Evaluation of the economic impacts of length and diameter measurement error on mechanical harvesters and processors operating in pine stands

Hamish D. Marshall, Glen E. Murphy, and Kevin Boston

Abstract: Value recovery studies from around the world have shown that on average mechanical log-making systems lose 18% of the potential value compared to 11% for motor manual systems. One of the potential reasons for their poor value recovery performance is the level of accuracy of their stem diameter and length measurements. Numerous studies have looked at the level of error in both the diameter and length measurements made by mechanical harvesters and processors; however, few have looked at the economic impacts of these errors. The paper investigates the economic impacts in terms of value loss of six different harvesting operations in three different pine species. The accuracy and precision of the measurements recorded in this study were similar to those of other studies from around the world. A simulation model was developed to estimate the value loss caused by these errors. The results of the simulation model showed that the operations were losing between 3% and 23% of the potential value because of measurement errors. Further analysis showed that the industry should concentrate on increasing the precision of the length and diameter measurements to optimize gains from reducing the measurement error rates.

Résumé : Des études de récupération de valeur lors du tronçonnage, menées à différents endroits dans le monde, ont montré que les procédés de récolte mécanisés entraînent en moyenne une perte de 18 % de la valeur potentielle comparativement à 11 % pour les procédés motomanuels. Une des raisons potentielles pour expliquer cette faible performance est liée au degré de précision des mesures de diamètre et de longueur des tiges. Plusieurs études ont porté sur l'estimation du degré de précision des mesures de diamètre et de longueur des abatteuses-façonneuses; cependant, peu d'entre elles en ont évalué les impacts économiques. Cet article examine les impacts économiques en termes de perte de valeur associés à six opérations de récolte différentes et ce, pour trois espèces de pins différentes. La précision et l'exactitude des mesures enregistrées dans cette étude sont similaires à celles d'autres études à travers le monde. Un modèle de simulation a été développé afin d'estimer la perte de valeur occasionnée par ces erreurs. Les résultats du modèle de simulation indiquent que les opérations de tronçonnage ont entraîné la perte de 3 à 23 % de la valeur potentielle à cause des erreurs de mesure. Des analyses plus approfondies montrent que l'industrie devrait se concentrer sur l'augmentation de la précision des mesures de diamètre et de longueur pour profiter au maximum de la réduction des erreurs de mesure.

[Traduit par la Rédaction]

Introduction

There is a worldwide trend toward mechanization and computerization in the forestry industry. The drivers for this trend include productivity and cost improvements (Anonymous 1997) and labor-related issues, for example, improving worker safety (Axelsson 1998) and addressing growing labor costs.

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Modern harvesters and processors are commonly equipped with merchandising computers that are connected to length and diameter sensors, which provide a continuous stream of stem dimensional data to the computer to assist the operator in making value-driven bucking decisions (Sondell et al. 2002).

Length measurements are commonly done using a measuring wheel (Andersson and Dyson 2002; Gellersedt 2002). The wheel is kept in contact with the stem by using either a spring or a hydraulic cylinder (Makkonen 2001). The wheel is reset either using the action of the cut-off saw or in some cases using photocells located near the cut-off saw. Some harvesters and processors do not have a measuring wheel; instead they use the feed rollers. The diameter of the log is measured using one or two potentiometers or encoders connected to the feed rollers or delimber arms (Andersson and Dyson 2002; Makkonen 2001).

As with all measurements, the length and diameter measurements made by the harvesting head sensors will contain some level of error, either random or systematic. Mistakes or

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Table 1. Summary of equipment and study sites used to develop length and diameter error distributions.

Study	Carrier, head	Merchandising computer	Site location	Species*	Operation type†
A	Valmet T500, s52	Valmet Maxi	Eastern Oregon	PP	CTL thinning
B	Valmet T520, s52	Valmet Maxi	Eastern Oregon	PP	CTL thinning
C	Ponsse Ergo, H73	Ponsse Opti	Alabama	LP	CTL thinning
D	Ponsse Ergo, H73	Ponsse Opti	Georgia	LP	CTL thinning
E	Ponsse Ergo, H73	Ponsse Opti	Alabama	LP	CTL thinning
F	Cat 330CL, Waratah HTH 626	Logrite	New Zealand	RP	POL clear-felling

*PP, *Pinus ponderosa* Dougl. ex P. & C. Laws.; LP, *Pinus taeda* L.; RP, *Pinus radiata* D. Don.
†CTL, cut to length; POL, processed on landing as full trees.

gross blunders are not errors and should never be called such (Barry 1978).

There are a large number of causes for measurement error; they include vibration and shocks, a lack of instrument calibration and inappropriate bark thickness functions, changes in environmental conditions and operating season, external stem shape, roughness and branchiness, and the skill level of the observer (Sirohi and Radha Krishna 1991; Morris 1996; Plamondon 1999; Makkonen 2001; Möller et al. 2002).

There have been few studies that have looked at the implication of measurement error. Olsen et al. (1989) investigated the effects of accuracy of length and diameter measurements on the optimal bucking solution. Their study was carried out on manual log makers using log tapes for length measurements in second-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) forest. Three different methods of measuring diameter were also used: bucker's tape, angle gauge, and calipers. The study found that length errors were not significant. Errors in diameter measurement, however, resulted in a substantial loss in potential value: 5.2% when using a logger's tape, 2.0% with the angle gauge, and 1.4% with calipers.

There is general agreement in the literature that the length and diameter measuring accuracy of harvesters will have an influence on the precision and quality of the bucking operation (Plamondon 1999; Chiorescu and Grönlund 2001; Sondell et al. 2002). There is, however, little literature on the effect of measurement error on either the value recovery of a harvester or the volume estimates made by a harvester. It has been estimated that in Norway spruce (*Picea abies* (L.) Karst.) that measurement error could cause approximately 1% loss in value (Sondell et al. 2002).

This paper focuses on single-grip harvesters and single-grip processors, since they are now, or are predicted to become, the dominant type of harvesters and processors used in many parts of the world (Hakkila et al. 1992; FERIC 1996; Anonymous 1997; Gellerstedt and Dahlin 1999).

The objective of this study was to investigate the economic impacts of a range of length and diameter measurement errors. Economic impacts are looked at from a landowner's perspective; the analyses use the log as the economic unit.

Materials and methods

Error distributions, stem databases, and log-grade specifications described in detail by Marshall (2005) were used to determine the economic impacts, in terms of value loss, of length and diameter measurement error. An optimal bucking and error simulation model was developed to help to determine these economic impacts. Brief descriptions of the distributions, databases, log specifications, and the simulation model are provided next.

