ADAPTIVE CONTROL OF BUCKING IN A DOUGLAS FIR STAND: ADJUSTMENT FREQUENCY EFFECTS

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ABSTRACT

Adaptive control, in conjunction with dynamic programming, has been shown in earlier research to provide superior results from stem and stand log bucking when the stand is subject to order book constraints. Adaptive control can be achieved by adjusting relative prices and small-end diameter specifications as the harvesting operation moves through the stand. We examined the effects on market fulfilment of varying the frequency with which adjustments are made. Apportionment degree was used as the metric for market fulfilment. We found that there was a significant positive relationship between adjustment frequency and apportionment degree; apportionment degree increased as the size of the harvest area between adjustments decreased from 1.2 to 0.2 ha.

Keywords: harvesting; market constraints; optimal bucking; apportionment degree.

INTRODUCTION

Bucking is the forest operations activity whereby felled tree stems are cut into logs. If done incorrectly, bucking can be one of the largest sources of value loss in the forest-to-mill supply chain. Optimal bucking of individual stems usually uses one of three optimisation techniques: dynamic programming (Pnevmaticos & Mann 1972), network analysis (Nasberg 1985), and rule-based log bucking (Laroze and Greber 1997). Optimally bucking individual stems based on market prices, also known as bucking-to-value, is unlikely to provide log product yields that meet order

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book constraints, which are a combination of market and production constraints, at the harvest unit or forest level.

Successful supply chain management involves managing activities in ways that improve customer service and operational efficiency (Pulkki 2001). The key to maximising the value from a forest supply chain is to cut the right quantities of customer grades in the right location to maximise revenues, minimise operational capital cost, and minimise downgrading from valuable grades (Jones 1999). The ability to adapt the grade mix being cut enables the right log grade distribution to be obtained, even when the trees being cut and the products being demanded by customers are constantly changing.

Procedures for meeting order book constraints have been described by Sessions *et al.* (1989) for Pacific Northwest Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) forests, by Pickens *et al.* (1997) for eastern U.S. hardwood forests, by Laroze & Greber (1997) for Chilean plantation forests, by Kivinen (2004) for Scandinavian forests, and by Marshall *et al.* (2006a) for pine plantation forests. Bucking-to-order formulations usually use a two-level hierarchical approach with the lower level model optimising the bucking of individual stems and the upper level model meeting constraints through the selection of the best bucking patterns (prices and specifications). Marshall *et al.* (2006a), in a review of some of the key bucking papers, noted that some formulations aimed to maximise market fulfilment while others aimed to maximise net value at the upper level. Apportionment degree, a measure of how closely the actual distribution of log-types meets the target distribution, is one of the commonly used metrics for market fulfilment (Kivinen *et al.* 2005). Marshall *et al.* (2006a) found that maximising apportionment degree did not necessarily lead to maximum net value and vice versa.

Duffner (1980) described an adaptive price control system which was used in a centralised log processing yard in Europe to adjust prices, based on whether too many or too few logs of a certain type were produced. Murphy *et al.* (2004) developed an adaptive price list control technique, using apportionment degree to determine optimal bucking patterns for stems. The adaptive control technique allowed for the optimisation to be adjusted as more stem information became available from the harvesting operation as it moved through the stand. Prices and specifications could be adjusted based on "better" information. Using time-of-harvest information for better decision-making is already a common feature on modern harvesters.

Murphy *et al.* (2004) found improvements of 19 to 26% in meeting order book target proportions for four stands when their heuristics were based on recent stem information gathered by the simulated harvester. The improvements were in comparison to optimal bucking based on unadjusted market prices. Adjustments were made approximately every 150 trees for three of the stands and every 50 trees for one of the stands.

In a follow-on study, Murphy *et al*. (2006) examined the effects on overall apportionment degree of varying (1) target proportions for given log-types, and (2) frequency of adjustments. They found that (1) holding the target proportions constant through the harvest of the stand usually provided the best overall apportionment degree, and (2) there were no significant differences in apportionment degree when adjustment frequencies ranging from four to 512 stems were examined. The authors noted that further research was required on adaptive control heuristics in a wider range of markets and stand types.

In this study, we examined the effects on market fulfilment of varying the frequency with which adjustments are made in a Douglas fir stand in western Oregon. A broader set of log-types was included in the analysis than in earlier studies by the authors.

