to ensure no bias is being included. This is done by running the model on different random number stream seed values and comparing the results. If the results do not differ significantly from one another at a specified confidence interval, the model's random number stream would be deemed acceptable. A slight difference in outputs due to the random numbers producing random observations is expected, but not to the extent that the models would be deemed dissimilar. However, with the improvements in random number generators over time, and the robustness of Arena commercial simulation software, random number stream validation was not necessary in this study.

Additional Model Construction

System 2 is a hypothetical system that employs exactly the same units of equipment as System 1 (Figure 1, next page) but differs in specific operating procedures. It was constructed primarily to simulate potentially advantageous alterations to System 1's operating procedures with the aim of improved equipment balance, productivity, production, and cost. Based on the time study information the following changes were made to System 1, resulting in System 2:

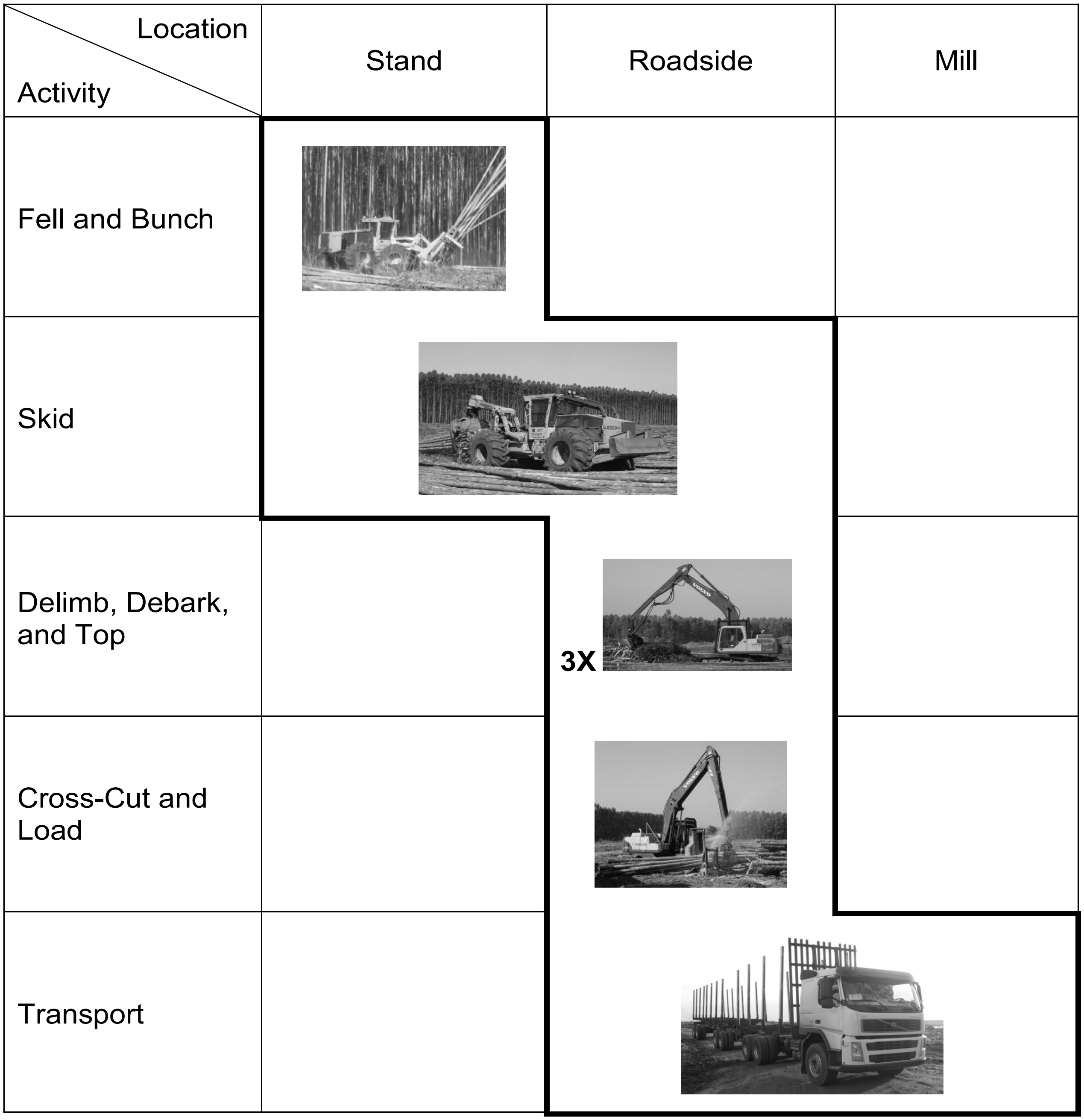
- Fuelling and greasing bottleneck equipment outside of scheduled work hours.
- Providing operators with more, shorter scheduled rest periods.
- Since the feller buncher's production capacity was the least utilized of all equipment, more time was used for good presentation of bunches for the skid-

