Development and evaluation of a pre-harvest inventory and cross-cutting simulation procedure to maximise value recovery

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Abstract

The development and evaluation of a pre-harvest inventory and value maximisation decision-support system for sawmill wood procurement is described. The system allows procurement managers to select the most suitable stands for tendering and subsequently to maximise the value of the logs produced during harvesting operations. The developed system consists of a generic taper equation, a stand-specific dbh/height model, and a computer simulation programme which provides detailed information on the potential volume, log count and diameter distributions for different log assortment specifications. The system was developed using data from five Sitka spruce (*Picea sitchensis* (Bong.) Carr.) clearfell sites in west Munster. The system was evaluated using seven data sets, three validation sub-sets from data sets used for the development of the taper equation and the dbh/height model, and four data sets from new sites, including two Sitka spruce clearfells, a Sitka spruce thinning and a Norway spruce (*Picea abies* (L.) Karsten) clearfell. The evaluation process showed that the developed procedure produced accurate results for a wide range of stand types, as long as sufficiently large data sets are used.

Keywords: Cross-cutting simulation, dbh/height models, forest inventory, taper equations, value maximisation.

1. Introduction

The three cornerstones of profitability of harvesting and sawmill operations are maximisation of volume output, minimisation of costs and maximisation of value. Too often the emphasis has been on minimising production costs and maximising volume output, while raising product value recovery took a back seat (Murphy *et al.*, 1991).

In order for a sawmill wood procurement manager to select the most suitable stands for tendering and subsequently to maximise the value of the logs produced in harvesting operations, information is required, not only on the mean tree dimensions and total volume of the stand, but more importantly, on the potential volume, the number of logs and the diameter classes, for different assortment specifications. Information of this kind will greatly assist production planning in the mill. Knowledge of the consequences of adopting a particular cross-cutting strategy will also enable mills to identify the optimum combination of log products to be harvested from a stand, subject to operational constraints and the need to satisfy customer demands for sawn timber. With a greater insight into the yield potential of a crop in terms of actual products, tender prices could also more accurately reflect the value of individual stands to different mills. This would enable each mill to confidently target those sales most appropriate to its specific requirements.

At present, the information provided to sawmills on standing timber lots is considered by them to be inappropriate for their planning and procurement needs. Currently the conventional pre-harvest inventory typically provides estimates of mean diameter at breast height, mean volume and total volume, in addition to a breakdown of volume into assortment categories. In the absence of more informative pre-harvest information, the scope for efficiently exploiting the forest resource is limited. More specific and end use-oriented information relating to the yield of stands in terms of actual products would, subject to competition, enable mills to procure the stands and cut the logs that best meet their needs and that satisfy the demands of their customers.

Accordingly, a pre-harvest measurement and analysis procedure has been developed to provide an efficient means of obtaining, relaying and analysing information on standing timber to generate predictions of the volume, number and diameter class breakdown of potential log assortments. The inventory procedure was designed to enable the timber procurement manager to acquire, at reasonable expense, information that, when analysed, provides a comprehensive insight into the yield potential of the stand.

A research project was undertaken in conjunction with Palfab Limited, a medium-sized softwood sawmill that purchases over 90% of the logs it processes from standing sales. The research was directed towards finding solutions to the problems encountered by Palfab, and toward developing a system specific to the needs of the mill (Malone, 1998). In previous publications, the development and testing of the inventory procedure has been outlined and discussed (Nieuwenhuis and Malone, 1996 & 1999). This article will briefly summarise this development work, but will focus on the evaluation of the output of the inventory procedure for a wide range of stands and will compare these results with the optimal cross-cutting output as produced by a dynamic programming procedure which uses detailed stem measurements.

2. Development of Inventory Procedure

The purpose of the research was to develop a decision-support system, incorporating pre-harvest measurement and analysis procedures, to provide the timber procurement manager of a medium-sized sawmill with estimates of the volume, number and diameter class breakdown of log assortments that could potentially be cut from standing timber lots of mature Sitka spruce (*Picea sitchensis* (Bong.) Carr.). The tree section data used in the construction and testing of the inventory procedure consisted of 5,543 observations of diameter and height made on 246 stems, from five Sitka spruce stands (Table 1). The standing timber lots, selected by Palfab, were considered representative, with respect to mean dbh, mean tree volume and location, of those normally purchased by the mill.

An identical data collection procedure was followed in each stand. The diameter overbark at breast height was measured, in millimetres, for all sample trees using an electronic callipers. The point at which this measurement was taken was marked on the standing tree to provide a means of determining stump height. All trees were allocated a unique number to allow for future identification. The trees were subsequently felled and the stems delimbed to facilitate the measurement of diameter overbark. Measurements were taken, in millimetres, at 0.5 m intervals to a distance of 6.0 m from the butt and at 1.0 m intervals thereafter

Table 1. *Summary characteristics of the stands used for model development. All stands were Sitka spruce clearfell sales.*

Stand	*Forest*	*Planting year*	*Yield class* $m^3\ ha^{-1}\ year^{-1}$	*Mean DBH cm*	*Number of sample trees*
1	Skibbereen	1958	24	27	54
2	Kenmare	1954	18	26	64
3	Killavullen	1956	18	23	38
4	Inchigeelagh	1956	22	32	59
5	Inchigeelagh	1956	22	30	31

Source: Coillte (The Irish Forestry Board)

to an approximate top diameter of 70 mm. In addition, the lengths, to the nearest centimetre, from the butt to the breast height diameter mark and to the tip were also recorded.

