MODEL FOR PREDICTING NET REVENUE OF HARVESTING OPERATIONS IN COASTAL SECOND - GROWTH STANDS

by

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ABSTRACT

As forest harvesting shifts from old-growth to second-growth stands, profitability is becoming an important issue. In a cooperative project involving Forest Engineering Research Institute of Canada (FERIC), University of British Columbia (UBC) and Canadian Forest Service - Pacific Forestry Center, a model was developed to predict economics of second-growth harvests.

The final result that can be obtained with the model is the net revenue produced after logging a second-growth stand. This is computed as a function of stand characteristics, company product requirements and harvest equipment used. Additional results computed by the model are total volume, distribution of volume by species and by sort, and estimate of time to harvest a block.

The model is a Windows[1] based program, written in Visual Basic 3.0 using some third party Visual Basic Extensions. The final product is a program that makes data input very easy. It ships on two diskettes with a set up kit, making installation simple.

The model was tested on two second-growth settings close to Powell River, B.C. In both cases the results were very good, value predicted by the model being within 3% of the actual value obtained. More testing is underway and considering input received from industry, some improvements are being considered.

The objective of this project and of the model, which is the final product of the project, is to demonstrate the potential benefits to users of this type of management tool and to serve as a medium term decision support tool that will predict economics of second-growth harvests.

[1] Windows and Visual Basic 3.0 are trademarks of Microsoft Corporation.

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1. INTRODUCTION

1.1 Background

There has always been a lot of interest associated with predicting the value of a stand before harvesting. This prediction is correlated with the inventory system used to evaluate the volume of timber and with sorts that are to be produced from the stand.

Initially, researchers focused on old growth. Later on, second-growth stands came into attention, because old-growth forests are constantly diminishing and public pressure to stop harvesting them is increasing.

In British Columbia, value prediction is performed according to Ministry of Forests scaling and grading system. The main purpose of currently used procedures, is to predict the volume according to statutory grades. This is done to estimate the value of the stand as a base for bidding and for stumpage appraisal. Later, after scaling of harvested wood, the result is used to calculate stumpage and royalties. The method of collecting stand data is regulated in the Forest Service Cruising Manual. The description of grades and legal procedures associated with scaling, are given in Forest Service Scaling Manual. Cruise data collected in the province are processed, using a cruise compilation program. The program considers the inventory zones and uses a cruise compilation loss factor table to estimate loss associated with various defects.

This paper presents the results of a research project involving the Forest Engineering Research Institute of Canada (FERIC), the University of British Columbia (UBC) and Canadian Forest Service - Pacific Forestry Center. In this cooperative project, a computer model was developed to predict the net value (revenue) of British Columbia coastal second-growth stands as a function of stand characteristics, harvest equipment used and company product requirements. In contrast with the existing method, which is designed for general use in the province, the model is

a tool intended to analyze economics of harvesting operations, based strictly on specific information collected from the stand under consideration.

The objective of this project and of the model, is to demonstrate the potential benefits to users of this type of management tool and to serve as a medium term (1-5 years) decision support tool that will predict economics of second-growth harvests.

1.2 Rationale

The utility and applicability of the model, is related to the fact that forest managers responsible for marketing, work study and logging planning require detailed information on the potential yield and log size distribution from a stand. Information is required on the potential of the stand to yield different types and qualities of logs as a result of different bucking patterns, average piece size, and the number, size and volume of the individual log types. Detailed data by product type, specific to locatable areas are necessary to maximize the contribution from the timber resource. After completion of a literature review, it was found that there were no such models that can reliably predict the net revenue generated by a stand.

The attempt to predict the value of second-growths was inspired by the practical observation that there are few defects associated with these stands. This is in contrast with old growth, where the presence of many defects and the imprecision of correlating them with loss in wood volume, can make the prediction less reliable (accurate).

In terms of predicting the cost of harvesting second-growth stands, it is estimated (Andersson and Jukes, 1995) that the change from harvesting old-growth to second-growth stands is presenting new operational challenges for the forest industry. The consensus is that if old-growth harvesting methods are used in second-growth forests, harvesting costs will be higher than when

the same methods are used in old growth. However, the smaller tree size of second-growth timber allows harvest planners to choose from a variety of mechanized harvesting systems, which could lead to reduced costs. Choosing appropriate systems for harvesting second-growth stands is presently difficult because little information exists concerning related costs and productivity.

1.3 Study Focus

The fact that this study focuses on second-growth is driven by the increasing importance of these stands in timber supply analysis. In 1985 approximately 12% of the annual allowable cut (AAC) of B.C.'s Southern Coastal Region, was harvested from these stands; for the same region, in 1995, second-growth timber was about 33% of the volume harvested and forecasts (Sauder, 1988) suggested that by the year 2005 second-growth volumes may be as high as 47% of total harvest. The same author has predicted that under current conditions there is only 20 to 30 years of harvestable old-growth remaining for most coastal operations.

For the purpose of this study, a second-growth forest is defined (Andersson et al., 1995) as being less than 150 years old, and having originated following harvesting or natural disturbance such as fire, wind storm, or insect infestation. The characteristics of the second-growth stands projected for harvest are diverse. They range in age from 50 to 150 years, have volumes from 400 to 1100 m^3/ha, and stand densities from 200 to 900 trees/ha. Many stands, especially those of natural origin, contain some large trees ("veterans") from the previous stand. In those cases, tree diameter at breast height (dbh) can range from 15 to 150 cm, and tree heights from 20 to 60 m. Slopes are generally gentle, but some sites may have slopes in excess of 80%. The presence of old growth stumps and large windfalls are also characteristic of second-growth stands.

2. OBJECTIVES

The main objective of the study is to develop a computer model that will be used to accurately predict the revenue generated by second-growth harvests. The revenue generated by a stand will be computed as the difference between the value of timber and the cost of harvesting it; other costs like stumpage and road construction are not considered. To complete the main objective, the following problems have to be addressed:

1. Establish the value of timber based on cruise data and on company sort descriptions for two silvicultural systems: clear-cut and partial cut.

   To accomplish the first objective, the following secondary objectives were addressed:

   1.1 Propose and test a modified method of cruising.

   1.2 Develop an algorithm that will theoretically buck each tree to its maximum value.

   1.3 Rank defects identified in second-growth stands, in terms of their impact on value prediction; study their effect by incrementally including them in the analysis.

   1.4 Determine breakage and other loss factors for the systems studied. Quantify the amount of wood lost during harvesting, and the impact on stand value.

2. Develop a quick analysis tool for estimating the cost of harvesting a cut block.

   This part of the project will offer the user data about productivity and cost of different machines. The majority of data used to derive these productivity equations were developed as part of FERIC studies; additional equations were obtained from published studies carried out in the Pacific North-West.

3. STUDY AREAS

As a part of this study, two operations were monitored; the first one was used for developing the model and the second one was used for testing it. Both blocks were situated on Crown land, near Powell River, in the biogeoclimatic region CWHvm1 - Submontane Very Wet Maritime Coastal Western Hemlock Variant.

The first block called # 921 Weldwood Main, was offered by MacMillan Bloedel Ltd., Stillwater Division. Species encountered in this study site were Douglas fir (Pseudotsuga menziesii (Mirb.) Franco var. menziesii), western hemlock (Tsuga heterophylla (Raf.) Sarg.) and western red cedar (Thuja plicata Donn). The total area of the block was 40 ha. The block was cruised by FERIC in November 1995. Logging started in January 1996 and lasted until April. Trees were manually felled and bucked into prime lengths (or combinations of prime lengths) then extracted to the roadside using a Madill 123 grapple yarder and two John Deere 690 excavator forwarders. Logs closer to the road (20% of total area) were loaded directly onto trucks. Results of the scale were obtained from the sortyard of the company.

The second block was offered by Granet Lake Logging Ltd. from Powell River. This block consisted of two settings, totaling 14.6 ha. It was a small business sale with the license number A 39750 and was located by Okeover Inlet. The species in the block were the same as in the first block. This stand originated after a fire that left many old growth cedars. These trees displayed poor form having the bottom almost destroyed by fire, and an average coefficient of utilization around 40%. Overall, in terms of density and tree diameters, this was a non-uniform stand as its characteristics varied greatly throughout the area. The full tree system was adopted in this block. Trees were manually felled, but not delimbed, except for large trees and the ones by the boundary. Extraction used a Madill 122 skyline yarder, with processing done mechanically in the first sub-block by a Keto 1000 processor, and manually by two buckers in the second sub-block. Some additional bucking and upgrading was done at the sortyard.

For both study sites, average stand characteristics are given in Table 1. In the rest of this paper the two blocks will be called Stillwater and Okeover, respectively.

Table 1. Average Stand Characteristics of Study Sites

	Tree dbh	Total height	Trees/ha	Avg. tree vol.	Gross vol./ha	Net vol./ha
	cm.	m		m^3	m^3	m^3
Stillwater	33	27	565	1.22	690	627
Okeover	29	33	1021	0.7	715	680

The data in Table 1 are based on operational cruises.

4. LITERATURE REVIEW

Maximizing tree value through optimal bucking and prediction of revenue has been of interest to foresters for a long time. However, as part of this study, only new models and methods will be presented, because older ones are obsolete either because of the programming language, the operating system, or from criteria related to scaling methods and units of measurement.

4.1 Review of Methods to Optimize Value for Individual Trees and For an Entire Stand

The definition of what maximizes value depends on the viewpoint of the decision-maker. Various viewpoints will be presented throughout this chapter.

It has been long recognized that undesirable reductions in managerial flexibility and substantial opportunity losses are incurred by bucking prematurely and in retrospect, inappropriately. The move, particularly in North America, to full tree logging and trucking and the development of log merchandisers to centralize the bucking decision and maximize realizable yields, provides ample testimony to the importance of bucking.

Murphy et al. (1991), outlined that the key finding of all research carried out with a view to maximize value recovery is that it is much easier to add $1 to unit product value by improving bucking than it is to reduce $1 from unit costs.

Pickens et. al (1992) identified the main causes of poor bucking decisions as follows:

- the complexity of industry specifications.
- unquantified or imprecise specifications.
- the number of log grades.
- production pressure.
- lack of incentives.

- lack of training, and
- lack of decision aids.

Murphy et al. (1996), present the findings of one of New Zealand's larger forest companies which stated that up to US $ 1.5 million improvement in annual revenue could be gained if they were able to capture an additional one per cent in value recovery. For all New Zealand, it was estimated that value recovered could be improved by over US $ 50 million per year.

4.1.1 Review of Optimum Bucking Systems for Individual Trees

Pnevmaticos and Mann (1972), outlined that the most important penalties of poor log production are: 1) the loss of volume from inefficient log bucking practices, and 2) the loss of value due to poor choice of end products. The authors outlined the general principles and structure of a dynamic programming problem and designed a method for log optimum bucking. Because there is no standard algorithm, they identified some simplifying assumptions:

- the problem is characterized by stages. In the example analyzed a stage is defined as the smallest possible log length. This assumption drastically reduces the computations required in the optimization process.
- sorts have the same length.
- the taper was considered to be zero, and
- no defects or quality remarks were considered.

With all the above simplifications, the problem looked trivial. However, this paper outlined the principles of dynamic programming in log bucking and generated further research.

Young and Waddell (1986), consider the following factors in the optimum bucking process: 1) species, 2) quality and size characteristics of the tree, 3) the various conversion plants and markets to which the logs can be allocated, 4) current product values, 5) log extraction costs, 6) transportation costs, and 7) worker safety. The combined effect of these factors makes tree

bucking for optimal value an important and complex decision process. They produced a hand held computer designed for fallers. The authors suggest that benefits of a bucking system, would be felt by logging divisions, the forest industry and the Crown. The system developed included information related to the tree (dimensions and other characteristics) and data about the market and extraction costs. The optimization system was comprised of two major components: 1) an office-based microcomputer and, 2) a sophisticated handheld field computer. The office-based microcomputer was used to store information about sorts that were downloaded to the handheld. For the handheld, prior to bucking, the faller was to input the relevant characteristics of the tree such as butt diameter, distance from the butt to each change in wood quality, and finally top diameter. Then, a dynamic programming algorithm used these data to determine the optimal cuts. The field computer could also be used to calculate the value of a proposed bucking policy based on a pattern chosen by the faller. This option allowed for unusual bucking situations where the faller could not buck at the optimal location due to safety considerations or if the tree has been damaged when felled. This option could also serve as a faller training guide. Once the tree characteristics were input, the faller could play "what if" analysis to determine the value of alternative bucking patterns. Linear taper was used, based on top diameter, butt diameter and the distance between these two measurements. Field tests of the system showed a net increase in value of 4%, in a study area that was bucked to higher standards than normal due to easy terrain and the additional training of the falling crew. Larger savings were expected to result in normal circumstances.

Considering significant value loss that occurred in New Zealand forests operations, Murphy and Twaddle (1986), conducted a value recovery control program. A system called AVIS (Assessment of Value by Individual Stems, Geerts and Twaddle 1984) that used dynamic programming for optimal bucking was used in conjunction with various statistical quality control techniques. The advantages and disadvantages of the sampling techniques used are underlined, but no final results (in terms of dollars recovered) are presented.

Sessions (1988), outlined the principles used in designing a hand-held computer used at the felling site to assist in optimal tree-bucking. The computer uses a network optimization method. It can simultaneously consider tree surface quality, taper, log lengths, diameters and grades, mill delivered prices, logging costs and transport costs. Background information must be entered into the computer before it is taken to the woods. Such information includes the delivered prices for logs of various grades, lengths, and diameters, transport costs to various destinations, and logging information by log size, scaling rules and stumpage payment rules. At the felling site the bucker enters information on tree characteristics into the handheld computer. Tree taper is entered by measuring length and diameter at various intervals along the tree. The bucker assigns a quality code to each zone of the tree after observing branch size, branch frequency and surface defects. Locations where bucking cuts must be made because of breaks or sweep, and intervals along the tree where it is not safe to buck, are also entered. Profit calculation can include costs beyond the tree itself, e.g. if slash cleanup costs can be related to the size of logs not removed from the forest, a penalty or negative profit can be used to assess the value of the tree.

Based on Sessions's (1988) work, Olsen et. al. (1990), developed BUCK, a computer optimizer that can be used for harvest planning. Apart from finding the best combination of logs to be cut from a given tree (no information is given about the method used), BUCK also evaluates the following problems:

- whether to remove or leave slash and marginal value logs. The cost of leaving slash at the stump can be weighted against yarding it to the landing or delivering it to a mill.
- weight limitations, which may be imposed on a logging system by one of the machines used during log handling.
- log-mix restrictions, i.e. a given percentage of a grade is required to be in logs longer than a given limit.

- payload efficiency: BUCK analyzes the trade-off between size of payload and number of logs that have to be handled.

Selected sample-trees measurements can be processed on a desktop computer, and this model can be used for evaluating management choices under various logging scenarios.