der, as well as placing them at 90º to the take-off direction (i.e., allowing greater skidder starting acceleration).

- Skidder log recovery grapple mounted on the skidder blade for collecting stems dropped during previous cycles.
- Minimal time delay between felling and debarking required for reduced bark adhesion (i.e., bark adhesion increases within even a few hours after felling in Zululand conditions, thus decreasing debarking productivity).
- Larger stock buffer between the delimber-debarkers and the slasher, meaning less slasher movement, less skidder indexing cycles, higher slasher productivity, and increased volume payloads per truck.

System 3 (Figure 2, next page) is also a hypothetical system and differs partially in equipment type and functioning from Systems 1 and 2. It was selected to determine the potential of simulation in evaluating alternative resource options, as well as to predict if this system could be better suited to the required task and conditions than Systems 1 and 2. It is made up of the following equipment:

Figure 1: System 1 and System 2 matrix.

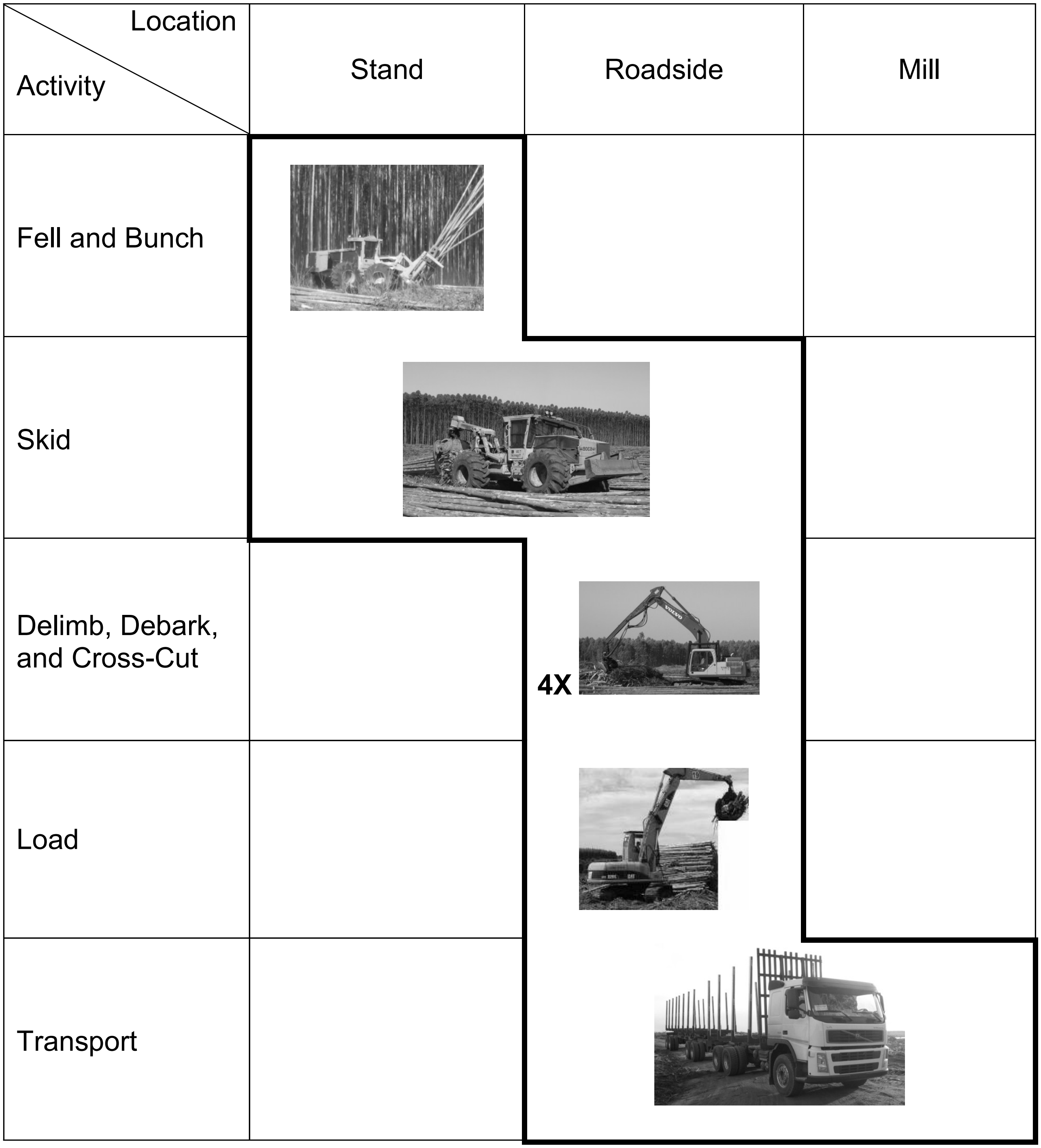


- 1 Tigercat 720D drive-to-tree wheeled feller buncher with continuous disc saw.
- 1 Tigercat 630C grapple skidder with dual arch and bunching grapple.
- 4 Volvo EC 210BLC excavators with Maskiner SP650 delimber-debarker-slasher heads.
- 1 Volvo EC 210BLC loader/excavator with Rotobec grab.
- Volvo FM400 6x4 rigid trucks with drawbar trailers.

In System 3, the feller buncher and grapple skidder operate in a similar manner to System 2. Subsequent to timber extraction by the skidder, four roadside processors delimb, debark, and cross-cut the full trees to 5.5 m lengths. Following this, the cross-cut timber is loaded onto trucks by the loader and transported to the mill.

Data for System 2 were gathered using System 1's real world time study data and external sources. System 1's data were streamlined where required to include only observations that represented the required operating methods per activity or

Figure 2: System 3 matrix.