The data were subjectively divided into a development subset and a validation subset at stand level. This exercise was performed in such a way as to ensure that both subsets were representative of the original data with regard to the distribution of dbh and tree height values. The development subset was subsequently used to determine which independent variables to include in the candidate equations and to estimate the regression coefficients. The validation subset was used as independent data for evaluating the performance of the equations.

Four taper equations, identified from an extensive literature review, were selected for evaluation. Performance ranking, based upon values of bias and standard error of estimate, revealed an eight-variable taper equation (referred to as the Kozak 1992 equation in this paper, see Appendix for details) developed from modifications proposed by Newnham (1992) to the 'variable-form' equation of Kozak (1988) to be best overall (Malone, 1998).

Eight dbh-height models were chosen from the literature for preliminary testing. The three models that generated estimates of tree height with the least bias and minimum standard error of estimate were further investigated. The recommendation is to employ a combination of the Curtis 6 dbh-height model (Curtis, 1967) and ten height sample trees drawn by simple random sampling in conducting the pre-harvest inventory (see the Appendix for model details). Further investigations were carried out to finalise inventory procedures, primarily with respect to minimum height sample size(s) (McHugh, 1998). An interactive computer programme was developed to simulate the process by which stems are cross-cut into logs. The programme employs the generic taper equation to profile the stems of sample trees of known dbh and estimated height (using the dbh-height model and height sample trees) drawn from the stand. Using log specifications supplied by the user, the programme then simulates cut-to-length harvesting and produces forecast estimates of yield for each log-type in terms of the volume and number of pieces in each of a series of small-end diameter categories.

3. Evaluation of the Inventory Procedure

In order to determine the accuracy of the results from the inventory procedure (developed as described above), data from a wide range of stands were analysed. These data were processed by both the inventory procedure and by an optimal cross-cutting program which uses a dynamic programming algorithm (Nieuwenhuis, 1989). As this program uses detailed stem measurements and an optimisation procedure, the results produced by this process are assumed to be optimal (i.e. the best possible cross-cutting strategy). The results of the inventory and cross-cutting simulation procedure were evaluated against these optimal results.

Three of the five data sets used in the development phase of the project were of sufficient size to also allow for their use in the evaluation phase. The validation subsets of the datasets from Skibbereen (stand 1), Kenmare (stand 2) and Inchigeelagh (stand 4) contained circa 20 dbh sample trees and allowed for the random selection of 10 height sample trees.

Four additional data sets were also used in the evaluation process (Table 2). The original purpose of these data sets had been the testing of the developed inventory procedure over a wider range of stand types than that used during the development phase (McHugh, 1999). The sites included two Sitka spruce clearfells, a Sitka spruce thinning and a Norway spruce (*Picea abies* (L.) Karsten) clearfell. As these data had not been used in developing the inventory procedure, all observations from the four data sets were used in the evaluation.

Table 2. *Characteristics of the four additional stands used in the evaluation process.*

Stand	*Forest*	*Planting Year*	*Yield class $m^3\ ha^{-1}\ year^{-1}$*	*Mean DBH cm*	*Species and harvest type*	*Number of sample trees*
1	Kenmare	1958	18	24	Sitka spruce clearfell	38
2	Bandon	1953	20	27	Norway spruce clearfell	48
3	Ballingeary	1952	16	29	Sitka spruce clearfell	33
4	Dunmanway	1958	20	24	Sitka spruce thinning	47

Source: Coillte (The Irish Forestry Board)

In the evaluation process three potential assortments were specified: sawlog (length 5.5 m, minimum small end diameter (min. sed) 160 mm); pallet (length 2.5 m, min. sed 140 mm); and pulp (length 3.1 m, min. sed 70 mm).

3.1 The simulation process

The inventory data consisted of measurements on dbh sample trees and on height sample trees. These data were processed as follows:

1. The data from the ten randomly selected height sample trees, consisting of the dbh and height measurements, were inputted to the dbh/height regression model (i.e. the Curtis 6 model). The output consisted of the coefficients of the model's independent variables.
2. Data from the dbh sample trees, consisting of the dbh measurements of the remaining trees in the data set, were inputted to the dbh/height model as generated in step (1) and an estimate of the height of each tree was produced.
3. The combined data set, consisting of a dbh measurement and a height measurement or estimate for every tree, was inputted to the cross-cutting simulator, together with the assortment specifications. The simulator used the generic Kozak 1992 taper equation to estimate the diameter of the tree at any point along the stem. The output of the simulator consisted of detailed frequency tables, giving a breakdown of assortment

volumes and assortment log numbers by 2 cm diameter classes.

