The Effect of Two Bucking Methods on Scots Pine Lumber Quality

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Modern harvesters are equipped with measurement and bucking optimization systems able not only to continuously measure the length and diameter of the stem but also to predict the profile of the unknown part of a stem and to calculate the optimal cross-cutting points for the whole stem. So far, tree-bucking optimization in the Nordic countries has been efficiently applied only with spruce because the quality of pine and birch varies much more both within a stem and between stems. Since limitations in the measuring equipment mean that the presence and position of grade limits as well as additional defects in the stem will normally have to be detected and estimated manually. Consequently, optimization works inefficiently because the harvester operator is continuously forced to disregard the cutting suggestions supplied by the harvester's automatic system. This paper presents the outcome of research intended to define how change from the current quality bucking principle to automatic bucking affects lumber quality. The study is based on field experiments and test sawing data on 100 Scots pine (*Pinus sylvestris*) stems from southwestern Finland in 2001. Automatic bucking does not markedly lower the amount of good-quality lumber compared to quality bucking. Since automatic bucking inevitably leads to log distribution that matches the length requirements of customers better, it may be regarded as appropriate for these harvesting conditions.

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1 Introduction

Tree-bucking optimization may be regarded as one of the classic research problems in the field of forest engineering. Several bucking optimization models capable of maximizing the value of total log output from an individual tree (Pnevmaticos and Mann 1972, Näsberg 1985, Sessions 1988), a stand (Eng et al. 1986, Mendoza and Bare 1986, Sessions et al. 1989, Pickens et al. 1997) or a group of stands (Kivinen 2003) have been developed. Modern single-grip harvesters employ the bucking-to-value and bucking-to-demand technology to tailor this process for the sawmill's optimal demand distribution. Modern harvesters are equipped with information systems able not only to continuously measure the length and diameter of the stem but also to predict the profile of the unknown part of the stem. In the normal implementation, the harvester head first feeds the tree through the measuring and delimbing device for a given length, after which the system predicts the profile of the rest of the stem and calculates the optimal cross-cutting points for the whole stem. If the difference between the real and predicted diameters exceeds the maximum allowed, a new prediction and optimization is performed. The prediction of the taper is usually based on a fixed number of previously cut stems of the same species and the data gathered from the current stem (Liski and Nummi 1995). The optimization procedures have proved to be efficient (Kivinen and Uusitalo 2002) and there is now growing interest in applying these optimization tools in the wood procurement of customer-oriented sawmills. A thorough presentation of bucking procedures appears in Uusitalo (2002).

Typically, the stem needs to be cut into two or more wood assortments or quality grades, requiring specific price and demand matrices for each assortment. The base price and the variation in the base price for each price matrix need to be set so that no overlap between different matrices can occur. The optimization works efficiently with several wood assortments, providing separation of the wood assortments is based only on diameter and length values registered by the measuring devices of the harvester.

Harvester drivers can apply bucking optimization tools in many different ways. If there are no significant quality differences within the stem, the bucking can be carried out almost completely automatically. The cross-cutting points are derived by the optimization system and are changed by the driver only occasionally. This principle is hereafter referred to as *automatic bucking*.

Most bucking optimization systems are equipped with a special function that enables the driver to record the starting and finishing points of particular quality zones. The optimization system can then take these quality zones into account in calculating the optimal bucking. This principle, which has been quite popular in Sweden but has not been applied much in other countries, may be referred to as *automatic quality bucking*. Its weakness is that it slows down cross-cutting. Moreover, we cannot be sure how the outer quality zones relate to the inner quality.

In many cases bucking is carried out manually. Bucking may be controlled easily by selecting one of the pre-selected log lengths (hot keys). When the harvester head has stopped at the selected point, the log length can be easily shifted one or two modules forward or backward by a hot key function. In this kind of bucking the quality of the stem is taken into account while processing and bucking is not necessarily managed according to price or demand matrices. This bucking principle is hereafter referred to as *unassisted quality bucking*.

Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) are the only commercially valuable conifers in Finland. The quality of Norway spruce does not vary much, the value differences between the lumber quality grades being quite small, while the value of pine lumber is heavily dependent on quality.

Scots pine is generally regarded as dividing into three quality zones; the slightly knotty or knotless butt log zone, the dead knot zone in the middle of the stem and the sound knot zone in the upper parts of the stem (Kärkkäinen 1980a, 1986, Björklund 1997, Björklund and Petterson 1999, Moberg 2000). The length of these quality zones varies according to growing conditions, genetic factors and tree age (Kellomäki and Tuimala 1981, Kärkkäinen and Uusvaara 1982, Kellomäki and Väisänen 1986, Björklund and Petterson 1999). Unfortunately, outer quality indicators do not necessarily correlate with inner quality (Kärkkäinen 1980a, 1986, Uusitalo 1994, 1997). By outer quality we understand the branchiness of the living tree and by inner quality the size, number and character of the knots in lumber sawn from the logs of that tree (i.e., whether they are dead, living or rotten). According to the current quality bucking principle practiced in Finland the length of the slightly knotty butt of the stem should be maximized, which is generally done by examining the branchiness of the stem. The general rule of thumb is that the butt log should be cut before the first dead branch. The dead branch height (the distance from stump height to the first dead branch) has been seen to correlate with the lumber quality of the butt logs (Heiskanen 1954, Kärkkäinen 1980a, Uusitalo 1997). The correlation between the dead branch height and the quality of the butt logs can be explained by the diameter growth of the branches at an early age. If the diameters of branches in the butt become large, natural pruning takes longer with the consequence of low dead branch height and poor stem quality. In addition to intra-tree variation, knottiness has some variation between the stems (within-stand variation) and stands (between-stand variation) (Kärkkäinen 1980a, Uusitalo 1997). Earlier investigations indicate that quite a large part of the variation of lumber grades between the stands can be explained by the variation in the dead branch height. Although the connection between the dead branch height and lumber quality is clear, considerable within-stand variation that cannot be explained remains (Kärkkäinen 1980a, Uusitalo 1994, 1997).

Until now, automatic bucking optimization has only been applied efficiently with spruce, since disregarding quality zones in bucking pine has been regarded as causing economic loss. Moreover, automatic optimization has been considered inefficient, since the harvester operator is continuously obliged to disregard the cutting suggestions supplied by the harvester's automatic system. According to sawmill managers, the significance of delivering the correct lumber lengths to customers is becoming increasingly important. It has been demonstrated that automatic bucking inevitably leads to length distribution that matches the customer needs better (Kivinen and Uusitalo 2002). Since we had no precise understanding of the significance of lumber lengths for lumber quality with Scots pine, we decided to test it in practice. This paper presents the outcome of research intended to show how change from the current quality bucking principle to automatic bucking affects the lumber quality of Scots pine.

2 Material and Methods

2.1 Data

Data collection was carried out in summer 2001 in close co-operation with the Metsäliitto company that had bought the logging rights to the study stands from the local private forest owners. The study material (Table 1) comprised 6 stands from southwestern Finland, situated close to Rauma (stands 1–3) and Turku (4–6). All stands were typical, privately owned, blueberry type (MT) or lingonberry type (VT) forest aged roughly 90–120 years. Stand 6 was mixed spruce-pine forest and stand 3 mixed pine-birch forest, the remainder being pure pine.

Table 1. Mean characteristics of the study stands. Mean values calculated from the sample trees.

No	Area ha	Volume m^3/ha	Mean dbh cm	Mean h m	Mean dead branch height m	No of sample trees
1	3.4	250	27.4	22.0	4.8	20
2	3.0	120	29.6	21.1	4.7	20
3	3.0	290	31.6	23.6	7.1	10
4	3.0	160	26.7	19.5	4.7	20
5	0.4	190	27.4	20.0	3.9	10
6	4.2	170	28.1	19.2	4.9	20

Table 2. Diameter class-specific cant and re-saw sawing patterns used in the study.