unit of equipment. Tests to ensure the streamlined data met the required sample sizes were carried out in the same manner as described for System 1. Systems' 2 and 3 model verification and validation followed similar processes to System 1. Following modeling completion, each of the three modeled systems was re-modeled with four trucks. This was done to ensure the transport operations did not limit the harvesting systems' throughputs.

Model Cost Calculation

All six simulation models (i.e., Systems 1, 2, and 3, each with three and four trucks, respectively) were costed using standard cost inputs, internationally accepted cost calculation formulas (Hogg *et al*. [in print]), results taken from simulation runs, and working hours and days taken from simulation model parameters. Cost calculations in this study did not include any equipment overhead, support personnel, support functions, support services, incentives, risk compensation, or profit margin. The cost calculation assumptions, made to ensure that the cost conditions represented modeled conditions, were as follows:

- All equipment units were scheduled to work 26 days/month (312 days/year).
- One shift was worked each day.
- Workplace time was 11 h/shift.
- Expected economic life (depreciation period) of all equipment was five years.

Results and Discussion

Time Study Validation

Required observation time per machine was determined by cycle time and work element time variation. All observations resulted in collected data that exceeded the required amount to describe the respective means with a 95.45% level of confidence and a margin of error, which was within 5% of the true mean (Table 1).

In addition to the time study noted in Table 1, the skidder was observed traveling for a total of 60.1 hours and the data used to produce equations defining average travel speed per distance traveled. Equations (2), (3), and (4) were defined for the skidder traveling loaded (dragging tree lengths), traveling with slash (when returning infield), and traveling unloaded, respectively.