Raghavendra (1994), overviews Operations Research methods in forestry. He focuses on dynamic programming and gives good theoretical explanations on how this method is applied in optimal bucking, paying special attention to logs with defects. His method consists in grouping logs into categories, thus reducing the variability existing in log descriptions.

Some optimum bucking systems have been included in mechanical harvesters. Sondell (1987), evaluates the systems available in Sweden. Although some sophisticated systems were available, like bucking to taper or bucking to value, many modern features were unavailable at that time.

The optimum bucking problem was also approached in a different stage of log processing - at the sawmill. The conditions are much better compared to woods bucking and consequently more sophisticated methods can be used.

Maness and Adams (1991), developed a method for combined optimization of log bucking and sawing strategies at the mill. The method consists of three models to address each aspect of the problem.

- A stem bucking model that solves the optimal bucking policy using dynamic programming.
- A cutting pattern optimizer that simulates the cant sawing of a log with a given diameter, taper and length, and determines the optimal sawing pattern given lumber values by dimension and length.

- A log allocation model (based on linear programming - LP) that introduces production constraints and optimizes the output of a sawmill based on first two models.

The three models are linked and solved simultaneously, the first two programs as sub-problems to the LP. Suggested cant breakdown patterns and log bucking solutions are generated for the LP as a function of the current marginal value of both primary and secondary products. The LP then chooses between the set of "suggested" patterns rather than the full set of feasible patterns. The set of "suggested" patterns continues to grow until no new pattern increases the objective function of the LP. At this point in time the problem is solved. Obviously, it is very likely that logs at the sawmill had already been bucked or had received some sort of manufacturing. Stems traveling into the sawmill are optically and the dynamic programming model determines the best bucking policy.

4.1.2 Review of Methods to Predict Stand Value Based on Cruise Data

The process of predicting stand value based on cruise data has to consider more information (constraints) than in the case of individual trees. This mainly consists of market requirements, mill demands, additional costs like trucking and sorting, etc. Some of the best models for this purpose are presented in the rest of this section.

Deadman and Goulding (1979), developed A Method for Assessment of Recoverable Volume by Log Types (MARVL), which accounts for stem quality and malformation plus log specifications and preferences. The method used to optimize revenue from each tree is dynamic programming. This method accounts for various defects, the prevalent being forking. Some features of this model follow:

- a complicated cruising method is used and the stem is partitioned into variable length intervals, each of which can be considered to be of uniform quality. One-letter

alphabetic codes (that incorporates various characteristics of the sort) are assigned to each interval. Forks, large branches and diameter reductions require estimation of diameters at 1.4 m above the top of the defect. Skilled staff are necessary for estimation of stem quality and dimensions. Lengths and diameters are usually estimated, although frequent checks are being made using a hypsometer and a relaskop.

- observations for each tree are recorded directly on a hand-held computer.
- a local taper equation (fifth degree parabola) is used to compute diameter inside bark at different heights. Volume is computed using also a locally developed function.
- a breakage simulator randomly selects breakage in such a way that all the trees have the same probability of breaking. For the selected trees, an expected relative break point height is derived from a general function based on average ground slope and total height. All material above the break point is treated as waste.

A test of the method at ten clearcutting sites (for each site a sample of twenty-five Pinus radiata tress was taken) indicated that good results were attainable. As a result of compensation between sorts, the overall error in recovered volume was 3.7 %. Although log value is the driving factor for the dynamic programming procedure, no comment is made about it. An operational system based on the method is now being used by the New Zealand Forest Service. The authors acknowledge that use of the system outside their country would not be an easy process.

Eng et al. (1986), prescribe appropriate bucking patterns to be applied to several stands over a specified period so as to meet market requirements and other side constraints. This model takes into account simultaneously the limitations of the forest resource in terms of quality and quantities and the market requirements for products. Other characteristics of this approach are:

- the bucking is done at the landing and dynamic programming is used to solve this problem. The algorithm is explicitly interfaced with a linear programming module through price. The dynamic programming subproblem is used to generate activities for the linear programming, so that bucking strategies reflect the opportunity costs resulting from critical constraints on demands and resources.
- the main assumption of the model is that trees can be grouped into classes, each defined by the size and quality of the stems found in one or more stands. In the example presented, the authors used 100 classes, which seems to make the field procedures cumbersome.
- no useable model is supplied. The authors recommend a mixture of three components (procedural language, linear programming solver and spreadsheet).

The model was applied in Fiji and the authors state that further work on extending this methodology to medium term (3 - 10 years) forecasts is merited.

Mendoza and Bare (1986), approached optimal bucking and log allocation as a two-stage decision problem. This approach allows for the formulation of a linear programming problem (usually with a large number of decision variables), as a two-stage decision problem where two interrelated and functionally dependent problems are solved at each stage. The first stage determines an optimal allocation policy for the logs; the second stage consists of generating alternative log bucking policies. The method used to solve the second stage problem is a modified dynamic programming algorithm. The following points are noted:

- trees and logs are grouped into stem classes based on length.
- the model does not include other quantitative and qualitative bases for categorizing or grading logs.
- log markets were not included in this formulation but they can be easily incorporated in the objective function and constraints.

TREEVAL (Briggs 1989) is a microcomputer model primarily developed for predicting the product value of stands grown under various silvicutural regimes. The stands of interest are often hypothetical or modeled rather than actual stands. The objective of this model is primarily for long-term strategic planning of silvicultural decisions rather than short-term or instantaneous decisions of how to buck a tree. A dynamic programming algorithm (written in FORTRAN) is used to find the combination of logs that maximizes the value of each tree. Some characteristics of this model are as follows:

- value of markets (lumber, veneer, pulp and chips) is obtained using empirical product recovery relations, prices and costs to estimate the conversion return.
- shape abnormalities such as sweep and crook are not considered. Because the intent of the model is to forecast product value from stands grown under intensive management, it is assumed that trees developing these defects will be a minor stand component.
- no breakage was considered. The dynamic programming formulation is applied to a situation like mill-length log bucking, i.e. the tree quality is considered known.
- only small end diameter and length are considered as log dimensions.
- taper equations are used to compute diameter inside bark at different heights. The user selects from three different taper equations. The first one has the coefficients already built-in; the other two require user input. One of the last two equations was developed by Kozak et. al. (1969).

Sessions et al. (1989), found that optimal tree bucking at the stump, that maximizes values of individual trees, does not reflect the price structure that log sellers face; i.e. many contracts specify that a given percentage of log volume must be contained in logs of a specific length. A method designed was to maximize individual-tree value under contracts with such volume-length restrictions. The following is a good example: if one mill offers \$ 220/m^3 and requires that 70% of the log volume be in logs exceeding 10m, and another mill offers \$ 205 /m^3 and requires

that 50 % of the log volume be in logs exceeding 8.5 m, the seller can determine which contract delivers the highest value considering the length-volume restrictions and the price schedules simultaneously. Input consists of description of a sample of the trees to be harvested. An optimal bucking pattern is found for each tree (using a Network Optimization method), based on the unadjusted set of log prices. The results are summed over all trees in the sample. If the percentage of long logs satisfies the requirements, log prices are not adjusted. If the long-log percentage must be increased, the prices for all long logs are increased by a multiplication factor determined through binary search. The solution proposed identifies a set of adjusted log prices that maximized the net value of each tree while meeting the length-volume requirement for the stand as a whole.

Based on the program BUCK (Olsen et al. 1990) an improved model called CRUISE/BUCK was developed by Olsen et al. (1991). BUCK was a bucking aid for felled trees ready to be cut into logs. CRUISE/BUCK applies to standing trees; measurements are done on sample plots and data are processed in the office. The CRUISE/BUCK method can estimate the type of logs which should be cut from a stand and evaluates the potential revenue if different sets of mills are chosen. The main objective of the program was to achieve more value from a timber sale by picking a set of bidders that would pay the highest net return. Input data includes market specifications (mill prices, transportation costs and harvesting costs) plus cruise data. Apart from usual measurements that are collected when cruising, three different methods were used to estimate diameters inside bark at different heights (dendrometer, relaskop and taper equations). Results were tested against diameter measurements made with calipers, after the trees were felled. The overall standard deviations were respectively 3.0 cm., 4.8 cm. and 3.6 cm. Surface quality assessments from sample trees were also estimated, using a clinometer. Each tree had an average of five different quality codes assigned. For the case analyzed, the log sortyard solution had 2.8% more volume but 6% less total value. The authors recommend taper equations, and acknowledge that the development of a surface-quality scheme is a difficult process and the person collecting field data must be well prepared in using it. Because

implementation of this method requires some training, it was recommended that a timber owner who cruises only occasionally would be better off hiring a consultant trained in the use of CRUISE/BUCK.

Warren (1995), conducted a study in Coastal B.C., where stands were cruised before logging, using fixed area plots, and the author developed local height as a function of DBH equations. Kozak's (1988) taper equation was used in conjunction with Mathcad[1] , to calculate diameters on the stem, given a set of sort descriptions. Apart from typical measurements taken for each tree, as a part of this project, the term "crown ratio" was introduced, which was defined as the fraction of the total height of the tree that is covered with branches. Each tree was analyzed independently and the optimization started from the butt. Step by step the author tried to fit for each tree the combination of logs that maximizes its value. Final conclusions have not been published yet, however, it seems that a drawback of this procedure is that it is a slow process, since most decisions are manual (Warren, F. - personal comm., 1996).

Nieuwenhuis and Malone (1996), describe the early stages of a method aimed at the development of cost-effective methods and data analysis software, with a view to maximize the value obtained from forest stands through optimal inventory and cross-cutting methodologies in Ireland. The decision support system which is being developed, is designed for the sawmilling industry, linking standing timber to mill specifications and demands. The project is based on the fact that relative uniformity of Irish plantations and cross-cutting practices provides an ideal context for the development of systems for maximizing the value of standing timber. As a part of this project, an attempt was made to develop a taper equation, relating lower stem taper to that of the entire stem, however, this approach did not seem to produce very good results and affects precision of the volume prediction. The authors consider that further studies will be required

[1] Mathcad is a registered trademark of MathSoft Inc.

before the most appropriate means of representing stem profile can be found, but overall the prototype software yields promising results.

Murphy et al. (1996), present the principles and first results of an integrated value management system, that is underway in New Zealand. Due to its complexity, the development of this tool may extend into the early 21st century. Single stem optimization of all stems, computer vision and market feed-back mechanisms are the key components of the Integrated Value Management System. The AVIS (Geerts and Twaddle 1984) dynamic programming algorithm was chosen as the key part of a larger system for optimizing log production in real time. The element that differentiates this model from the previous one is a computer vision system. The geometric information (e.g. diameter, sweep, ovality and length) will be captured through the use of stereo images, obtained with digital photography, as the log-maker walks the length of the stem. The same images will be used to assess externally visible qualities along the length of the stem. The data captured by the computer vision system will be used by the AVIS algorithm to optimize single stems. To ensure that single stem optimization also meets market and operational constraints, new procedures are being developed to allocate the best cutting patterns and stands to each logging crew. Tabu search heuristics are used to solve this last problem. Instead of providing the optimal solution to the problem, a heuristic may only provide a good solution, but it is used because of its ability to solve difficult problems in a reasonable amount of time. Although not mentioned by the authors, it seems that the major problem will be the time required for collecting the image of each tree.

Apart from methods described above, there are other method developed for sawmills or other places (log sortyards) where a higher degree of mechanization can be obtained:

- Green (1994), reviews scanning systems and approaches. Optimization methods are also analyzed, along with their implications on overall activity of the sawmill.

- Hardison (1995), describes the advanced methodology employed at bucking stations in sawmills. Two trends are obvious; one consists of scanners and computer-based optimizing programs, another one uses cameras at the log deck and video monitors to give the operator a vantage point as if he were personally examining the logs on the deck.

4.1.3 Literature Review for Fiber Recovery and Value Loss in Harvesting Operations

Related to predicting volume and value of a stand, is the evaluation of losses that occur during harvesting. Some of the methods developed to estimate and to account for this follow.

Murphy (1983), identified that forest industry was in many cases production not value oriented, i.e. not much attention is paid to recovering the entire value of trees. He identified the following losses for various logging phases:

- thinning 1 - 2 %.
- felling damage exclusively due to breakage 4 -7%.
- felling damage due to other causes (high stumps, butt damage in the form of slabbing, side-splitting etc.) 4 - 5%.
- extraction losses 1 - 2%.
- processing losses 20 - 25%.

Gingras (1992), defined fiber recovery efficiency as how completely a given harvesting system recovers the merchantable fiber. In other words, this is the volume recovered divided by the sum of volume recovered plus merchantable slash. He evaluated six different systems, producing recovery indices between 91 - 99%.

Copithorne and Young (1994), monitored two sites in Coastal B.C. and found that total losses in log recovery value was 5.7%. Broken down by harvesting stage it was: 1) falling 3.6%, 2) bucking at stump 1.5%, 3) yarding 0.2%, and 4) bucking at the log sortyard 0.4%. The authors conducted a detailed analysis of causes that produced these losses. Typical second-growth stands, consisting of Douglas fir, western hemlock and red cedar were studied. No information is given about crew skill, but if is assumed that an average crew was monitored, then the above results can be considered average losses that occur when harvesting in coastal British Columbia stands.

Apart from factors that are inherent to harvesting process, decisions taken by log makers can be of great importance in value recovery.

The operator's ability to produce optimum value under production conditions was tested by Geerts and Twaddle (1984). A program called AVIS (Assessment of Value by Individual Stems) was developed to evaluate what skidworkers can achieve in optimal crosscutting of the stems. In this logging system workers were in a confined area shared with large machines and given a set of log-making instructions (which are ambiguous and/or imprecise), then were expected to do a rapid assessment of each stem, recognize the various log qualities, and optimize the stem's value. As a part of this study each tree was scaled after being felled, but before extraction. Rather than using a general volume or taper equation, sectional measurements are made on each stem. If the tree broke, AVIS enables pieces to be grouped to calculate the optimal cutting pattern of each piece and the maximum value of each tree. The optimal crosscutting algorithm used is the same as the one used by MARVL (Deadman and Goulding 1979). There were no restrictions on the maximum or minimum quantities of any of the log types produced throughout the study period. Two studies had been conducted as part of this project. The first result showed that 26% of potential stem value was being lost from sub-optimal log-making by the skidworkers. This was reduced to 11% after the introduction of practices designed to aid the workers in their choice of individual stem cutting patterns.

Cossens and Murphy (1988), studied human variation in optimal log making. Two groups of people with about the same age and years of experience, but differing very much in education and training, marked 31 trees for cutting into logs. The conclusion was that the first group that included supervisors (better educated) were significantly better than the second group, that included skidworkers. The value lost averaged (for both groups) 6.6%, ranging from 4 to 10%. The data showed that 56% of errors were due to dimensional errors (such as diameter and length), 35% were due to missed or misinterpreted quality features, and 9% were due to other reasons. However, even though all people were involved in forest related activities, and were familiar with log grade specifications, none of them had any formal training in the task of log-making.