METHODS

Test Stand

An area of about 8 ha of Douglas fir in McDonald Forest, Oregon, (1230°19' 52" W, 440° 36' 46" N) was selected as a test stand. Some hardwoods, predominantly big leaf maple (*Acer macrophyllum* Pursh.) and Oregon white oak (*Quercus garryana* Dougl. ex Hook.), were also present in the stand. Stand records for this part of McDonald Forest indicated that two age classes were present — one in which the average breast height age was 68 years, and one in which it was 100 years. The exact boundary between these two age classes was difficult to define.

The area was located on a small south-facing ridge. Part of the area faced south-east and part faced south-west.

Every tree over 150 mm in the test stand was tagged and its location mapped using ground surveying methods. The diameter at breast height of every tagged stem was recorded. All tagged conifers were measured for height and cruised using the ATLAS Cruiser system (Gordon *et al*. 2006). Cruised conifers were measured for changes in diameter, branch size, sweep, structure, and defects. A stem description file was then generated that contained the coordinate location of each tagged conifer and its under-bark diameter and volume, its qualities, and its sweep deviations in decimetre increments from the ground to the stem tip.

Stem data summaries are included in Table 1. There was an average of 290 stems /ha within the 7.2 ha test area — 235 conifer stems/ha and 55 hardwood stems/ha. The average conifer volume per hectare was 596 m^3 and the average tree volume was 2.53 m^3.

Market Requirements for the Test Stand

For the purposes of this study it was assumed that hardwoods in the test stand were not harvested. Hypothetical conifer market requirements (Table 2) were applied

TABLE 1–Stem data summaries for stems > 150 mm dbh

	Conifers		Hardwoods
	Diameters (mm)	Heights (m)	Diameters (mm)
Mean	499	33.7	347
Minimum	150	7.6	149
Maximum	1550	58.6	1225

to the test stand. Eleven log-types plus waste were included. Many included multiple lengths, some in multiples of 0.6 m, others in multiples of 0.3 m, and waste in multiples of 0.1 m. They are representative of log-types found in the Pacific Northwest of the United States. A total of 63 lengths were included in the analyses. Each log-type, and some sub-groups of log-types, had target volumes that were required. In addition to these constraints, we included two others; a minimum average small-end diameter (s.e.d.) for Domestic Sawlog #1 of 330 mm was required, and no less than 21% of the combined volume of the Export Sawlogs could be in Export Sawlog #2 category. Penalties were applied to the objective function if these constraints were not met (Murphy *et al*. 2004).

Adaptive Control Heuristic

The two-level hierarchical adaptive control heuristic called FASTBUCK (described by Murphy *et al*. 2004) was used to evaluate the effects of adjustment frequency as the simulated "harvester" worked its way through each block within the test stand (Fig. 1). We noted that many of the trees in the test stand would be too big for a mechanical harvester and would need to be manually felled and bucked in coordination with the harvester and in conjunction with optimal bucking callipers, as described by Boston (2001). FASTBUCK uses a threshold accepting algorithm (Dueck & Scheuer 1990) to guide the upper level search for maximum apportionment degree, and dynamic programming to optimise relative value. Search parameters for the heuristic were set at five threshold steps (decreasing from 0.050 to 0.001), a maximum of two log-types changed per iteration, a maximum expansion factor of two for price increments or s.e.d. increments, variations in both price and s.e.d. allowed, a single run per evaluation, and 400 iterations per run.

Apportionment degree (AD%) is a measure of how closely overall market requirements are fulfilled (K-G.Bergstrand unpubl. report). It is defined as:

