ECONOMIC EVALUATION OF IMPLEMENTING IMPROVED STEM SCANNING SYSTEMS ON MECHANICAL HARVESTERS/PROCESSORS

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ABSTRACT

Use of mechanical harvesting/processing systems in timber harvesting is increasing worldwide, with advantages in terms of increasing productivity and safety. However, despite these systems giving operators access to advanced computer and measuring systems, their ability to extract the maximum value from a tree is, on average, less than motor manual log bucking systems. The productivity, cost, and value recovery of several simulated procedures for scanning and bucking *Pseudotsuga menziesii* (Mirb.) Franco (Douglas fir) and *Pinus ponderosa* Lawson & C.Lawson (ponderosa pine) trees were evaluated from a log seller's perspective. The procedures evaluated were (a) conventional operating where quality changes and bucking decisions were made by the machine operator, (b) an automatic full scan of the stem prior to optimisation and bucking, and (c) partial scanning where a portion of the stem was scanned and then qualities and dimensions were forecast before the optimal bucking took place. After subtracting costs, the net value improvement for the automated scanning procedures over the conventional procedure ranged from –7% to 8%. The best net value improvement for both species was obtained using the procedure that fully scans the stem prior to bucking. Breakeven capital investment costs for new scanning, forecasting, and optimisation equipment ranged between zero and US$2,120,000 depending on tree species, markets, scanning speed, volume scaling rules, and scanning procedure.

Keywords: value recovery; mechanical harvesters/processors; productivity; cost; scanning.

INTRODUCTION

The adoption of mechanical timber harvesting systems is increasing worldwide. These systems allow stems to be delimbed, bucked, sorted, and sometimes felled by a single machine. In Scandinavia, almost 90% of logging is carried out using mechanical harvesting systems (Nordlund 1996). Within the last 10 years, the number of harvesters and processors sold in eastern Canada increased from 200 to 900 (Godin 2000). In Australia, by the late 1980s mechanisation had almost eliminated motor-manual felling in *Pinus radiata* D.Don (radiata pine) thinning operations (Raymond 1988). Factors causing this shift from the traditional motor manual harvesting systems to mechanical harvesting systems include the need to continually increase productivity and to improve the safety record of forestry operations.

A recent survey of value recovery studies (Murphy 2003a) showed that, on average, mechanical log making systems are losing 21% of potential value whereas manual log making systems* are losing on average only 11%. In the mechanical log making studies, value recovery losses ranged from 1% to 67%. Losses occurred when logs did not meet log grade specifications (e.g., inaccurate lengths, diameters too small or large, too much sweep, non-allowable quality features) or when the combination of logs cut from a stem was sub-optimal. The worst losses occurred when computerised optimal bucking tools were not used (Murphy 2003a). Stand characteristics, market complexity, equipment design and maintenance, and operator skill can all also affect the level of loss.

A number of mechanical harvester manufacturers such as Ponsse, Timberjack, and Valmet have implemented bucking algorithms on their machines. To produce accurate optimal bucking decisions these systems require highly accurate detailed information on stem shape and quality characteristics.

Most modern mechanical harvesting systems use mechanical sensors, some combining these with photocells to measure diameter and length (Andersson & Dyson 2002). Operators have to visually assess changes in quality along the length of each stem and determine, with or without the use of "optimal" bucking systems, the log types to be cut. There have been several studies looking at the accuracy of modern mechanical sensors used to measure diameter and length. One Swedish study tested five of the most common measuring and merchandising systems and concluded that, with the exception of one system, either the length sensor or the diameter sensor was unsatisfactory (Sondell *et al.* 2002). There have been few scientific studies specifically looking at how well operators assess changes in either stem quality or form as the stem is being processed. Gellerstedt (2002), however, reported that Scandinavian harvester operators indicated that they have problems seeing defects in the log at the current feeding speed of 4 m/s and that more "sensing" in the harvester head is required for faster operation and better judgments on stem quality.

Although improved selection and training of operators may provide one of the higher benefit-to-cost ratios from investments in ways to reduce value losses (T.Evanson, Logging Industry Research Organisation, unpubl. data), there is a limit to human ability to capture and process information and, therefore, to the potential improvements from training.

In the future wood users may become increasingly specific about the type and quality of wood that they are receiving. The indications are that they may start placing minimum and maximum specifications not only on external features such as log shape and external quality but also on internal characteristics such as wood density, extractives content, and stiffness (e.g., Walker 2000; Young 2002). These additional specifications will add extra complexity to the already complex task of log making. If the industry wants to increase the value recovery from its mechanical harvesters, it needs to look at investing in improved scanning, forecasting, and optimisation systems to assist operators in log making.

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* "Manual log making systems" refers to log making that is carried out by a person using a logger's tape for measuring length and a chainsaw for cutting stems into logs.

For many years, the sawmilling industry has utilised different log scanning technologies for collecting data on external log features (e.g., Dashner 1993; Green 1993; Brisky *et al.* 2004). The data are used for optimisation of bucking and sawing patterns as well as for automated grading. The commercial use of laser and camera scanning technologies is well advanced, while other technologies capable of capturing internal log features such as computer-aided tomography and nuclear magnetic resonance (NMR) are now being investigated for their potential for log scanning (e.g., Chang *et al.* 1989; Schmoldt *et al.* 2000; Gupta *et al.* 1998) and computer-aided tomography is slowly making its way into the sawmill (Anon. 2004).

