The Development and Validation of Pre-Harvest Inventory Methodologies for Timber Procurement in Ireland

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This article describes the development and validation of a decision-support system for sawmill wood procurement, dealing specifically with the integration of the pre-harvest inventory procedures, site-specific dbh/height models and a generic taper equation, with a crosscutting simulator. The crosscutting simulation program faithfully mimics the process of cut-to-length harvesting and provides detailed information on the potential volume, logs count and diameter distributions for different log assortment specifications. Four data sets, consisting of a total of 4153 diameter and height measurements, were used in the validation process. The sites included two Sitka spruce clearfells, a Sitka spruce thinning and a Norway spruce clearfell. The evaluation process has shown that the developed decision-support system produced accurate results for a wide range of stand types, as long as sufficient large data sets were used, and that it provides the wood procurement manager of a sawmill with an efficient means of gaining a comprehensive insight into the yield potential of standing timber lots and, as such, represents a valuable aid to timber procurement and production planning.

Keywords pre-harvest inventory, value maximisation, optimal crosscutting, simulation, dynamic programming

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1 Introduction

The three cornerstones of profitability of harvesting and sawmill operations are maximisation of volume, 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 was not given enough attention (Murphy et al. 1991). In order for the wood procurement manager of a sawmill 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 total volume but, more succinctly, on the volume, the number and the diameter classes of different types of log assortments that could potentially be cut from a stand (Uusitalo 1995).

Advances in and the wider availability of computer technology in recent decades has seen the development of sophisticated approaches to predicting timber yields prior to harvesting. Although many developed applications have remained academic, some have become the basis of operational systems that are used to predict harvest yields and to improve pre-harvest planning and decision-making processes. MARVL, the Method for the Assessment of Recoverable Volume by Log-types (Deadman and Goulding 1979, Deadman 1990), was developed in New Zealand, where it now receives widespread use as a means of predicting the volume and dimensions of log grades that a stand could potentially yield. Eng et al. (1986) found that conventional formulations that maximise the value of individual stems or stands may result in a serious discrepancy between the required volume of certain types of logs and that actually produced. Consequently, the authors addressed the challenge of prescribing, subject to both resource and demand constraints, an appropriate crosscutting strategy for an entire forest stand. Sessions et al. (1989) also discovered that value maximisation on a stem-by-stem basis often failed to produce the desired log distribution at stand level. In response, the authors developed a heuristic procedure which achieved near-maximum stand value subject to log volume constraints. Olsen et al. (1991) extended these techniques to develop a pre-harvest analysis programme to estimate optimal log crosscutting and allocation strategies.

In 1997 a research project was initiated in Ireland to develop a decision-support system 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 system 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. The development process consisted of the following tasks (Nieuwenhuis and Malone 1999):

1) Design an efficient inventory procedure, including a stand specific dbh/height model, to collect data on the dimensional properties of a standing timber lot prior to sale or harvesting (Malone 1998);
2) Develop a generic taper-estimating system to provide accurate predictions of stem diameter applicable to mature Sitka spruce (*Picea sitchensis* (Bong.) Car.) stands harvested by Palfab (Malone 1998);
3) Develop a computer programme that employs stand specific inventory data and the generic taper equation to forecast the volume and value yield and dimensions of potential log products from a stand (Malone 1998, McHugh 1999);
4) Evaluate the developed system, using data from a variety of stands (McHugh 1999).

This article introduces the results of research into tasks 1 and 2, and discusses in detail the research associated with tasks 3 and 4.

2 Material and Methods

2.1 The Inventory Methodology and Generic Taper Equation

Research into task 1 involved the evaluation of 8 potential dbh/height models, namely the Peterson model (Levack 1986), the Näslund model (Uusitalo 1995), and 6 models proposed by Curtis (1967). The evaluation process resulted in the selection of the site-specific Curtis 6 dbh/height model, in combination with a sample size of 10 (randomly selected) height trees, as the basis of the inventory procedure. Research into task 2 involved the evaluation of four basic taper models, namely the variable-form model of Newnham (1988), a slight variant of this model (Newnham 1992), the variable-exponent model of Kozak (1988), and a modification of this model, proposed by Newnham (1992) but referred to hereafter as Kozak 1992. As a result of this evaluation, the Kozak 1992 model was selected as the generic taper equation for inclusion in the decision-support system. It should be noted that the statistical procedures used in the above evaluations did not take into account the correlation between stem forms of trees in the same stand, or between diameters along the same stem.