Diameter class, mm	Cant sawing pattern, mm	Re-saw sawing pattern, mm
150–159	100	19-50-50-(19)
160–179	100	19-50-50-19
180–199	150	25-50-50-25
200–219	150	25-50-50-25
220–239	175	25-50-50-25
240–259	175	25-25-50-50-25-25
260–	200	25-25-50-50-50-25-25

The study stands were first inventoried by a pre-harvest measurement procedure suggested by Uusitalo (1997), and a theoretical diameter distribution of the trees was then created by the EMO software (Uusitalo and Kivinen 2000). Ten or 20 sample trees were selected from each stand, using two different principles. Half of the sample trees were chosen systematically from all mature pines and the other half selectively from those trees with a dead branch height between 3 and 4 meters. It was assumed that it is very difficult to find the right bucking principle for the lower quality trees (dead branch height 3…4 meters).

The sample trees were numbered and marked with colored ribbons to allow easy detection during harvesting. The sample trees were measured for dbh, tree height, dead branch height and crown height while still standing. The study stands were harvested with two modern Ponsse single-grip harvesters owned by small contractors, stands 1–3 by one machine and operator and stands 4–6 by the other. Both machines had a similar operating system. The non-sample trees were harvested first and the sample trees with the colored ribbons last. The trees were bucked applying the unassisted quality bucking principle (see earlier section). The harvester operators primarily decided the crosscutting point by quality, although they were aware of desirable and acceptable log lengths (Table 3). The demand for certain lengths and diameter-length combinations were relatively constant in that area and the harvester operators were accustomed to searching for those lengths. After felling and bucking, the logs of the sample trees were marked carefully, indicating the location of the log (i.e., stand, stem and location in the stem).

2.2 Test Sawing

Test sawing was carried out by a small-scale circular saw at the North Karelian Polytechnic, Joensuu. Before test sawing, the taper of each log and stem (above the bark) was measured with calipers. The logs of each stem were arranged in the normal order from butt log to top log so that the taper of the whole stem could be measured at 50 cm intervals. In addition, the diameters of the large end and the small end of each log were measured. The diameter was measured twice at each measurement point; first in a random direction and then at 90 degrees from the first measurement. The mean of the two diameter measures was later used as the real value for the diameter at that point.

The logs were sawn according to normal cant sawing patterns (Table 2). During sawing the locations of sawn items were registered and marked with special code numbers. Altogether 272 logs were cut from 100 stems, 1366 sawn goods being produced from these. After sawing, the products were kiln-dried to 18% moisture content.

2.3 Simulation of Automatic Bucking

As already mentioned, the bucking was done according to the unassisted quality bucking principle. In order to compare the two major bucking principles, the automatic bucking was later simulated by OptiSimu (ver. 3.00) marking for a bucking simulator (Ponsse Oy 1999). OptiSimu simulates the PonsseOpti marking for bucking optimization employed by Ponsse harvesters. According to the Ponsse company, the PonsseOpti

Table 3. The sawmill demand matrix employed in the bucking simulation.

Top diameter, mm	Log length, cm 370	400	430	460	490	520	550
150	9	6	32	18	22	7	6
160	9	6	32	18	22	7	6
180	9	6	32	18	22	7	6
200	8	1	33	22	22	9	5
220	8	1	30	25	20	11	5
240	8	2	25	26	19	14	6
260	8	2	25	26	19	14	6
280	8	2	25	26	19	14	6
300	8	2	25	26	19	14	6
320	8	2	25	26	19	14	6
360	4	2	12	13	59	7	3
400					100		

bucking optimization follows the algorithm developed by Näsberg (1985, p. 57). The simulator also follows the StandforD standard which means that stem profiles (i.e., diameter measurements carried out at the log yard) need to be presented in the stm format (Forestry Research Institute of Sweden 1997) and price and demand matrices in the apt format.