If scanning technologies such as laser, optimal scanners, and computer-aided tomography can be used in the sawmilling industry there is little reason why they cannot be used within the forest. Although there have been numerous scientific papers on potential new scanning and measuring systems in sawmills (e.g., Chang *et al.* 1989; Schmoldt *et al.* 2000; Gupta *et al.* 1998; Kaestner 1999; Benson-Cooper *et al.* 1982; Rayner 2001), there are only a small number on the use of this technology with mechanical harvesting systems (Tian & Murphy 1997; Lofgren & Wilhelmsson 1998; Moller *et al.* 2002) .

Scandinavian researchers and equipment developers invested considerable resources into determining and implementing the best procedures for scanning and optimal bucking on mechanised harvesters for their stand and market conditions. For example, Berglund & Sondell (1985) found that by measuring a portion of the stem of *Picea abies* (L.) Karst. (Norway spruce) and forecasting the taper of the unmeasured portion of each stem, productivity impacts could be reduced and value losses minimised. Näsberg (1985) used a similar forecasting procedure and found that loss in value due to incomplete information was less than 2%. Liski & Nummi (1995) developed a linear mixed model for predicting stem curve measurements in Norway spruce. Their model used measurements from previous stems plus a number of known measurements on the current stem to predict the diameters of the unknown section. They found that value losses decreased as the length of the known portion of the stem increased. The minimum loss found was 5%. A study by Sondell *et al.* (2002) using modern log merchandising computers suggested that losses could be contained to less than 1% for log value recovery.

Automatic bucking using these forecasting techniques is generally not applied in *Pinus sylvestris* (L.) (Scots pine) forests in Scandinavia. This is mainly because Scots pine has considerably more inter- and intra-stem variation in quality and form than Norway spruce, making accurate prediction of these characteristics less likely (Uusitalo *et al.* 2002). This is also likely to happen in other species such as radiata pine and Douglas fir. In an optimal bucking study done on Douglas fir using a Hahn Harvester where diameters for part of the stem were predicted using a taper equation, the value of the logs produced was 12% less than the optimal solution where all the stem diameters were known (Olsen *et al.* 1991).

Murphy (2003b) looked at the economic potential of different approaches to scanning stem dimensions and quality on mechanised harvesters. His study was based on New Zealand conditions and markets and focused only on the processing of radiata pine. The study used generic productivity, cost, and value recovery figures. He found that for radiata pine the breakeven capital investment that may be made in scanning systems could, in some cases, exceed the combined cost of the carrier and harvester head.

Objective

The objective of this study was to determine, from a log seller's perspective, the economics of placing advanced scanning and measuring systems on mechanical harvesters/ processors to improve value recovery. The study continues work done by Murphy (2003b) by looking at two different mechanical harvesting/processing operations in two different species (i.e., Douglas fir and ponderosa pine) to determine a breakeven capital investment for new scanning, forecasting, and optimisation technology for these species. Five simulated procedures for scanning were evaluated for each operation.

METHOD

Field Sites and Tree Stem Data Sets

Two sites, which were representative of the two dominant industrial forest types that exist in the Pacific Northwest, were used for this study — Douglas fir-dominated stands west of the Cascade Mountains, and the dry pine-dominated stands east of the Cascades. Sites were selected based on logistics (location, and crew willingness to be studied) and number of log grades being cut. The studies were carried out during the summer of 2002.

Site 1 was a Douglas fir-dominated stand in southern Washington State. Net stocked area of the stand was 12.18 ha (30.1 acres), with an average stocking of 273 stems/ha. It was on mainly flat ground with an access road through the middle, and was clearfelled. The average tree size was 2.35 m^3, and the average diameter at breast height (dbh) was 46 cm. These stand parameters were obtained from the forest owner's stand record system. They were based on field measurements made in 1997 and grown-on using tree growth models to give the stand parameters at the time of harvesting.

Site 2 was a ponderosa pine stand in eastern Oregon. The slope of the site was not more than 5%. The stand was scheduled for thinning and trees to be removed were marked. The average dbh was 27 cm and the average stocking was 415 stems/ha prior to thinning and 102 stems/ha post-thinning. The average tree size for the selected trees was 0.35 m^3. The forest owner did not possess any stand records for this stand, and so before the harvesting started 11 pre-harvest inventory plots, each of 0.04 ha, were installed. In these plots diameters at breast height of all trees were measured and their thinning status was noted. The height of one tree in each plot was also measured so that a diameter/height relationship could be developed. These plot measurements were then scaled up to give the stand parameters.

At each site 120 trees were selected and felled; on 100 trees detailed measurements were then made of over-bark stem dimensions and qualities. The bark thickness of the other 20 trees was measured at regular intervals up the stem, and these measurements were used to develop a bark thickness equation to convert over-bark diameter measurements to under-bark.