2.2 The Development of a Cut-to-Length Simulator

A computer program was developed with the Visual Basic for Applications (VBA) programming language to simulate the process by which stems are converted into logs at the stump (Malone 1998). No programming skill or specific computer knowledge is required to operate the system. The graphical user interface allows the user to readily access each part of the system (McHugh 1999). The programme requires from the user:

- inventory data in the form of a dbh value for each sample tree and values of both dbh and height for each height sample tree;
- a prioritised list of up to 12 log types, specifying, for each, its length and minimum small-end diameter and the corresponding value per cubic metre;
- an estimate of average stump height for the stand.

The developed inventory procedure, including the selected dbh/height model, together with the selected taper equation and the cross-cut simulator, were integrated into a decision-support system. The simulator program reads in the dbh associated with each sample tree, in addition to the dbh and total height (H_t) of each height sample tree. The latter are employed in a regression analysis, using the Curtis 6 model, to estimate the site-specific coefficients of the diameter-height equation (Equation 1). This equation is then used to predict the height of each of the remaining dbh sample trees. The stump height is deducted from the predicted height to give the length of the felled stem (H_s). The subsequent use of the generic Kozak 1992 taper equation allows for the diameter to be estimated at any point on the tree stem (Equation 2).

$$\ln(H_t) = f\{D^{-1}\} \tag{1}$$

$$\begin{aligned}\ln(d/D) = f\{&\ln(X)X^6,\ \ln(X)X^2(D/H_s),\\ &\ln(X)X^3(D/H_s),\ \ln(X)X(D/H_s)^2,\\ &\ln(X)X^2(D/H_s)^2,\ \ln(X)(1/h),\\ &\ln(X)(H_s/\sqrt{h}),\ \ln(X)(H_s^2/\sqrt{h})\}\end{aligned} \tag{2}$$

where:

X = $(H_s - h)/(H_s - H_{bh})$;

D = diameter at breast height (i.e. at 1.3 m above ground level);

d = diameter at height h;

H_t = total height of the tree;

H_s = total length of felled stem;

H_{bh} = distance from butt end to breast height (on felled tree);

h = height above ground level at which diameter is estimated.

The crosscutting simulation program uses the greedy algorithm approach (Hu 1982), which is based on the principle of local optimisation. It always attempts to "cut" the highest value log type from the sample trees by comparing the diameter of its stem at a distance from its butt equal to the length of the log. If this diameter is greater than or equal to the minimum permissible small-end diameter for that log type, the log is cut, its volume is calculated with Smalian's formula and it is assigned to one of a number of small-end diameter categories. The programme then attempts to cut another of the highest value logs from the remainder of the stem in a similar fashion. In the event that the stem diameter is less than the permissible small-end diameter value, the programme attempts to cut a log of the next highest value. This process is repeated for the first sample tree until either all log types have been considered or a diameter less than 70 mm is reached on the stem. Once either of the above events occurs, the programme moves onto the next sample tree and recommences the simulated cutting action. The programme terminates when all sample trees have been evaluated. The results generated for each analysis include:

- the total volume of each log type;
- the total value of each log type;
- the total number of pieces of each log type;
- the mean volume per log of each log type;
- the number of pieces of each log type that lie in each sed category;
- the volume of each log type that lies in each sed category.

2.3 Validation Data

The generic taper equation, the dbh/height model and the inventory procedures were developed based on data consisting of 5543 observations of diameter and height, made on 246 stems, from

Table 1. Characteristics of the four stands used in the validation process (where SS = Sitka spruce, NS = Norway spruce, CF = clearfell, TH = thinning).