Since the diameter values for each stem at the log yard were measured every 50 cm, they were interpolated for every 10 cm interval and were then converted into the stm format. The demand matrix used in simulations was the same as that in use at the local Finnforest sawmill in Kyrö in summer 2001 (Table 3). The demand for each diameter-length class was expressed by diameter class, which means that the sum of each row (diameter class) is 100. This is the most common procedure employed today since the distribution of diameter cannot be affected as much as the distribution of length.

The PonsseOpti simulator employs the adaptive price-list technology in bucking-to-order optimization, which means that the value of each log category in the value matrix is continuously adjusted according to the difference between the target proportion (demand matrix) and the real proportion for each log class. Since the price list is adjusted after each stem, it is difficult to determine what the "optimal" bucking alternative for each stem is. In order to get only one optimal bucking alternative for each stem, the price lists were optimized separately for each stand by the genetic algorithm developed by Kivinen (2004). This algorithm creates strings of value matrices, evaluates the soundness of each matrix, creates offspring matrices for the next generation and repeats this loop until the fitness value of the best solution is no longer increasing. The algorithm employs the same Näsberg algorithm (1985) as the PonsseOpti simulator. The optimal price matrices for each stand derived by Kivinen's algorithm appears in appendix A. The PonsseOpti simulator has special tracking procedures that list the simulated bucking stem by stem (start and end height of each log and diameter of stem at those cutting points).

2.4 Lumber Grading

Each sawn item was divided into 10 cm sections. The following measurements were made on each 10 cm section: number of dead knots and sound knots, the diameter of the largest dead and sound knots and the amount of wane. The characteristics were measured from the outside face and one edge of the sawn item. The knot measurement data for each 10 cm section of each sawn item was stored in the Excel format. Special formulas were created that calculated the most important quality criteria for each 10 cm section separately following the Nordic Lumber grading rules (Nordic Timber 1994). In this grading system sawn timber is divided into the main grades A, B, C and D. A is the highest main grade, which includes a falling proportion of sub-grades A1–A4 from the production, A1 being the highest. The grade is determined by the number, location, type and maximum permitted values of the wood characteristics. The basic grading principles are as follows:

- Each side of the piece shall be graded separately.
- The grade is decided on the basis of the outside face and both edges.
- The maximum values of the wood features of certain sawn good is determined by the worst one meter of length.
- The inside face may be one grade lower.

Only the battens of the logs (2 × 50 mm × 100 mm, 2 × 50 mm × 125 mm, 2 × 50 mm × 150 mm, 2 × 50 mm × 175 mm or 2 × 50 mm × 200 mm) were taken into account in the calculations. The battens of the logs of one stem were arranged in the normal order from the butt log to the top log so that they formed two continuous strings of battens that consisted of the 10 cm long quality sections from the butt to the top of the stem.

Although all important quality characteristics were registered, our calculations were restricted to the most crucial knot criteria of the grading system:

– Maximum diameter of a sound knot (on outside face and edge separately)
– Maximum diameter of a dead knot (on outside face and edge separately)
– Maximum diameter of an unsound (rotten) knot (on outside face and edge separately)
– Number or knot sum of sound knots per worst 1 m length (on outside face and edge separately)
– Number or knot sum of dead knots per worst 1 m length (on outside face and edge separately)
– Number or knot sum of unsound knots per worst 1 m length (on outside face and edge separately)

The knot sum refers to the compensation rule for the number of knots. If the knot size is smaller than the maximum knot size for the grade in question, a greater number of knots is permitted. The sum of knot sizes (number of knots × diameter) cannot, however, be exceeded for the corresponding types of knot. Size and type of knot were determined and calculated according to the Nordic Timber (1994) grading rules. In distinction to the original grading rules, barkringed knots were classified as dead since in most cases it was very difficult to determine whether the knot was barkringed or a dead knot. In addition, the gradings were based on measurements on the outside face and one edge, while according to the Nordic Timber rules, both faces and edges should be taken into account. The amount of wane grade was also registered but was disregarded when final calculations were made since the most important reason for wane grade is inappropriate set-up.