Once all the stems had been measured, the processor operator delimbed and cut them into logs as usual. The lengths and grades of the logs produced were recorded.

Markets

Log specifications and confidential prices that were being used at each site to process each stem into logs were obtained from the forest owners. The Douglas fir market included nine log-types and each log-type could have multiple lengths, ranging from 3.6 to 12.2 m. The highest value log-type was an export-grade saw log with an average stumpage value of US\$157/m^3. The lowest value log-type was a pulp log with a value of \$22/m^3. The ponderosa pine market included three log-types, each of which also had multiple lengths ranging from 2.4 to 6.7 m. The highest value log-type was a saw log with a value of US\$62/m^3. The lowest value log-type was a chip log with a value of \$4/m^3.

Machine Productivity and Costs

At the Washington site a Logmax 750 harvesting head was operated on a Caterpillar 325C Forest Machine with a bucking computer. The harvester essentially sat at one location processing stems brought to it by a shovel. The operator of the Logmax had over 1.5 years' experience operating this setup plus over 20 years' experience in the forestry industry. In eastern Oregon a Valmet T500 with a Valmet 965 s-2 harvesting head and MAXI bucking computer operated as part of a cut-to-length thinning operation. The harvester moved through the stand felling and processing (at the stump) the marked trees. The Valmet operator had 5 years' experience operating cut-to-length harvesters.

Long-term production studies were not carried out to determine percentage utilisation and mechanical availability of the harvesters/processors, but a survey of published articles on production studies of harvesters operating in similar situations to those described above was undertaken (e.g., Raymond 1989; Richardson 1989; MacDonald 1990; Jackson *et al.* 1984). A utilisation level of 75% was assumed to be appropriate for both sites.

Detailed productivity was determined by video-recording at least 5 hours of each machine working under "normal" operating conditions. The videos were analysed using activity sampling which was developed in 1934 by Tippett. The technique involves taking snap-readings, at either set or random time intervals, of the element or activity occurring at the time the reading is taken. Due to the semi-random nature of these operations, snap-readings at set intervals were considered to be appropriate and were taken every 15 seconds. The results of these time studies were used to calculate productivity in terms of trees and cubic volume per hour.

To predict delimbing/processing time for each of the processors working under the different scanning procedures, a mathematical model was developed using scanning/delimbing distance (m), head travel distance (m), and total saw-cut diameter (cm) as dependent variables. The dimensional data used to develop these models were collected from the processor's on-board computerised measuring system, while the time data were collected using video recorded from inside the cab of the processor. The general form of the model is given below (Eq. 1):

$$\text{Processing time} = \frac{\text{scanning distance}}{\text{a}} + \frac{\text{head travel distance}}{\text{b}} + \text{c} \times (\text{total saw-cut diameter}) + \text{d}$$

where: a and b are travel speeds of the harvester head (m/s).

c is the slope coefficient from regressing time to make a saw cut against diameter of the cut (s/cm).

d is the sum of the intercept coefficient from regressing the time to make a saw cut against diameter of the cut and the additional time that was required to process a stem but which was not recorded in the detailed time study. The detailed time study was used only to model the head travel and cut time. It did not provide data on the delays that often occur during the stem delimbing and bucking process. The additional time was calculated by determining the difference between the average time to process a stem, as determined from the activity sampling time study and from the model (s).

The costs were calculated using standard costing procedures described by Bushman & Olsen (1988). The machine and scanning equipment were costed out separately. Productivity and cost information were combined to determine a cost per productive machine hour. It was assumed that the productivity of the whole operation was limited by the harvester.

Procedures for Scanning

To determine the best procedure for scanning, five simulated scanning, forecasting, and optimisation patterns were included in the study:

(1) CONVENTIONAL — stem diameters and length measured mechanically by the processor; the machine operator assesses quality breaks and selects log types to cut with or without computer assistance. The bucking is done as the delimbing is done.

(2) FULL SCAN — the processor scans the full stem for changes in stem dimensions and quality, and then optimally determines log types that should be cut to maximise value recovery.

(3–5) PARTIAL SCAN — the processor scans a certain length for stem dimensions and quality, then forecasts a certain length (Table 1), optimises to the end of the forecast length, cuts a log length, and then repeats to the end of the stem. Three partial scan/ forecast combinations were evaluated for both species.

TABLE 1–The three partial scanning scenarios for each of the species

	Douglas fir			Ponderosa pine		
	Scan 6.1	Scan 4.6	Scan 3.0	Scan 4.6	Scan 3.0	Scan 1.5
Scan distance (m)	6.1	4.6	3.0	4.6	3.0	1.5
Forecast distance (m)	6.7	8.2	9.8	2.1	3.7	5.2

These scanning and forecasting lengths were selected so that their combined length would be at least as long as the longest marketable log length for each species. If the “optimal” solution required a cut to be made in the forecast zone, resulting in a log not meeting specifications because of either its quality or diameter, a revised bucking solution was determined based on the new information.

Taper was forecast ahead for the distances given in Table 1 using the taper over the previous 3 m (approximately) of the stem. Quality (such as knot size, rot, crook, and scars) was forecast ahead based on the last 0.1 m of stem. It was assumed for the simulations that sweep was measured consistently and correctly, regardless of scanning procedure. This assumption was made due to the difficulty surrounding the measurement of sweep when the stem is dangling from a processor head.

