Abstract

Detailed time studies are used to estimate productivity of individual machines, but due to high costs of field data collection, applications are often limited to a short observation time period for a few case studies. On the contrary, shift-level data are less costly and involve less effort, but provide limited insights on individual machine performance and interactions among machines. In this study, stochastic, discrete event simulation techniques are used to simulate two ground-based harvesting systems (i.e., lop-and-scatter and whole-tree harvesting) applied to beetle-killed stand harvesting in Colorado, to evaluate and compare the two systems under a variety of operating conditions. To capture uncertainties during field operations, stochastic events such as personnel delays and machine downtime are also included in the model. Machine interactions, bottleneck operations and system performance are simulated to provide a realistic estimate on the productivity of each system. Results show that adopting whole-tree harvesting system will generate a unit production cost of 6.98 $/m³, representing a 7.2 percent lower cost than the 7.84 $/m³ lop-and-scatter system production cost. Sensitivity analyses on equipment operating efficiencies indicate that the current bottleneck for both systems are delimiters. More efficient delimiting processes reduce production cost significantly and are more favorable for lop-and-scatter systems. Avoiding mechanical failures during harvesting operations can bring down production cost by 5.1 percent and 8.2 percent in lop-and-scatter sand whole-tree harvesting systems, respectively.

Keywords: Discrete-event, machine interactions, sensitivity analysis

1. Introduction

Various timber harvesting systems have been developed to implement silvicultural treatments (e.g., clearcut, commercial thinning, selective cutting) under a wide variety of vegetation and terrain conditions (Uusitalo & Pearson, 2010). Ground-based systems are the preferred harvesting systems for terrain with gentle slopes (normally less than 30 percent). Typical ground-based systems for clearcut operations consist of feller bunchers for cutting trees down, grapple skidders for primary transportation (i.e., from stump to landing), stroke delimiters for delimiting and bucking, and loaders for sorting and loading.

Lop-and-scatter is a widely used ground-based harvesting system for clearcut operations in Colorado. In the system, a feller buncher cuts trees down and stacks them in piles. Two delimiters move from pile to pile to process trees into logs. A skidder then brings logs to the landing.
The loader stays at the landing to sort and deck the logs. Because logs are processed at the stump, logging residue is dispersed over the harvest unit. The lop-and-scatter system is often favored since it is easy to implement, more economical for slash management, and leaves nutrients on site (Berryman, Battaglia, & Hoffman, 2015). However, due to the increasing interest in utilizing forest residue for bioenergy and fire risk mitigation (Gan & Smith, 2007; Agee & Skinner, 2005), whole-tree harvesting systems have been getting more attention, especially in the Southern Rockies where the mountain pine beetle has caused extensive lodgepole pine mortality. The major distinction between the two harvesting systems is where deliming occurs. In a whole-tree system, delimers stay at or very close to the landing, and process trees that are transported by a skidder in the form of whole trees. This practice generates logging residue piles at the landing (Figure 1). Relative to lop-and-scatter, whole-tree harvesting often requires a larger landing size for residue piles and a higher level of coordination among machines, and may result in lower skidder efficiency (Bolding, Kellogg, & Davis, 2009; Hartsough, Zhang, & Fight, 2001).

![Figure 1. Post-harvesting Site Scenes of Lop-and-scatter and Whole-tree Harvesting Conducted in the Colorado State Forest](image)

However, despite the apparent differences in configurations and processes, the difference in system productivity between the two systems remains uncertain as many external factors affect the system efficiency, and thus production costs. In order to understand the full characteristics of each system under large external factor variability, it has been suggested that multiple detailed time studies might be warranted (Han-Sup Han, Lee, & Johnson, 2004).