Each criterion was tested for each 10 cm sections separately, and quality grade following each quality criterion was derived. The worst quality grade then gave the final quality grade for each 10 cm section. Although quality criteria were specified for each 10 cm section separately, our worksheet formulas were able to grade sawn goods as complete pieces respecting the Nordic Timber grading rules (e.g., the maximum values of the wood features of a specified sawn good is determined by the worst one meter of length). The lumber grades for both the original and the simulated bucking alternatives were derived using this calculation.

3 Results

Automatic bucking clearly differed from the original unassisted quality bucking. The different bucking principles produced exactly the same log output only in two out of 100 stems; understandably so, since theoretically one stem has hundreds of different alternatives. The original quality bucking produced 272 logs, while the simulated automatic bucking produced 7 more (2.6%). In the original quality bucking, one log

Table 4. The mean of log lengths (mm) by stand and bucking alternative. Quality refers to quality bucking and auto to automatic bucking.

Stand	First log		Second log		Third log		Fourth log		All logs	
no	Quality	Auto	Quality	Auto	Quality	Auto	Quality	Auto	Quality	Auto
1	4735	4555	4840	4555	4525	4450	3900	4150	4671	4498
2	4645	4705	4884	4885	4260	4380	4300	4300	4616	4675
3	4528	4630	4630	4540	4233	4510	3800	3800	4543	4490
4	4300	4585	4078	4480	4245	4180	-	-	4204	4462
5	4360	4450	4167	4390	3775	3850	-	-	4182	4325
6	4300	4180	4135	4120	3828	4300	-	-	4117	4190
All	4528	4513	4470	4501	4200	4341	3914	4037	4409	4452

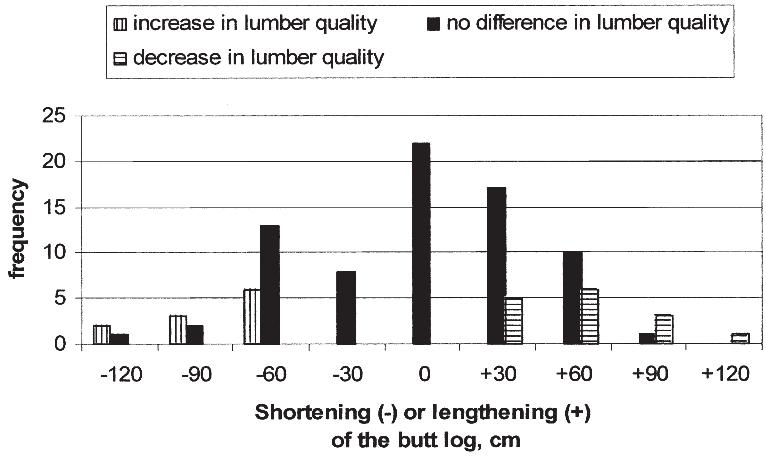

Fig. 1. The difference in butt log lengths and how often the lumber quality is changed when the bucking principle is changed from quality to automatic.

Table 5. The proportion of lumber grades by log and stand.

Stand no	First log A	First log B	First log C	Second log A	Second log B	Second log C	Third log A	Third log B	Third log C
1	19.9	78.0	2.1	0	96.4	3.6	0	97.1	2.9
2	50.9	48.1	0.9	13.2	80.4	6.4	0	96.0	4.0
3	40.0	51.9	8.1	21.3	50.9	27.8	0	73.4	26.6
4	71.7	28.3	0	28.3	71.0	0.7	9.8	89.4	0.9
5	74.3	25.7	0	24.6	72.7	2.7	0	91.8	8.2
6	90.1	9.0	0.9	28.3	69.9	1.8	9.2	88.8	2.0
All	59.9	39.8	0.2	19.8	79.6	0.7	4.1	95.2	0.7

was cut from 3 stems, two logs from 27 stems, three logs from 64 stems and four logs from 6 stems. The length of the first log was the same in 22 out of 100 stems. The simulated bucking produced a one module (30 cm) shorter log than the original quality bucking in 22 cases, two modules shorter in 16 cases and three or more modules shorter in 5 cases. Similarly, the simulated automatic bucking produced one module longer logs in 8 cases, two modules longer in 19 cases and three or more modules longer in 8 cases.