Parker et al. (1995), found that a high number of log grades (14 or 19 in their study), increased the number of out-of-specification logs. On the other hand, cutting a greater number of log grades has many advantages, increasing the flexibility of the operation, and thus providing customers with requested log grades plus achieving greater value recovery. The authors consider that the optimum number of grades to be cut by a logging contractor is about ten.

Conclusions at Section 4.1 : After reviewing all studies presented so far, none of them seem to respond to specific needs of the forest industry in B.C. Various approaches are considered for bucking individual trees to their optimal value. Some models extend these algorithms to the entire stand, taking into account breakage and various types of loss, plus additional factors that occur in the logging process. However, none of these methods can be used in conjunction with the inventory (cruising) method used in B.C. Also, none of them was design to use specific company sort descriptions as used by the local forest industry.

Some of the algorithms described, are in fact good starting points for optimal bucking of individual trees. Concepts and ideas from others models can be changed and used to satisfy specific requirements of B.C. forestry. There are described in the remainder of this thesis.

4.2 Review of Models Used to Predict Machine Productivity and Cost of Harvesting

Developing harvesting models was a major preoccupation in North American forestry. As presented in the rest of this chapter, two trends can be distinguished in this activity. The first one consisted of producing computer models that were able to chose machinery to harvest a given block with greatest economical efficiency. These models are commonly called expert systems. The second trend consisted of predicting results of the harvesting operation (mainly in terms of productivity and cost) based on stand data and existing machinery. Conclusions about these models and how the model developed in this study relates to other models, will be presented at the end of the chapter.

Gibson (1979), presents a computerized planning and evaluation system for cable logging operations. The planning model is segmented into three main levels: sale area, sub-block area and profile (deflection line). Input consists of a digitized map of the area and general data about the stand. Regression equations that predicted turn time based upon characteristics of the stand were developed and programmed into the model. Using interactive graphics, the engineer can view the area to be logged, select locations of corridors and query the system for various output, such as system mechanics and time to log any particular logging unit. The system included various cable systems (running and live skyline and hi-lead) and different silvicultural prescriptions (shelterwood, clear-cut and group selection).

Goulet et al. (1980) present the criteria for a harvesting computer model that was to be design in the southern US. The purpose of the paper was to ask the forest harvesting community for an evaluation and an idea exchange. The model objective is to provide a means for addressing questions that relate to wood flow and costs, so that intelligent management decisions about the

harvesting operation can be made. A tree-to-mill flow diagram of southern harvesting operations, with each node representing a harvesting phase, is presented. The main feature of the model is modularization, which is achieved by:

- executing only those nodes that are on the user's path.
- allowing for different implementations of each node, and hence explicitly admitting into the design the great variability present within any one harvesting function.

Comments are made about the level of detail and variables that are to be implemented into the model. The variables will be production, time and costs - by machine, by function and by total system. Other information presented to potential users includes technical tests for the model, how flexible and user friendly the model should be, computer language and machine requirements for this model.

Meng et. al (1981) presented two approaches to predicting performance of logging machines. The study was primarily oriented towards evaluating new machines; however, the same methodology can be used for existing ones. The first approach was to develop simple analytical formulae, in which equations express average harvesting time per tree as a function of stand, tree and machine variables (average values are substituted for each variable). The second approach involved tree-by-tree simulation of harvest. The authors consider that the first type of analysis can be done reasonably well by hand, whereas the second requires a computer and detailed programs that incorporate assumptions about the behavior of the machine and its operator during logging. The best (to that date) Canadian simulation model for harvesting machines, CANLOG (Newnham, 1971) was selected for comparison. The Larson Shortwood Harvester was selected as the subject machine. Results from the two methods did not differ appreciably, despite the greater complexity and cost of the simulation approach. However, when compared with available field data, neither method was particularly reliable. The authors conclude that simulation may be an effective alternative where considerable interaction exists between machines or machine functions, where variable distributions are given substance through empirical studies, and where adequate program documentation exists.

A very comprehensive package (Harvesting Analysis Technique), developed over a period of fourteen years is presented by Stuart (1981). This is a three-part system for modeling the environment, individual machine activities and harvesting system interactions. It consists of three major components: 1) procedures for stand definition, 2) a generalized machine simulator and 3) a harvesting system simulator. These components may be linked in different ways. Stands may be selected from the library of mapped stands or with the stand generator included in the model. Each tree is identified using sixteen characteristics, e.g.: coordinates, species, dbh, diameter at ground line, double bark thickness at ground line, crown width etc.. Based on these, four more characteristics are computed for each tree. These variables are passed to the machine simulator and used in modeling machine movements and performance time. This module can be linked with a growth simulator that can accept details for various combinations of thinnings and fertilization strategies. The user can vary stand age at time of thinning and stand development after thinning. The machine simulator is capable of handling the most common harvesting machine activities. The area to be treated at one time by the machine being simulated is defined by a swath width parameter, which determines the width of the strip harvested by the machine each time it passes across the face of the stand. Trees to be harvested and the order of removal is given by individual tree data previously entered. Different functions may be simulated for each machine: travel empty, travel loaded, move, process, turn, cut, etc. The performance time for each of the functions is generated either by sampling from a user supplied distribution or through equations provided. the user must select the equation type and supply the coefficients required. The last part of the model, the Harvesting System Simulator (HSS), can be used to simulate systems up to a maximum of fourteen machines operating on areas containing up to fourteen different harvesting units. The harvesting strategy is controlled by assigning priorities to each area for each machine in the system. The model can include up to twenty different types of down or delay times. Reports include a set of production, income and cost data for the entire operation and for each machine in the system, plus other more specialized report types. The authors state that the program was in use during its entire

evolution, being tested in various circumstances, but they do not provide any result of these tests. Although it seems that the model was getting to a great level of detail, the authors state that the model is in a ongoing state of evolution and refinement.

Webster et al. (1983) present the major features of a feller-buncher module which is one part of a new timber harvesting simulation model. In this article, authors present some of the basic principles of the model. As in Goulet et al. (1980), the most important design criteria for the model is modularity, which allows portrayal of a variety of different harvesting operations. The user can combine different modules to depict a total harvesting system or select one module and simulate only a part of harvesting, such as felling. The article describes the features of a feller-buncher module which simulates the actions of a drive-to-tree feller-buncher with an accumulating shear head. To simulate the harvesting movements, the module requires both machine functions and the consideration of site factors which affect harvest operations. The stand to be harvested is modeled by overlaying a map of the stand with a grid. Cruise data are used to describe the grid cells, giving the average percent slope of the land in each grid cell, the maximum bunch cross-sectional area, the maximum bunch volume etc. Tree characteristics are: coordinates, dbh, volume, species and status (harvestable tree, leave tree or obstacle). In addition to the physical characteristics of each grid cell, the model considers the harvest pattern desired. The feller-buncher is assumed to produce a uniformly arranged bunch of trees having a volume and total bunch diameter matching the requirements of a companion skidder. It can move through the plot avoiding leave trees and obstacles, selecting trees, harvesting them and depositing bunches along a predetermined pattern. When a tree is selected as a candidate for shearing, its dbh and volume are examined to see if the shear head and bunch will hold the tree. If not, the next closest tree is examined. Several influencing factors are chosen, like machine interaction and stand characteristics (density, growth pattern, distribution of trees by species and dbh, and obstacles and leave trees, stand brushiness. Delay elements like scheduled delays, equipment failures, and machine interferences are also considered. The output produced by the model includes: productive machine hour, total length of delays, total volume of

wood bunched, average length of a cycle, average volume per schedule machine hour, average volume per productive machine hour etc. End of simulation reports include summaries of utilization, production and costs of the feller-buncher. The authors mention that much effort has been expanded to develop this module which faithfully mimics the operation of a feller-buncher and allows considerable flexibility. No comment is made about the time required to run the model or about any trials of the model. No more detail about the other phases of the harvest were found.

A computer model (HARVEST) that has the purpose of simulating harvesting operations with cable skidders, is described by Howard (1987). The model was written in Fortran IV and could be executed on both CP/M and MS-DOS systems. Previously developed models for predicting productive and non-productive time for felling, skidding and bucking were programmed in HARVEST. A data processing program (FOREST), which is capable of generating stand and stocking tables (from either marking tallies or inventory data) is linked to HARVEST. The model incorporates a detailed methodology for logging costs analysis. Author states that these programs in combination with user-interactive programs represent a decision support system which is common in southern New England. In the case presented, the system was used to investigate the relationships that influence logging profitability. HARVEST can also generate information helpful in the development of silvicultural and operational management strategies.

Reisinger et al. (1988), analyzed three of the most recent and comprehensive programs developed for analyzing harvesting system costs and production problems. These are: Auburn Harvesting Analyzer (a spreadsheet program developed by Auburn University - School of Forestry), Harvesting System Analyzer (a menu-driven program written in Pascal, developed by the Tennessee Valley Authority) and Harvesting System Simulator (component of the Harvesting Analysis Technique - Stuart, 1981). The authors present a description of each program, along with the results of a test using data for a mechanized tree-length system. Results of the analysis of the three programs compare closely with each other, and computed cost per unit was only

slightly higher than an industry average for a similar system. However, data input for all programs was tedious and time-consuming, particularly for analysis of large systems. In several cases, individual programs were not flexible enough to accept input data in different formats. Programs produced comparable results using realistic system data, even though there were some inconsistencies in the way harvesting costs and productivities were computed. The authors do not recommend a specific program as the best, because the choice ultimately rests with the user and depends on that person's specific needs.

Mellgren (1990) acknowledges that many of the logging machine types used in Canada were studied and evaluated. However, it was always recognized that the results obtained were site and operator specific. A best guess performance correction factor had to be added to forecast the performance of similar machines in different logging conditions. To assist logging managers in the selection of the optimal logging system, and for budgeting and control, the author developed a series of baseline performance curves related to average tree size. These baseline curves are for commonly used logging machines or logging systems working in what was defined as ideal conditions where machine performance would be optimized. The shortwood at roadside harvesting system was chosen as a common point for comparison. The same comparison logic can be used for tree-length or full-tree systems. Correction factors were provided so that machine performance and logging costs can be predicted for a variety of stand conditions. Results are presented in a graphical form to illustrate the analysis and comparison logic. The main purpose of the study was to present a methodology along with the appropriate equations. Potential users should substitute their own data for variables according to their experience and practice. The performance graphs and system comparisons presented in the study are meant to apply to large-scale logging operations, and may not be valid in very different conditions such as smaller-scale operations where performance is affected by various limitations.

Randhawa et. al (1992) describe Timber Harvester, a microcomputer system designed to automatically generate feasible harvesting systems. Harvesting system selection is based on the interaction of two major components: 1) site and stand data plus processing variables and 2) the operating attributes of the available equipment. The alternatives selected depend on the information provided in the equipment and support databases, that includes production equations and costs. The best-first search algorithm is used to find a solution. It uses production cost to guide the search process in the direction which minimizes the total production cost. The authors stress that selecting an appropriate degree of mechanization to avoid underutilization of expensive resources is a critical decision, and requires that the product mix, environmental and user constraints be matched against the available technology and required performance criteria. This tool is especially intended to aid long-term, strategic planning by both government agency engineers and private industry managers and owners. It could also be used for short term tactical planning by contractors.

Koger (1992) developed a Skidding, Trucking and Landing Simulation (STALS). This is a timber harvesting program that utilizes production by function, queuing theory and simulation technique to analyze skidding, loading and trucking interactions. Input consists of general data about the block (volume and value) and the number of machines that are to be used. Help screens with harvesting rates, cycle volumes, and equipment hourly costs are provided to assist the user in estimating values for skidding volumes and cycle times, loading cycle times, trucking volumes and cycle times and hourly equipment costs. Queuing theory is used to analyze the system. For both skidder and truck arrival times at the landing it is assumed that the probability of more than one event occurring in a small time interval is negligible, and the probability of an event occurring in this time interval is independent of other intervals. Finally, STALS performs a simulation analysis of the system. Several dynamic interactions such as equipment delays, full landing conditions, and wood shortages can be modeled using this technique. As mentioned before, to simplify the complex interactions that occur in a normal timber harvesting operation, only the activities of skidding, loading and trucking were modeled. The author acknowledges that

the model lacks the detail that is required in real situations, and the fact that it does not consider many non-productive times (scheduled work breaks, end-of-shift times, random down times, etc.).The emphasis in this model has been to keep data input to a minimum while obtaining as much information as possible by using queuing theory methods. No information is given about validation of this model.

Baumgras et al. (1993), developed GB-SIM (A Ground Based Harvesting Simulation model) to estimate stump-to-truck production rates and multiproduct yields for conventional ground-based timber harvesting systems in Appalachian hardwood stands (clear-cuts and partial cuts). The model tries to link the real attributes of the operating environment (e.g. skidding distance, slope, topography) to the harvest stand attributes (e.g. stand density, product volume) and harvest system characteristics (e.g. numbers and types of equipment, utilization rates, volumes skidded). GB-SIM is a stochastic, discrete-event model that applies the next-event approach to update the system state and advance simulation time. One of the main features of the system is the random assignment of tree attributes, including X and Y coordinates that locate each tree within the harvest unit. The model simulates production cycle attributes and calculates cycle times for each type of equipment. While the authors do not expect stochastic simulation models such as GB-SIM to be applied directly by commercial loggers, these research applications can continue to provide valuable information regarding harvesting production and cash flows for the economic analyses of timber harvesting, wood utilization, and forest management alternatives.

An expert system called X-Harvester was produced by Linehan and Corcoran (1993). The system was created for commercial forests under the legal, physical and economic conditions existing in Maine, but it can be adopted for other regions. Expert Systems (ES) have the ability to evaluate both quantitative and qualitative information at the same time providing an important advantage in complex problems such as forest management. The authors acknowledge that although some earlier claims of success of ES (that they would entirely replace human decision makers in many areas) has not proven realistic, they have become

valuable tools to assist decision making in many areas. The model includes separate modules (which may pass data from one to another) for the following functions :

- calculate machine rate costs for individual logging machines.
- evaluate market prices for logs and pulpwood delivered to the mill.
- build a harvesting system from individual machines and determines how costs should be calculated.
- evaluate stumpages for a harvest operations.
- determines financial viability of the harvest by computing the estimated costs and revenues for the operation.
- evaluates Maine cutting rules and performs an advisory function to evaluate physical operability, regulatory status and soils suitability for forest growth.

The model was tested by back analyzing an easy to evaluate situation (small block, a stand with only pulpwood-grade trees) and results produced agreed with the real ones. At the time it was elaborated, the system was not very flexible (data were stored in so called frames), but authors claim that future development of the model (storing data into databases) would increase its applicability. The framework of the system provides a useful foundation to assist land managers in making timber harvesting decisions.