Stand	Forest	Planting year	Yield clas ($m^3ha^{-1}an^{-1}$)	Mean DBH (cm)	Specles and harvest type	Number of sample trees
1	Kenmare	1958	18	24	SS/CF	38
2	Bandon	1953	20	27	NS/CF	48
3	Ballingeary	1952	16	29	SS/CF	33
4	Dunmanway	1958	20	24	SS/TH	47

five Sitka spruce (SS) stands at the time of clearfell. The standing timber lots were considered to be representative, with respect to mean dbh, mean tree volume and location, of those normally purchased by the mill. Four additional data sets, consisting of a total of 4153 diameter and height measurements, were used in the validation process (Table 1). The sites included two Sitka spruce clearfells (SS/CF), a Sitka spruce thinning (SS/Thinning) and a Norway spruce (*Picea abies* (L.) Karsten) clearfell (NS/CF). An identical data collection procedure was followed in each stand. The diameter overbark at breast height was measured, in millimetres, for all sample trees with the aid of an electronic calliper. The point at which this measurement was taken was marked on the standing tree so as to provide a means of determining stump height. All trees received a unique number to allow for future identification. The trees were subsequently felled and the stems delimbed to facilitate the measurement of diameter overbark. Diameter 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, to an approximate top diameter of 70 mm. In addition, the lengths, to the nearest centimetre, from the butt to the breast height mark and to the tip were also recorded.

2.4 The Validation Process

2.4.1 The Generic Taper Equation

Using actual (as measured on the tree) and predicted (as generated by the taper equation) diameter value, it was possible to calculate statistically the accuracy of these diameter predictions. This was done on a site by site basis, first for all diameters together, next for the diameters at each measurement location on the stem separately. Paired t-tests were used to establish whether significant differences existed between measurements and predictions. A total of 3788 pairs of measurements and predictions were included in these tests.

2.4.2 The Decision-Support System

In order to get an overview of the accuracy of the results produced by the developed decision-support system, data from the four validation stands were analysed. These data were processed by both the decision-support system (using the greedy algorithm approach) and by an optimal crosscutting program, which used a dynamic programming algorithm with the forward-solution procedure (Hillier and Lieberman 1980, Dykstra 1984). The algorithm is based on the following recursive relationship:

$$f_i^*(s) = \max_{x_i}\{v_i(s,x_i) + f_{i-1}^*(s - x_i)\}$$

where

$f^*_i(s)$ = value associated with optimal policy for all previous stages, including stage i, given that the process has reached state s at end of stage i (with $f^*_0(s) \equiv 0$);

x_i = any state in stage i into which current state s could be transformed;

$v_i(s,x_i)$ = value of the log x_i meters in length, associated with state s at stage i;

$f^*_{i-1}(s-x_i)$ = value associated with optimal policy for all stages previous to the start of stage i, given that the process will have reached state x_i at end of stage i.

Näsberg (1985) reported on the importance of identifying the context in which dynamic programming techniques are employed in tree bucking optimisation, as the resulting strategies will be optimal only for the specific set of parameters included in the analysis. The dynamic programming software developed for this study utilised large numbers of detailed stem measurements and concise log assortment values and dimensions in the optimisation process. As a result, the output produced by this process was assumed to be optimal in the context of this study. The volume and value recovery results obtained using the inventory and crosscutting simulation procedures were evaluated against these optimal results.

The data used in the decision-support system only consisted of the dbh measurements on all trees in the sample and the height measurements on the height sample trees. These data were processed by the decision-support system in the following steps:

1) The data of 10 randomly selected height sample trees, consisting of the dbh and height measurements, were inputted in the dbh/height regression model (i.e. the Curtis 6 model). The output consisted of the regression coefficients of the model's independent variables.
2) The data of the dbh sample trees, consisting of the dbh measurements of the remaining trees in the data set, were inputted into the dbh/height model as generated in step (1) and an estimate of the height was produced for each tree.
3) The combined data set, consisting of a dbh measurement and a height measurement or estimate for every tree, was inputted into the crosscutting simulator, together with the assortments specifications (Table 2). The simulator used the generic Kozak 1992 taper equation to estimate the diameter of the tree at any point along the stem.
4) In order to be able to evaluate the individual impact on the accuracy of the results of the taper equation estimates and the dbh/height equation estimates separately, 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 decision-support system when compared with the optimal crosscutting results.