Altogether, the original bucking produced slightly shorter logs. The mean length of all logs sawn according to quality bucking was 4409 mm, while with automatic bucking it was 4452 mm. The mean lengths of the first, second, third, fourth and all logs by stand are shown in Table 4.

Table 5 shows the proportions of lumber grades related to the original quality bucking. The proportion of butt log A-battens is roughly 60%, which is in accordance with previous studies (e.g. Uusitalo 1997). However, there seems to be a considerable variation between the study stands. Those close to Turku (stands 4–6) seem to be of markedly better quality, the stems being considerably smaller and shorter than the stems from stands 1–3. The stems from stands 4–6 were also cut into shorter logs.

Automatic bucking did not change the proportion of lumber grades markedly. Fig. 1 shows how often and how much the log length of the butt log changed compared to quality bucking and what effect it had on lumber quality. Surprisingly, there were no cases in which change in log length

Table 6. Correlation coefficient between change in quality in butt log battens (ΔQ), quality of butt log battens ($A_{butt\ log}$), dead branch height (H_{dbr}), small-end diameter (SED), change in butt log length ($\Delta L_{butt\ log}$) and butt log length ($L_{butt\ log}$). Significance for each variable is given in parentheses.

	ΔQ	$A_{butt\ log}$	H_{dbr}	SED	$\Delta L_{butt\ log}$	$L_{butt\ log}$
ΔQ	*	–0.261 (0.009)	0.096 (0.344)	0.118 (0.245)	–0.636 (0.000)	0.318 (0.001)
$A_{butt\ log}$		*	0.070 (0.492)	–0.144 (0.155)	0.212 (0.034)	–0.337 (0.001)
H_{dbr}			*	0.135 (0.184)	–0.160 (0.112)	0.237 (0.018)
SED				*	–0.189 (0.061)	0.171 (0.090)
$\Delta L_{butt\ log}$					*	–0.559 (0.000)
$L_{butt\ log}$						*

changed the lumber grade of both battens. Fig. 1 gives the number of those cases in which change in log length changed the grade of either batten. A one 30 cm module change in log length does not usually change the lumber grade. When the log length is changed by two 30 cm modules, lumber quality changes in roughly half the cases.

A correlation analysis was conducted to determine the relationship between change in butt log length ($\Delta L_{butt\ log}$), lumber quality and the most important characteristics influencing lumber quality (Table 1). The most important stem characteristics include butt log length ($L_{butt\ log}$), small-end diameter (SED) and dead branch height (H_{dbr}). We define a new variable $A_{butt\ log}$ to indicate lumber quality and ΔQ to indicate change in lumber quality. $A_{butt\ log}$ is the proportion of A-battens in butt logs. Since we only have two battens in the butt logs, $A_{butt\ log}$ can only have values of 0, 50 or 100. Let ΔQ denote the change in quality grade in either of butt log battens. ΔQ gets a value of –1 when quality is downgraded; 1 when quality is upgraded and 0 when quality remains the same. Table 6 shows the correlation matrix .