Error distributions, stem databases, and log-grade specifications

Table 1 gives a description of the equipment, sites, and operator experience that were studied to obtain error distributions. All six studies were carried out in pine stands between July 2002 and July 2004. Three were carried out in Georgia and Alabama and were done as part of an M.Sc. thesis by Conradie (2003). One was carried out with the help of Scion Research in New Zealand. The other two were carried out in eastern Oregon. The equipment was studied "as is", that is, the machine operators were not specifically asked to recalibrate their equipment prior to the studies, although at least one of the machines had recently been checked by the equipment dealer.

Table 2 shows the error statistics from each of the six studies that were used to determine economic impacts. The errors were obtained by subtracting the actual log measurements from those shown by the mechanized harvester display. Actual length measurements were collected using a logger's tape, and actual diameter measurements were collected with calipers.

Three stem databases were developed by taking accurate measurements of trees that had been felled. Measurements included diameters, lengths, stem curvature, location of changes in knot size, and the presence and severity of defects. A summary of the three stem databases is given in Table 3.

Table 4 summarizes the log-grade specifications used. They were obtained from the forest owners of the stands from which the stems in the databases were collected. The full specifications included characteristics such as minimum and maximum log length and small- and large-end diameters, minimum acceptable quality features (e.g., maximum branch size), and maximum allowable sweep. The end uses of the different log grades were unknown; however, from the specifications many of them were clearly destined for sawmills, with the low-value grades probably being supplied to pulp mills. Supplying logs that meet the specifications is extremely important; whole truck loads can be rejected by

Table 2. Univariate statistics for length and diameter errors distribution.

	Length error (m)			Diameter error (cm)		
Study	No. of observations	Mean	SD	No. of observations	Mean	SD
A	116	–0.01	0.39	81	–0.65	1.54
B	108	0.04	0.23	77	–0.46	2.40
C	217	0.03	0.10	217	–0.40	0.81
D	143	–0.02	0.11	143	–0.02	1.06
E	250	–0.03	0.23	257	–0.31	1.87
F	902	0.01	0.25	1413	0.60	3.60

Note: SD, standard deviation.

Table 3. Summaries of the stem databases obtained from measurements of felled pine trees in Alabama, Oregon, and New Zealand.

Stem database	Species	Avg. stem length (m)	Avg. stem size (m^3)	No. of trees
PP	Ponderosa pine	13.3	0.39	100
LP	Loblolly pine	21.1	0.61	60
RP	Radiata pine	29.0	2.34	107

mills if the logs do not meet the mill's specifications. The number of log grades and specifications used differed greatly between the species (ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.); loblolly pine (*Pinus taeda* L.); radiata pine (*Pinus radiata* D. Don)). The relative prices were developed in consultation with the forest owners and took into account not only the market price, but also the market demand. Price lists for studies A, B, and F were developed in a consistent way. Price lists for studies C, D, and E were independently prepared in a consistent way by Conradie (2003), but under the guidance of the second author of this paper.

Description of the optimal bucking and error simulation model

To determine the economic impacts of diameter and length measurement errors, an error simulation model with an imbedded optimal bucking algorithm was developed. The model simulated the processes that a harvester goes through in the bucking of a stem. The model assumed that the harvester was operating an optimal bucking system and that each stem was completely scanned before the stem entered the optimization process. Although the authors have observed some operations where the stem is completely delimbed and scanned before bucking the stem into logs, most modern harvesters do not completely scan the stem (Uusitalo and Kivinen 2001; Sondell et al. 2002); many, such as the Ponsse harvesters (Ponsse 2002), have a taper equation prediction system so a near optimal solution can be generated without scanning the full stem. However, studies have shown that for a number of species it is more economic to do a complete prescan than to use the partial scan and forecast technique (Murphy 2003; Marshall and Murphy 2004). The decision to completely scan the stem before bucking was made so the effects of the errors could be determined independently of any stem forecasting system.

The model assumed that the following bucking process was completed by the harvester for each stem. The stem was lifted and scanned for dimensions, quality, and form. This information was used by an optimal bucking algorithm to create an optimal bucking pattern for the stem. The harvesting head then moved along the stem, measuring the length and stopping at the location where optimal cuts were to be made. The model simulated a completely automated scanning and bucking operation with no human input. The simulation model was designed to simulate measurement errors that occur not only during the initial scanning phase, but also when the actual logs were being cut. In the cutting phase, only length errors were applied, as it was assumed that the machine uses the log lengths to cut the stem up into logs. The initial length, diameter, and the log length errors could be applied independently of each other or used together.

Figure 1 is an overview of the whole optimal bucking and simulation model. The simulation model takes the stem description stored in the stem database and develops a "stem piece". A "stem piece" is a model of a stem, in which the stem is broken into stages of a set length (0.1 m). For each stage, the large- and small-end underbark diameters are calculated as well as the quality and sweep code, the number of defects, and the stem volume of that stage. The model randomly generates length and diameter errors from user-supplied error distributions and applies them to each stage of the selected stem piece.