In order to be able to evaluate the individual impacts of the taper equation estimates and of the dbh/height equation estimates on the accuracy of the results, the simulator was also run using the actual height data of the stems, instead of the height estimates as produced by the dbh/height model. The difference between these results and the results from the optimisation procedure gave an indication of the performance of the generic taper equation. The results produced, when both the taper equation and the dbh/height equation were used, gave an indication of the overall performance of the simulator when compared with the optimal cross-cutting results. The results were also used to evaluate the performance of the dbh/height model when compared with the results where the actual heights were used.

3.2 The optimal cross-cutting process

As outlined in Section 2, the data used in the dynamic programming procedure consisted of detailed stem measurements. These data were reformatted to be compatible with the computer program. The procedure also required the identical assortment specifications as used in step 3 in section 3.1. The dynamic programming algorithm determined the optimal cross-cutting strategy for each stem. The output of the optimiser consisted of individual cross-cutting patterns for each stem. In addition, these individual results were combined into frequency tables that were compatible with the ones produced by the simulator.

3.3 The evaluation process

The output frequency tables produced by the simulator (both for the combination of taper equation and actual heights (Sim1) as well as for the combination of taper equation and dbh/height equation (Sim2)) and by the optimiser (Opt) were compared. First, the breakdown of total volume into assortment categories was examined on a cubic metre and on a percentage of total volume basis. Similarly, the breakdown of the total log count into the number of logs in each assortment category was analysed (both on a number and on a percentage of logs basis). This gave a clear indication of the capacity of the simulator to determine overall assortment estimates.

The next step was to evaluate the breakdown of the sawlog assortment volumes and log counts into the small end diameter (sed) categories. The capacity of the simulator to predict the correct sed frequency distributions within the general sawlog assortment is important, as this provides the wood procurement manager with the information needed to accurately value the stand and to predict the best possible combination of assortments to cut from the specific stand. As each site was evaluated separately, differences between single site estimates produced by the optimiser and by the simulator for each of the variables analysed were not statistically compared.

4. Results

4.1 The validation data sets

The results of the comparisons of the breakdown of total volume and total log count into assortment categories for the three validation data sets are presented in Tables 3 to 5. In these tables (as in subsequent tables) Sim1 results refer to simulator estimates where the taper equation was used with the actual tree heights; Sim2 results refer to estimates where the taper equation and the dbh/height model were used; Opt results refer to outputs from the optimisation procedure.

The simulator estimates for total volume and number of logs for the Skibbereen data set (Table 3) were too high (total volume was 14% higher and number of logs 11% higher than the optimal values), however the percentage breakdown into the assortments was very close (within 2%). Sim1 results were closer to the Opt values than the Sim2 results when actual estimates are considered, but there was no difference when percentages were used.

Table 3. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Skibbereen validation data set (19 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	1.10	1.37	9.84	12.31
Volume m^3	Sim2	1.01	1.61	10.48	13.10
	Opt	0.97	1.25	9.30	11.52
	Sim1	9	11	80	100
Volume %	Sim2	8	12	80	100
	Opt	9	12	79	100
	Sim1	26	22	33	81
# of logs	Sim2	24	25	33	82
	Opt	22	20	32	74
	Sim1	32	27	41	100
% of logs	Sim2	29	31	40	100
	Opt	32	29	39	100

Total volume and log estimates for the Kenmare data set (Table 4) of Sim1 were closer to Opt than the Sim2 estimates. The assortment results were close, both for the actual values as for the percentages. It was interesting to see the reduction in potential sawlog at the Kenmare site compared with Skibbereen (down from 79% of total volume to 72%), reflecting the smaller average tree size at Kenmare.

Table 4. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Kenmare validation data set (21 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	1.17	1.43	7.18	9.78
Volume m^3	Sim2	1.08	1.49	7.63	10.20
	Opt	1.06	1.56	6.78	9.40
	Sim1	12	15	73	100
Volume %	Sim2	10	15	75	100
	Opt	11	17	72	100
	Sim1	29	24	31	84
# of logs	Sim2	26	25	31	82
	Opt	27	27	31	85
	Sim1	34	29	37	100
Logs %	Sim2	32	30	38	100
	Opt	32	32	36	100

In the case of the Inchigeelagh data (Table 5), the Sim2 pulp estimates were accurate. However the sawlog estimates were too high, with too little pallet being estimated (sawlog 10% over-estimated by volume, 8% by number of logs). The Sim1 sawlog results are clearly closer to Opt than the Sim2 results, both for actual volume estimates as well as for the percentages. This was more than likely caused by the dbh/height equation, probably as a consequence of the dbh/height sample trees used to establish the regression coefficients not being representative of the stand.