Work Element	Observations Conducted	Observations Required	Time Observed (h)
FB: dist per cycle	119	42	N/A
FB: head accumulation 1	119	50	2.5
FB: head accumulation 2	119	47	2.6
FB: head accumulation 3	119	46	2.8
FB: head accumulation 4	119	59	2.1
FB: open landing (Step 1)	64	52	1.3
FB: open landing (Step 2)	64	55	1.4
FB open landing (Step 3)	64	43	1.5
SKID: Grapple load	305	217	4.2
SKID: collect slash	261	229	3.7
DDB1, Op1 cycle time	807	86	6.9
DDB1, Op2 cycle time	953	123	11.5
DDB2, Op3 cycle time	1,083	88	18.0
DDB2, Op4 cycle time	744	175	9.2
DDB3, Op5 cycle time	508	188	7.8
DDB3, Op6 cycle time	547	113	6.8
SLASH: no index X-cut	308	249	10.0
SLASH: index X-cut	412	249	4.2
SLASH: load from X-cut	427	176	2.3
SLASH: load from stack	317	170	2.7
SLASH: stack from X-cut	317	142	1.9
TRUCK: arrival rate	1,283	865	1542.8
Stems per bunch	406	80	N/A

Table 1: Real World System Observation.

Table 2: Weighted system costs per m^3 and monthly production.

Category	3 Trucks In System			4 Trucks In System		
	System 1	System 2	System 3	System 1	System 2	System 3
Feller Buncher	$0.79	$0.68	$0.68	$0.79	$0.68	$0.69
Skidder	$1.06	$0.87	$0.87	$1.07	$0.86	$0.87
Delimb.-Debark.	$2.43	$1.94	-	$2.43	$1.93	-
Slasher	$0.83	$0.76	-	$0.83	$0.63	-
Processor	-	-	$2.77	-	-	$2.76
Loader	-	-	$0.55	-	-	$0.45
Trucks	$2.92	$2.80	$2.80	$3.44	$2.92	$2.92
Weighted Cost *	$8.03	$7.06	$7.67	$8.56	$7.03	$7.70
Trucks/month	224.2	233.3	233.6	225.2	288.5	287.8
m3/month	12461	13,213	13 230	12 517	16 340	16 300

Note: Study done in South Africa and costs calculated in ZAR, currency conversion as of August 31, 2009, 12:30PM ET: R7.7835 = US $1.00.
* Weighted Cost refers to the cost for the operation, divided by the total operation tonnage.

Traveling loaded $(m \cdot s^{-1})$:

$$0.579 + 0.181*\mathrm{Ln}(dist) - 17.279*(1/dist) \qquad [2]$$

Traveling with slash $(m \cdot s^{-1})$:

$$0.003 + 0.404*\mathrm{Ln}(dist) - 18.905*(1/dist) \qquad [3]$$

Traveling unloaded $(m \cdot s^{-1})$:

$$-0.818 + 0.541*\mathrm{Ln}(dist) + 2.511*(1/dist) \qquad [4]$$

Where: dist = distance (m) from departure location to arrival location.

One should take note that these travel speed functions include acceleration from stationary at takeoff and deceleration to stationary at the end of the work element.

In comparing modeled output data with real world data, none of the modeled frequency distributions were rejected when compared with reality based on the Chi-square test. This was due to the Chi-Square values being well below the allowable values, based on the respective degrees of freedom per distribution. In comparing modeled system outputs (System 1 with three trucks) with corresponding outputs from the real world system, the t-value calculated from this test at 78 degrees of freedom was 0.58. This was less than t(.05), which had a value of 2.00. The null hypothesis of no significant difference between the means at a 95% confidence interval was therefore not rejected. The models were not rejected based on rates either, as changes in inputs resulted in the appropriate output changes.

Cost and Production Results

Weighted equipment costs specific to each modeled system are given in Table 2. The weighted cost for each system is not equal to the sum of the equipment cost components respective to that system because the skidder does not extract the tons of timber felled by the feller buncher in the landing area.

Note should be taken that any comparisons of the numbers of trucks per month between systems in Table 2 should be carried out with the understanding that System 1's trucks were loaded with average payloads of 55.6 m^3, whereas System 2 and 3 had average payloads of 56.6 m^3. This is the result of an increased buffer between delimber-debarkers (or processors) compared to System 1, leading to the timber being a day drier before being loaded onto trucks (Schonau, 1974).