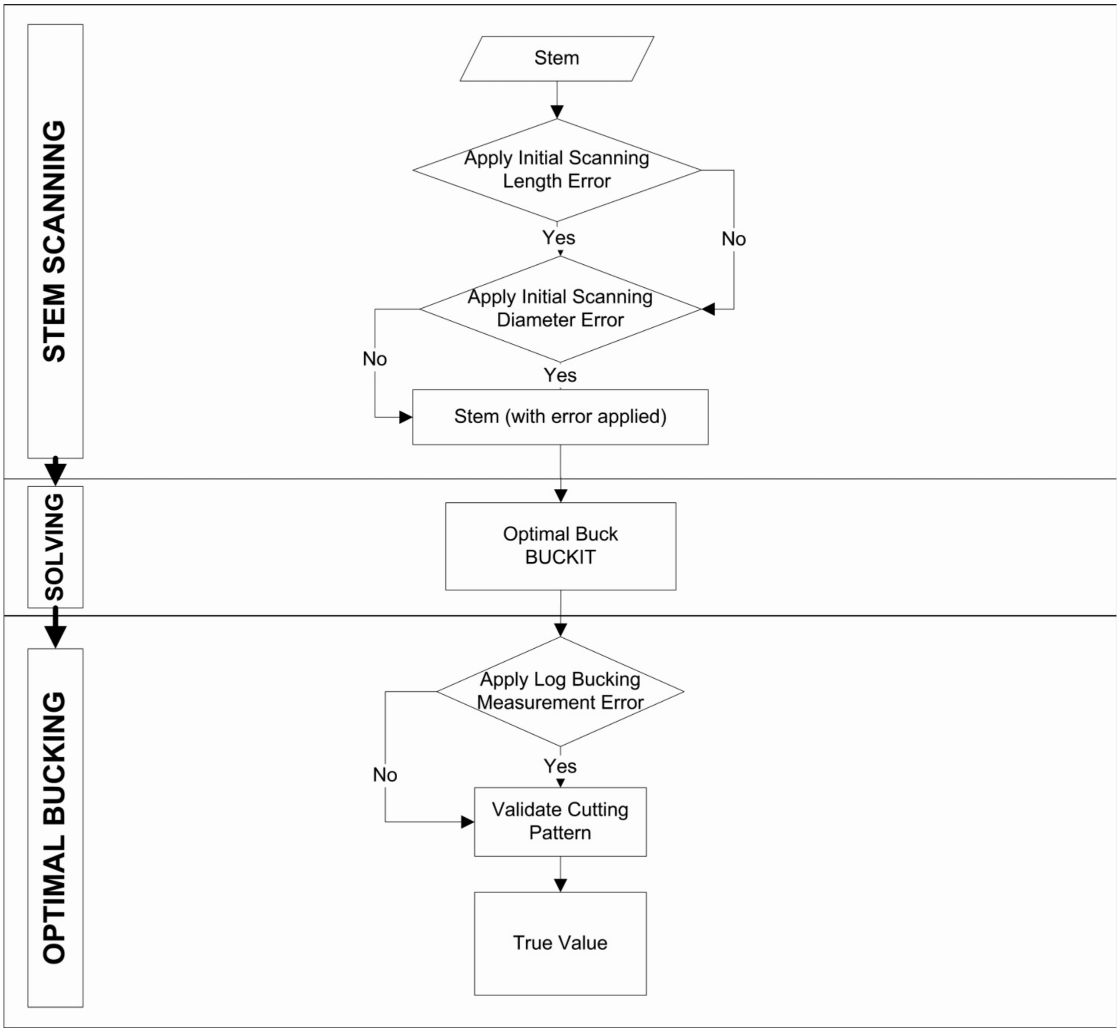
Applying the length error

When a length error is applied, it is applied randomly to every stage in the "stem piece". The model attempts to mimic how a harvester on-board computer and measuring system would measure a stem. For example if a harvester measuring system was undermeasuring every 0.1 m stage by 0.02 m, then the harvester on-board computer would make diameter, quality, and sweep measurements at 0.08 m intervals while still recording the stage length as 0.1 m. Consequently, a stem that should have had only 300 stages of 0.1 m each would have 375 stages on average, and to the computer's knowledge the stem will be 37.5 m long rather than being only 30 m. The length errors were collected for full log lengths; therefore, the mean and standard deviation of the length error distribution were adjusted using the following formulas (adapted from Freese 1967) so that they could be applied to each stage. The assumed average log length used in these equations was 4 m.

Table 4. A brief description of the log specifications used with each stem database.

Log specification	Stem database	No. of log grades	Length range (m)	Relative price range ($/m^3)
PP	Ponderosa pine	7	2.4–6.7	4.00–62.00
LP	Loblolly pine	4	3.0–6.1	2.50–35.00
RP	Radiata pine	20	1.0–12.1	31.20–153.40

Fig. 1. Overview of the optimal bucking and error simulation model.



$$\text{[1]}\qquad \mathrm{E}(\text{length\_error\_for\_stage}) = \frac{\bar{x}(\text{error})}{\dfrac{\bar{x}(\text{log\_length})}{\text{stage\_length}}}$$

$$\text{[2]}\qquad \mathrm{Var}(\text{length\_error\_for\_stage}) = \frac{\mathrm{Var}(\text{error})}{\dfrac{\bar{x}(\text{log\_length})}{\text{stage\_length}}}$$

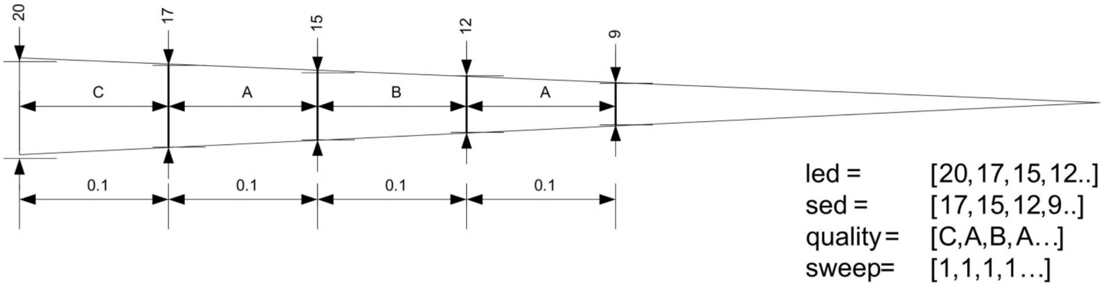
$$\text{[3]}\qquad \mathrm{SD} = \sqrt{\mathrm{Var}(\text{length\_error\_for\_stage})}$$

The simulation model, for a given “stem piece”, creates enough randomly generated stage lengths (i.e., 0.1 + ε, where $\varepsilon = \mathrm{N}(\mu, \sigma^2)$) so that their cumulative total is equal to the total length of the original stem. The polar method, as described by Law and Kelton (1991), was used to generate random numbers from a normal distribution with a mean of μ and variance of σ^2 based on the data collected for each machine. A new “stem piece” was then created with enough elements to account for the error-adjusted length. The next step was to recalculate each stages’ small- and large-end diameter, quality and sweep code, and volume from the original stem database data using the stage lengths (0.1 + ε).

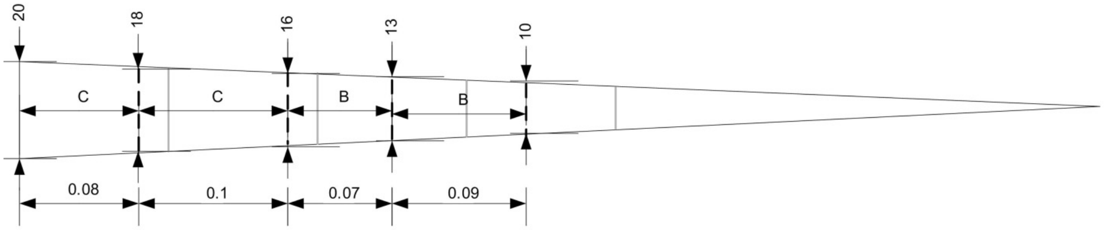
Figure 2 gives a simplified example of how the addition of errors affects the stem description used by the optimal bucking computer. It shows only the first four diameter and quality measurements that have been made on the stem.

In this example, the measurements made to describe the stem are supposed to be made at 0.1 m intervals (stage length). The first stem (A) is the true stem as it would appear if the machine were making perfectly accurate measure-

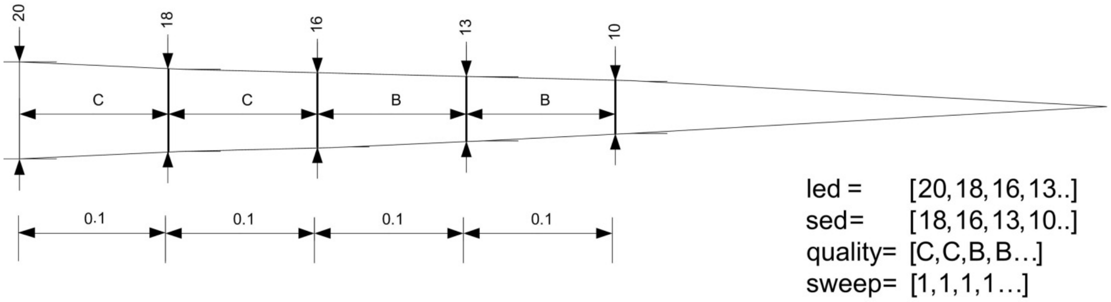
Fig. 2. An example of how length measurement error is applied to a stem. led, large-end diameter; sed, small-end diameter.