Table 5. *Assortment breakdown of volume and number of logs, by quantity and percent, for the validation data set of Inchigeelagh (19 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	0.99	1.61	6.64	9.24
Volume (m^3)	Sim2	0.97	1.46	7.69	10.12
	Opt	0.96	1.49	6.74	9.18
	Sim1	11	17	72	100
Volume (%)	Sim2	10	14	76	100
	Opt	11	16	73	100
	Sim1	22	25	23	70
# of logs	Sim2	22	23	26	71
	Opt	22	23	24	69
	Sim1	31	36	33	100
Logs (%)	Sim2	31	32	37	100
	Opt	32	33	35	100

The sawlog frequency distributions for the three validation data sets are presented in Figures 1 to 3. Because of the limited number of stems in each data set, the distributions are not as smooth as would be expected with larger data sets. Overall there is a very close similarity between the estimates produced by the simulator and the optimal values from the detailed stem data, with the Inchigeelagh estimates especially accurate.

The average sawlog volumes for the three validation data sets, as produced by the three procedures, are presented in Table 6. It can be seen that all estimates for both the Sim1 and Sim2 procedures are higher than the actual values as produced by the optimiser. This is the result of an over-estimation of the volumes, based on data sets that are too small to produce accurate estimates. The estimated numbers of sawlogs are however very close to the actual values. The use of the dbh/height equations for the Sim2 estimates introduces a further deviation from the actual values compared to the Sim1 estimates.

Table 6. *Average sawlog volume (m^3 log^{-1}) for the three validation data sets, as estimated by the simulator and as calculated by the optimal cross-cutting procedure.*

Site	*Sim1*	*Sim2*	*Opt*
Skibbereen	0.298	0.317	0.291
Kenmare	0.232	0.246	0.219
Inchigeelagh	0.289	0.296	0.281

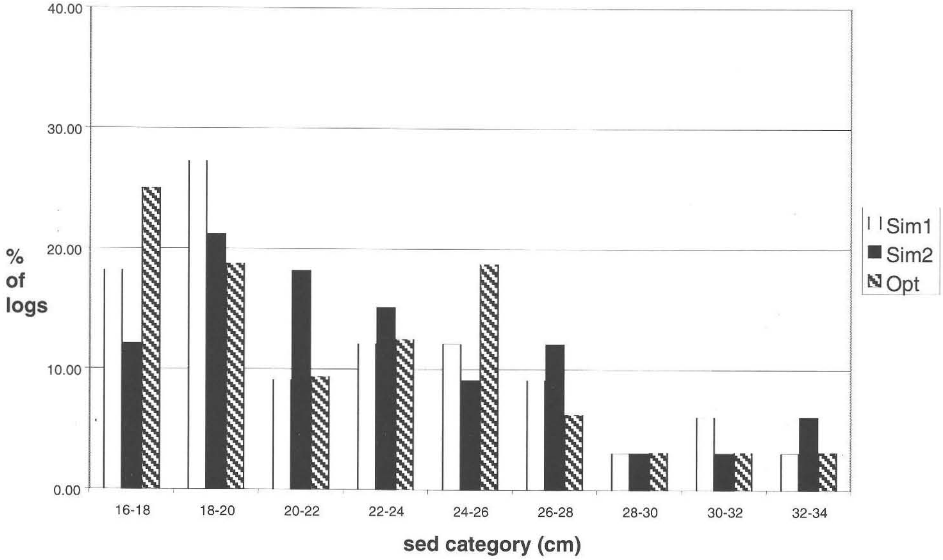

Figure 1. *Sawlog frequency distributions (in percent of number of logs) by small end diameter (sed) category for Skibbereen.*

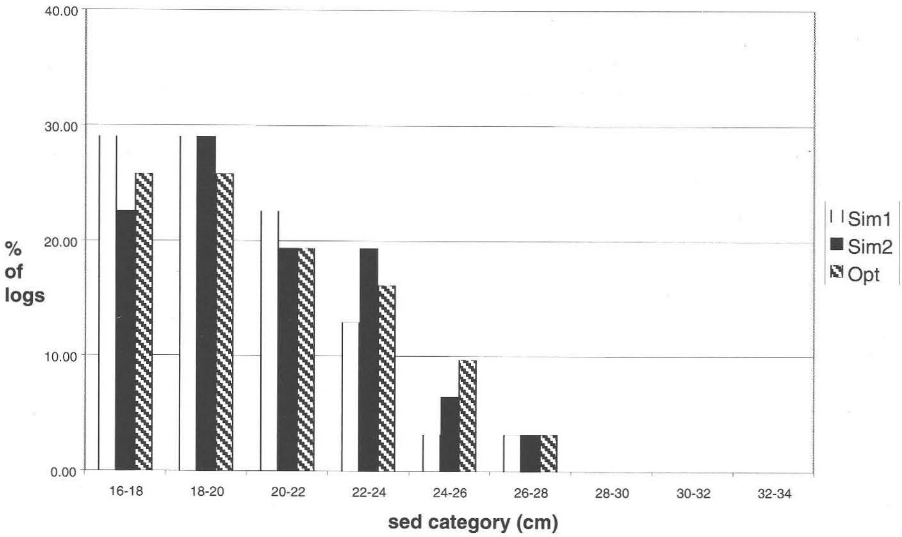

Figure 2. *Sawlog frequency distributions (in percent of number of logs) by small end diameter (sed) category for Kenmare.*