Table 2. Standard log specifications employed in the validation of the candidate taper equations.

Product	Log length (m)	Minimum sed[a] (mm)	Value (IR£/m^3)
Sawlog	5.5	160	40
Palletwood	2.5	120	15
Pulpwood	3.1	70	5

[a]Small-end diameter

The data used in the dynamic programming procedure consisted of all detailed stem measurements as outlined in section 2.3. These data were reformatted to be compatible with the computer program. The procedure also required the assortment specifications as given in Table 2. The dynamic programming algorithm determined the optimal crosscutting strategy for each stem and the output of the optimiser consisted of individual crosscutting patterns for each stem. In addition, these individual results were combined into frequency tables that were compatible with the ones produced by the simulator.

The output frequency tables produced by the simulator (both for the combination of taper equation and real heights (Sim1) as well as for the combination of taper equation and dbh/height equation (Sim2)) and by the optimiser (Opt) were compared in detail. Differences between Sim1 and Sim2 results were analysed to evaluate the performance of the dbh/height model. The differences between the Sim2 results and the results produced by the optimiser were used to evaluate the performance of the overall system. First of all, the breakdown of total volume into the different assortments was examined on a cubic metre and on a percentage basis. Similarly, the breakdown of the total log count into the numbers of logs in each of the assortment categories was analysed (both on a number and a percentage basis). This gave a clear indication of the capacity of the decision-support system 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

Table 3. Statistics associated with comparisons of measured and predicted diameters for the 4 validation sites (where SS = Sitka spruce, NS = Norway spruce, CF = clearfell, TH = thinning)

	Kenmare	Bandon	Ballingeary	Dunmanway
Species/Harvest type	SS/CF	NS/CF	SS/CF	SS/TH
Mean of measured diam. (mm)	190.8	215.8	211.9	176.6
Mean of predicted diam. (mm)	187.9	216.3	211.5	179.2
Bias (mm)	–2.9	+0.5	–0.4	+2.6
t-value (calculated)	–5.475	+1.030	–0.511	+5.108
t-value (tabulated, 95%)	±1.962	±1.962	±1.962	±1.962
Significant difference	yes	no	no	yes

diameter (sed) categories. The capacity of the decision-support system to predict the correct sed frequency distributions within the general sawlog assortment was important, as this provides the wood procurement manager with the information needed to accurately value a stand and to predict the best possible combination of assortments to cut from a specific stand. The final step involved the investigation of the suitability of the decision-support system for other types of analysis (e.g. sensitivity analysis). As an example of this type of "what if?" analysis, the impact of the introduction of an additional (high value) assortment on the value recovery for each of the four validation data sets (with their different diameter and height distributions) was investigated.

3 Results

3.1 The Validation of the Generic Taper Equation

The results of the paired t-tests on a site by site basis for all diameter measurements combined (Table 3) showed that there were no significant differences between the actual and predicted diameter values for trees on the Bandon and Ballingeary sites (with diameter differences of approximately 0.5 mm). For the Kenmare and Dunmanway sites the differences (approximately 3 mm) were significant. However, from a practical viewpoint these differences were very small. If diameters had been recorded to the nearest cm (as is normal in the standard inventory procedures), the differences would not have been significant.

When the paired diameter values were compared on the basis of the locations along the stem where the measurements were taken, the results indicated that for all four sites the taper equation generally produced accurate results, with significant differences for only short sections of the stems (Table 4). In all cases, these differences did not have a large impact on the important estimation of sawlog size and quantity, as they occurred at the upper sections of the stems. The only site for which differences in diameter values in the lower part of the stem were significant was Bandon, where the equation produced over-estimates for the 2 m and 3 m sections. As this was a Norway spruce stand this was not surprising, and even here the bias at the 5 m and 6 m points (on either site of the potential 5.5 m cut) was not significant. The taper equation also produced under-estimates for the 14 m to 17 m stem sections at the Bandon site. For the Kenmare site, the taper equation significantly under-estimated diameters at the 15 m and 16 m locations along the stems. Under-estimates were also produced for the 14 m to 18 m stem sections at the Balingeary site, while the diameters at the 10 m to 13 m sections at the Dunmanway site were significantly over-estimated.