(A) The true shape of the stem



(B) The actual measured shape of the stem



(C) The shape of the stem used in the optimal bucking computer

ments. The second stem (B) is the actual measurements that are made assuming that the system is undermeasuring the stage length. The last stem (C) is the stem description that would be used by the optimal bucking algorithm. Stem A and stem C are quite different in terms of the stage large- and small-end diameters and quality code. The quality and sweep codes change because the quality or sweep code applied to a stem is the lowest code that exists in the length of the stem that the stage covers. Due to the changes in the large- and small-end diamaters, the stage volume will also change. These changes will have an effect on the optimal bucking solution produced.

Applying the diameter error

Once the length error has been added to the stem description the diameter error can be added (Fig. 3). This is done by adding or subtracting a randomly generated diameter error term. The diameter errors were generated in the same manner as the length errors but from a different normal distribution. If the error-adjusted diameter is less than zero, that is, it has a negative diameter, then the diameter of that stage is changed so that it is zero. Once the diameters are adjusted for error the stage volumes are recalculated.

Optimal bucking solution generation

The two “stem pieces”, true and error adjusted, are then optimally bucked with the BUCKIT optimal algorithm. BUCKIT uses a similar dynamic programming algorithm to that found in AVIS (Geerts and Twaddle 1984) and was developed by the senior author.

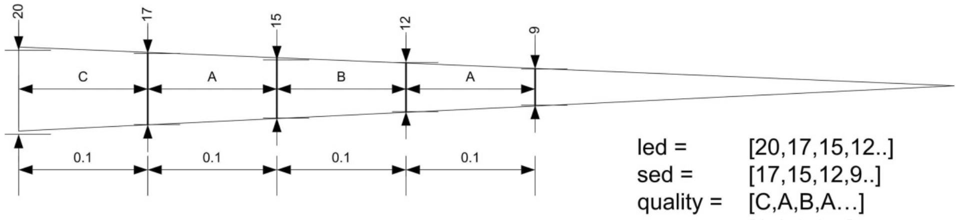
Processing the stem using the bucking solution

The next step in the stem processing simulation after the optimal solution has been generated is to cut the logs as specified in the optimal solution. This requires the processor to measure the length of each log, starting most probably at the large end of the stem and making cuts at the appropriate lengths. The model can also apply a length error to this part of the simulation. It does this by taking the log lengths from the optimal bucking solution and adding a randomly generated length error.

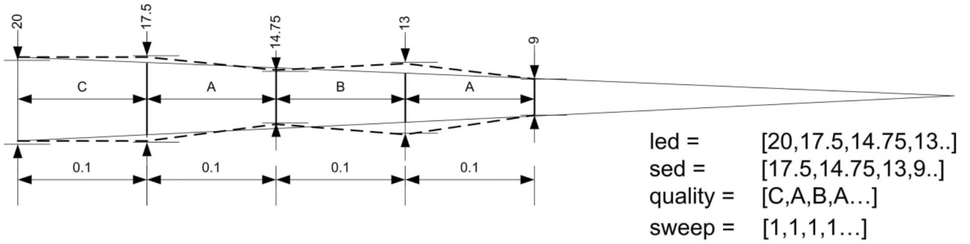
Calculating value loss

The true value of the logs cut from each stem must be determined to calculate the value loss associated with any mechanical processor measurement errors. In a real operation, logs that do not meet specification, after being scaled at ei-

Fig. 3. An example of how diameter measurement error is applied to a stem. led, large-end diameter; sed, small-end diameter.



(A) The true shape of the stem.



(B) The actual measured shape of the stem (with diameter error applied).

ther the logging site or mill, will either have to be cut shorter to meet the desired specification or be downgraded to a lower value product.

To mimic this quality-control procedure, each log cut by the bucking simulation model was checked against the true stem measurements. If it was found that the log would not meet its intended specifications, it would either be shortened or downgraded to the next highest value log product. The volume and value of the recut or newly allocated log product would then be recalculated. The total value of the stem would then be reduced to reflect this change.

Many companies have a tolerance of ±5 cm around their length measurements and ±1 cm tolerance around the small- and large-end diameter measurements. The simulation model has a ±5 cm tolerance for logs being out of specification for length, but a zero tolerance for diameter measurements. Allowing a nonzero diameter tolerance on the small- and large-end diameter measurements would have generated total stem values that were greater than those obtained from the optimal solution based on error-free diameter measurements.

The simulation model was run on the stem databases listed in Table 3 with

(1) The error distributions measured in the field to determine the value loss associated with each operation. Analysis of variance was used to determine the level to which the length, diameter, and bucking errors interacted with each other. The experiment was designed as a 2 × 2 × 2 factorial experiment, where the experimental unit was a tree and the response variable was the average value recovery from the 10 simulations.

(2) The simulation model was also run on a range of error distributions with different mean error rates and standard deviations. The results from these simulations were used to produce production surfaces of value recovery. The error distributions collected in the field from the harvesters were used to give guidance in determining the range of the error distribution that needed to be simulated. Table 5 lists the ranges of simulated error distributions.

Table 5. Range of error distributions simulated.

	Means	SD
Length stage error (m)	–0.002 to 0.002	0 to 0.09
Diameter error (cm)	–1.2 to 1.2	0 to 6
Bucking error (m)	–0.08 to 0.08	0 to 0.6

Note: SD, standard deviation.

Owing to the stochastic nature of this model, a pilot study was carried out and the simple sample number formula ($n = t^2s^2/e^2$) was used to calculate the number of replicates required for a 95% confidence level and a 10% margin of error. It was calculated that 10 replicates would be required for this confidence level and margin of error.

For each of the six studies the simulation model was run 10 times with eight different combinations of the three error types: length measuring error (L) at the time of scanning the stem, diameter measuring error (D) at the time of scanning the stem, and length measuring error at the time of bucking (B) the stem into logs. The total value of the logs from the stems contained in each of the databases was added up and averaged over the 10 simulations. For each error simulation type the total value was divided by the optimal value to give a percent value of recovery.

Results

Figures 4, 5, and 6 show the results of the simulations using the error distributions given in Table 2. The studies were subdivided into different graphs by species. The asterisk at the top of the bars indicates that the effect is significant at a 95% confidence level.