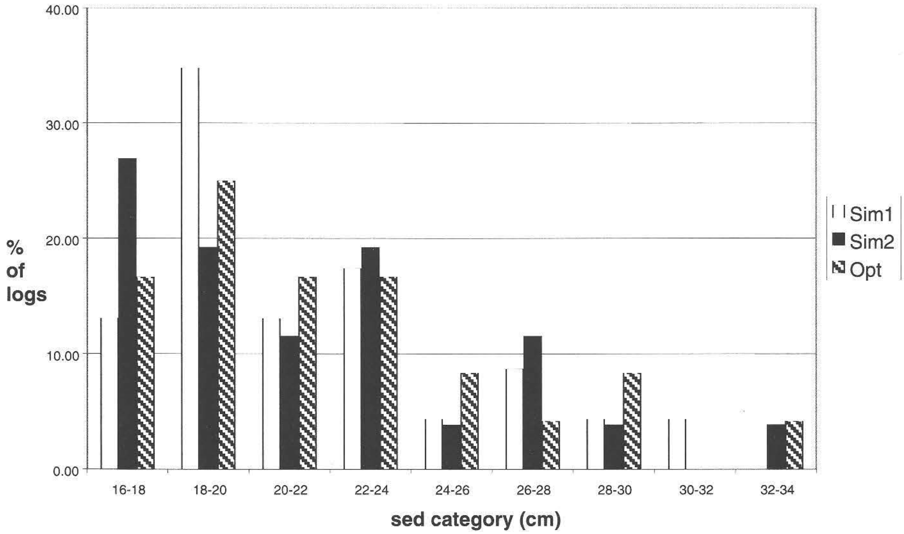

Figure 3. *Sawlog frequency distributions (in percent of number of logs) by small end diameter (sed) category for Inchigeelagh.*

4.2 The new sites

Data from four new sites were analysed. As these data were not used during the development of the simulation procedure, and as some of these stands were outside of the range of data used in the development of the taper equation, the objective was to evaluate how well the procedure would perform under these circumstances. The breakdown of the total volume and of the log count into the assortment categories for the four sites is presented in Tables 7 to 10.

The estimates of total volume by the simulator for the Kenmare site (Table 7) were too low (by 7.6% for Sim1 and 3.4% for Sim2) compared to the optimal value. However, the simulator estimates for percent volume breakdown, for total log count and for percentage breakdown of total log count into the assortments were accurate, especially for the sawlog category.

Both the sawlog volume and log count estimates as well as the sawlog percentage estimates for the Bandon site (Table 8) were over-estimated by the simulator by about 2 or 3%, while the pallet category was generally under-estimated.

Again the simulator over-estimated the sawlog component of the Ballingeary stand as shown in Table 9, in terms of both volume and number of logs. This is especially the case where both the taper equation and the dbh/height model were used (i.e. Sim2 results). This indicated that the height sample trees, used to establish the dbh/height relationship, did not fully represent the stand.

Table 7. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Kenmare validation data set (Sitka spruce clearfell, 38 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	2.36	2.67	13.78	18.81
Volume (m^3)	Sim2	2.36	3.15	14.16	19.67
	Opt	2.12	3.33	14.92	20.37
	Sim1	13	14	73	100
Volume (%)	Sim2	12	16	72	100
	Opt	11	16	73	100
	Sim1	64	47	53	164
# of logs	Sim2	60	52	53	165
	Opt	54	52	55	161
	Sim1	39	29	32	100
Logs (%)	Sim2	36	32	32	100
	Opt	34	32	34	100

Table 8. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Bandon validation data set (Norway spruce clearfell, 48 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	2.46	3.46	26.56	32.48
Volume (m^3)	Sim2	2.27	3.00	26.47	31.74
	Opt	2.25	3.77	25.05	31.07
	Sim1	7	11	82	100
Volume (%)	Sim2	7	10	83	100
	Opt	7	12	81	100
	Sim1	54	48	86	188
# of logs	Sim2	52	45	87	184
	Opt	52	55	83	190
	Sim1	29	25	46	100
Logs (%)	Sim2	28	25	47	100
	Opt	27	29	44	100

The estimates for percentage sawlog volume and percentage sawlog count for the Dunmanway thinning site were very accurate (Table 10). The assortment and total log count estimates of the simulator, specifically the Sim2 estimates, were very high compared to the optimal values, especially the pulp log count. This indicated that the combination of the generic taper equation (developed for clearfell sites) with the dbh/height model overestimated the upper dimensions of the stems at this thinning site.