System 1 with three trucks is the benchmark model shown in Table 2 as it represents the real world operation. When compared with this system, System 1 with four trucks was more expensive by \$0.53/m^3, and it was only slightly more productive (56 m^3/month). For the harvesting section, it was only \$0.01/m^3 more expensive, but in the transport section, the additional truck resulted in an increase of \$0.52/m^3. This result highlights the fact that the inclusion of the fourth truck in this system resulted in the trucks becoming underutilized, leading to the increase in cost. It can be concluded that System 1 (and the real world system it represents) has the correct number of trucks serving it, specific to the harvesting system production and transport distance.

System 2 with four trucks predicted the greatest improvement on System 1 with three trucks. This system cost was predicted to be \$1.00/m^3 less than the real world system (12.5% cost reduction), making it the cheapest of all models. It was also the most productive modeled system, predicting an increase in production from 12,461 m^3/month (System 1 with three trucks) to 16,340 m^3/month – a 31.1% production increase using exactly the same harvesting equipment as System 1. There is, however, no guarantee that this most improved system model is in fact an optimization of the original due to the nature of simulation studies (Hillier and Lieberman, 2005). The ultimate test would be to study the actual system in the field after the recommended alterations have been implemented.

System 3 with four trucks was predicted to be cheaper than System 1 with three trucks by \$0.33/m^3, but more expensive than System 2 with four trucks by \$0.67/m^3. Since the feller buncher and the skidder portions of System 2 and System 3 models are identical and operate in the same manner and the number of trucks in the systems are the same, the predicted difference between System 2 and System 3 lies in the delimbing, debarking, cross-cutting, and loading activities. The simulated process of turning full trees at the landing into pulpwood loaded on a truck for System 2 with four trucks cost \$2.57/m^3, whereas in System 3 with four trucks it cost \$3.22/m^3 (a difference of \$0.65/m^3). Based on this result, delimbing and debarking full trees into tree lengths at roadside with delimber-debarkers before cross-cutting and loading with a slasher was predicted within the study conditions to be a more economical option than delimbing, debarking, and cross-cutting full trees into pulpwood with processors at the landing before loading with a loader.

In all simulated models, the debarking machines (i.e., delimber-debarkers and processors) were the bottlenecks. Two of the most important manipulations made during the system alterations from System 1 to Systems 2 and 3 were having less stock between the feller buncher and the debarking machines and adopting a first-in-first-out approach from the feller buncher to the debarking machines. Debarking resistance increases as timber and bark dry out (Grobbelaar & Manyuchi, 2000), meaning the moment of least debarking resistance in a harvesting operation under normal circumstances is the instant after the tree has been felled. Reduction of bark adhesion was the primary rationale behind reducing the amount of time between felling and debarking in Systems 2 and 3. Judging by the debarking productivity results obtained from these two systems (16,340 and 16,300 m^3/month, respectively) in comparison with that of System 1 (12,461 m^3/month), one can predict that this adjustment resulted in the expected outcome. Debarking machines remained the bottlenecks in Systems 2 and 3 even with the accelerated cycle times due to other machines within the systems having undergone productivity improvements. The issue of bark adhesion and its impact on the operation brings into question the potential suitability of a cut-to-length (CTL) system as opposed to multi-stem system in these conditions.

Conclusions

Outcomes of the study, based on the objectives, were as follows:

1. In System 1 the simulation model acceptably represented reality on every level, with the real world and the model differing by an average of 0.85% in overall production over 40 simulated months. The conclusion is that Arena 9 commercial simulation software can be used in forest harvesting operation applications to adequately simulate reality. The simulations predicted that system balance could be improved most noticeably in the decrease of feller buncher waiting time from 43.1% of its total scheduled work hours (System 1 with three trucks) to 26.2% (System 2 with four trucks). Predicted production improvements were clearly evident with simulated timber over the weighbridge/month increase of 31.1% and a cost/ton of timber decrease of 12.5%.
2. Several beneficial operation and application practices were identified in System 2, which led to the successes mentioned above. Not all changes made in this study, however, would necessarily produce the same positive result in other multi-stem operations. Improvements were gauged according to the studied harvesting operation under specific conditions. Applicability of these operation adjustments to improved operation in other systems and operating conditions would therefore be expected to vary according to the system configurations and operating environment.
3. Arena 9 commercial simulation software was found acceptable in some parts and difficult to work with in other parts. Some of the more prominent points regarding this include:
    - The software requires a fairly qualified level of user expertise due to the complexities associated with forestry operations, which lead to the user inevitably having to use more advanced aspects and functionalities of the software. This led to model logic construction carrying many inter-dependencies between logic components. Numerous attributes, conditions, assignments, variables, and expressions were required as a result, making adjustments to

model logic a substantial task.