3.2 The Validation of the Site-Specific Dbh/height Model

The appropriateness of the Curtis 6 dbh/height model to represent the relationship between dbh and height in individual stands was tested on

Table 4. Bias (mm), mean diameter (mm) and significant differences between the actual and predicted diameters at one metre intervals along the stems of all sample trees for the 4 validation sites.

Distance from the butt (m)	Kenmare		Bandon		Ballingeary		Dunmanway	
	Bias	Mean diameter	Bias	Mean diameter	Bias	Mean diameter	Bias	Mean diameter
1	6.29*	252.13	4.52	191.68	7.77	295.53	3.44	232.40
2	0.42	235.31	–6.04*	264.77	2.61	272.09	–1.42	218.44
3	–0.83	228.67	–8.01*	253.15	–4.14	254.56	–1.99	212.27
4	0.58	221.42	–3.67	248.02	–0.95	247.65	–1.02	206.34
5	0.53	215.35	–1.32	241.37	–3.11	236.18	0.44	200.34
6	1.78	207.23	–1.20	233.29	–7.06	223.71	–2.76	189.91
7	1.81	200.28	–2.00	224.83	–8.28	214.15	–3.02	182.91
8	2.10	193.84	0.13	219.16	–8.36	208.35	–3.93	175.21
9	2.05	186.76	–1.23	208.93	–3.83	207.26	–4.93	167.56
10	2.19	178.54	0.31	199.66	–4.05	193.96	–8.28*	156.78
11	2.34	169.55	1.39	190.38	–1.26	180.90	–9.17*	146.14
12	4.57	158.77	4.48	177.41	3.29	167.03	–8.44*	141.05
13	4.46	146.92	7.29	161.06	7.57	155.03	–8.49*	126.87
14	6.35	140.48	11.14*	145.31	12.53*	138.79	–4.43	119.10
15	12.65*	131.93	9.37*	126.38	11.36*	120.65	–1.75	106.95
16	11.27*	115.90	10.48*	111.34	14.16*	110.72	–2.77	90.78
17	10.97	103.42	14.16*	97.70	21.67*	104.33	–3.80	78.96
18	7.20	86.19	6.91	82.05	14.08*	81.64	–3.96	70.61
19	2.26	68.18	7.52	77.62	13.29	75.10	0.71	68.27

Note: an asterisk beside a bias value indicates a significant difference between the actual and predicted diameter at the 95% confidence level. Positive values of bias indicate under-estimation, negative values indicate over-estimation.

Table 5. Results of the regression analysis (at 95% confidence level) for the 4 validation sites, using the Curtis 6 model $\{\ln(H_t) = a + b\,(D^{-1})$, with H_t in metres and D in millimetres$\}$ with 10 randomly selected height sample trees.

Site	R^2	'a' estimate (p > t)	'b' estimate (p > t)
Kenmare	0.85	3.510 (0.0001)	–108.517 (0.0001)
Bandon	0.74	3.455 (0.0001)	–126.905 (0.0014)
Ballingeary	0.71	3.299 (0.0001)	–96.834 (0.0021)
Dunmanway	0.84	3.587 (0.0001)	–128.217 (0.0002)

data from each of the four validation sites, by generating sets of 10 randomly selected height sample trees and performing regression analysis using each set. The analysis produced highly significant regression models with R^2 values ranging between 0.70 and 0.85 (Table 5). The evaluation of the capability of these models to produce, in combination with the developed inventory procedures and the generic taper equation, accurate stand-level volume and value estimates could only be performed as an integral part of the validation process of the overall decision-support system and is therefore included in the next section. Differences between the Sim1 and Sim2 results indicate how accurate the model height estimates for all dbh sample trees were compared to the real height measurements, while comparisons with the Opt results indicate the accuracy of the estimates produced by the combination of the generic taper equation and site-specific dbh/height models.