$$AD\% = 100 * (1 - \sum_{j=1}^{n} |D_{aj} - D_{rj}|/2)$$

where: n = number of log-types

j = log-type number

TABLE 2–Market requirements and constraints for conifers in the test stand

Log-types	Lengths (m)	Small-end diameter range (mm)	Maximum knot size (mm)	Maximum sweep allowance (% of s.e.d.)	Relative market prices ($/m^3)	Target proportions (%)
Export Sawlog #1 (ES1)	8.6–9.8	305–700	38	50	100	18
Export Sawlog #2 (ES2)	11.0–12.2	305–700	38	50	88	11
Export Sawlog #3 (ES3)	8.6–9.8	305–700	63	50	84	15
Export Sawlog #4 (ES4)	9.8–11.0	229–700	38	50	62	8
Domestic Sawlog #1 (DS1)	4.9–7.3	305–700	63	25	70	5
Domestic Sawlog #2 (DS2)	11.0–12.2	305–700	76	50	65	5
Domestic Sawlog #3 (DS3)	4.9–7.3	203–520	76	25	52	9
Oversize Sawlog (OS)	6.1	600–1400	76	50	48	10
ChipNSaw #1 (CNS1)	4.9–7.3	127–520	>76	50	45	6
ChipNSaw #2 (CNS2)	7.9–9.1	127–520	>76	50	46	2
Fiber (Fiber)	3.7–12.2	102–650	>76	200	15	3
Waste (Waste)	0.1–6.0	0–1990	No limit	No limit	0	8

Additional constraints:
Minimum average small-end diameter for Domestic Sawlog #1 is 330 mm
Export Sawlog #2 should be at least 21% of the total Export Sawlog volume

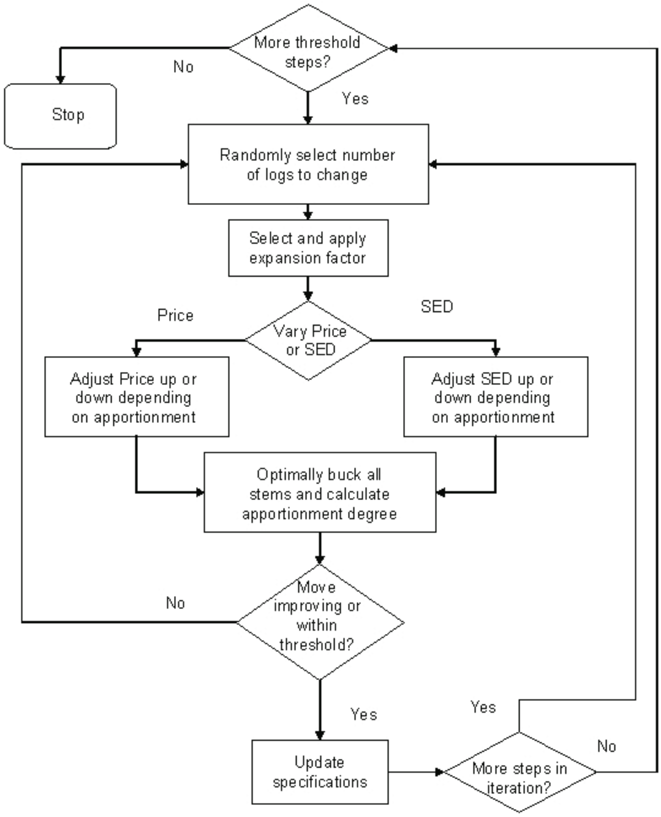

FIG. 1–Adaptive control heuristic implemented in FASTBUCK

D_{aj} = actual decimal portion of total volume that is log-type j
D_{rj} = required decimal portion of total volume that is log-type j

Varying Adjustment Frequency

Within the test stand, six adjacent 1.2-ha rectangular blocks (100 × 120 m), totalling 7.2 ha, were selected (= replications). Each block included trees from the south-east and south-west aspects. Each block was split into six 0.2-ha, three 0.4-ha, two 0.6-ha, or one 1.2-ha sub-blocks. This enabled comparisons to be made of the effect of adjustment frequency on market fulfilment (AD%). For the stand conditions included in this study, a double skidder/tractor harvesting operation would extract and process about 0.6 ha per day. The size of the sub-blocks would therefore be equivalent to adjusting prices and specifications from as infrequently as once every 2 days to as frequently as three times daily.

Ten, randomly located, 0.02-ha plots were established within the test stand to provide base inventory data. This equated to a 3% sample by area of the stand. A fixed target approach for adaptive control was used (Murphy *et al.* 2006).

AD% for the "current" sub-block of trees harvested was predicted based on either the forest inventory if the sub-block was the first to be harvested within the block, or the most recently harvested sub-block. The predicted yields were compared with simulated yields for the current block. A root mean square error (RMSE%) statistic was calculated based on these comparisons for each adjustment frequency.