Conventionally, detailed time studies are used to estimate the productivity of individual machines and the entire system. But due to high costs of field data collection, applications are often limited to a short observation time period for a few case studies (Aedoortiz, Olsen, & Kellogg, 1997). Shift-level time studies are less costly, but provide limited insights on machine performance and interactions. To overcome these shortcomings, simulation techniques can be used as an effective approach to facilitate and rationalize productivity and cost calculations (Ziesak, Bruchner, & Hemm, 2004). Discrete-event simulation is the modeling of systems in which the state variable changes only at a discrete set of points in time, where systems are analyzed by numerical methods rather than by analytical methods (Banks, 1984). This is an advantage when there are a large number of variables, parameters and functions and various interactions occur among system components. In addition for decision support, various scenarios can be tested in the model without disturbing the actual workflow. By changing simulation inputs and observing the resulting outputs, the performance differences between systems can be compared (Banks, 1984).

Simulation techniques have been applied to operational studies in forestry for a long time, but only a handful of applications exist. Because of its flexibility, simulation models are suitable for analyzing a wide range of forest stands, operating conditions and system configurations under...
which timber harvesting systems should be compared (Chris B. LeDoux, 1981). Once coupled with field data, a discrete-event simulation model is well suited for tracking the flow of materials during the processing steps in a mechanized forest harvest system (Aedoortiz et al., 1997). Wang & LeDoux (2003) developed an estimation model to generate harvest stands, and simulate different harvesting scenarios and equipment combinations that included chain saws, drive-to-tree feller bunchers, swing-to-tree single-grip harvester felling, grapple skidders and forwarders to analyze the costs and productivity of ground-based timber harvesting. In addition to investigating production in forestry, where the primary usage is planning and controlling production processes, an educational tool can also be created by separating forestry activities, stand characteristics, and operating specifics in the model (Ziesak et al., 2004).

Although many studies have been conducted to compare system productivity in different scenarios, most have addressed only limited elements of the entire production process, and machine interactions in particular were seldom addressed. Moreover, the complete production system from stump-to-road has not yet been investigated. In this study, a stochastic, discrete event simulation is used to model both lop-and-scatter and whole-tree harvesting systems applied to beetle-killed stand harvesting in Colorado. The purpose of this simulation model is to evaluate and compare the two systems under a variety of operating conditions. Machine task times and their corresponding probability distributions were estimated using time study data collected from on-site observations. To capture uncertainties during field operations, stochastic events such as personnel delays and machine downtime are also included in the model. Machine interactions, bottleneck operations and system performance are simulated to provide a realistic estimate on the productivity of each system. System production costs and critical factors for system performance are assessed and discussed.

2. Methods

The base data used to generate parameters for the simulation model were collected during a detailed time study conducted in the Colorado State Forest State Park in December 2015. Preliminary data analysis shows that the number of trees or logs processed in each cycle have a significant influence on the cycle time distribution of feller buncher and delimiters. Here, a cycle is defined as the procedure in which equipment grab trees/ logs, process them, and stack them in piles. In order to identify this difference and obtain higher resolution of the cycle times, machine (i.e., feller buncher and delimiters) cycle times were categorized into groups based on the number of tree/log pieces simultaneously processed in each cycle. A two sample t-test is done cross groups to show if the average cycle times of the two groups are significantly different. If so, these groups were separated when generating best fit theoretical distributions for their cycle time. In the end, three instinct groups were identified, which are the one-piece cycle, two-piece cycle, and three or more-piece cycle. During the simulation process, the number of tree/log pieces processed in each machine cycle is drawn from an empirical probability distribution for each process.

In addition to the number of pieces processed and the cycle time distribution, frequencies of machine movements and position adjustment (feller buncher and delimiters in lop-and-scatter, and feller buncher in whole-tree harvesting) are also modeled with empirical distributions. However, machine movement time, mechanical delay occurrences and are estimated according to information from literature and field observations.