Final Comment on Chapter 4: Similarly to the conclusion drawn at Section 4.1, at the end of this section I can state that none of existing models fit the specific needs of B.C. forestry. In terms of general approach, most of these programs are restrictive, i.e. lack the degree of flexibility that is required in this field of activity. Also, productivity equations used are inappropriate for conditions existing in Coastal B.C. However, some of these models use concepts that are generally valid, like modularity (Goulet et al. - 1980, Webster et al. - 1983), that was used in my model as well. Apart from design criteria presented at the end of the previous section, the model developed in this study eliminated shortcomings exiting in older models, and has the following features:

- various harvesting systems and various scenarios can be easily analyzed for a block.
- for all phases of the harvesting system, the user is offered a large variety of methods.
- for each one of these methods, existing or new machines can be used.
- default productivities and costs are offered for each phase, but these can be always overwritten by the user, based on experience and knowledge.

Each one of the features and a detailed description of the entire model are given in the remaining parts of the thesis.

5. STUDY DESIGN

The model developed as part of this project is an office tool, intended to be used by planners and foresters working in second-growth forests that are to be clear-cut or partial cut. According to the main objective, the final result of the model will be the net revenue generated by the block; however, during the process of obtaining this result, other important results like distribution of volume by species and sorts, need to be computed and reported. The process of developing the model is presented in the rest of this chapter.

The phases identified in the development of the model are:

1. define the problem and objectives.
2. study the logging activity as a physical system and determine its discrete components (various phases of the process).
3. identify input and output pathways; construct flow charts for the system and for each phase.
4. convert the flow chart to computer code.
5. collect a first set of input data and use it to build the model.
6. refine the model using results produced by the first set of data.
7. collect a second set of data and use it to verify the model.

The very last step consists of offering the software to forest industry for production situations.

5.1 Model Development

A step by step description of the methods used for model development and the factors considered throughout this process are described next.

5.1.1 Basic Features of The Model

The design of the model was mainly determined by the consideration of steps taken during planning of the harvest. These steps must provide a good estimate of the volume to be logged and find the best methods to do it (i.e. accomplish the work in an economically efficient way without producing damage to the site or generating undesirable side effects).

In British Columbia, the physical process of planning a harvest consists of:

- selection of the block.
- survey boundaries and calculate the total area.
- cruise the block according to B.C. Ministry of Forests regulations. The cruise is analyzed with a standardized cruise compilation program, that will estimate volume by species according to Ministry grades. The grading system assigns a grade to each log produced and these are used to calculate the value of stumpage.
- engineer road layout and, if cable systems are to be used analysis of deflection lines.
- select equipment to ensure economical feasibility of the operation and compliance with environmental and legal requirements.

From the above description, one can see that there is little information about the value of the wood produced from a block and consequently of the revenue that will be generated. Since this value is dictated by the sorts manufactured, my model was designed to incorporate company sort descriptions. The model was also designed to accept standard cruise data as the basic stand description, which ensures easier implementation of the model. However, some modifications to incorporate additional tree description data to Ministry cruising methods were considered. More details about the data will be given in the rest of this chapter. Full description of office procedures are given in the user manual (Pavel et al., 1997) which is available upon request from FERIC.

Considering its main features, my model will:

- calculate the volume by sort and value of timber, using cruise data and company log sort descriptions.
- allow various harvesting systems to be quickly specified for a block (environmental and legal constraints are considered to be satisfied).
- estimate the cost of harvesting a block, using productivity functions and cost data provided by the model or supplied by the user.
- estimate the net revenue from harvesting a block.

In this model, net revenue is obtained by subtracting the cost of harvesting from the value of the timber. As mentioned in the introduction, other data necessary to compute the net revenue are stumpage and the cost of roads, however, these are not included in this model. The user can supply them and manually make adjustments.

5.1.2 Factors Considered During Model Elaboration

The specific needs that are satisfied by the model are described below:

- need to consider alternatives to clear-cutting.
- need to determine value in fluctuating log markets.
- need to evaluate many, complicated log sort descriptions.
- the need to stratify a block according to specific conditions related to site and legal requirements. For each stratum, the user has the option to select from a wide variety of harvesting equipment and systems for each phase of the harvesting system.
- need to consider interactions between harvesting phases, and
- need to estimate net revenue.

With the above features, the model should be a useful tool for planning second-growth harvests because it responds to the above needs.

5.1.3 Presentation of Software Used

A preliminary analysis of the problem showed that the operating system used as a platform for this project has to be common in the B.C. forest industry. In terms of programming language used, it was desirable that it has the capacity to address all needs of the model and create an easy and attractive interface. Windows[1] was found to be the most suitable operating system, and Visual Basic (current version when this program started was 3.0) was considered to be the most suitable programming language. The interface of the model was designed so that it will be both user friendly and error resistant.

Data are stored in an Microsoft Access 2.0 database. To improve the user interface and to make it more portable, the following third party Visual Basic Extensions (VBX) were used:

- TrueGrid.VBX 2.1[2] - this improves the capabilities of Visual Basic to display data stored in a database.
- VS.VBX 5.0[3] - this is a tab control, which is very useful when displaying multiple choices and an elastic which ensures that various forms always fill the screen, regardless of screen size.

Error proofing consists of directing the user input in various instances and making available in some cases only the choices that are consistent with previous decisions.

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[1] Windows, Visual Basic 3.0 and Access 2.0 are trademarks of Microsoft Corporation.
[2] TrueGrid.VBX is a trademark of Apex Software Corporation.
[3] VS.VBX is a trademark of VideoSoft Company.

Finally, the model has to provide an easy installation method. This was also solved using the capabilities of Windows and Visual Basic 3.0. A more detailed description of all these features is given in the user manual. The program has more than 4500 lines of code (including comments).

The end product is an independent program, i.e. the user will not need to have other software installed, other than Windows 3.0 or a later version, plus DOS. The program ships on two diskettes with a set up kit making installation simple.

5.1.4 Data Requirements and Basic Assumptions of the Model

Input of the model consists of cruise data and sort descriptions. Based on these data the model computes the volume by sort and total value of the wood in the cut-block. Next, the cost of harvesting processes for that block can be computed using either default productivities or input provided by user. The block diagram in Figure 1 illustrates the principles of this model:

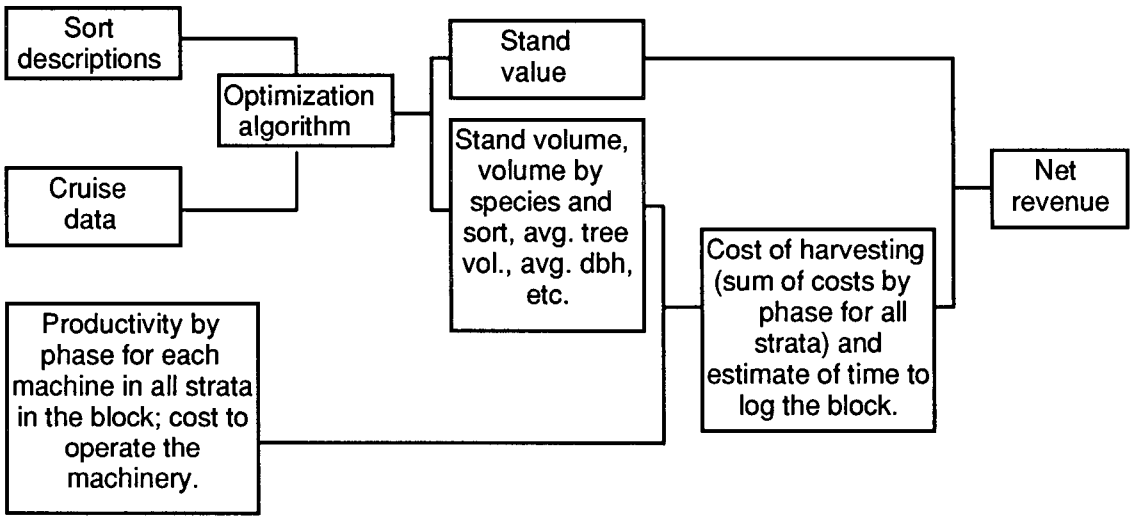

Figure 1. Block diagram of the model.

Data requirements will be further detailed according to computation of stand value and computation of harvesting costs.

5.1.4.1 Data Requirements to Compute Stand Volume and Value

To compute volume and value of the wood harvested from a block, the model needs cruise data and sort descriptions.

The main objective of the cruise is to obtain an estimate, to a specified degree of accuracy and with a specified level of confidence, of the volume of timber on the block. Apart from that, the cruise provides the essential data for determining stumpage rates, for establishing conditions of sale and for planning of the logging operations by the licensee. All details about this activity in B.C. are given in the Ministry of Forests Cruising Manual (1983). The manual sets out the minimum cruising standards including specifications for the statistical design of the cruise, the accuracy of the field measurements and a standard compilation procedure. The reliability of any cruise is based on statistical concepts and this is a function of the intensity of sampling, the uniformity of the timber on the area cruised and the degree of fit of the volume equation to the particular stand. A more detailed description of the method will be given in Chapter 5.2.

The type of data collected for each tree in the cruise are:

- general data about the tree: current number, total height, species, dbh, tree class, crown class.
- pathological remarks: conk, blind conk, scar, fork or crook, frost crack, mistletoe, rotten branch, dead or broken top.
- quality remarks: spiral grain, sweep, lean, location of the first live limb and the first stub, data about knots in the first two 5-m. logs.
- other type of data collected only for damaged stands.

The tree is divided into thirds for recording pathological and quality remarks. Codes are assigned to corresponding thirds (one or more

.

There is no standard for log sort description. Each company describes them in a different manner and includes details that make a certain log acceptable in a specific sort. These data are generally not made public by forest companies. An analysis of company sorts showed the following common features:

- data related to dimensions:
    1. length - usually given as a prime length, i.e. a length preferred by the mill and for which a premium price is paid.
    2. diameters - minimum top diameter, maximum top diameter, minimum butt diameter (less common), maximum butt diameter or a combination of these.
- information about knots: the maximum diameter of knots accepted and if they are required to be well spaced. Sometimes this is done by specifying the portion of the surface of the log that must be clear.
- other defects: sweep, crook, twist, various types of rot, heart check or splits, conk, rotten knots, presence of Ambrosia, shatter, catface, weather check, butt shake, goiter, burls, powder worm, bark seams, flare butt.
- ring count: for valuable timber such as saw logs and gang logs, second-growth blocks usually have a thrifty and a high grade sort—based on the number of rings per unit length.
- value: as expected, sorts with larger diameters, clear of defects and greater ring count have a greater values than sorts that do not satisfy these requirements.

As one can see from the above descriptions, the data collected about trees when cruising and the specific requirements for a log are not described in a similar manner. Some of these specifications are difficult to quantify, or their quantification may not be necessary because they

are not found in second-growth stands. To match tree descriptions in these two data sets (cruise and sort descriptions) some simplifications had to be made as described in Section 5.1.4.3.

5.1.4.2 Data Requirements to Compute Machine Productivity and Cost of Harvesting

The data requirements of this part of the model are mainly related to the level of detail desired and the objectives set forth. In the logging activity, when predicting machine productivity (m^3/hour) three levels of detail can be used:

- Mean times for harvesting phase activities; this approach is efficient in terms of programming but offers the least amount of detail.
- Regression models; this method also has advantages and disadvantages. The advantage is that, for most logging activities researchers selected the same independent variables for their regression models, which seems to make them portable. The main problem is that these equations were developed in specific conditions (different machines were monitored and different range for variables resulted) making their predictions less reliable in other conditions.
- Simulation; represents the most detailed level, and it seems to provide good results for scheduling systems and interactions between phases within systems, but this is the least desirable method in terms of programming effort.

From the characteristics presented above, and all models that were presented in the literature review, it was concluded that simulation is not an appropriate method to be used in this project. This decision was because there are an infinite variety of situations existing in practice, and the accuracy offered by these models does not justify the effort to develop them. Therefore, in this study, productivity functions based on regression were chosen. When these were not available, averages were used. The majority of equations programmed in the model were developed by the Forest Engineering Research Institute of Canada (FERIC) in coastal second-growth stands.

When not available, other data developed in similar stands in Pacific North-West were used. All productivity functions and averages programmed in the model are presented in Appendix 2.

5.1.4.3 Basic Assumptions and Limitations of the Model

The main assumption made for the calculation of volume and value was that coastal second-growth trees are generally clear of surface and hidden defects. From experience (confirmed also during the field work that was undertaken during this project), it was known that only a few defects can be found in second-growth, i.e. shallow scars that do not affect the sort, fork or crook, dead or broken tops and sweep. To improve accuracy of predictions made by the model, cruises recorded more detailed data about these defects, as described in the field procedures (Chapter 6).

As expected, log dimensions have a major impact on grading. In this study, logs that can be bucked from a tree are based on total height of that tree (which is considered to be measured or estimated accurately), and diameters on the stem at different heights which are computed from a taper equation. Of great importance in log grading, was knot dimensions and spacing. More detailed information about this was collected in this project, as described in the field procedures.

The approach taken in this project consisted of considering the above mentioned factors to compute stand volume and value; all other data collected when cruising will be used as criteria for partial cut.

To compute the cost of harvesting, the main assumption was that stands are uniform, i.e. volume is evenly distributed over the entire area of the block. Another assumption, based on experience, was that blocks will not be stratified into more than 5 strata. In this part of the model, for each phase, the user can select from a wide variety of harvest system configurations. Several configurations can be simulated and the best one selected for the cutblock conditions.

Due to the large variety of systems in the industry, almost no restrictions are imposed when a system is configured.

The most common species in Coastal B.C. were included in the model, namely Douglas-fir, western hemlock and western red cedar. Comments about including additional species in the model, are made in the last chapter.

The following sections of this chapter, include a description of methods used to compute the total block value and cost of logging.

5.2 Method of Calculating Block Volume and Value

The following is a description of the B.C. inventory method that was used as a foundation to compute volume and value of the block.

The cruise plan and the accuracy requirements are affected by the timber selling procedures and the timber appraisal. The most common are scale-based sales, for which the cruise provides the basis for estimating the stumpage rate while the amount billed is based on the scale.

The technique of collecting cruise data consists of systematic sampling used in conjunction with sampling with probability proportional to size (PPS); i.e. plots are placed systematically in the block (unless special circumstances indicate otherwise) and in each plot, the probability for one tree to be measured (cruised) is proportional to its size (dbh). In B.C. (and basically in entire North America), trees are selected using a prism. This type of plot is usually called a prism plot, or a variable radius plot or a point sample plot.

Brief description of variable radius plots method (adopted from LeMay and Marshall, 1991). The method establishes several fixed area plots of different sizes at each point. As a practical method of doing this, instead of measuring different radius for each tree size, an angle (called the critical angle) is projected from plot centre, using a prism. The plot size varies directly with the tree size and so the probability of a particular tree being "in" increases with the size of the tree. Consequently, the number of stems per hectare represented by each tree varies inversely with the tree dbh. In point sampling, the probability of tree selection is proportional to basal area and the large diameter trees therefore, are sampled with the same intensity as the small diameter trees. However, because the tree dbh and the plot size are inversely proportional, the basal area per hectare for each tree tallied remains constant for a given critical angle and is called the basal area factor (BAF) of that angle. Therefore, for each critical angle there is a corresponding BAF. The BAF represents the basal area per hectare for a tallied tree and is defined as:

$$BAF = ba_t * Ft$$

where

ba_t - basal area for tree "t".