Gross and Net Value Recovery

An optimal bucking program (BUCKIT) was developed by the authors for this study; it uses a similar dynamic programming algorithm to that included in AVIS (Geerts & Twaddle 1984). BUCKIT was used to determine gross optimal value for the full and partial scan procedures. The volume scaling model used by BUCKIT to determine the log volume was the same as that used in practice for the two operations. This meant that the Douglas fir logs were scaled using the cubic foot scaling rule and the ponderosa pine logs were scaled using the Eastside Oregon Scribner scaling rules. The log lengths and grades that were actually cut by the processor were used to determine the gross value of the conventional scan procedure (i.e., the logger's value). The lengths for these logs were recorded from the harvester's computer which was assumed to be measuring accurately. The trees were numbered so that log lengths cut by the harvester could be matched to the stem description measured manually. These lengths were entered into BUCKIT as forced cuts, meaning BUCKIT was forced to cut the stem in that location.

The different scanning procedures accrued different log-making costs due to the processing head travelling different distances under the different scanning procedures Fig. 1). The net value recovery for the different scanning procedures was calculated by subtracting the log-making costs from the gross value recovery.

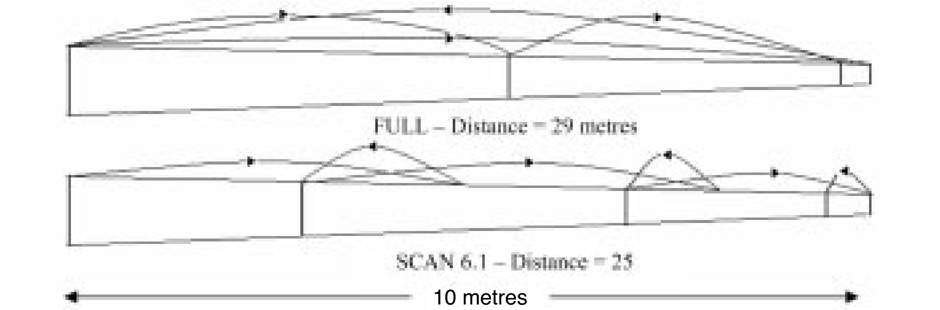

FIG. 1–Example of movement of processor head for a full scan and a partial scan (Murphy 2003b).

Breakeven Capital Investment Costs

The Microsoft EXCEL function "Goal Seek" was used to calculate breakeven capital investment that could be spent on new scanning, forecasting, and optimisation systems for the different scanning procedures. The Goal Seek function varies an input value to a formula until the formula returns the result the user wants (Microsoft 2003). The costs associated with operating the processor were kept constant while the capital and associated costs of investing in scanning, forecasting, and optimisation systems were increased until net value recovery by implementing the new scanning procedures equalled that of the CONVENTIONAL scanning method.

These breakeven capital costs were rounded down to the nearest US$10,000. They provide an indication of the maximum amount that could be spent on new scanning, forecasting, and optimisation systems. Sensitivity of these breakeven costs to changes in net value recovery and scanning speeds was investigated.

RESULTS

Machine Productivity and Cost

Productivity data were collected, using activity sampling methods, for a total of 256 and 364 trees at the Washington and eastern Oregon sites respectively. At Washington the productivity was 146 m^3/productive machine hour (PMH) which was considerably more than the eastern Oregon site where the harvester had a productivity of 14 m^3/PMH. On average, the harvester at the Washington site was processing 63 trees/PMH compared to the harvester at the eastern Oregon site which was processing 68 trees/PMH. The difference in productivity between the two sites can be attributed to difference in tree size, operation (cut-to-length *versus* on-landing-processing), and tree species.

For both systems approximately half the harvester's time was spent processing the stem (Fig. 2).

Two separate models for the two processors were developed to estimate the processing element under the different scanning procedures. The processor/site-specific coefficients for the generalised equation (Eq. 1) are given in Table 2.

The relationships between stem diameter and time to cut were generated by regressing the data displayed in Fig. 3. Time to cut a stem increased as diameter increased for both