The discrete event simulation models of the lop-and-scatter system and whole-tree harvesting systems were developed using Rockwell Arena software (Kelton, 2015; Automation, 2007). The underlying assumptions in the model are:
• Realizations of random variables for the same process are independent and identically distributed
• All trees are processed into one log
• There is no leakage or loss during processing

The simulation models developed for each of the two systems are applied to the harvesting of 1,800 individual trees. For each machine, production activities, movement, and various delays are simulated as different discrete random events. For instance, for each cutting cycle of the feller buncher, the model checks if the cycle would include a machine movement. If yes, add a randomly generated movement time to the cycle. Then, the model generates the number of trees to be cut in this cycle and estimates a cutting time from the pre-defined cutting time distribution. After completing one cycle of cutting, the feller buncher gets ready for the next cycle. During the operation, machine failures may happen in any cycle at any time. Low productivity or failure of one machine may also affect the productivities of other machines. All of the other machines are simulated in a similar manner.

A total of 100 replications are run for each system in order to generate the distribution of individual machine cycle times, total duration of harvesting (1,800 trees), utilization rate, productivity, and unit production cost. To simulate operations in practice, the feller buncher is scheduled to start working 30 minutes earlier than other equipment (i.e., feller buncher starts at t = 0 and other equipment start at t = 30) to accumulate harvested tree piles. Machine rates ($/scheduled machine hour (SMH)) used in our analysis are estimated from multiple literature and other sources. They are $130.04/SMH for the feller buncher, $114.69/SMH for delimiters, $90.97/SMH for the skidder, and $79.26/SMH for the loader. A constant log volume of 0.32 m³ per piece was used, since it was the average log volume obtained from the field study.

Besides the aforementioned base cases, multiple scenarios were developed to investigate the effects of machine operation efficiency, skidding distance, and mechanical delays on the entire system productivity and unit production costs. In each scenario, 100 replications are run to obtain the average and variability of the system productivity. These multiple scenarios are also used to construct the sensitivity analysis for various ranges of model parameters.

3. Results

The mean duration of harvesting operations (project duration) is 599 minutes for the lop-and-scatter system, while it is 538 minutes for the whole-tree system (Table 1). For unit production cost, the mean values for the lop-and-scatter system (LS) and whole-tree harvesting systems (WT) are 7.84 $/m³ and 6.98 $/m³, respectively. According to our simulation results, the whole-tree system is more efficient with a 11 percent lower unit cost and a 10 percent shorter project duration compared to the lop-and-scatter system. However, the coefficients of variation (not shown) for these two systems are 6.2 percent and 8.6 percent in project duration and 5.1 percent and 7.2 percent in unit cost. This shows that the whole-tree harvesting system, although with a lower average cost, is more variable compared to the lop-and-scatter system.

---

4 Adapted from Brinker et al. (2002)
Website http://www.machinerytrader.com
Website http://www.bls.gov/oes/current/oes_co.htm#45-0000
Website http://www.wdol.gov/wdol/scafiles/non-std/77-0079.sca
Table 1 Operation Time and Unit Cost Comparison (Base case)

<table>
<thead>
<tr>
<th>System</th>
<th>Project duration (min)</th>
<th>Unit production cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Half width</td>
</tr>
<tr>
<td>LS</td>
<td>599</td>
<td>7.4</td>
</tr>
<tr>
<td>WT</td>
<td>538</td>
<td>9.1</td>
</tr>
</tbody>
</table>

* Half widths are based on 95% confidence interval
* SD stands for standard deviation

Statistics on individual machine operations are shown in Table 2. For all equipment in whole-tree harvesting, the actual production time is shorter than that in the lop-and-scatter system. Thus the equipment productivity is higher and the production cost is lower. Nevertheless, this does not ensure a higher utilization rate for all equipment in the whole-tree harvesting system. This is because more coordination among equipment is required in whole-tree harvesting and the discrepancy between equipment productivity leads to frequent idle state during operations.