Ft - tree factor, which is the number of stems per hectare represented by each tree.

BAF is a function of the critical angle and is known for each prism. More exactly, each prism is calibrated as a certain BAF. To calculate the volume per hectare obtained with this method, the volume per tree must be calculated first. Next, the tree factor is calculated for each tree. The volume per hectare represented by each tree is then the volume per tree times the tree factor. The volume per hectare represented by each plot is the sum of volume per hectare represented by each tree for all tallied trees. The volume per hectare can be broken down by species. To obtain the stems per hectare represented by a plot, the tree factors have to be summed over all tallied trees. As with volume, the number of stems can be broken down by species, or by species and dbh classes. Average volume per tree is obtained by dividing the volume per hectare by the

stems per hectare represented by the plot. The average diameter can be calculated in a number of ways, the most common method is to weight each diameter by the tree factor:

$$Ave.dbh = \frac{\sum (Ft * dbh_t)}{\sum Ft} \qquad [1]$$

The combination of several variable radius plots to obtain estimates of the stand is performed using per hectare estimates for the plots. The way in which per hectare attributes are combined will depend on the sampling design chosen. With all the above comments, for each species, the volume per hectare for sort "i" can be computed with formula [2]:

$$\overline{y}_i = \frac{y_{i\bullet}}{n} \qquad [2]$$

where:

$\overline{y}_i$ - volume (m^3/ha) for sort i.

$y_{i\bullet}$ - total volume from sort "i", (m^3) produced by all plots.

i - current number of the sort.

i = 1 .. m

m - maximum number of sorts in the set.

n - total number of plots in the cruise.

Total volume from sort "i" produced by all plots ($y_{i\bullet}$) is computed with formula [3]:

$$y_{i\bullet} = \sum_{j=1}^{n} y_{ij} \qquad [3]$$

j - current number of plot (cluster).

j = 1 .. n

y_{ij} - volume (m^3/ha) of sort "i" produced in plot "j".

The total volume per hectare for a given species $(\overline{y})$ can be computed by summing up volumes for each sort:

$$\bar{y} = \sum_{i=1}^{m} \bar{y}_i \qquad [4]$$

A complete description of theoretical basis of the method can be found in LeMay and Marshall (1991) and Avery and Burkhart (1994). Details are provided in the Cruising Manual, developed by the B.C. Ministry of Forests (1983).

The sample size (which is the number of plots to be placed in a block) is a function of the t-statistic, the coefficient of variation and the allowable sampling error. The coefficient of variation (which is the standard deviation expressed as a percentage of the mean), can be obtained by running a small initial sample (pilot sample), or may be estimated from experience gained from sampling similar stands. Since n is dependent upon t, and t is indirectly dependent upon n through its degrees of freedom, the sample size needs to be computed by iteration. In B.C., for scale-based sales, the allowable sampling error is 15% at a significance level of 95%.

A block diagram for the process of computing stand volume and value is given in Figure 2.

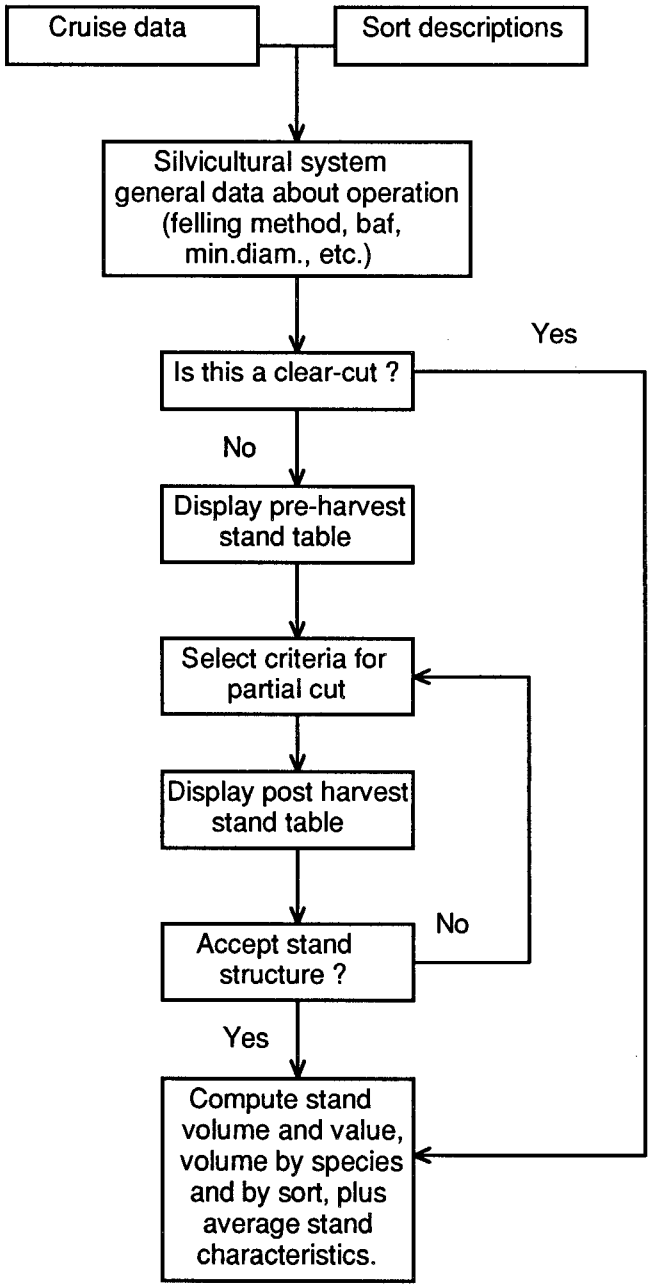

Figure 2. Block diagram for computation of stand volume and value.

The steps taken in this part of the model are:

- input a set of sort definitions that will be used to optimally "pencil buck" the trees.
- input a set of variable plot cruise data for the area.

- input general data about operation (BAF, method of felling, minimum diameter recovered, etc.) and select a silvicultural system.
- for each tree, a dynamic programming algorithm is used to "buck" the combination of logs that will maximize the value. Merchantable height and diameter at different heights on the stem are computed using the following taper equation (Kozak, 1988).

$$d_i = a_0 D^{a_1} a_2^{D} X^{b_1 Z^2 + b_2 \ln(Z+0.001) + b_3 \sqrt{Z} + b_4 e^{Z} + b_5 (D/H)} \quad [5]$$

where:

d_i - diameter inside bark at height h_i (cm.)

$a_0, a_1, a_2, b_1, \ldots b_5$ - regression coefficients

D - diameter outside bark at breast height i.e. dbh (cm.)

$$X = (1 - \sqrt{h_i / H})(1 - \sqrt{p}) \quad [6]$$

h_i - height from the ground (m)

H - total height (m)

p - inflection point (percentage of total height where function which represents the bole shape changes form)

$$Z = h_i / H \quad [7]$$

Values for regression coefficients ($a_0, a_1, a_2, b_1, .., b_5$) and percent inflection points (p) were produced by Kozak by species, by mature and immature trees and by inventory zones in British Columbia (Kozak, A., 1996 - Pers. comm.). With this equation, the merchantable height for a given top diameter can not be calculated directly and must be obtained by iteration.

Volume of individual logs is computed with Smalian's formula.

- volume and value of each log is accumulated into corresponding plot/species/sort.
- by averaging values for all plots, volumes and values per hectare, by species and by sort are obtained.

- total volume and value per hectare are obtained by summing the above results.
- given the total area, per hectare results are extended to the entire block.
- other parameters of interest computed are: average dbh, average tree volume, average piece volume.

The items listed above make a complete description for analysis of a clear-cut. For a partial cut, the user will be asked to input the area of corridors, then the analysis will consist of two parts:

- corridors will be analyzed as clear-cuts.
- for the block itself, the model presents the stand table. Then, an input form is displayed, where criteria can be input for the partial cut. The input from this form is used by the program to extract from the cruise data only the trees that correspond to the partial cut criteria. The following partial cut parameters are considered, separately for each species:
    1. crown class.
    2. diameter class.
    3. tree class.
    4. presence of pathological indicators (conk, scar, mistletoe etc.) or existence of trees displaying poor form (spiral grain, sweep).

  According to criteria set in the previous form, the stand table after the partial cut is displayed. At this point, the user can switch back and forth between the form that displays the stand table after logging and the form that accepts criteria for the partial cut, until an acceptable stand structure is obtained. The analysis will be performed for trees that were selected, and results will be extended from a per hectare basis to the area of block minus the area of corridors.

With the above features, the model has the desired power and flexibility to address specific needs of both clear-cuts and partial cuts.

5.2.1 Optimal Bucking of Cruise Data

Cruised trees are analyzed one by one by a dynamic programming algorithm, which maximizes the value from each tree:

1. the tree is divided in "stages". The total number of stages for a given tree is based on the total merchantable height of the tree, which is determined by stump height and minimum diameter that has to be recovered (usually 10 cm.). In the program, each stage can take information about the following items:
    - diameter of the stem.
    - diameter of knots.
    - knot spacing.
    - presence of sweep.
    - presence of fork or crook.
2. for each stage, diameter (or more exactly the large end diameter) is computed using the taper equation.
3. information from the cruising sheet is attached to corresponding stages and used in the decision process (e.g. if sweep was recorded from 5 to 15 m., this will be attached to corresponding stages and used in the optimization algorithm).
4. the algorithm (forward pass) runs from the top to the bottom of the tree and finds for each stage the log that will maximize the value of the tree, from top up to that stage.
5. once the entire tree has been analyzed, a subroutine (backward pass) picks up the combination of logs that maximizes the value for the entire tree. This starts at the butt of the tree and proceed towards top.

Volume and value is accumulated per sort within each species and each plot. Results per hectare are computed based on individual plots. By multiplying these numbers by block area, block results are obtained.

A detailed description of the dynamic programming method, including how was it applied in this project is given in the remainder of this section.

Description of Dynamic Programming Algorithm

Hillier and Lieberman (1974), state that there is not a standard mathematical formulation of the dynamic programming problem. Rather, dynamic programming is a general type of approach to problem solving, and the particular equations used must be developed to fit each individual situation. The same authors present the basic features which characterize dynamic programming problems. Based on these features and other studies (Pnevmaticos and Mann 1974, Raghavendra 1994), my final dynamic programming formulation, adjusted for the log bucking problem is presented as follows.

1. The problem can be divided into stages, with a policy decision required at each stage. The total number of stages for a tree will be found by dividing the merchantable height by the unit length of a stage, which is established in such a way to provide good results in a reasonable solution time. The policy decision consists in maximizing tree value up to each stage.

2. Each stage can have a number of states associated with it. In general, the states are the various possible conditions in which the system might be at that stage of the problem. In our case, for each stage there is only one state. However, there are a number of different decisions that can be taken at any stage, represented by the various logs (different sorts and different preferred lengths for each sort) that can be bucked.

3. The effect of the policy decision at each stage is to transform the current state into a state associated with stage (n-k), where k is the length of the log to be tried, expressed in stage intervals.

4. Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages.

5. The solution procedure consists of two passes: the forward and the backward pass. It begins by finding (as the first step in the forward pass) the optimal policy for each state of the last stage (top of the tree). The solution of this one-stage problem is usually trivial.

6. The forward pass moves from the top to the butt of the tree, stage by stage, each time finding the optimal policy for each stage, until it finds the optimal policy when starting at the initial stage (butt).

7. The backward pass moves from the butt to the top of the tree in steps equal to log lengths. This very last step consists in picking-up the logs that produce the highest value of related stages, and thus the combination of logs that maximizes value of the entire tree.

In this approach, a problem may be produced by defects that extended over a small number of stage intervals. A good example for this is fork or crook. If this defect is present on a tree, the value will increase to the stage just before the defect, and then, because none of the sorts considered accepts this defect, the value will decrease for a number of stages. Specifically, the value of the tree will be less than the value before the defect, at least for a number of stages corresponding to the minimum preferred length. A solution to that, would be to advance stage by stage in the backward pass. However, this will dramatically increase the computing time for this algorithm (which is already very time consuming). To account for this problem, bucking will be enforced outside the dynamic programming procedure, at stages where a fork or crook is present. Consequently, optimization will be carried out for two stem sections, instead of one entire tree.

Recursive relationship formulations for dynamic programming in log bucking, were done by Pnevmaticos and Mann (1973), MacPhalen (1978), Faaland and Briggs (1984), Dykstra (1985), Young and Waddell (1986), Eng et al. (1986), Briggs (1989), Sessions et al. (1989) and Raghavendra (1994).

The dynamic programming recursive equation used in this project was developed starting from those used by Young and Waddell (1984) and Eng et al. (1986). Due to the different approach taken in this model, some modifications have been made.

The general form of the dynamic programming recursive relationship is given as follows:

Let:

n - current stage

d - stage resolution (m)

k - decision in stage intervals (no. of stage lengths to make log)

l - log length (m)

$l = kd$

D_n - tree diameter at stage n (cm)

D_{n-k} - tree diameter at stage (n-k) (cm)

C = 0.0000392699 - constant used for computing log volume with Smalian's formula

$U_{S,g}(q_1, q_2, q_3, q_4, q_5)$ - unit price ($/m^3) for species S and sort g, subject to all the following conditions (that can take true/false values):

- q_1 - condition related to small end diameter
- q_2 - condition related to large end diameter
- q_3 - condition related to knot diameters
- q_4 - condition related to knot spacing
- q_5 - condition related to sweep

$V(D_n, D_{n-k}, l)$ - volume of log with diameters D_n respectively D_{n-k} and length l (m^3)

$$V(D_n, D_{n-k}, l) = l \cdot (D_n^2 + D_{n-k}^2) \cdot C \qquad [8]$$

$R[V(D_n, D_{n-k}, l), U_{S,g}(q_1, q_2, q_3, q_4, q_5)]$ - log value based on volume and unit price ($)

$$R[V(D_n, D_{n-k}, l), U_{S,g}(q_1, q_2, q_3, q_4, q_5)] = V(D_n, D_{n-k}, l) * U_{S,g}(q_1, q_2, q_3, q_4, q_5) \qquad [9]$$

The total length of the tree is divided into N stages as defined by the stage resolution (d) and the recursive relationship becomes as follows:

$$f_n = \max_k \{ R[V(D_n, D_{n-k}, l), U_{S,g}(q_1, q_2, q_3, q_4, q_5)] + f_{n-k} \} \qquad [10]$$

where

f_n - maximum value of the tree from the top to stage n.

f_{n-k} - maximum value of the tree from the top to stage (n-k).

k - set of feasible sort lengths at stage n.