3.3 The Decision-Support System

The breakdown of the total volume and of the log count into the assortment categories for the four validation sites is presented in Tables 6 to 9. The estimates by the simulator of total volume for the Kenmare site (Table 6) were too low by 7.6% for Sim1 and 3.4% for Sim2 compared to

Table 6. Assortment breakdown of volume and number of logs, by quantity and percent, for validation data set of Kenmare (SS/CF, 38 trees).

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

Table 7. Assortment breakdown of volume and number of logs, by quantity and percent, for the validation data set of Bandon (NS/CF, 48 trees).

Units	Procedure	Pulp-wood	Pallet-wood	Sawlog	Total
Volume (m^3)	Sim1	2.46	3.46	26.56	32.48
	Sim2	2.27	3.00	26.47	31.74
	Opt	2.25	3.77	25.05	31.07
Volume (%)	Sim1	7	11	82	100
	Sim2	7	10	83	100
	Opt	7	12	80	100
Logs (#)	Sim1	54	48	86	188
	Sim2	52	45	87	184
	Opt	52	55	83	190
Logs (%)	Sim1	29	25	46	100
	Sim2	28	25	47	100
	Opt	27	29	44	100

Table 8. Assortment breakdown of volume and number of logs, by quantity and percent, for validation data set of Ballingeary (SS/CF, 33 trees).

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

Table 9. Assortment breakdown of volume and number of logs, by quantity and percent, for the validation data set of Dunmanway (SS/Thinning, 47 trees).

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

the optimal value. However, the decision-support system estimates for percentage 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 volume and percentage sawlog estimates, as well as the estimates for the number and percentage of sawlog logs, for the Bandon site were over-estimated by the decision-support system by about 2 or 3%, while the pallet category was generally under-estimated (Table 7). The decision-support system over-estimated the sawlog component and under-estimated the pallet component of the Ballingeary stand, both in terms of volume and number of logs (Table 8). This was especially the case where both the taper equation and the dbh/height model were used (i.e. Sim2 results). This indicated that the specific set of 10 height sample trees, used to establish the dbh/height relationship, did not adequately represent the stand. The estimates for percentage sawlog volume and percentage sawlog count for the Dunmanway thinning data were very accurate (Table 9). The assortment and total log count estimates of the decision-support system, specifically the Sim2 estimates, were very high compared to the optimal values, especially the pulp log count. This indicated that the combination of

Table 10. Average sawlog volume (in m^3 log^{-1}) for the 4 validation data sets, as estimated by the decision-support system and as calculated by the optimal crosscutting 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

Table 11. Values per stem and percentage value increase for the four validation sites under the three and four assortment scenarios.

Site	Value per stem (IR£) 3 assortment scenario	 4 assortment scenario	% value increase for the 4 assortment scenario
Kenmare	17.27	19.31	11.8
Bandon	22.29	25.23	13.2
Ballingeary	20.94	23.18	10.7
Dunmanway	13.24	14.25	7.7

the generic taper equation (developed for clearfell sites) with the dbh/height model, over-estimated the (upper) dimensions of the stems. The fact that the taper equation generally over-estimated the diameters of the trees in the Dunmanway stand was already shown in Table 4.

In Table 10 the average sawlog volumes, as estimated by the decision-support system and calculated by the optimiser, for the 4 validation sites are presented. The Kenmare, Bandon and Ballingeary Sim2 estimates were all very accurate (within 2% of the Opt 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.

The sawlog frequency tables for the 4 validation data sets are presented in Figures 1 to 4. Overall there was a very close similarity between the estimates produced by the decision-support system and the optimal values produced from the detailed stem data. For the Kenmare site both the Sim1 and Sim2 estimates for the 18–20 cm sed category were clearly too high (Fig. 1). The estimates for the Bandon Norway spruce stand (Fig. 2) were very accurate over the full range of sed categories, while in the Ballingeary data (Fig. 3) the only discrepancy in the estimates seemed to be 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 (Fig. 4) was remarkable, as this stand was completely outside of the range of stand types on which the procedure (i.e. the combination of taper equation and dbh/height model) was based. However, as the operation on this site involved a thinning from below, the trees that were removed were selected from narrower and more uniform dbh and height ranges than those for all trees in the stand.