Of the three measurement errors, diameter and bucking errors result in the biggest value losses. Value loss due to diameter error is relatively easy to understand; it is greatest when the diameter is under measured, as in studies A–E. Only in study F was the value loss from length error during the stem scanning greater than the loss due to diameter error.

More difficult to understand is the large value loss due to bucking length (B) error, especially when compared to the

Fig. 4. Simulated value recovery based on errors found in studies A and B in ponderosa pine.

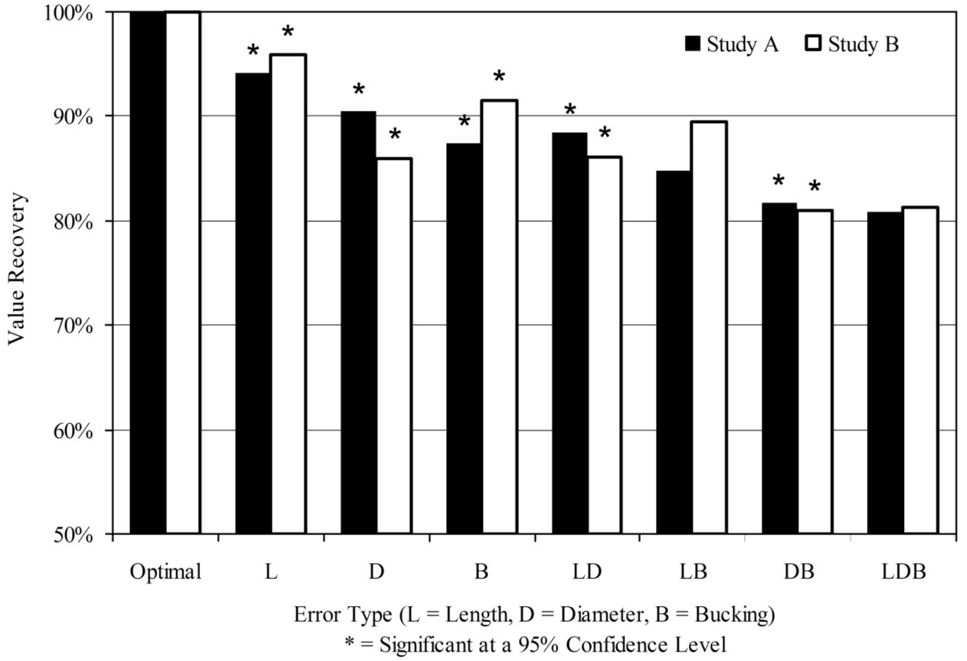
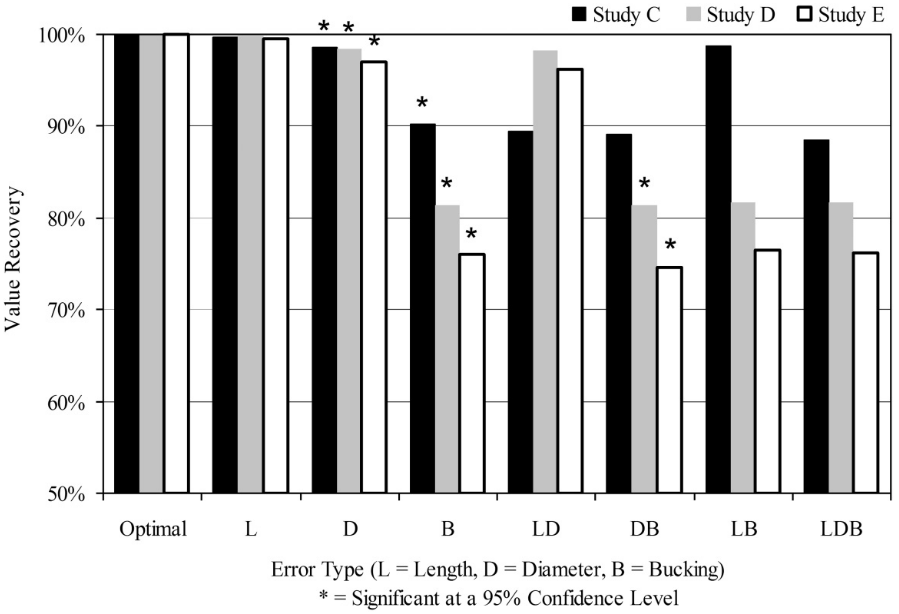


Fig. 5. Simulated value recovery based on the errors found in studies C, D, and E in loblolly pine.



value loss due to scanning length measurement (L) error, given that the same error distributions were used in both sets of simulations. For example, in study F (radiata pine), the value loss due to length measurement errors (L) during log scanning was 5% compared to 13% from length measurement errors (B) during the bucking process. The easiest way to explain this is to use a simplified example, as illustrated in Tables 6–8. This example has three log types: pruned sawlogs, which have to be 5 m long with a minimum small-end diameter of 25 cm; unpruned sawlogs, which have an allowable length range of 3.5–4.5 m in 0.1 m steps with a minimum small-end diameter of 15 cm; and pulplogs, which have a minimum length of 1 m and a minimum small-end diameter of 5 cm.

Tables 6–8 are laid out in the same format. The second column in the tables gives the scanning length error, the third column is the solution produced by the dynamic programming bucking algorithm. The next two columns give the bucking length error and the cumulative length at which the cuts are to be made along the stem. The final column gives the actual feasible logs produced; in some cases these logs have to be rebucked to meet the log specifications.

The solution, without any measurement errors added, is given in Table 6. The pruned log is limited by its length and

Fig. 6. Simulated value recovery based on the errors found in study F in radiata pine.

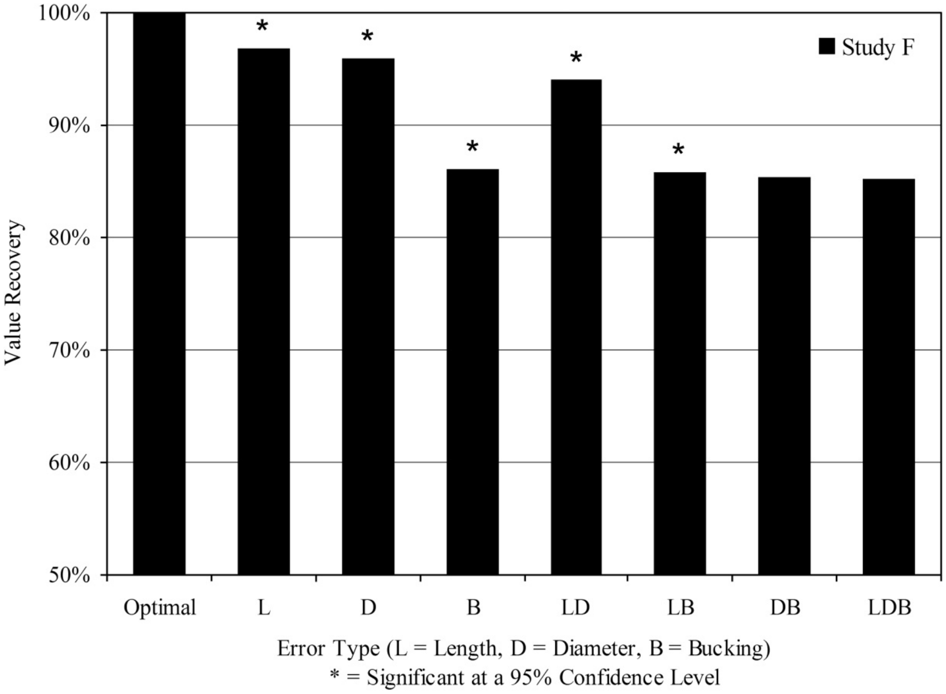


Table 6. The optimal bucking scenario of a simple stem without any errors being added.