As already shown in Fig. 1 and then statistically proved in table 6, change in butt log length ($\Delta L_{butt\ log}$) has a relatively high correlation with the change in quality in butt log battens (ΔQ). This correlation was also calculated by stand. Within all stands there were quite high negative correlations between $\Delta L_{butt\ log}$ and ΔQ. Stand-specific correlations varied from 0.491 to 0.814 and were all statistically significant ($p = 0.05$). The original butt log length ($L_{butt\ log}$) had a moderate positive correlation with the change in butt log batten quality (ΔQ) which means that we have less probability of quality change with shortening of long butt logs than middle size long butt logs. It also means that we have less probability of quality change with lengthening of short butt logs than middle size long logs. This correlation was also analyzed by stand. Stand-specific correlations between $L_{butt\ log}$ and ΔQ varied from 0.189 to 0.461 in all study stands, but the correlation were statistically significant in only one ($p = 0.05$).

Change in quality in butt log battens (ΔQ) and quality of butt log battens ($A_{butt\ log}$) have no obvious correlation with dead branch height (H_{dbr}). Since this was not in accordance with the earlier findings of Kärkkäinen (1980a) and Uusitalo (1994, 1997), correlations were calculated by stand. Stand-specific correlations between $A_{butt\ log}$ and H_{dbr} varied from 0.149 to 0.567, the correlations being statistically significant in two stands ($p = 0.1$).

4 Discussion

Study materials were collected from six Scots pine stands located near Turku and Rauma. Despite the quite small number of test sawing stems, the results may be considered relatively reliable and valid in similar conditions. The comparison was only based on quality differences in the battens that form two-thirds of the entire lumber volume. Excluding the boards sawn from the outer parts of the log (i.e., the sideboards) from our calculations certainly influences the outcome, since they include greater variation in relation to lumber quality and price. On the other hand, including the sideboards would have made the calculations more complicated and unreliable with this simulation technique.

The technique applied has some shortcomings that might slightly influence the results. In most cases the butt log and the second log are sawn with different sawing patterns. When battens are arranged in normal order to form continuous strings, we get a small "step" when the actual battens change from the first to the second one. The step is not very significant since in most cases thickness of the battens remain the same (50 mm). However the batten width decreasing might affect the maximum size and character (dead or sound) of knots. When we hypothetically increase the log length we actually grade those sections in a slightly different way. We still do not believe that this distortion has a significant influence on results and conclusions.

The results show that the quality of butt log battens seems to be relatively sensitive to butt log length. Shortening the butt log tends to increase lumber quality and, vice versa, lengthening the butt log tends to decrease quality. This is in accordance with theoretical assumptions and earlier investigations (Kärkkäinen 1980a, 1986, Uusitalo 1994, 1997). Surprisingly, dead branch height had no obvious correlation with the quality of butt log battens, although Heiskanen (1954), Kärkkäinen (1980a) and Uusitalo (1994, 1997) have found fairly strong correlations between lumber quality and dead branch height. There are two major reasons for this. First, it seems that strong between-stand variation in quality within this sample changes the correlation between lumber quality and dead branch height negligibly, although stand-specific correlations were found to be at the same level as the earlier investigations by Kärkkäinen (1980a) and Uusitalo (1994, 1997). There were a smaller number of sample trees in two stands of six which somewhat increases between-stand variation. Second, the study material was collected in southwestern Finland, close to the coastal region, where the quality of Scots pine forest has been reported to be slightly different than in other parts of southern Finland (Kärkkäinen 1980 b).

The results show that the original butt log length affects the probability of quality change if the log is shortened or lengthened. The greater the original butt log length is, the smaller the probability of quality change when shortening the butt log, whereas the shorter the butt log length is the higher the probability of quality change when lengthening the butt log. This indicates that harvester drivers have succeeded in the original unassisted quality bucking. They have cut longer logs with stems of good quality and shorter logs with stems of low quality.