The above validation analyses were carried out using only three assortments (i.e. pulp, pallet and sawlog as outlined in Table 2). To investigate the suitability of the developed system to provide valuable sensitivity information, the benefit of increasing the number of potential assortments in a stand was analysed. The factor considered in this analysis was the increase in value per stem as a result of including an additional high value assortment, for instance a large sawlog specification (i.e. length 6.1 m, minimum sed 18 cm, value IR£50/m^3). The stand best suited to this new assortment (i.e. the Bandon stand) obviously benefited most from this change (Table 11). The value per stem in the thinning site (i.e. Dunmanway) was least affected by the introduction of this assortment, as a majority of stems in this stand were too small to accommodate this new log specification. The increase in value recovery, as a result of the introduction of the new assortment, has to be evaluated against the potential for higher crosscutting and handling costs associated with this increase in decision-making and operational complexity.

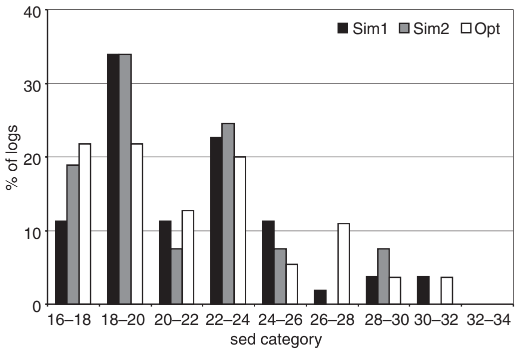

Fig. 1. Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Kenmare (SS/CF).

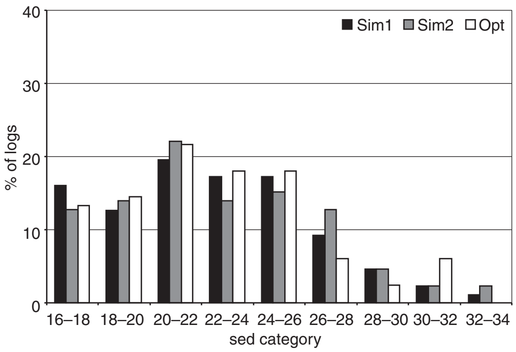

Fig. 2. Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Bandon (NS/CF).

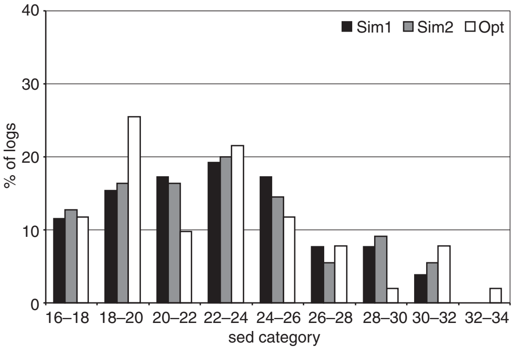

Fig. 3. Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Ballingeary (SS/CF).

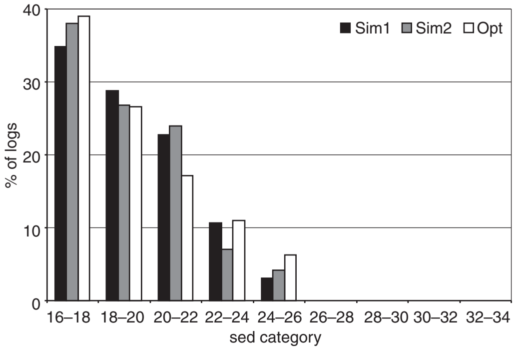

Fig. 4. Sawlog frequency distribution (in percent of number of logs) by small end diameter (sed) category for Dunmanway (SS/Thinning).