Figure 3 illustrates the computational scheme:

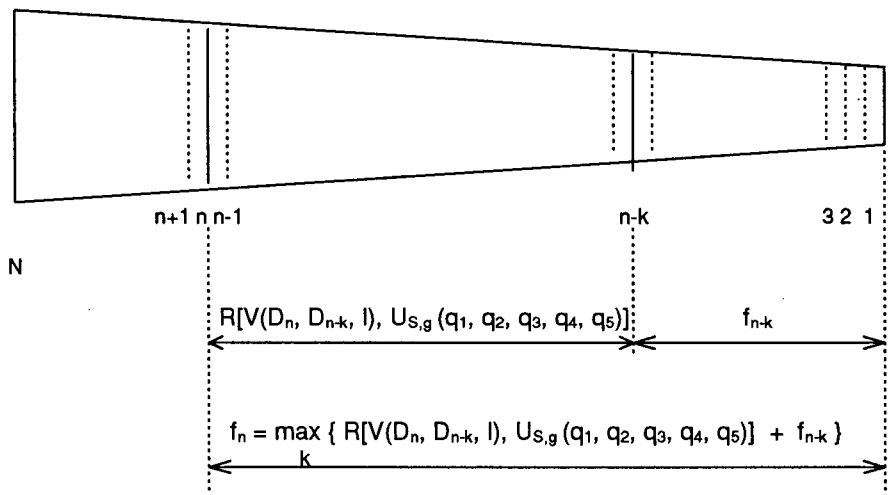

Figure 3. Dynamic programming representation of stem.

Essentially, the principle is that given the optimal result for each of the preceding (n-1) stages, the sum of the value at the n-th stage after cutting a log of length k stages plus the value of the optimal result for the first (n-k) stages, can be calculated for all feasible log lengths. The log type and value of k that give the maximum value are retained as the optimal combination (decision) for the n-th stage.

A block diagram for the dynamic programming algorithm is presented in Figure 4. The following notations have been used, assuming a given stage length:

Let

p - number of stages corresponding to minimum pulpwood length

q - number of stages corresponding to the minimum sort length for a given species.

It is well known that $p < q$

N - total number of stages for a given tree

n - current stage

Each stage will store the following information:

- value to stage n
- log length - length of the log to be bucked at stage n to maximize tree value up to that stage
- log volume
- log value
- sort name - name of the sort to which the above log was assign

Before the dynamic programming algorithm is started, data on current diameter, knot diameter and knot spacing are stored at each stage of the tree. Sorts are arranged in increasing order of length.

For an individual tree, at the end of algorithm described in Figure 4, each stage stores information that will maximize its value; i.e. maximum value up to that stage, log length, log volume, log value and the corresponding sort for that stage.

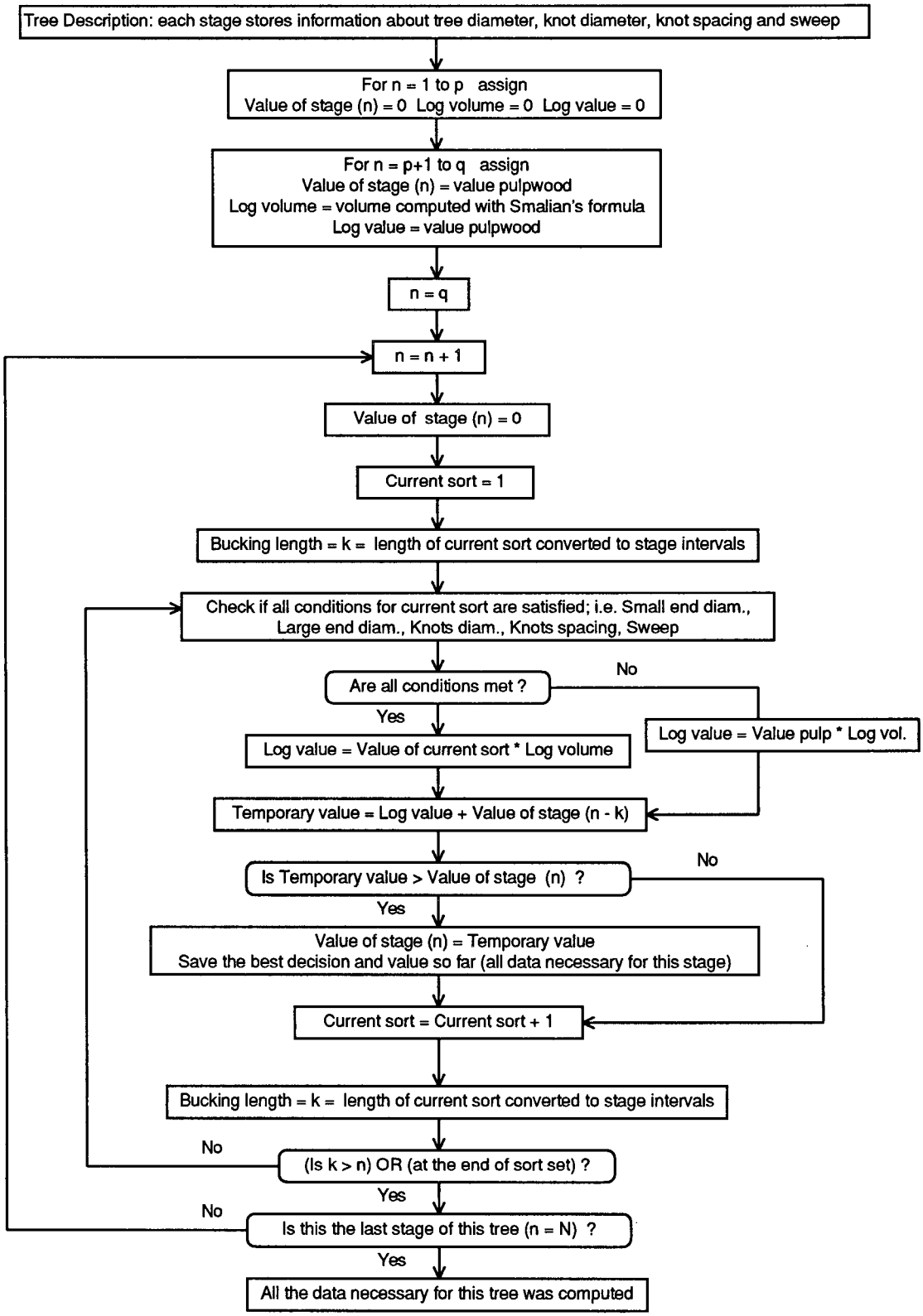

Figure 4. Block diagram representation of dynamic programming - forward pass.

Once the optimal decision and optimal value have been determined for each stage in the forward pass, the optimal bucking policy for the tree can be determined through a backward pass. The process starts at stage N (the tree butt) and obtains the optimal length of the first log to be bucked. Since the optimal solution has been determined and saved for all stages in the tree, the optimal length of the second log is known at the stage where the tree is bucked for the first log. This process continues until the complete bucking policy for the tree is determined.

The part of program related to computation of stand volume and value is described using pseudocode in Appendix 1A. The forward pass of the dynamic programming algorithm is presented in the subroutine DynamicProgramming; the backward pass is described in the subroutine BackPass.

5.2.2 Factors That Can Affect Prediction of Stand Volume and Value and Methods to Account for Them

In the process of analyzing cruise data and optimizing value that is obtained from each tree, we acknowledge the existence of some factors that may affect prediction. In the first part of this section there is a presentation of these factors. Methods used to account for them are introduced later.

1. Factors due to sampling method.

2. Factors due to inventory procedure (independent of people doing the work and that can not be avoided).
   - Errors due to defects that could not be detected during cruising (different types of rot and other internal defects).
   - Errors in estimating wood quality. This refers mainly to estimating the numbers of rings per inch. This is an important criterion in grading and may produce bias when evaluating the total value of the block. It is not possible to get these data during cruising, without a major impact on productivity and cost.

3. Factors that produce a loss in the total volume and value recovered due to harvesting procedures:
   - Breakage during falling. Breakage will produce some volume loss because some broken pieces will become non-merchantabe and, value loss because it may produce downgrading of logs.
   - Breakage during primary transportation. Depending on the extraction method, additional breakage may occur while logs or trees are being moved from felling site to roadside.
   - Non-optimum bucking. Bucking takes place at the stump or at the landing. In the case of a full tree system, it may also take place at the sort yard. Non-optimum bucking occurs more frequently in the bush, and produces a loss in value, because the faller may be under production pressure or concerned about safety. Errors in bucking may also occur in other locations, however, with less severe impacts.

4. Factors that affect computations in the program (equation error). This consists primarily of errors in computing the taper of trees cruised.

The following methods will be used to account for factors described above:

1. To analyze the sampling error, cruises will be more intensive than is legally required. Results produced by the model will be compared to results obtained after harvesting the block. Comparisons will be done by species and by sort using a t test. The following hypothesis will be tested:

   H_0 : Value produced by model = Actual value obtained after scaling

   H_1 : Value produced by model $\neq$ Actual value obtained after scaling

   The significance level (α) chosen is 95%; the t test will be:

$$t_{n-1} = \frac{\bar{x} - v}{S_{\bar{x}}} \qquad [11]$$

where:

n - total number of plots.

$\bar{x}$ - mean volume per species and sort computed from all n plots.

v - real volume after scaling.

$S_{\bar{x}}$ - standard error of the mean.

This is a two-tailed test, and the critical region consists of intervals $(-\infty, -t_{n-1,\alpha/2})$ and $(t_{n-1,\alpha/2}, \infty)$. H_0 is rejected if t test is in the critical region. If H_0 is rejected the two values are statistically different. If t test is outside critical region, we fail to reject H_0, and the two values are statistically the same.

Because the distribution of volume by species and sort determines the value of the wood, this test will be the main validation of the model.

2. For inventory procedure factors, the following methods are considered:
   - It is usually expected that defects that could not be seen during cruising will produce downgrading for some sorts and may cause an overall loss of wood. As presented earlier, it was known from experience that in coastal second-growth stands, little defect of this kind is encountered. The assumption was confirmed during field work carried out during this study, i.e. no defect of this nature was identified. Consequently, the model was not design to account for this type of problem when computing volume and value of individual trees.
   - Ring count is difficult to collect during cruising but should be considered because in some second-growth blocks there is a significant volume that satisfies the requirements of more valuable sorts (high grade instead of thrifty). In the model, a combined sort should be included, and its value should be weighted by the value of the two sorts in question. The numbers used in this process will come from the user's experience. For

example, if it is known from experience that about 20% of the saw log volume in a region is high grade and the rest is thrifty, these percentages should be used to compute a weighted average price for the combined thrifty/high grade saw log sort introduced in the set.

To analyze breakage, non-optimum bucking and equation error, fixed area plots were placed in the Stillwater block. To account for the three different harvesting methods used in the block, two plots were located in the area of each system, each one in terrain with different slope conditions. Within each plot, trees were cruised the same way as for the rest of the block, and numbered in such a way to ensure easy and accurate retrieval of each log. Trees were located after felling and bucking and marked accordingly. The length and diameters of logs were recorded. Logs were also tracked to the log sortyard, and their final dimensions (as taken by scalers), volume and company sort were recorded. The detailed field procedures for this phase will be fully described in Chapter 6.

3. A description of methods chosen to account for each factor follow:

- Breakage during falling: the approach taken to solve this problem is similar to the one taken by Deadman and Goulding (1979). The main purpose was to develop a frequency function that will predict the height of break point relative to total height. The differences relative to the previously mentioned function are:

    I. The breakage frequency will be a function of species and dbh class. Trees will be grouped in 20 cm. classes for which it is assumed that break point is the same .

    II. As other studies proved (Warren 1994), due to good falling techniques (the tree is felled parallel to the contour lines so as to minimize breakage), ground slope is not a significant factor in the breakage function, except for very steep slopes (greater than 60%). Therefore it will not be considered in this model.

In this model, the portion of stem above the break point is considered recoverable. Obviously, this will overestimate the volume harvested and the user will be warned about it in the manual that will accompany the software. Analysis was carried out on what happens if this assumption is not true, and the entire portion of the stem above break point is unrecoverable.

Based on practical observation that the volume of breakage differs greatly between manual and mechanical felling, breakage analysis was conducted separately for these two methods. Although not collected as part of this project, data from another FERIC project (Young, 1996) were used to analyze mechanical falling.

- Breakage during primary transportation: previous studies (Copithorne and Young, 1994) showed that in Coastal B.C. this is about 0.2 % of volume. In this project, it will be assumed that loss in volume and value that occurs during this phase is negligible.

- Non-optimal bucking: theoretical (pencil bucking) of standing trees (as cruised before felling) in the fixed area plots, was compared with what was actually achieved at the log sortyard.

Sampled logs from the fixed area plots (measured and marked in bush) were retrieved at the roadside and repainted to ensure easy retrieval. Next, logs were tracked to the log sortyard and scaling and grading were recorded. Company sort and B.C. Ministry of Forests grades were assigned to the log. At this stage, scalers from MacMillan Bloedel Ltd., made a substantial contribution, recording on their hand-held computers, the identification number of logs.

On the other hand, the cruise for fixed area plots were analyzed with the algorithm developed as a part of this project. For each tree, the combination of logs that maximized its value was determined.

The purpose of the analysis was to compare the value produced by each method, for as many trees as possible. Obviously, that necessitated that all logs (or at least the most representative ones) be identified at the sortyard. As presented in next chapter, due to practical considerations, this was only partially achieved. However, valuable conclusions could still be drawn, by comparing for each tree and for each individual log results from the model and the scalers at the sortyard.

4. To evaluate the effect of taper equation estimates, differences between predicted and measured diameters were evaluated.

   Diameters measured at stump height and at each one-tenth of the height, were compared to diameters produced by the taper equation at the same points. Predicted vs. real results were checked using the same statistics used by the author of the taper equation (Kozak, 1988), i.e. average bias (B) and the standard error of the estimate (SEE); formulae are given below:

$$B = \frac{\sum_{i=1}^{n} (Yi - \hat{Yi})}{n} \qquad [12]$$

where Yi - measured value

$\hat{Yi}$ - estimated value

n - number of observations

$$SEE = \sqrt{\frac{\sum_{i=1}^{n} (Yi - \hat{Yi})^2}{n - m}} \qquad [13]$$

where m - number of parameters used in estimation.

all the other parameters are the same as above.

For these statistics, results were compared to those in Kozak (1988).

Considering all factors outlined in this chapter and methods to account for them, the t-test will be used to compare prediction vs. actual result by species and by sort. This will be presented in Chapter 7 - Results. The remaining factors are the taper equation estimates, evaluation of breakage and comparison between theoretical and real bucking. To evaluate the effect of these three factors, specific field work was done as presented in next chapter.

5.3 Method to Calculate the Cost of Harvesting

The cost of harvesting is determined by analyzing and comparing the results of several harvesting options. When this result is computed, the revenue generated by the block can be found, by subtracting the cost of logging from total value of the stand. In the second part of the model, the user defines the harvesting system by selecting the desired harvesting technique for each phase. The options offered for each phase are the following:

- Falling

  Mechanical: Feller buncher, Feller processor.