	Scanning →	Solve dynamic programming algorithm →				Cutting logs →		Regrading to feasible solution				
		Optimal solution from the bucker						Regrade solution of actual logs				
Scenario	Length error per stage (L)	Product	Length (stages)	Length (m)	SED (cm)	Bucking error per log (B) (m)	Actual cuts made (no. of stages)	Product	Length (stages)	Length (m)	SED (cm)	Value ($)
Optimal	+0.00	Pruned	50	5.0	33	+0.00	50	Pruned	50	5.0	33	78.55
		Sawlog	40	4.0	15		90	Sawlog	40	4.0	15	14.21
		Pulp	20	2.0	6		110	Pulp	20	2.0	6	0.92
								Total	110	11		93.68

Note: SED, small-end diameter.

the sawlog is constrained by its minimum small-end diameter restriction. The optimal value for this stem is $93.68 (all monetary values are in US dollars).

Table 7 gives the solutions for when a positive length error, a bucking error, or combination of both errors are added to the stage length. When a positive error is added to the stage length during the scanning of the stem, the 15 cm small-end diameter restriction is reached in fewer stages than in the error free solution. This means that the sawlog was cut 0.1 m shorter than in the optimal solution and so reduced the value of the stem by $0.03. However, when the same effective error is added as a length bucking error, meaning that every log cut will be 0.1 m longer than in the optimal solution, the value of the stem drops by $0.90. This is due to overcutting the length of the pruned log at 5.1 m, which in turn causes a sawlog's small-end diameter to be less than the minimum small-end diameter constraint. Rebucking of these logs produced 0.3 m of waste. When both errors were added the value dropped less than when just the bucking errors were added alone. This is due to the errors having a compensating effect on each other.

The results (Table 8) of the negative errors being added are quite different from those of the positive error results. When the negative stage length errors are added, there is no drop in value from the optimal solution, as the exact same logs are cut. However, when the negative bucking error is added, the value drops by over $20. This is caused by the 5 m pruned log being cut 0.1 m short, meaning that it needed to be downgraded to a 4.5 m sawlog. When both negative errors are added the errors do not have the same compensating effect found for the positive errors.

Downgrading of value, in terms of percentage of logs not meeting specification, can be found in Table 9. The major reason for downgrading depends on the type of errors that are applied. In the case when all error types are applied (as in Table 9), logs not meeting the length specifications are the main cause for downgrading logs.

Validation of the model

Validation is the process of testing a model to see that it is a valid representation of reality. The validity can often be assumed if the model is able to accurately mimic reality

Table 7. The optimal bucking of a simple stem with positive length (L) and bucking (B) errors added.

Scanning →	Solve dynamic programming algorithm →				Cutting logs →		Regrading to feasible solution				
	Optimal solution from the bucker						Regrade solution of Actual Logs				
Length error per stage (L) (m)	Product	Length (stages)	Length (m)	SED (cm)	Bucking error per log (B) (m)	Actual cuts made (no. of stages)	Product	Length (stages)	Length (m)	SED (cm)	Value ($)
Scenario L											
+0.002	Pruned	50	5.1	32.95	+0.00	50	Pruned	50	5.0	33	78.55
	Sawlog	39	4.0	15.37		89	Sawlog	39	3.9	15.45	14.10
	Pulp	21	2.1	6		110	Pulp	2.1	2.1	6	1.00
							Total	91.1	11		93.65
Scenario B											
+0.00	Pruned	50	5.0	33	+0.1	51	Pruned	50	5.0	33	78.55
	Sawlog	40	4.0	15		92	Waste	1	0.1	32.5	0.00
	Pulp	20	2.0	6		110	Sawlog	39	3.9	15	13.58
							Waste	2	0.2	14.1	0.00
							Pulp	18	1.8	6	0.75
							Total	110	11		92.88
Scenario LB											
+0.002	Pruned	50	5.1	32.95	+0.1	51	Pruned	50	5.0	33	78.55
	Sawlog	39	4.0	15.37		90	Waste	1	0.1	32.55	0
	Pulp	21	2.1	6		110	Sawlog	39	3.9	15	13.58
							Waste	1	0.1	14.55	0
							Pulp	19	1.9	6	0.83
							Total	110	11		92.96

Note: SED, small-end diameter.

Table 8. The optimal bucking of a simple stem with negative length (L) and bucking (B) errors added.

Scanning →	Solve dynamic programming algorithm →				Cutting logs →		Regrading to feasible solution				
	Optimal solution from the bucker						Regrade solution of actual logs				
Length error per stage (L) (m)	Product	Length (stages)	Length (m)	SED (cm)	Bucking error per log (B) (m)	Actual cuts made (stages)	Product	Length (stages)	Length (m)	SED (cm)	Value ($)
Scenario L											
–0.002	Pruned	50	4.9	33.04	+0.00	50	Pruned	50	5.0	33	78.55
	Sawlog	40	3.9	15.08		40	Sawlog	40	4.0	15	14.21
	Pulp	21	2.1	6		110	Pulp	20	2.0	6	0.92
							Total	110	11.0		93.68
Scenario B											
+0.00	Pruned	50	5.0	33	–0.1	49	Sawlog	45	4.5	35.25	55.48
	Sawlog	40	4.0	15			Waste	4	0.4	33.45	0.00
	Pulp	20	2.0	6		88	Sawlog	39	3.9	15.9	14.58
						107	Pulp	19	1.9	7.35	1.05
						110	Waste	3	0.3	6	0.00
							Total	110	11		71.11
Scenario LB											
–0.002	Pruned	50	4.9	33.04	–0.1	49	Sawlog	45	4.5	35.25	78.55
	Sawlog	40	3.9	15.08			Waste	4	0.4	33.45	0.00
	Pulp	21	2.1	6		89	Sawlog	39	3.9	15.9	13.58
						110	Pulp	19	1.9	6.9	0.83
							Waste	3	0.3		
							Total	110	11.0	6	92.96

Note: SED, small-end diameter.