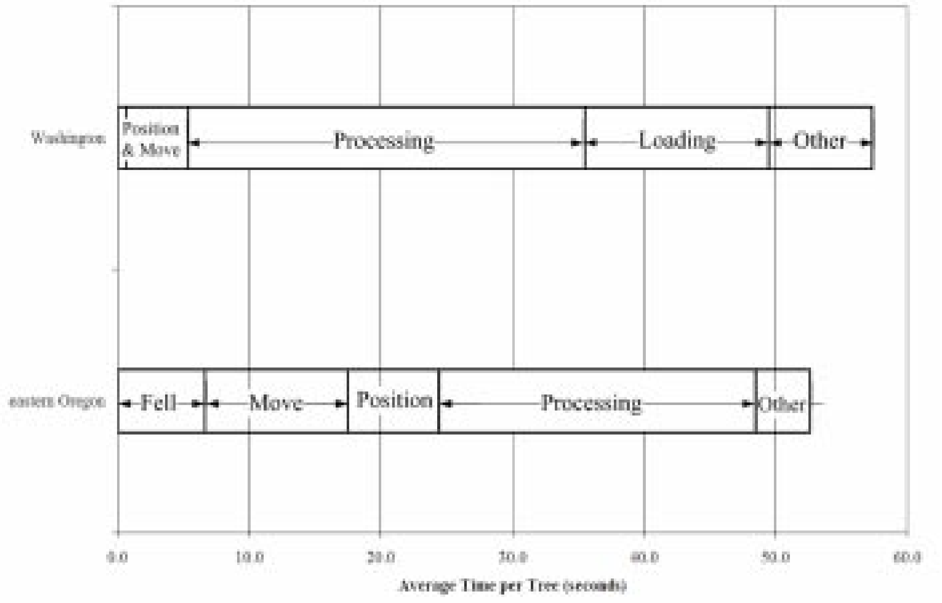

FIG. 2–Average time spent on the different elements of processing a stem into logs.

TABLE 2–Coefficients for the stem processing model in Equation 1.

	a (m/s)	b (m/s)	c (s/cm)	d (s)
Washington	1.67	2.02	0.0676	2.57
Eastern Oregon	1.13	1.55	0.0275	10.99

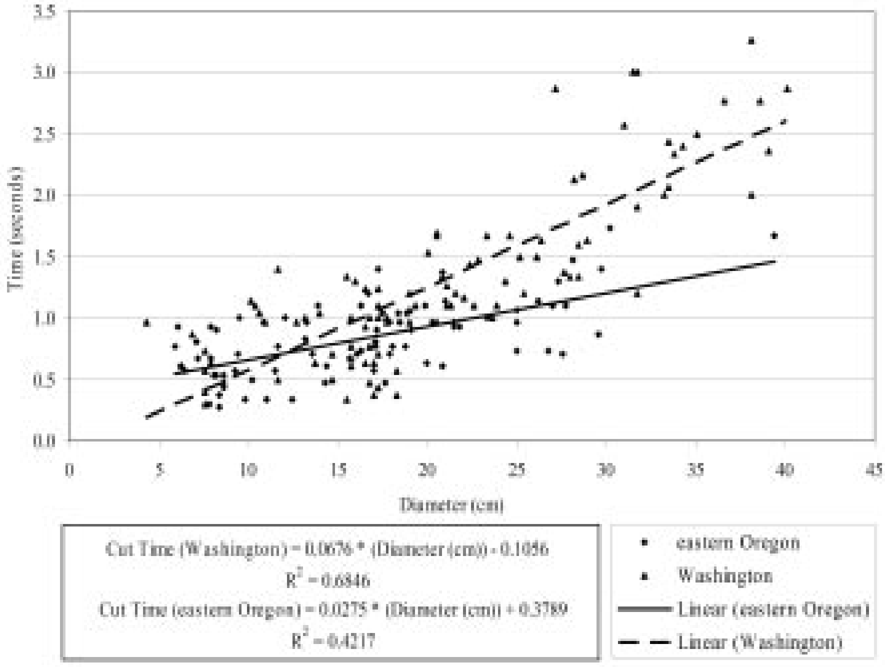

FIG. 3–Relationship between cut time and diameter of the cut.

machines; however, the rate of increase was much greater at the Washington site than at the eastern Oregon site.

Head travel speed for delimbing (a) and simply moving (b) along the stem were both significantly different for both sites. The p-value calculated using two sample t-tests were $P(t_{82}>2.044|\mu_1 = \mu_2) = 0.022$ for the Washington site and $P(t_{82}>3.138|\mu_1 = \mu_2) = 0.001$ for the eastern Oregon site.

The time it takes to process a stem is not totally accounted for by adding travel time and cut time together; these two elements do not take into account the time it takes to cut out a multi-leader, etc. The constant d in Table 2 is the sum of the regression intercept from Fig. 3 and the amount found by subtracting the predicted processing time using Eq. 1 from the processing time recorded using the activity sampling time study. It represented the time per tree spent doing activities other than those captured during the detailed time study.

The simulated productivity of the full scanning procedure was about a quarter to a third less than that for the conventional operating method (Fig. 4). Scanning only a portion of the stem reduced productivity impacts but the level of reduction was dependent on species, market type, and stand type.

The capital cost of the Caterpillar 325C Forest Machine with the Logmax 750 was US$560,000 with an operating cost of US$161.65/PMH. The Valmet T500 capital cost was US$438,480 with an operating cost of US$149.02/PMH. The costings assumed a machine life of 6 years, an interest rate of 12%, and cost of repairs and maintenance to annual depreciation ratio of 110%. These costs were calculated assuming that the processors were