4 Discussion

This article describes the development of a cross-cutting simulator and the subsequent validation and integration of this simulator and pre-harvest inventory procedures into a decision-support system for use in timber procurement. The system was designed to enable the procurement manager of a sawmill 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 inventory procedures were developed with data from five Sitka spruce stands which were scheduled for clearfell and which were of the correct size and quality for the sawmill involved in the study. The validation process has shown that if sufficient large data sets are used, the developed system produced accurate results for stands that were not part of the development and testing process (i.e. the Norway spruce stand in Bandon and the Sitka spruce thinning operation in Dunmanway). It should be noted that the results of this validation process for Norway spruce clearfell and Sitka spruce thinning sites were based on only one site each. However, in subsequent operational use, analyses of data from similar (diverse) stands have shown that in all cases the decision-support system produced sufficiently accurate estimates for assortment volumes, numbers of logs and log size distributions.

Internationally, optimal stem crosscutting is a key component of the process of maximising the value of logs produced in harvesting operations (Deadman and Goulding 1979, 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 together regardless of variation in quality, the value of stem optimisation is limited. The crosscutting simulator developed in the course of this research was designed to imitate current harvesting practices in Ireland. As such, it did not include a mathematical stem optimisation algorithm, such as those developed by Pnevmaticos and Mann (1972), Briggs (1977) and Bobrowski (1994). However, the introduction of modern mechanised harvesters into Irish forestry operations has the potential for changes in the crosscutting decision-making process. Currently, Irish contractors use harvester measurements only for the recording of volume production. However, modern measurement systems 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. The functions used at present to predict stem profile are however relatively simplistic. The introduction of sophisticated taper equations and dbh/height models (as developed in this project) in the harvesters' computer systems could greatly enhance their value maximisation capabilities.

It should be remembered however, that in Ireland the number of different log assortments that are cut in any one stand in the course of a harvesting operation is relatively low. 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 has limited 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" crosscutting systems of modern harvesters, using accurate taper and dbh/height models, would greatly facilitate such an approach to harvesting.

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 diameter at breast height and tree height within a managed stand would include variation in the values of height generated by the diameter-height model for a given dbh. 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).

As a continuation of this research project, the linkage of the crosscutting decision-making process with not only assortment specifications and supply parameters, but with more complex demand parameters (e.g. changing product prices, market restrictions, production constraints, etc.), as reported by Eng et al. (1986), Sessions et al. (1989) and Olsen et al. (1991), is currently being investigated in the specific context of the Irish forestry and sawmilling industries.

5 Conclusions

The developed decision support system, combining the inventory procedures, taper equation, dbh/height models and crosscutting simulator, provides a comprehensive insight into the yield potential of a stand and, in so doing, represents a valuable tool for the timber procurement manager of a sawmill. The crosscutting simulator performed rapid analyses in a familiar, user-friendly interface. It required as inputs only the dbh and height data obtained in the pre-harvest inventory, an estimation of average stump height for the stand, and details of log assortment specifications and values. The programme faithfully mimics the process of cut-to-length harvesting and generates all of the information required by the sawmill procurement manager, from conventional stand parameters to a detailed break-down of yield by product and diameter class. With the aid of this decision-support system, the most appropriate stands can be chosen, accurate valuations of these stands performed and decisions as to the best crosscutting strategy made. Integrating this system with a production planning system will allow information on sawing yields, mill-yard stock levels and the demand for and price of sawn timber to contribute further to the accurate valuation and efficient utilisation of logs, trees, stands and, ultimately, of the total timber resource.

Since the validation process was completed, the decision-support system has been in operational use by the sawmilling industry on a daily basis, for the purposes of pre-sale valuation as well as pre-harvest selection of the optimal mix of assortments. The system is relatively simple to use and is meeting the industry's requirements for accuracy, efficiency and economy. Only the conventional stand parameters of dbh and tree height are measured and standard mensuration equipment is employed. The use of electronic callipers and a laser-equipped height measuring device allows for data to be collected rapidly by one person, and for the swift transfer of this information to a computer for subsequent analysis.

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