(Daellenbach 1995). The best way to validate a model is to compare the model's results against the actual results from the same situation. Both sets of results should be obtained independently of each other.

Two of the studies (C and F) have actual value recovery percentages determined from real value recovery studies that were used to validate the model. One important difference between the actual value recovery values and the simulated ones was that the simulated results assumed that each stem was fully measured before the solution was determined. This was not the case for the actual machines; when the operator was processing the stem the cutting solution was generated as the stem was measured. Comparing the actual value recovery with that determined by the simulations gives an indication of how well the model is modeling reality. For study C, both the actual and simulated value recoveries were 90% (Conradie 2003) when all errors were simulated. For study F, the simulated value recovery was 86% compared to 79% for the actual value recovery study (Murphy et al. 2005). These results indicate that the simulation model is reasonably accurate although, given that the model is simulating neither the losses due to quality and sweep measurement errors nor those due to lack of use of optimization software, the differences between measured and simulated operations are much lower than would be expected. It is postulated that this could be due to an overestimate of the error distribution used in the simulation and that experienced machine operators are able to make adjustments to the cutting pattern that reduce the effects of the measurement error. The model could not simulate adjustments by experienced operators.

It could be expected that the difference between actual and simulated recovery in study C would be less than that in study F, as study C had much simpler tree quality descriptions and cutting patterns than study F. The machine in study C also used computer-assisted bucking. These features of study C would mean that there would be no value losses associated with quality errors, sweep measurement errors, and lack of computer-assisted bucking; hence the "total value loss" would equal the value loss caused by length and diameter measurement errors.

The results from the analysis of variance showed that the value losses from the measurement error are not additive. The three-factor factorial design tested the following linear model, which included both the main effects (L, D, and B) and interaction effects (LD, DB, LB, and LDB):

$$[4] \quad \text{Value loss (measurement error)} = L + D + B + LD + LB + DB + LDB + \varepsilon$$

The asterisk above the bar in Figs. 4, 5, and 6 show that there is not one model to describe value loss due to measurement error for all the studies. The results also show that the three types of error do interact, many times producing a value loss much less than would be expected from a simple additive model. In some cases the interaction between two of the error types gives a value loss that is less than one of the individual error types.

Table 9. Sources of value downgrading for all log grades (percentage of total number of logs cut).

Study	Length (%)	Diameter (%)	Quality (%)	Any combination of length, diameter, and quality (%)
A	16	12	0	21
B	12	12	0	21
C	42	18	0	4
D	37	3	0	7
E	39	14	0	14
F	26	6	1	29

Response surfaces for different levels of error

Figure 7 contains a series of graphs that show the effects of different levels of accuracy and precision of length and diameter measurements on percentage value recovery. The results show that increasing the precision is of greater importance than increasing accuracy for the distributions that were simulated. The simulation results also indicate that overmeasuring either length or diameter produces lower value losses than undermeasuring length alone. This is simply because overmeasured logs can generally be rebucked without having to be downgraded to a lower value product. Undermeasured logs, however, often have to be rebucked and downgraded, meaning that significant value is sometimes lost. The interesting dip in results for the zero standard deviation in the radiata pine length and bucking simulations is due to rounding the bucking error, up and down to the nearest stage. This effect is particularly apparent in the radiata pine study, as a number of the grades had only one allowable length.

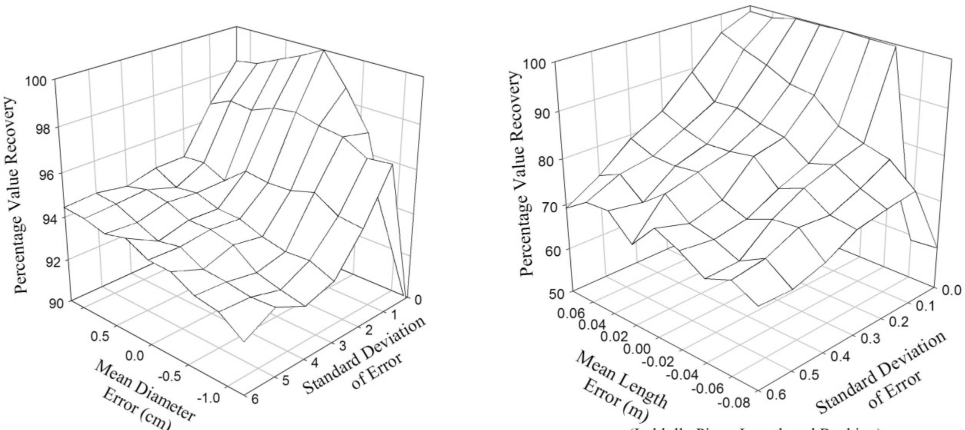
The effects on the response surfaces of relative price differences between log grades were not evaluated in this study but deserve future research efforts.

Discussion

The average value loss for the six studies when all three error types (L, D, B) were applied was 18%, which is similar to the average value loss of 21% from value recovery studies on mechanical harvesters from around the world (Murphy 2003). Given that many harvesters and processors do not fully measure the stem before bucking, a more realistic comparison is with the average value loss when only the length and diameter errors (L, D) are included; this value loss is 7%. The difference between 21% and 7% could easily be attributed to incorrectly assessing sweep and quality and the lack of optimization systems.

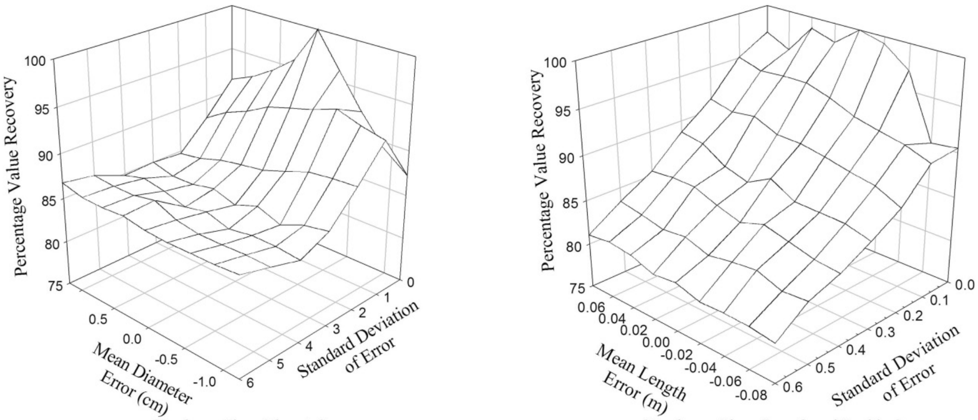
In the five studies where the diameters were on average being underestimated, the losses due to diameter error were much greater than those due to length measurement error during stem scanning. This is consistent with a study by Cossens (1991) on a Hahn harvester in New Zealand, where he reported that conservative diameter measurements were the main cause for the 9.7% value loss, given that 83% of the length measurements were within a 5 cm tolerance. This is also consistent with the work of Chiorescu and Gronlund (2001), who looked at the effect of stem length and diameter measurement accuracy of mechanical harvesters on the value

Fig. 7. The effects of different levels of accuracy and precision of length and diameter measurements on percent value of recovery.