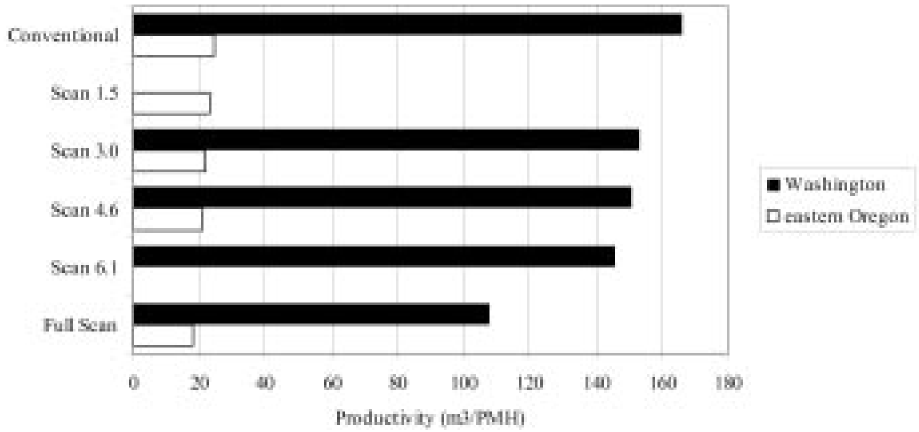

FIG. 4–Processing productivity for the operating procedures involving scanning.

operating the conventional scanning procedure — i.e., without equipment fitted for scanning quality features. Cost per productive machine hour was combined with machine productivity to determine production costs per cubic metre. The changes in scanning cost for the different scanning and processing procedures were in line with changes in productivity for both operations.

Forecasting Accuracy

To determine the accuracy of the simple forecasting method used, the predicted and actual diameters were recorded for each of the forecast sections. The accuracy of the diameter predictions was evaluated by calculating Root Mean Square Error (RMSE):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n}}$$

where: y_i was the actual diameter at each 0.1-m section and
$\hat{y}_i$ the predicted value.

The measures of the diameter prediction accuracy for the species and the different scanning procedures are given in Table 3.

The results are similar to those of Liski & Nummi (1995) — RMSE decreases as length of the known section increases. Liski & Nummi found that a low RMSE value for the predicted diameters along the unknown section of the stem does not necessarily guarantee lower value losses.

TABLE 3–The RMSE for the forecast diameter for each species and scanning procedure.

	Washington			eastern Oregon		
Scan	6.1	4.6	3	4.6	3	1.5
RMSE (mm)	27.4	42.7	75.1	10.3	26.9	28.5

The accuracy of the quality prediction was expressed as the mean percentage of the forecast section for which quality was inaccurately predicted. These mean percentages are given in Table 4 for each species and scanning procedure.

The simple forecasting technique used in the study obtained results that were better than expected. It can be seen that, as the forecast length increased, the level of accuracy decreased. The number of quality codes used to describe the tree is also likely to have an impact on the level of the accuracy using this forecasting technique. In these two examples there were six quality codes for the Douglas fir and four for the ponderosa pine.

TABLE 4–The percentage of the forecast stem for which the quality was incorrectly predicted.

	Washington			eastern Oregon		
Scan	6.1	4.6	3	4.6	3	1.5
Stem (%)	18	21	22	5	8	10

Gross Value and Potential Value Loss

Difference in tree size and markets meant there were very large differences in gross values for the two species. As an indicator of this difference, the gross value per tree was about US$12 for the ponderosa pine and US$276 for the Douglas fir stand. The eastern Oregon operation was losing 17% of potential value recovery, whereas the Washington operation was losing 8%. In absolute terms the Washington operation lost more value (over US$2000 per hour, or approximately US$22 per tree) than the eastern Oregon operation (US$200 per hour, or approximately US$2 per tree). The percentage value loss figures were below the international average of 21% (Murphy 2003b).

In comparison with gross value recovery differences, the range in processing cost was small: US$1 to US$3 per tree.

At both sites, maximum net value recovery was obtained from full scanning (Fig. 5). This conclusion, however, is dependent on the scaling rules used to calculate the volume. When the 100 ponderosa pine stems were bucked using cubic scaling rules (Bell 2002) as opposed to the Scribner scaling rules used to obtain the results for the ponderosa pine stems in Fig. 5, the Scan 4.6 obtained a higher net value recovery than the full scan (not shown in Fig. 5). As the scanning distance reduces and the distance of stem that is forecast increases, value recovery falls to the point where the net value recovery for the 100 stems is less than the value recovery for the conventional scan procedure. This occurred at the Washington site using the Scan 3.0 scanning procedure and at the eastern Oregon site using the Scan 1.5 scanning procedure.

Breakeven Capital Investment Costs

The breakeven capital investment costs that could be invested in new scanning and optimisation technology are shown in Table 5. These were in addition to the capital investment already made in the harvester/processor head and the carrier. These values have been rounded down to the nearest US$10,000. At both sites the breakeven cost was highest when using the FULL scan procedures; however, once again this was dependent on the