Automatic bucking changed the bucking outcome compared to the original unassisted quality bucking but did not change the lumber quality greatly. Although connection between the quality of lumber and butt log length is significant, it seems to be quite difficult to determine when it is worth shortening or lengthening the butt log. Automatic bucking procedures producing bucking outcomes similar to unassisted quality bucking in terms of average butt log length should produce similar lumber quality proportions within one stand. Since the between-stand variation in lumber quality seems to be high, more attention should be paid to predicting the quality differences between stands. Providing more accurate information about the quality level of a particular stand was available, harvesters could use different demand matrices for each stand in order to maximize the amount of good-quality lumber. It seems quite likely that automatic bucking can be employed in similar Scots pine forest. Automatic bucking does not noticeably lower the amount of good-quality lumber compared to quality bucking. Since automatic bucking inevitably leads to log distribution that matches the length requirements of customers better (Kivinen and Uusitalo 2002), it may be regarded as appropriate for these harvesting conditions.

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Total of 27 references

Appendix A. Stand-specific price matrices for pine logs. The matrices have been optimized using the genetic algorithm developed by Kivinen (2004).

Top diameter, mm	Log length, cm						
	370	400	430	460	490	520	550
Stand 1							
150	208	237	244	245	234	222	209
160	241	181	236	191	238	226	205
180	187	213	235	238	230	208	215
200	191	212	240	241	237	233	185
220	211	215	243	245	243	235	199
240	219	216	230	234	235	210	193
260	181	183	237	220	183	245	219
280	241	226	211	226	229	207	238
300	207	241	225	216	226	193	202
320	227	187	191	196	240	218	195
360	234	227	194	186	246	231	190
400	0	0	0	0	202	0	0
Stand 2							
150	196	219	246	181	226	191	233
160	204	194	246	236	220	194	183
180	212	207	244	208	243	197	233
200	188	199	235	228	227	234	205
220	217	202	236	236	227	238	221
240	195	183	243	246	234	185	246
260	183	242	229	220	215	203	196
280	181	192	236	244	190	206	225
300	221	197	214	210	239	194	239
320	223	189	186	204	193	246	192
360	219	215	238	197	196	224	213
400	0	0	0	0	211	0	0
Stand 3							
150	201	193	221	190	214	194	187
160	243	243	187	242	190	226	239
180	222	222	237	235	242	223	180
200	187	195	240	234	237	195	207
220	237	192	230	243	236	239	225
240	223	181	236	233	224	212	193
260	186	182	232	234	233	235	225
280	203	182	233	235	201	212	203
300	202	206	198	244	197	201	193
320	200	184	202	237	245	239	207
360	181	221	235	194	231	183	234
400	0	0	0	0	206	0	0

Stand 4

Top diameter, mm	Log length, cm						
	370	400	430	460	490	520	550
150	215	224	242	245	236	197	196
160	243	227	236	199	220	220	207
180	189	197	213	218	227	230	206
200	208	185	237	238	236	222	198
220	216	211	233	240	241	222	208
240	233	181	240	243	237	228	184
260	209	206	204	209	241	201	240
280	186	186	213	235	224	180	244
300	187	238	233	236	209	219	205
320	202	199	236	199	218	225	242
360	239	229	240	224	245	242	195
400	0	0	0	0	207	0	0
Stand 5							
150	188	224	219	217	191	183	203
160	244	209	243	218	235	222	182
180	246	184	229	186	223	213	184
200	209	199	213	221	220	185	206
220	240	214	236	231	194	186	197
240	232	209	241	234	182	208	234
260	198	184	198	182	221	218	184
280	222	221	195	195	223	224	193
300	222	192	207	243	228	213	216
320	198	218	205	189	218	184	219
360	208	228	216	215	208	193	209
400	0	0	0	0	225	0	0
Stand 6							
150	189	189	239	223	235	224	211
160	224	235	245	181	239	186	198
180	217	194	238	229	222	184	184
200	216	190	223	216	222	182	187
220	242	198	241	243	217	230	193
240	220	227	238	234	242	225	199
260	245	197	209	238	206	197	203
280	223	212	245	180	188	199	223
300	191	184	243	209	183	230	236
320	207	200	193	233	195	200	219
360	182	225	193	211	236	191	183
400	0	0	0	0	218	0	0