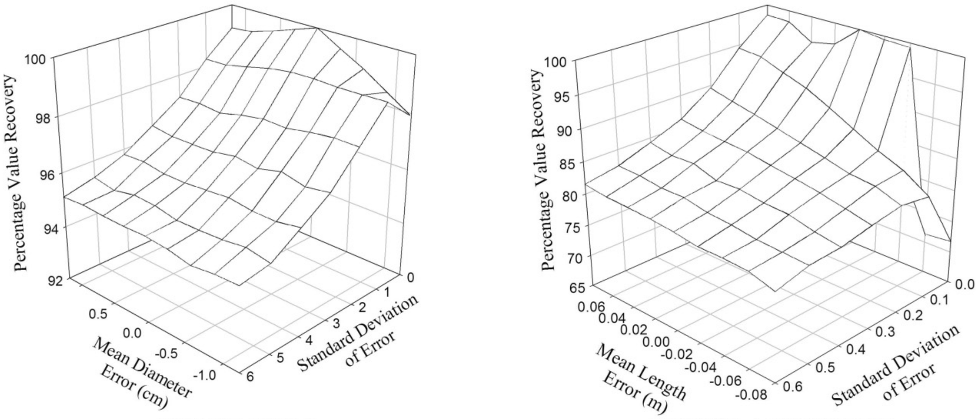
(Loblolly Pine - Diameter)

(Loblolly Pine - Length and Bucking)



(Ponderosa Pine - Diameter)

(Ponderosa Pine - Length and Bucking)



(Radiata Pine - Diameter)

(Radiata Pine - Length and Bucking)

obtained from optimal bucking, sawing, cross-cutting, and board-grading procedures at the saw mill. They found that the harvester's performances on measuring length and diameter are both important, with the accuracy of the diameter measurement being of greater importance.

The most surprising result from the simulation in this report, which has not been reported in any of the other studies on harvester measurement accuracy, was the large value loss that occurs when a length measurement error was applied at the time of bucking. Length measurement errors during the bucking process had a significant effect on value recovery in all six studies. In study F, over 20% of the value was lost, which is significantly greater than the 1% value loss that Sondell et al. (2002) estimated in Norway spruce. This may be because a partial scan system is most often used. In the Sondell et al. (2002) study, all the machines were getting a minimum of 69% of the logs within 5 cm of the correct length, which equates to a standard deviation for length error of 0.05 m. The diameter accuracy for their study was measured in percentage of trees within 4 mm. The worstperforming machine after calibration achieved a diameter accuracy of 62.2%, which means that the maximum standard deviation for diameter error was around 4.5 mm. The level of accuracy reported in the Sondell et al. (2002) study was considerably higher than that found for the machines studied in this paper.

Although not simulated in this study, mismeasured logs can have a significant impact on the revenue obtained by lumber producers or other solid wood processors. Andersson and Dyson (2002) calculated that, when a harvester was manufacturing 20% of its logs below the minimum length specification, a 2.5% reduction in lumber yield and a 1.5% drop in mill productivity would follow. Another study, using a sawing simulator, showed that measurement error distributions with standard deviations for diameter and length of 6 mm and 4 cm, respectively, could produce between 18% and 37% of boards that were off-grade (Chiorescu and Gronlund 2001).

All measurement systems are likely to be subject to measurement error. The diameter and length measurements made by harvesters are made under very difficult mechanical and environmental conditions. One of the easiest ways of reducing measurement error is to have a regular checking, calibration, and maintenance program. A good calibration program such as suggested by Makkonen (2001) should eliminate much of the bias in the error distributions. A number of the new harvesting heads now come with calipers to calibrate the harvesters' measurement system.

One procedure that is sometimes used for reducing the cost of length measurement errors is to deliberately buck over length to avoid missing trim allowances. However, while bucking under length can result in high value losses, deliberately bucking over length will also lead to value losses (Fig. 7). The problem is that log lengths are usually rounded down to the nearest log length specified in the log grades. The buyer will only pay based on that rounded-down volume. There is also always the potential that by cutting logs longer than the specification requires, a potential log at the top of the tree will be lost.

Training and communication are extremely important tools in reducing error. Operators need to understand the measuring system they are using and how important accurate log measurements are to the profitability of an operation. As Andersson and Dyson (2002) suggest, log specifications must be clearly understood by operators, machine owners, and company staff.

The current measuring sensors for measuring stem length and diameter on most harvesting heads are relatively simple. Large increases in accuracy and precision can be achieved by redesigning the measuring equipment. Two New Zealand studies carried out 12 months apart showed that by redesigning the length measuring systems the percentage of logs within 5 cm of the target length rose on average by over 10% (Evanson and McConchie 1996). There have been a number of attempts at using more advanced sensing technologies such as laser and digital cameras. In the mid-1990s a Swedish project investigated the development of a touch-free measurement system for diameter. They estimated that the new system could produce 90% of all logs within a 4 mm range and lead to potential increases in revenue between US$5000 and US$85 000 per single-grip harvester per year. The estimated purchase cost of the fully developed system was estimated to be about US$20 000 (Löfgren and Wilhelmsson 1998).

In some high-value stands the "high-tech" solution may not be the best option. In some stands, manual log making may be the most profitable option, as manual log making has been found to be more accurate on length and diameter measurements than mechanical harvesting systems (Cossens 1989). In low-value stands with simple cutting patterns, maintaining good maintenance and calibration systems may be all that could be justified.

Conclusions

The trend towards mechanical harvesting of the world's production harvest has been driven by desires to improve productivity and costs or to resolve labor-related issues, for example, worker safety or labor shortages. With mechanization comes the use of state-of-the-art communication and measurement technologies and powerful on-board computers, giving this system the potential to increase value recovery at the time of bucking.

Like all measuring systems, these are subject to measurement errors. The simulation model described in this paper showed that the cost of measurement errors, in terms of the percent value of loss, for these six harvesters could be significant, ranging from 3% to 23% depending on the type of error, the level of error, and the species. It was found that value loss seemed to increase more rapidly with decreasing precision compared to decreasing accuracy. Based on the losses reported in this paper, operators, machine owners, forest owners, and researchers need to investigate different methods of reducing the level of error in stem length and diameter measurements. There are a number of different methods available to the industry, both procedural and technological. Choosing which method best suits a particular operation, however, requires a detailed knowledge of the causes and implications of the errors. The amount of investment that can be made in any particular method depends not only on the error rate of the machine, but also on the value of the forest in which the machine is working.

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