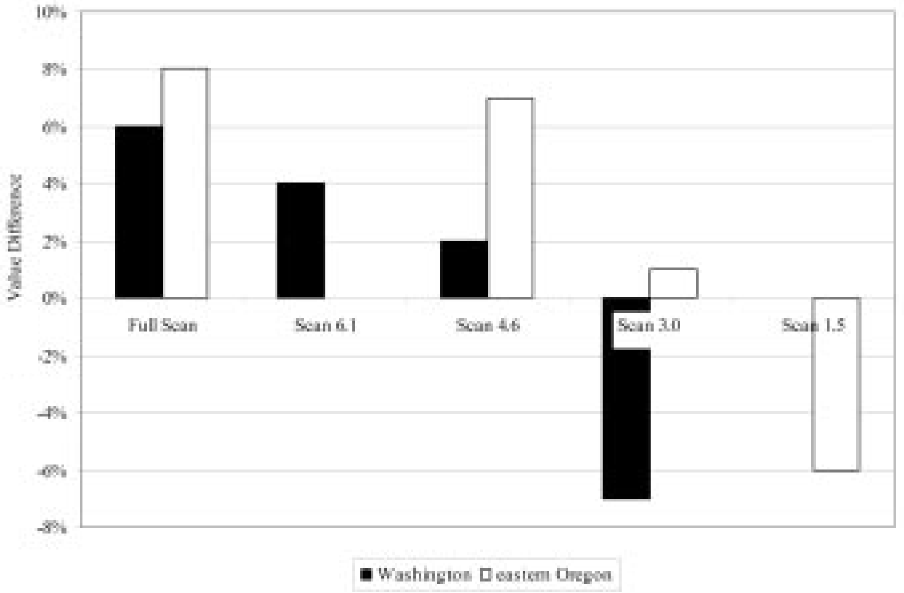

FIG. 5–Change in net value recovery from 100 stems using five different scanning procedures, in comparison to conventional processing.

TABLE 5–Summary of breakeven investment cost (US$) for the five scanning procedures.

	Full scan	Scan 6.1	Scan 4.6	Scan 3.0	Scan 1.5
Washington	$2,120,000	$1,810,000	$800,000	–	N/A
Eastern Oregon	$80,000	N/A	$70,000	$10,000	–

scaling rules (Bell 2002). When cubic scaling (Bell 2002) was used on the eastern Oregon site, the SCAN 4.6 produced the highest breakeven cost.

As in the study by Murphy (2003a), it can be concluded that the breakeven capital investment costs were dependent on stand-type, market, and scanning approach.

To investigate the effects of initial value recovery of the system and the speed at which the stem is scanned, the following sensitivity analyses were carried out on the full scan procedure.

(a) Net value losses can vary between different operations (*see* Murphy 2003b). The breakeven capital investment cost was therefore calculated using initial net value losses of 5, 12.5, and 20%. As the initial net value loss increases, the breakeven capital investment cost also increases (Fig. 6) meaning that the most money can be invested in the poorest performing operations. This conclusion should, however, be treated with some caution as the reasons for some operations performing poorly may not be removed by implementing automatic scanning, forecasting, and optimisation systems.

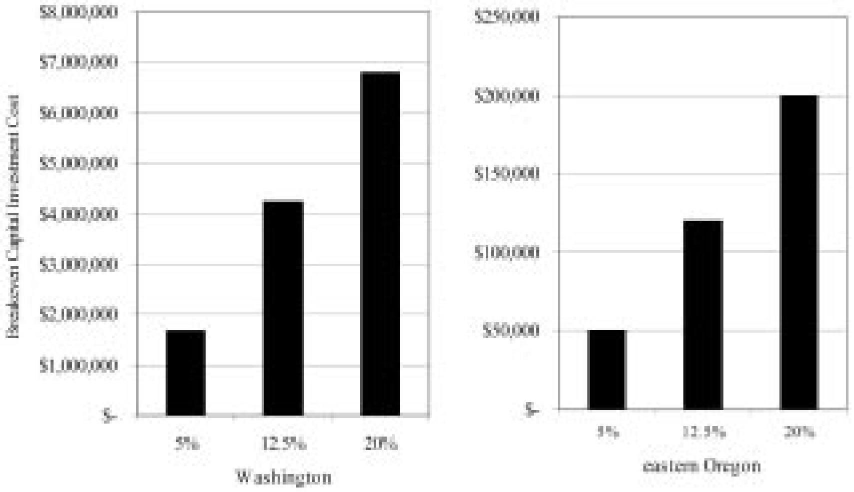

FIG. 6–Effects of assumed initial value loss of operation on breakeven capital investment cost (US$).

(b) In previously published reports, the range of potential scanning speed that a system such as X-ray can achieve is quite large, ranging from a low of 0.04–0.16 m/s (Schmoldt *et al.*2000) up to 3 m/s (Oja 1999). If new scanning technology were to be implemented on harvesting/processing heads, it is likely that scanning speeds would have to be less than current scanning speeds of 1–2 m/s for mechanical harvesters. To simulate the effects of reducing the measuring speed, the breakeven capital investment cost was calculated when the scanning speed was reduced by a half, and by two-thirds (Fig. 7).