Table 9. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Ballingeary validation data set (Sitka spruce clearfell, 33 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	1.69	2.20	16.98	20.87
Volume (m^3)	Sim2	1.54	2.01	17.64	21.19
	Opt	1.51	2.55	16.13	20.19
	Sim1	8	11	81	100
Volume (%)	Sim2	7	10	83	100
	Opt	7	13	80	100
	Sim1	37	32	52	121
# of logs	Sim2	36	30	55	121
	Opt	35	38	51	124
	Sim1	31	26	43	100
Logs (%)	Sim2	30	25	45	100
	Opt	28	31	41	100

Table 10. *Assortment breakdown of volume and number of logs, by quantity and percent, for the Dunmanway validation data set (Sitka spruce thinning, 47 trees).*

Units	*Procedure*	*Pulp*	*Pallet*	*Sawlog*	*Total*
	Sim1	2.80	3.22	14.16	20.18
Volume (m^3)	Sim2	3.04	2.88	15.02	20.94
	Opt	2.64	2.88	14.14	19.66
	Sim1	14	16	70	100
Volume (%)	Sim2	14	14	72	100
	Opt	13	15	72	100
	Sim1	72	56	66	194
# of logs	Sim2	80	53	71	204
	Opt	68	50	64	182
	Sim1	37	29	34	100
Logs (%)	Sim2	39	26	35	100
	Opt	38	27	35	100

The sawlog frequency tables for the four new data sets are presented in Figures 4 to 7. Overall there was a very close similarity between the estimates produced by the simulator and the optimal values produced using the detailed stem measurement data.

Both the Sim1 and Sim2 estimates for the 18-20 cm sed category (Figure 4, Kenmare data) were too high. The estimates for the Bandon Norway spruce stand (Figure 5) were very accurate over the full range of sed categories, while for the Ballingeary data (Figure 6) the only discrepancy in the estimates was a transfer of logs from the 18-20 cm sed category to the 20-22 cm category. The accuracy of the estimates for the Dunmanway thinning site (Figure 7) was remarkable, as this stand was outside of the range of stand types on which the procedure (i.e. the taper equation and the dbh/height model) was based.

The average sawlog volumes as estimated by the simulator and calculated by the optimiser for the four new sites are presented in Table 11. The Kenmare, Bandon and Ballingeary Sim2 estimates were all very accurate (within 2% of the real values), while the Sim2 estimate for the Dunmanway thinning operation was within 4% of the Opt value. It is interesting to note that the Sim2 estimates (i.e. estimates based on the use of both the taper equation and the dbh height equations) for Kenmare, Bandon and Ballingeary were more accurate than the ones based on the taper equation and actual height data (i.e. the Sim1 estimates). Only in the case of the Dunmanway thinning site were the Sim1 estimates more accurate than those produced using the Sim2 procedure.

Table 11. *Average sawlog volume (in m^3 log^{-1}) for the four new data sets, as estimated by the simulator and as calculated by the optimal cross-cutting procedure.*

Site	*Sim1*	*Sim2*	*Opt*
Kenmare	0.260	0.267	0.271
Bandon	0.309	0.304	0.302
Ballingeary	0.326	0.321	0.316
Dunmanway	0.215	0.212	0.221

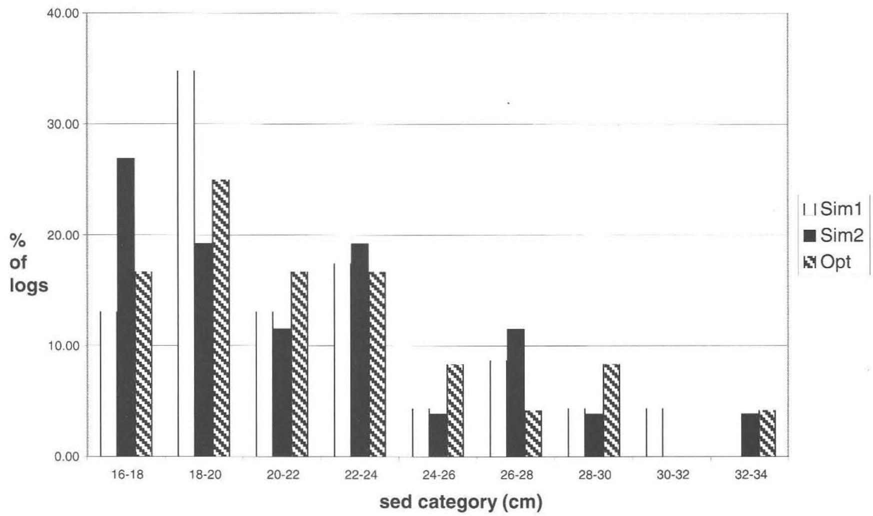

Figure 4. *Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Kenmare (Sitka spruce clearfell).*