RESULTS

Compared with the buck-to-value solution for the six blocks combined, adjusting prices and specifications as the harvest operation moved through the stand resulted in a 2 to 12% improvement in overall AD%.

Mean AD% values ranged between 78 and 89% for the four adjustment frequencies. Individual AD% values ranged between 68 and 93%. Analysis of variance indicated that there were statistically significant differences between the adjustment frequencies ($p = 0.004$). Simple linear regression analysis indicated that there was a statistically significant, although rather weak, relationship between AD% and adjustment frequency (Table 3, Fig. 2). For each tenth hectare that harvester adjustments were delayed, market fulfilment (AD%) fell by 2%. The standard error for the regression estimates was 4.3%.

TABLE 3–Analysis of variance for the relationship between adjustment frequency and market fulfilment (AD%).

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	364.46	364.46	19.56	0.0002
Residual	22	409.92	18.63		
Total	23	774.39			

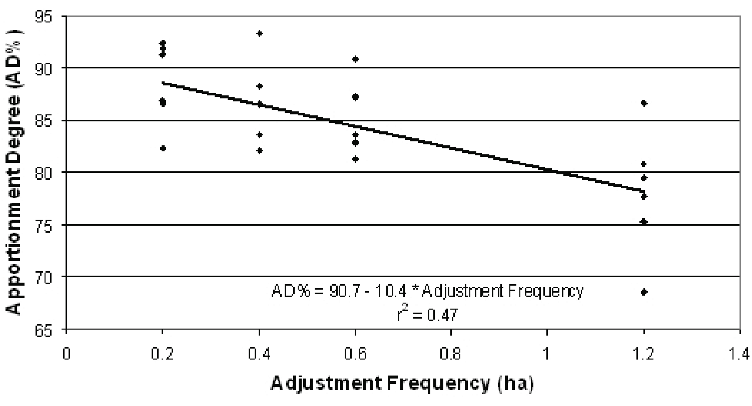

FIG. 2–Relationship between adjustment frequency (how often prices are adjusted on the "harvester") and market fulfilment as indicated by the apportionment degree (AD%) metric.

There was no significant difference ($p = 0.05$) between adjustment frequencies in the prediction errors for the test stand. RMSE% for market fulfilment (AD%) ranged from 19.0 to 22.3% for the four adjustment frequencies.

The target order requirements and the simulated product yields obtained from the six treatment blocks are given in Table 4. Although overall market fulfilment (AD%) was higher with the adaptive control buck-to-order system, none of the product yields was met exactly.

DISCUSSION AND CONCLUSIONS

Without perfect knowledge of all stems in a stand, tree bucking cannot be optimally executed with a single price list at the stand level when there are order book constraints (Kivinen & Uusitalo 2002). Adaptively controlling bucking as stems pass through a central processing yard (Duffner 1980), or as a harvest operation works its way through a stand, can lead to product yields which closely match market requirements (Sondell *et al.* 2002; Murphy *et al.* 2004, 2006). Achieving high levels of market fulfilment (AD%) is partly a function of what is available in the set of stems being evaluated and partly a function of the adaptive control procedures used. For example, with respect to the former, if the market requires a high proportion of the volume produced to be in large log categories, it will be difficult to meet market needs if the harvest operation is working in a part of the stand where the trees are small.

With respect to adaptive control procedures, one of the questions is "how often should prices and specifications be adjusted to meet market requirements"? The results from this study indicate that the more often adjustments are made, the more closely could market requirements be met; in this case, making adjustments every 0.2 ha would result in an AD% that was 10% higher than making adjustments every 1.2 ha.

These findings differ from those reported by Murphy *et al.* (2006), who found no significant differences in AD% between adjustment frequencies ranging from every 4 to every 128 trees in a real-world *Pinus radiata* D. Don (radiata pine) stand. The average tree size was similar for the radiata pine stand and the Douglas fir stand (2.24 *vs* 2.53 m^3), as was the average stand density for the conifers (249 *vs* 235 stems/ha). Their adjustment frequencies were equivalent, on average, to making adjustments every 0.016 ha to every 0.514 ha.