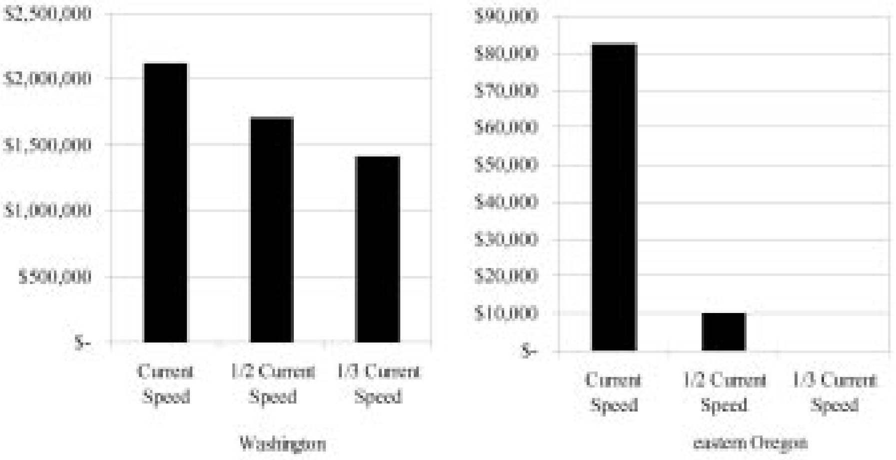

FIG. 7–Effect of scanning speed on breakeven capital investment (US$) under the full scan procedure.

It appears from these simulations that breakeven capital investment cost is relatively sensitive to scanning speed. Given the current scanning speed for X-ray suggested by Schmoldt *et al.* (2000), the breakeven capital investment for the Washington site would be US$480,000; so, at least for the Washington site, the scanning speed of current X-ray scanners is sufficient to make its implementation economically viable. Other scanner technologies such as NMR whose scanning speeds are much slower than X-ray would probably not be economically viable.

Along with stand-type, market, and scanning approach, the breakeven capital investment cost is also dependent on the initial amount of net value loss and scanning speed.

DISCUSSION AND CONCLUSIONS

Simulations reported in this paper indicate that substantial investment can be made by the log seller into scanning systems to improve the accuracy of stem quality and dimension measurements. The size of this potential investment is dependent on species, stand-type, markets, the scanning system and procedure, and the current value recovery performance of the operation.

Scandinavian researchers have found that by measuring a portion of the stem, and forecasting taper for the unmeasured portion of the stem, value losses could be contained to less than 2% (Nasberg 1985; Sondell *et al.* 2002). In this study, where quality was forecast as well as taper, gross value losses for the longer scanning distances (6.1 m for Douglas fir and 4.7 m for ponderosa pine) were contained to less than 4%. These losses are similar to value losses found by Liski & Nummi (1995).

The full scan procedure produced the highest net value recovery. It was concluded that there was no advantage in only partially scanning the stem when using the simple forecasting procedure used in this paper. This result agrees with experience in Finland where automatic bucking used in Norway spruce is considered economically inefficient in pine or birch (Uusitalo *et al.* 2003). This study showed that scanning less than 3 m produces a lower net value recovery than the conventional scanning procedure.

It should be noted that a forecasting system that more accurately forecasts both stem form and quality may yield higher net value recovery results and therefore justify the use of partial scanning in Douglas fir and ponderosa pine harvesting. Research done on Scots pine in Sweden (Möller *et al.* 2003) and Finland (Nummi & Möttönen 2003) on prediction models for accurately forecasting a number of lumber and wood quality characteristics during the stem processing operation is showing promising results. If the Douglas fir and ponderosa pine harvesting industries want to increase their mechanical log bucking productivity while achieving high levels of value recovery they need to invest time and money into developing more accurate stem forecasting models.

The large difference in breakeven capital investment costs indicates that vastly different scanning, forecasting, and optimisation technologies are likely to be applicable for different stand and market conditions. At the Washington site, where the breakeven capital investment was US$2,120,000, the potential for implementing a new scanning and optimisation system is extremely promising. However, at the eastern Oregon site the breakeven capital investment of US$80,000 may limit investment to (1) improvement of current measuring systems, (2) improved training, (3) better calibration procedures, or (4) some combination of the three.

An investment in training, at both operator and managerial levels, may be a simpler and more effective way to improve value recovery than investing in technology. As Gellerstedt (2002) pointed out, however, it takes years for an operator to gain the training and experience to effectively operate a harvester and, even then, there is a limit to how quickly operators can perceive and process information about each tree stem. Increases in machine delimbing/processing speeds and a trend towards matching internal wood properties to markets will probably lead to a greater use of scanning technology and log bucking decision support systems on processors where log value warrants such an investment.

Although US$2,120,000 seems a large investment, in many situations the amount required to invest in new scanning, forecasting, and optimisation systems is of at least this order of magnitude. In the sawmill industry, scanning and optimisation systems cost US$500,000 to US$1,000,000. However, the large body of value recovery studies (Murphy 2003a) shows that significant gains in profitability can be made if the optimal value can be achieved from every stem.

The breakeven values reported in this paper are only an indication of the level of investment that could be made in stem scanning systems. The breakeven values reported will be affected by measurement, prediction, and sampling error. No analysis has been done to determine the effect of these errors, as they will be minimal compared to those caused by differences in stand and market conditions.

Although not considered in this study, many new scanning and forecasting systems are capable of scanning for internal quality features of a stem. Further research is required to determine the effects of alternative procedures for internal quality scanning on productivity, costs, and value.

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