Table 2 Equipment Operation Statistics

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Job completion time (min)</th>
<th>Production time (min)</th>
<th>Utilization (%)</th>
<th>Productivity (m³/h)</th>
<th>Production cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LS</td>
<td>WT</td>
<td>LS</td>
<td>WT</td>
<td>LS</td>
</tr>
<tr>
<td>Feller buncher</td>
<td>362</td>
<td>316</td>
<td>301</td>
<td>271</td>
<td>83.5</td>
</tr>
<tr>
<td>Delimber A</td>
<td>581</td>
<td>525</td>
<td>444</td>
<td>396</td>
<td>80.8</td>
</tr>
<tr>
<td>Delimber B</td>
<td>581</td>
<td>522</td>
<td>449</td>
<td>369</td>
<td>81.7</td>
</tr>
<tr>
<td>Skidder</td>
<td>594</td>
<td>533</td>
<td>379</td>
<td>319</td>
<td>67.4</td>
</tr>
<tr>
<td>Loader</td>
<td>599</td>
<td>538</td>
<td>394</td>
<td>384</td>
<td>69.5</td>
</tr>
</tbody>
</table>

In order to quantify the effects of individual machine performance on system outputs, sensitivity analyses are conducted with changes in feller buncher, delimber, and loader cycle times within a range of ±50 percent from the average. The results show that for the given site conditions, an increase in the efficiency of the feller buncher and the loader has minimal positive effects on system production costs (Figure 2). However, the efficiency of the delimber appears to be critical. Improving delimbing not only reduces unit cost in both systems, but it also has a decisive influence on the selection of a harvesting system. As the efficiency of the delimber increases over 25%, the lop-and-scatter system starts outperforming the whole-tree system because the system productivity of the whole-tree harvesting system is constrained by a different machine (i.e., loader).

![Figure 2 Sensitivity Analysis of Equipment Operating Efficiency](image-url)
To address the effects of mechanical delays, scenarios are created for both systems where no equipment mechanical failures occur (Table 3). Compared to the base cases, the mean values of project duration and unit production cost are reduced by 6.2 percent and 5.1 percent in the lop-and-scatter system respectively, and 9.1 percent and 8.2 percent in the whole-tree harvesting system. Moreover, standard deviations are also reduced greatly. This is because mechanical failures during operations not only lower the operating efficiency, making the entire system unbalanced, but they also make the system unstable and unpredictable during harvesting operation planning.

<table>
<thead>
<tr>
<th>System</th>
<th>Project duration (min)</th>
<th>Unit production cost ($/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Half width</td>
</tr>
<tr>
<td>LS</td>
<td>562</td>
<td>1.5</td>
</tr>
<tr>
<td>WT</td>
<td>489</td>
<td>2.0</td>
</tr>
</tbody>
</table>

### 4. Conclusion

Two ground-based harvesting systems, lop-and-scatter and whole-tree harvesting, are modeled using stochastic, discrete-event simulation. Results show that given the field observed site conditions and equipment performance, the whole-tree harvesting system would generate a unit production cost 7.2 percent lower than that of the lop-and-scatter system. Performance of individual machines as well as balance among different machines are critical in the selection and configuration of harvesting systems. The deliming process is the current system bottleneck in both systems. Particularly in the lop-and-scatter system, delimiters have longer average cycle times as they have to move between tree piles, resulting in a lower productivity compared to the whole-tree harvesting system. Efficient delimiters would make the lop-and-scatter system more favorable especially when the delimming function no longer becomes the limiting factor of the system.

Our observation confirms that a whole-tree harvesting system requires a higher level of interactions among machines (i.e, skidder, delimiter and loader) compared to the lop-and-scatter system. Therefore, system balancing and coordination is critical to maintain a high system productivity during whole-tree harvesting. Nevertheless, the whole-tree harvesting system allows collection of logging residues, and thus may be desirable if treatment objectives include utilization of non-merchantable biomass materials or fuel reduction.

Although our study successfully demonstrates the use of stochastic simulation for timber harvesting operations analysis, it, in its current form, does not account for many other cost factors, such as landing construction, slash management, additional coordination among machines, etc. Future studies should include a more thorough analysis on costs, advantages, effectiveness, and influencing factors of the two systems for more complete comparisons under varying conditions.

### Acknowledgments

This research was supported by the Agriculture and Food Research Initiative Competitive Grant no. 2013-68005-21298 from the USDA National Institute of Food and Agriculture.
References