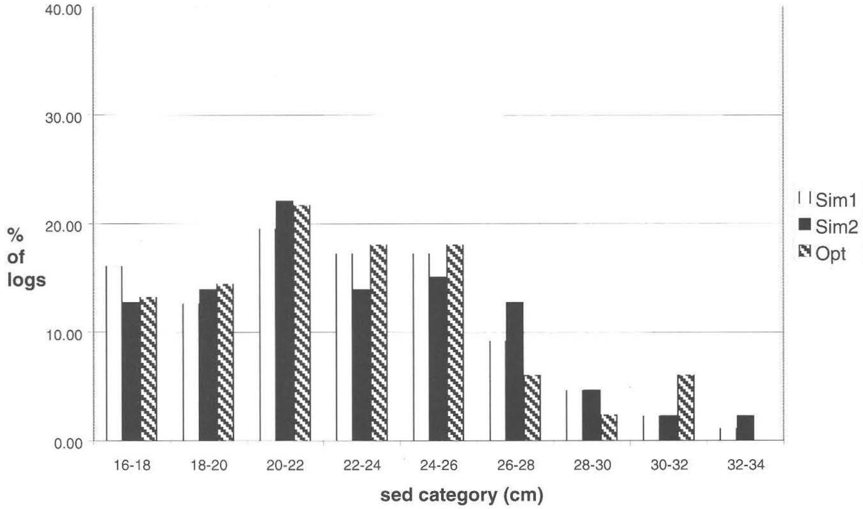

Figure 5. *Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Bandon (Norway spruce clearfell).*

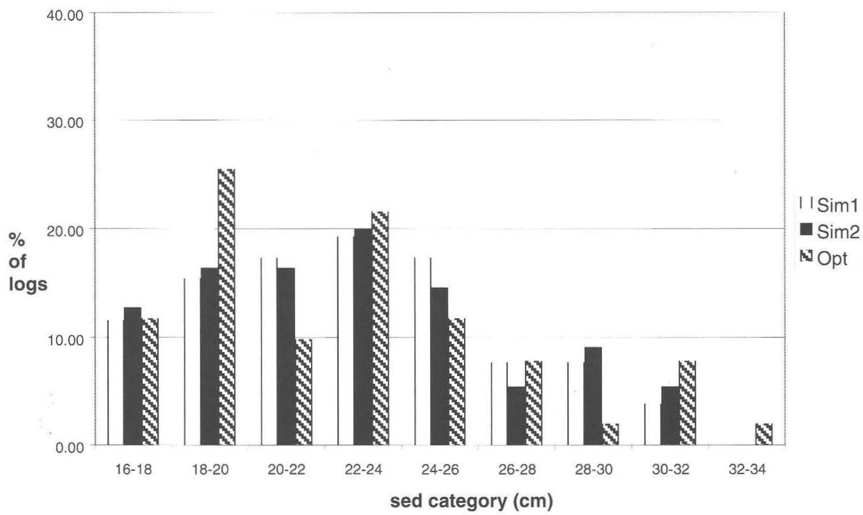

Figure 6. *Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Ballingeary (Sitka spruce clearfell).*

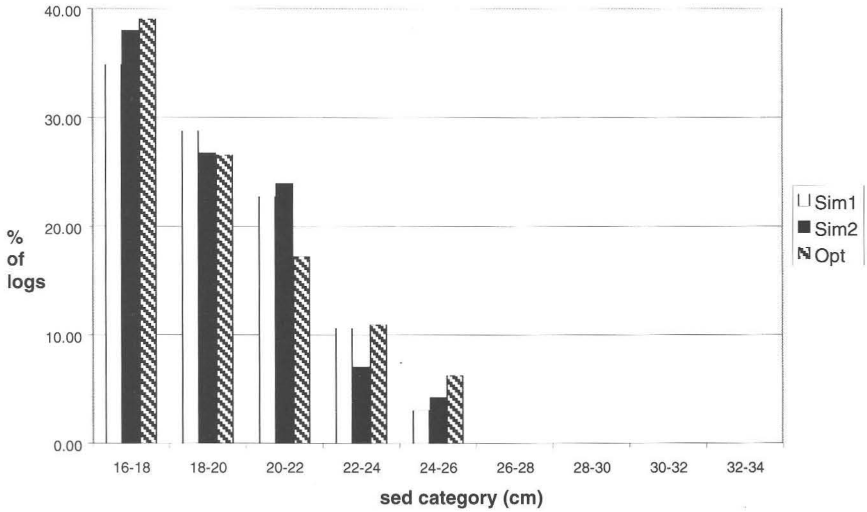

Figure 7. *Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Dunmanway (Sitka spruce thinning).*

5. Discussion

This article describes the development and evaluation of a pre-harvest inventory and cross-cutting procedure for use in sawmill timber procurement. The system was designed to enable the procurement manager to identify the best combination of log types to harvest from Sitka spruce clearfell stands so as to accurately value the stand for tendering purposes and to maximise the value of the timber produced. The use of the procedure involves the collection of tree dbh and height data from a stand and the subsequent processing of these data, together with log assortment specification data, by the cross-cutting simulator. The combination of a generic taper equation and a site-specific dbh/height equation worked well with a sufficiently large dbh data set and with a dbh/height data set of 10 trees. The overall procedure allows for a cost-efficient data collection and stand valuation process.