  Manual: Falling only, Falling and bucking.
- At-stump processing: Delimber, Processor.
- Log alignment: Excavator log alignment.
- Primary extraction:

  Cable extraction: Grapple yarder, High lead yarder, Super snorkel

  Ground based extraction: Choker skidder, Grapple skidder, Short wood forwarder, Hoe forwarder
- Roadside processing: Manual, Delimber, Processor.

- Loading: Front end loader, Hydraulic loader.

The model allows stratification of the stand. Up to five different harvesting techniques can be used in different portions (strata) of the same cutblock.

The cost by phase and the total cost of logging is based on productivity equations and cost per hour of machines used in each phase. The bulk of these equations were developed by FERIC. In case the appropriate function was not found in a study carried out in the coastal region of B.C., equations developed in similar conditions were considered. The main parameters of the block (total volume, total value, average piece size etc.) will be available for this submodule, to compute the cost of the harvesting system.

The user is given full control over this part of the model. There is no restriction in configuring various harvesting systems and, values offered by productivity equations programmed in the model, can be overwritten anytime.

This portion of the model is represented in Figure 5.

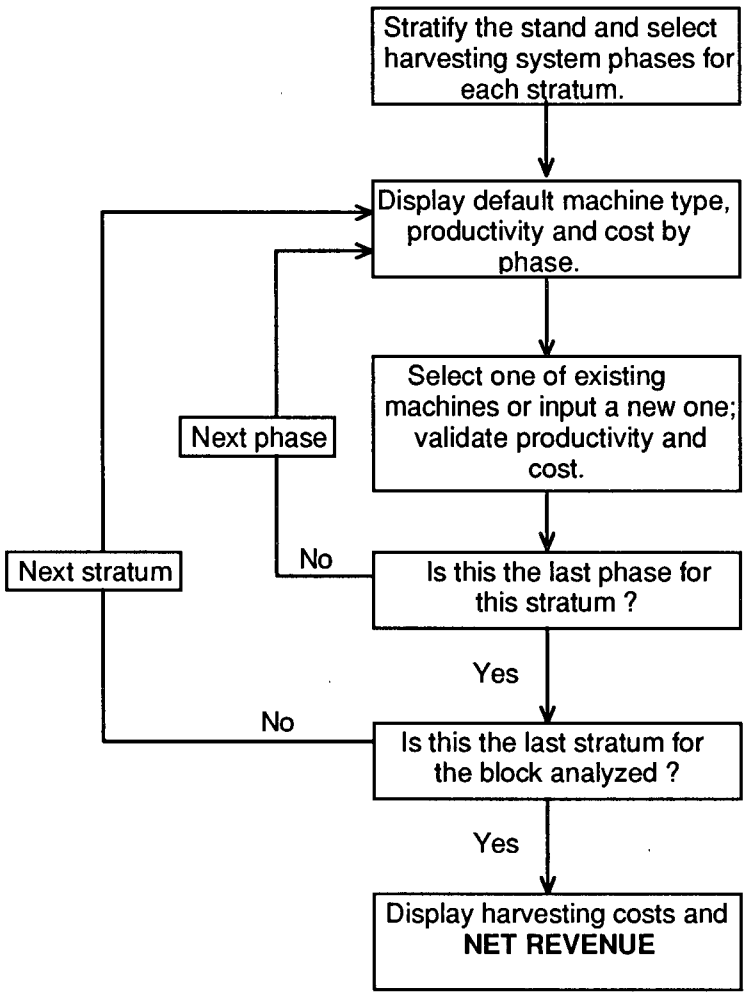

Figure 5. Flow chart for computation of harvesting cost and net revenue.

The steps taken in this part of the model are described as follows:

- each block can be split into five strata based on logging system.
- for each stratum, a harvesting system can be configured using the options available for each phase.
- based on the system, the user will compute the cost of each phase and each stratum. Productivity, cost, yarding distance and other data can be changed. At each phase, the user can use the default machine offered by the model or input a new one.
- based on above numbers, total cost for harvesting the entire block will be computed.

- the revenue generated by the block will be computed by subtracting from the value of the stand the cost of the harvesting process.

The user interface of this section of the model consists of three forms. The code attached to each one of these forms is presented using pseudocode, in Appendix 1B.

Productivity equations (or averages) used in the model and machinery costs are presented in Appendix 2. As mentioned before, these data will be considered only as recommendations that can be anytime overwritten by the user, based on his experience and on better knowledge of available machinery and field conditions.

5.4 Model Validation

As presented in the objectives of this study, after its completion, the model was validated. The Stillwater block was used to develop the model and, as part of model development, all factors that affect prediction were analyzed, as described in Chapter 5.2.2:

- taper equation was assessed.
- a breakage model was elaborated.
- an analysis of bucking was performed.

Predicted results by species and sort were compared with the actual ones. With all the above factors included, the model was validated by analyzing the Okeover block. This block was cruised using the method proposed in the project and the final result was compared with what the model predicted. For both blocks, different runs were produced, by incrementally including specific cruise data that were collected.

For the second part of the model (prediction of cost of harvesting) no validation was planned. This is due to the nature of this module, more exactly, due to the fact that it offers only some

approximate values for a specific harvesting phase, that will be validated by the user based on experience, machine availability and considering the specific conditions of the block.

Results obtained in the process of model validation are presented in Chapter 7.

6. FIELD DATA COLLECTION

The first part of this chapter will describe the field procedures used to compute stand volume and value. Next, specific data collection methodology related to the design of the harvesting system, will be presented.

6.1 Data Collection for Prediction of Stand Volume and Value

First, field procedures that were used to account for factors that can affect prediction of stand volume and value are introduced. As described in Chapter 5.2.2, these factors are: the taper equation, breakage and differences between optimum (theoretical) and actual bucking. Finally, the specific cruising procedures that were used in this project will be described.

6.1.1 Field Procedures For Checking the Taper Equation, Evaluation of Breakage and Comparison Between Theoretical and Real Bucking

For fluency of presentation, a partial description of the method used to account for these factors was given in the previous chapter. This method consisted of laying out six fixed-area plots in the Stillwater block.

For statistical reasons, it was desirable that at least 30 trees (all logs of the tree) be retrieved after falling and tracked to the sortyard. From experience it was decided that at least twice the number of standing trees should be marked. Given the stand density of 550 stems/ha, a plot area of 0.125 ha was chosen. To account for specific terrain conditions, the shape of the plot was circular for grapple yarding and hoe-forwarding (radius of 20 m) and rectangular for direct loading (15 m x 80 m). In these six plots a total of 393 trees were recorded, with an average of 65 trees / plot.

Each tree in the plot was cruised the same way as for the rest of the block), and numbered to ensure easy and accurate retrieval of each log. Trees were located after felling and in-bush bucking and marked accordingly. The following data were recorded for each tree:

- number of the tree.
- species
- diameter at breast height (dbh)
- stump height
- diameter at stump height inside bark (as an average of two measurements) or, if this was not accessible, butt diameter of first log was measured.
- information collected for each log is the following:
    1. log number
    2. diameter outside bark (dob) at large end - only if previous log was not found or the stump was not accessible.
    3. total length / length where breakage occurred - if this is the case.
    4. diameter outside bark (dob) at the small end.
    5. bark thickness (measured with a bark gauge).

Specific methods and formulae used to solve each of the three problems addressed in this section were given in Chapter 5.2.2.

6.1.2 Field Procedure for Cruising

In general, cruises performed as part of this project were done in accordance with B.C. Ministry of Forests regulations. However, more details were collected for individual trees, to test if this would improve accuracy of prediction, namely:

- data collection about knots was completely changed; diameter and spacing of knots were estimated, by dividing the bole into uniform portions with respect to these

parameters. While cruising, it was noted that downed trees (naturally or for road right-of-way) could be used by cruiser to check his calls about diameter and knot spacing.

- for all defects recorded in the cruise tally sheet, height of occurrence was measured if possible, or at least estimated.
- for defects that affect a large portion of the stem (sweep was the only defect of this nature that was encountered), apart from height of occurrence, total length was measured or estimated.

Higher intensity cruising was performed during field trials, with a view to analyze how sampling intensity affects prediction. For the Stillwater Block, 39 plots including 191 trees, were laid out, and for Okeover block 26 plots including 162 trees were used. The cooperating companies placed 21 operational cruise plots (92 trees) in Stillwater block, and 15 plots (96 trees) in the Okeover block.

6.2 Data Collection for Harvest System Design

No specific field procedures were carried out as part of this submodule. As mentioned in the study design, existing equations developed as part of other studies were implemented. The user has the possibility either to use the results provided by these equations, or to overwrite them, based on experience, knowledge of specific site conditions and machinery used.

This submodule is mainly theoretical, the main concern being how to offer a user-friendly and comprehensive interface, rather than how to collect field data.

7. RESULTS AND DISCUSSION

The model was thoroughly tested both at the individual tree level (the combination of logs that maximizes value for each tree) and at the stand level. It was noticed that due to the large number of computations and their complexity, this part of the program was very time consuming. To account for this problem, the model was designed to accept two stage lengths for the dynamic programming algorithm, i.e. 0.1 m. and 0.2 m.. The first choice is designed to handle detailed analysis, whereas the second one can be used for quick analysis. Accuracy of results produced by these two options depends mainly on the lengths of sorts that are to be bucked. If these lengths are multiples of 0.2 m., then the second option can produce results very close to the first one. If the above condition is not met, then results may be quite different.

In terms of time performance, when running the model on a 486 machine, with 16 MB RAM, it required about 3 seconds per tree for the version quick analysis (0.2 m. stage length) and almost double for detailed analysis (0.1 m. stage length). For clear-cuts, to find the total time to analyze a cruise, these numbers should be multiplied by the number of trees. For partial cuts, time will increase proportionally to the number of trees that will be processed (removed) outside corridors (in the residual stand).

Although the model was designed primarily to handle data in the format that was recorded in this project, it can be very easily used to analyze standard cruises. For cruises performed according to B.C. MoF regulations, the model offers default values for fields that are not included in the tally sheet. Details on how to address this process are given in the user manual.

While the model was developed to assess both clear-cuts and partial cuts, only clear-cut results were validated. The rest of this chapter will present results produced by the model. The first sub-chapter will introduce evaluation of factors that may affect prediction of stand volume and value.

7.1 Results for Evaluation of Taper Equation, Evaluation of Breakage and Comparison Between Theoretical and Real Bucking

Results presented in this chapter were obtained using principles and formulae described in Section 5.2.2. Specific comments and additional information is given for each item addressed.

7.1.1 Evaluation of Taper Equation

Overall, 283 measurements were used to check the taper equation and to develop the breakage function. Results are presented in Table 2. The format chosen to present these data is the same that was used in Kozak (1988). Diameters were measured at the ends of logs and then, grouped together by percentages of total height of the tree. Both bias and standard error of the estimate are presented in cm.. No attempt was made to represent them in percentages, since this way of presentation is affected by the base to which the comparison is made, and many times misrepresents results.

In the data analysis process, some measurements were eliminated. The most frequent case was when details pertaining to a tree were not recorded; e.g. it was noted that a log was missing, therefore the height where a diameter was measured could not be computed. Eight parameters are used by the taper equation to estimate a diameter. Therefore, the standard error of the estimate (SEE) was computed only when the number of measurements (n) available was greater than or equal to 9.

Table 2. Biases and Standard Errors of Estimate - SEE of diameter inside bark from ground to top.

Height from ground	Douglas-fir			Cedar			Hemlock		
	n	Bias (cm)	SEE (cm)	n	Bias (cm)	SEE (cm)	n	Bias (cm)	SEE (cm)
< 0.5	24	1.03	1.78	21	0.88	1.84	54	0.97	1.98
20%	3	1.10							
30%	9	1.09	2.04				7	0.97	
40%	6	1.05		4	1.01		19	0.96	1.71
50%	9	0.97		5	1.16		8	0.99	
60%	7	1.08		7	1.03		5	0.95	
70%	16	1.00	2.09	8	1.05		22	0.90	2.02
80%	5	0.84		10	1.12	1.54	16	1.08	1.21
90%	10	1.01	1.14	4	1.09		4	1.19	
All	89	1.02	1.76	59	1.05	1.69	135	1.00	1.73

Results in the table compare well with results presented in Kozak (1988). According to Kozak (1997 - Personal comm.), an acceptable limit would be 2.0 cm. for bias and 4.0 cm. for SEE. Results obtained in this project are well under these limits. As one can see in Table 2, values for bias are positive for all species and all classes. This is despite the fact that some real measurements were greater than theoretical ones. However, this doesn't affect accuracy of computations because of the small difference between values, and because of the scaling rule used in B.C.: all diameters are rounded-off to the nearest even number.

In conclusion, the taper equation predicted diameters very well in this study.

7.1.2 Evaluation of Loss due to Breakage

This analysis was performed to estimate a ratio of breakage, in terms of how many trees will break (by species and by dbh classes), and percentage of total height where breakage will occur. Also, the portion of the stem that has to be trimmed off after breakage was estimated according to the same criteria.

To extend applicability of the model, analysis was carried out both for manual and mechanical felling. Results obtained for manual felling are presented in Table 3:

Table 3. Analysis of breakage for manual felling.

Species	DBH limit (cm)	Breakage frequency (%)	Height of break point (% of Total Height)	Length of trim (m)
CE	20	50	60	0.4
CE	40	100	74	0.8
CE	60	100	77	0.8
CE	>60	100	72	0.8
DF	20	50	60	0.4
DF	40	100	60	0.8
DF	60	100	69	0.8
DF	>60	100	59	0.8
HE	20	50	60	0.4
HE	40	100	66	0.8
HE	60	100	67	0.8
HE	>60	100	59	0.8

The frequency of breakage and length of trim are presented after rounding numbers. The actual numbers were within ± 10% of numbers displayed. This solution was chosen to avoid complications related to programming tasks.

Average heights of breakage (as a percentage of total height) per species are: Cedar 71%, Douglas-fir 62%, Hemlock 63 %. As one can see in the Table 3, the length of stem that had to be trimmed off due to breakage was the same for each species. Also, this length was the same for all trees with dbh greater than 40 cm.

For mechanical falling, the only species available was Douglas-fir. Results obtained from the analysis are presented in Table 4.

Table 4 . Analysis of breakage for mechanical felling of Douglas-fir.

Species	DBH limit (cm)	Breakage frequency (%)	Height of break point (% of Total Height)	Length of trim (m)
DF	20	50	81	0.4
DF	40	100	75	0.8
DF	60	100	85	0.8
DF	>60	100	78	0.8

Results obtained for Douglas-fir were extended to other species as well. For the same reasons presented above, breakage frequency and length of trim were rounded.

As one can see comparing Tables 3 and 4, the only difference between the two falling methods consists of the height (as percentage of total height) where breakage occurs. For mechanical felling, this averaged 80% for Douglas-fir and was used for all species in the model.