- Input fields and output reports were not always in formats that proved to make much sense or be much use for interpretation into a forestry context.
- Simulating and tracking resource and entity movements within a stand requires much model logic and error checks.
- Built-in user aids such as error checks and extensive help functionality make the program easier to work with.
- Software interface layout is user friendly and easy to work with.
- Module flowchart construction is made simple by the "drag and drop" modules that can be opened and closed for logic inclusion as required.
- Once constructed, models were found to be easily adjustable on the flowchart level. Any changes in background logic, however, were more difficult.
- Input Analyzer made data incorporation into the model an easy task.
- The software is capable of handling heavy simulation runs with numerous entities for extremely long periods of time.

Acceptable models were produced using the Arena commercial simulation software, meaning it has a framework that can be used for the construction and simulation of forest harvesting operations. The software was clearly not designed for forestry applications per se, but it can be manipulated into providing the required results in a usable format based on specific inputs.

A recommendation for future simulation study would be to collect CTL time study data and simulate a CTL system. Simulated comparison between CTL and multi-stem systems could be explored, as well as potential improvements to the CTL system. Another potential future study area is the effect of changes in bunch sizes produced by the feller buncher on skidder and system productivity and cost.

The process of forest harvesting operation abstraction and simulation has been confirmed as acceptable by this study. The potential for system improvements has also been confirmed by this study. The ultimate test of the appropriateness of the simulation results will be through applying the improved system scenario in reality and monitoring the outcome. This requires implementing the simulated adjustments (the changes made to System 2 with four trucks in this case) into the real world system and carrying out further time studies to evaluate how accurately the model predicted reality.

References

Asikainen, A. 1995. Discrete-event simulation of mechanized wood-harvesting systems. Research notes 38, University of Joensuu, Faculty of Forestry, 86pp.

Baumgras, J.E., Hassler, C.C. and LeDoux, C.B. 1993. Estimating and validating harvesting system production through computer simulation. *Forest Products Journal* 43(11/12): 65-71.

Erasmus, D. 1994. National terrain classification system for forestry. ICFR Bulletin No. 11/94.

Grobbelaar, F.R. and Manyuchi, K.T. 2000. Eucalypt Debarking: An international overview with a Southern African perspective. FESA Report. June 2000. 68pp.

Hillier, F.S. and Lieberman, G.J. 2005. Introduction to operations research. 8th ed. McGraw-Hill, Boston. 1061pp.

Hogg, G.A., Krieg, B.W., Laengin, D.W., Ackerman, P.A. [In print] Harvesting system and equipment costing. Chapter 4. In South African Forestry Handbook, 5th ed., South African Institute of Forestry.

Kelton, W.D., Sadowski, R.P. and Sturrock, D.T. 2003. Simulation with Arena. 3rd ed. McGraw-Hill, Boston. 668pp.

Meimban, R.J., Mendoza, G.A., Araman, P. and Luppold, W. 1992. A simulation model for a hardwood sawmill decision support system. *International Journal of Forest Engineering* 4(1): 39-47.

Reynolds, M.R. Jr., Burkhart, J.E. and Daniels, R.F. 1981. Procedures for statistical validation of stochastic simulation models. *Forest Science* 27(2):349-364.

Rummukainen, A., Alanne, H. and Mikkonen, E. 1995. Wood procurement in the pressure of change – resource evaluation model till year 2010. Acta Forestalia Fennica 28. 98pp.

Schonau, A.P.G. 1974. Air-drying rate of debarked eucalyptus grandis roundwood in tree lengths. Wattle Research Institute Report for 1974-75.