The inventory and cross-cutting procedure was developed with data from five Sitka spruce stands in west Munster which were scheduled for clearfell and which were of the requisite size and quality for Palfab Limited, the sawmill involved in the study. The evaluation process has given some indication of the applicability of the procedure outside of these confines. The procedure produced accurate results for a wide range of stand types, including ones that were not part of the development and testing phase (i.e. the Norway spruce clearfell in Bandon and the Sitka spruce thinning in Dunmanway), if sufficiently large data sets were used. The validation data sets, consisting of only around 20 trees each, were clearly too small to produce very accurate estimates, even though they contained data from the same stands that were used in the model development process. The four new data sets, consisting of between 33 and 48 trees, on the other hand, produced very accurate estimates for volume, number of logs and average log size.

One factor that has been identified as contributing to the over-estimation of the volumes by the simulator is that the diameter estimates from the taper equation include fractions of millimetres, whereas the optimiser uses values truncated to the nearest millimetre. Especially in the case of the sawlog assortment (with its larger dimensions), this had a noticeable impact on the resulting volume calculations.

The use of a fixed dbh/height model generates a single height estimate per dbh class. This approach ignores the fact that, within a stand, height can vary for a given diameter. A more realistic description of the relationship between dbh and tree height within a managed stand would include variation in the values of height generated by the dbh/height model for a given diameter. This could be achieved with the use of probability density functions, as proposed by Schreuder and Hafley (1977) or the mixed models of Lappi (1991) and Uusitalo (1995).

Assessment of stem quality is not currently included in the inventory and cross-cutting procedures. The generally uniform, high quality stems within a well-managed Sitka spruce stand at the clearfell stage, resulting in a low proportion of downgrade, makes the cost of inclusion of detailed quality information during the inventory process unwarranted. However, the future inclusion of stem quality information in the cross-cutting simulation procedure would not cause any technical problems.

A further aspect which has kept the development and implementation of the procedure relatively simple is the omission of optimisation technology. Internationally, optimal stem cross-cutting is a key component of the process of maximising the value of logs produced in harvesting operations (Deadman and Goulding, 1979; Olsen *et al.*, 1991 & Uusitalo, 1995). However, in a situation where trees are of limited size, are comparatively low in value, where a limited number of log types are cut in any one stand, and where logs of a particular type are valued *en masse* regardless of variation in quality, the value of stem optimisation is limited. It seems unlikely that the additional costs associated with optimal cross-cutting, in terms of lost productivity arising from the need for intensive stem measurement at the stump, could, in the current situation, be justified by the increase that could be achieved in the value of timber recovered. However, the introduction of mechanised harvesters has the potential to change this. Harvester measurement systems are used extensively by Irish harvesting contractors for recording volume production figures. Modern measurement systems, such as the Ponnse *Opti* and Timberjack *3000*, also include (limited) stem optimisation capabilities. These systems predict the profile of each stem based upon the initial length of the stem fed into the head together with complete diameter measurements from trees of the same species previously processed in the stand. However, the functions used at present to predict stem profile are relatively simplistic. The introduction of sophisticated taper equations and dbh/height models (as developed in this project) in the harvester computer systems could greatly enhance their value maximisation capabilities.

It should be remembered however, that in Ireland the number of different types and lengths of logs that are cut in any one stand in the course of a harvesting operation is relatively small. As few as three permissible log lengths may be cut in the case of a clearfell operation. This lack of flexibility in the choice of logs to cut from a stem or stand limits the potential for achieving greater value recovery. However, a continuation in the recent spate of acquisitions within the sawmilling industry may change this. Individual stands may be purchased to supply timber to several sister mills, thus increasing the number of products cut in any one operation and, with it, the scope for improved utilisation of the timber resource. The optimal cross-cutting systems of modern harvesters, using accurate taper and dbh/height models, would greatly facilitate such an approach to harvesting.

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APPENDIX

Kozak 1992 taper equation:

$\ln(d/D) = f\ \{\ln(X)\ X^6, \ln(X)\ X^2\ (D/H_s), \ln(X)\ X^3\ (D/H_s), \ln(X)\ X\ (D/H_s)^2, \ln(X)\ X^2\ (D/H_s)^2, \ln(X)\ (1/h), \ln(X)\ (H_s/\text{Ö}h), \ln(X)\ (H_s^2/Dh)\}$

where:

X	=	$(H_s\text{-}h)/(H_s\text{-}H_{bh})$;
D	=	diameter at breast height;
d	=	diameter at height h;
H_s	=	total length of felled stem;
H_{bh}	=	distance from butt end to breast height mark (on felled tree);
h	=	distance from butt end at which diameter is estimated.

Curtis 6 dbh-height model:

$\ln(H) = f\ \{1/D\}$

where:

H	=	total height of standing tree;
D	=	diameter at breast height.