There are at least three reasons why there could be differences in these findings. Firstly, the stem variability throughout the radiata pine stand was less than in the Douglas fir stand. Delaying the adjustment of prices and specifications, therefore, had little effect on AD%.

TABLE 4–Simulated product yields for two bucking systems (buck-to-value and buck-to-order) and four adjustment frequencies

Log-types	Target order (%)	Simulated yields (%)									
		Buck to value		Buck to order							
				Adjust after 1.2 ha		Adjust after 0.6 ha		Adjust after 0.4 ha		Adjust after 0.2 ha	
		Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
Export Sawlog #1	18	32.6	19.3-39.4	10.6	3.8-20.5	13.5	8.7-22.2	14.2	9.8-22.7	15.5	10.6-19.2
Export Sawlog #2	11	0.0	0.0-0.0	6.6	3.4-10.1	8.8	6.6-10.8	9.1	7.4-11.2	9.0	6.9-10.3
Export Sawlog #3	15	14.8	8.3-23.3	25.2	19.5-31.0	20.1	15.5-28.1	18.2	14.2-24.3	17.2	15.8-19.6
Export Sawlog #4	8	7.0	3.3-10.9	9.4	4.3-14.0	8.5	4.3-12.4	7.9	5.5-11.7	7.9	5.6-9.1
Domestic Sawlog #1	5	5.3	4.2-6.4	4.9	3.1-6.6	4.9	3.6-6.0	5.6	3.6-7.5	4.5	2.7-6.3
Domestic Sawlog #2	5	4.5	2.0-7.2	6.9	4.0-9.8	6.1	3.6-8.4	5.1	3.7-5.9	5.5	4.1-6.9
Domestic Sawlog #3	9	9.7	5.6-13.6	12.2	7.9-16.9	10.1	6.6-12.9	8.9	6.2-10.8	8.3	6.5-10.6
Oversize Sawlog	10	9.7	3.4-21.2	8.0	2.7-18.6	8.0	3.4-13.4	8.7	4.1-13.9	8.6	4.1-13.1
ChipNSaw #1	6	5.9	3.7-8.5	5.3	3.1-8.0	5.9	3.5-7.9	6.7	3.6-9.2	7.1	5.0-10.5
ChipNSaw #2	2	2.9	1.4-4.4	2.3	0.7-3.9	2.7	0.7-5.6	2.6	0.6-4.4	2.9	0.2-4.7
Fiber	3	0.8	0.3-1.9	1.4	0.8-2.7	2.3	0.9-5.7	1.8	0.9-2.2	2.5	1.1-3.9
Waste	8	6.7	4.1-10.4	7.1	4.1-11.5	9.0	5.2-16.4	11.3	5.3-18.5	10.9	5.1-17.9

Secondly, by examining adjustment frequency on an area basis rather than a fixed-number-of-trees basis, we introduced stand density variability into the adaptive control procedure.

Thirdly, the market complexity (number of log-types) was greater in the Douglas fir study than in the radiata pine study.

The mechanisation of tree bucking has enabled the increased use of computers as part of the process. There is easily enough computing power on modern harvesters to complete the calculations required by the algorithm described in this paper. Many of the systems now installed on harvesters have both an integrated global positioning system (GPS) and geographical information system (GIS) functionality (Sondell *et al*. 2002) which will enable the area calculation required by this methodology. An important component of the success of this system is communication between the harvesting operation and main production planning office. Although most harvesters have the ability to communicate over wireless networks (Sondell *et al*. 2002), in some countries wireless coverage does not extend to many of the production-forested areas.

This study did have limitations. Only one stand and one set of market conditions were evaluated. The analyses were also based on simulations only. In these simulations, it was assumed that there was perfect knowledge of each stem as it was being optimally bucked with the aid of a computer; taper, sweep, and changes in quality along each stem were known with certainty. In real life, each stem is rarely measured in full before bucking; some characteristics are forecast (e.g., taper) and some are estimated by the harvester/processor operator. Errors in stem descriptions can occur, leading to suboptimal product distributions and value recovery (Marshall *et al*. 2006b).

Since the results from this study contradict those of an earlier study, further research on adaptive control adjustment frequency is required. Such research would seek to evaluate whether gains from making frequent adjustments are dependent on stand variability, geospatial variability within the stand, on adjustment basis (area or number of trees), and on market complexity.

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