The model also compares the height of break point and the merchantable height for each tree. Depending on the result produced by this comparison, a tree can be analyzed as one or two separate portions. The model assumes only one break point for a tree, i.e. if the top log is long enough, it is considered fully recoverable and analyzed by the optimization algorithm. Obviously, this will produce an overestimation of volume of the stand. Comments about this situation are made in the remainder of this chapter. Detailed description of these procedures are provided in Appendix 1.

Although none of the blocks analyzed in this study were mechanically felled, test runs of this method evaluated differences between the two falling methods. Results are presented in Section 7.2.

7.1.3 Comparison Between Theoretical and Actual Bucking

The comparison of bucking efficiency was seriously affected by the fact that the cooperating company changed the method of scaling during the project and manually scaled only one in seven loads. This resulted in 241 logs being lost. Eventually, an agreement was reached and special attention was given to loads that included logs marked in this project. However, due to this perturbation, only logs from three plots (out of six) were used for comparison between theoretical and real bucking. Although each plot was selected to represent one of the harvesting systems used, this reduced the size of the sample to half.

A number of 83 logs were found at the sortyard, of these, 8 were eliminated because the values measured did not agree with the initial cruise data. It is believed that this was produced by misreading of identification numbers that were covered with mud during logging. The final situation is presented in the Table 5. In Table 5 and in the rest of this section, the word match is used when actual and predicted logs were the same. Since each tree is analyzed in the same way, the analysis was not carried out by species.

Table 5 . Match of logs found at the log sort yard.

No. Logs Found From a Tree	No. Trees	No. Logs	No. Logs That Matched
One log	30	30	19
Two logs	21	42	29
Three logs	1	3	0
TOTAL	52	75	48

As shown in the table, there was only one tree for which three logs were found. Unfortunately the bottom log was missing and the ones found did not match, thus making any analysis impossible.

A note should be made that in the first class (one log found) ten of the logs recorded were log number two. It is obvious that, when butt diameter of a real second log and of the second log produced by the model were equal, the previous log (if found) would have matched as well. This happened in six cases. When two non-consecutive logs were found (logs number one and three)

and they matched the model logs, the log in between would also match. This happen three times in this analysis. These missing logs were assumed to validate model performance.

Overall, results for sampled trees that were tracked from the woods to the sortyard, can be considered good, but not enough logs were recovered to validate the model. Because all logs were not retrieved for any plot, it is difficult to evaluate the role played by the breakage model. The final scale for the entire block will be used as the main criteria to test model performance.

7.2 Comparison of Block Volume and Value - Predicted vs. Actual

Analysis of block value and the influence of different factors was conducted for the two blocks. Different runs were produced to account for all factors that could influence the final result. To ensure maximum accuracy, all these runs used a dynamic programming stage interval of 0.1 m.

Each set of values obtained with the procedure described above, was compared with the scale obtained after the entire block was harvested. This comparison helped draw conclusions about the effect of more detailed tree description on accuracy of predictions.

Results are presented separately for each block.

7.2.1 Results for the Stillwater Block

Fourteen runs were considered in the analysis of the Stillwater block. Factors included in each one of these runs and results produced are presented in Table 6.

These predictions are split into four groups as presented below:

- First group (Predictions 1-3): excludes the effect of breakage. This is an unrealistic assumption but, it was considered to calculate the maximum volume and value per

hectare for the stand. Downgrading factors were included in groups of two, i.e. fork and sweep first and then knot diameter and spacing.

- Second group (Predictions 4-8): includes the effect of breakage. Since this is what happens in real life, the analysis was conducted in more detail, and factors were included one by one. The most complete is Prediction No.8, which represents the actual function programmed in the model.
- Third group (Predictions 9-10) was done to test the capabilities of the model. As presented before, the model assumes that from each tree that breaks (based on frequency presented in previous chapter), the top section is recoverable. Of course the shattered portion between the two sections is lost. Prediction 9 was done assuming that breakage is so severe, that the top log is entirely lost. Since a breakage frequency function was developed for mechanical falling with no chance to test it, Prediction 10 was done to estimate volume recovery had the first block (Stillwater) been mechanically felled.
- Fourth group (Predictions 11-14) is described below.
    1. Prediction 11: presents results obtained by the cooperating company, based on their operational cruise, and using Ministry of Forests compilation program. Because ministry grades are used, for this prediction, only volumes can be compared with the model.
    2. Prediction 12: includes results obtained using company cruise in the model.
    3. Prediction 13: was carried out to analyze the influence of the sample size and to make it comparable with the sample size used by the company. Even number plots were used in this run.
    4. Prediction 14: same as above but using odd number plots.

All predictions are described in Table 6. The actual total volume recovered from the block was 630 m^3/ha. Due to an agreement with the cooperating company, value is not disclosed. Instead, the percentage between value at different runs versus actual value is presented.

Table 6 . Fourteen predictions of total volume and value for the Stillwater block[1] .

Prediction	Factors					Volume	Volume	Value
No.	Breakage	Fork	Sweep	KnotDiam.	Knot Sp.	m^3 /Ha	(%)	(%)
1						694	110	112
2		x	x			694	110	111
3		x	x	x	x	693	110	108
4	x					665	106	107
5	x	x				665	106	106
6	x	x	x			665	106	106
7	x	x	x	x		665	106	104
8	**x**	**x**	**x**	**x**	**x**	**664**	**105**	**103**
9	Top Section Not Recoverable					608	97	99
10	Mechanical Falling					681	108	107
11	Company Cruise & MoF Compilation					561	89	-
12	Company Cruise Analyzed with the Model					550	87	86
13	Feric Cruise - even no. plots					761	121	120
14	Feric Cruise - odd no. plots					570	90	86

The four groups of predictions will be presented one by one in the rest of this chapter. Results will be presented by species and by sort. For reasons presented in the previous chapter (i.e. percentages may be misleading), percentages are given only for totals by species and the grand totals . For comparison, each table will also contain the actual scale result obtained at the log sortyard.

First Group - Predictions 1-3: Results are presented in Table 7. As expected, the volume per hectare produced by these runs was above the actual volume. Total volume was 110% of actual and volumes per species ranged from 101% to 140%. The overestimation of volume for hemlock may look severe, but this species represented only 21% of total volume in the actual scale. Volumes of the three runs are not exactly the same because of rounding and because including a defect may cause some portions of a tree to become unmerchantable. Some variations may be due to Smalian's formula.

[1] In this table Knot Diam. stands for Knot Diameter and Knot Sp. is the abbreviated form for Knot Spacing.

Table 7 . Results of predictions 1-3 vs. actual, by species and sort.

		Actual	Prediction 1		Prediction 2		Prediction 3	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3	
CE	Saw Log	8	6		6		6	
	Gang	22	38		38		33	
	Chip & Saw	11	13		13		17	
	Utility	2	0		0		0	
	Pulp	14	8		8		9	
	Total CE	57	65	114%	65	114%	65	114%
DF	Saw Log	281	265		264		265	
	Gang	106	167		167		124	
	Chip & Saw	20	0		0		17	
	Utility	9	2		2		24	
	Pulp	27	13		14		16	
	Total DF	443	447	101%	447	101%	446	101%
HE	Saw Log	15	28		28		23	
	Gang	77	121		121		119	
	Chip & Saw	10	0		0		2	
	Utility	1	10		10		15	
	Pulp	27	23		23		23	
	Total HE	130	182	140%	182	140%	182	140%
	VOLUME	630	694	110%	694	110%	693	110%
	VALUE			112%		111%		108%

By considering fork and sweep (there are 11 trees with fork and 1 tree with sweep), value per hectare dropped by 1%. Knot characteristics produced an additional drop in value of 3%.

Second Group - Predictions 4-8: values are presented in Table 8. Similar to the first group, volume per hectare is about the same for these five predictions but because breakage was considered, the volume predicted was reduced by 5% for prediction No.8 and 4% for the others.

By including defects one by one, value per hectare dropped from 107% to 103% relative to actual value. These values are reasonable because, the model assumes that for broken trees, the top section is entirely recoverable. Note that the only tree that displayed sweep did not produce any decrease in volume or value. As for prediction of volume per species, again the worst prediction is for hemlock because of the small sample.

Prediction 8 represents the final version of the model. Overall, overestimates of 5% in volume and 3% in value were achieved.

The detailed distribution of volume per sort for each species for Predictions 4 - 8 is given in Figure No. 6.

Table 8. Results of predictions 4-8 vs. actual.

		Actual	Prediction 4		Prediction 5		Prediction 6		Prediction 7		Prediction 8	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3		m^3		m^3	
CE	Saw Log	8	6		6		6		6		6	
	Gang	22	38		35		35		34		30	
	Chip & Saw	11	13		15		15		15		20	
	Utility	2	0		0		0		0		0	
	Pulp	14	7		7		7		7		7	
	Total CE	57	64	112%	63	111%	63	111%	62	109%	63	111%
DF	Saw Log	281	256		255		255		256		256	
	Gang	106	151		153		153		122		119	
	Chip & Saw	20	0		0		0		23		23	
	Utility	9	0		0		0		5		8	
	Pulp	27	21		21		21		23		23	
	Total DF	443	428	97%	429	97%	429	97%	429	97%	429	97%
HE	Saw Log	15	28		28		28		28		23	
	Gang	77	119		119		119		117		117	
	Chip & Saw	10	0		0		0		1		1	
	Utility	1	6		6		6		8		11	
	Pulp	27	20		20		20		20		20	
	Total HE	130	173	133%	173	133%	173	133%	174	134%	172	132%
	VOLUME	630	665	106%	665	106%	665	106%	665	106%	664	105%
	VALUE			107%		106%		106%		104%		103%

Figure 6. Results per Species Produced with the Model (Predictions 4 - 8)

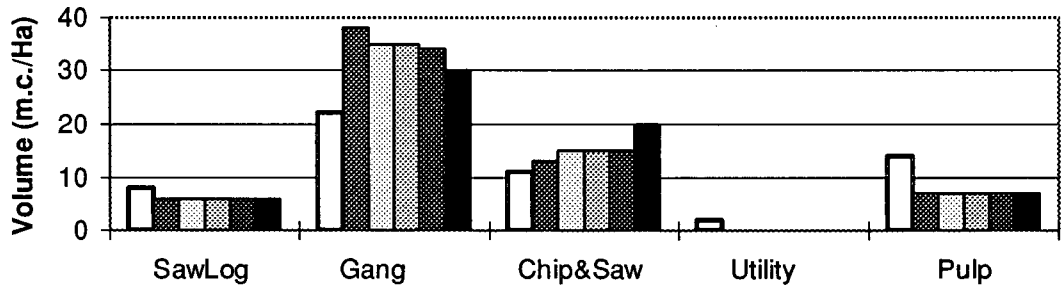

Figure 6a. Distribution of volume per sort for Western Red Cedar.

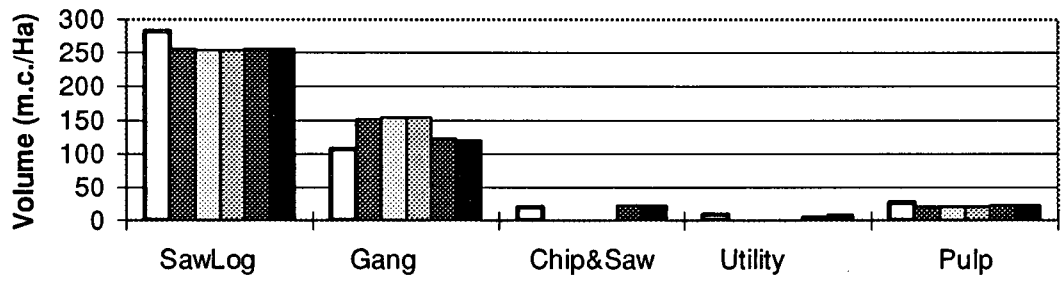

Figure 6b. Distribution of volume per sorts for Douglas Fir.

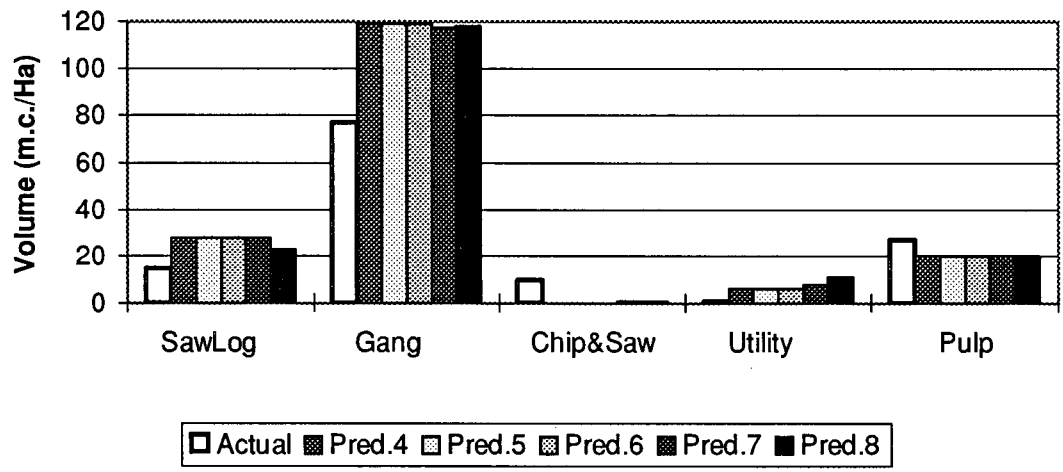

Figure 6c. Distribution of volume per sorts for Western Hemlock.

As seen in Table 8 and Figure 6, by introducing factors one by one, the volume distribution gets closer to the actual. The exceptions are the sorts Chip & Saw for Cedar and Utility for Hemlock. A possible explanation for this, may be that a detailed description for these sorts was never obtained and the description used in the analysis had to be mainly inferred from the B.C. MoF Scaling Manual.

The Student t-test described in the study design, was used to compare for each species and sort, if the values produced by Prediction No.8 and the actual values, are statistically the same. This test proved that for the entire distribution only three sorts are statistically different: cedar pulp wood sort and hemlock chip & saw and utility sorts. Various factors could produce this effect, but none of them can be clearly identified. One of them could be the incomplete description of the two sorts mention above. Another factor could be that these two species are less represented in the stand (both comprise 35% of total volume), therefore the sampling intensity is lower for these species. For the most representative species in the stand (Douglas fir), real and predicted values are statistically the same for all sorts.

Third Group - Predictions 9-10: Prediction 9 shows results of the model, assuming the top log of broken trees is not recoverable. This produced an underestimation of volume and value, as displayed in Table 9. Prediction 10 was done as if the block was mechanically felled, the result being an overestimation of volume and value. In fact, these values are very close to the ones produced by Prediction 3, when all defects were considered but, it was assumed that there is no breakage. This shows that height of breakage for mechanical felling is close to merchantable height and therefore, does not produce great losses. Results of these predictions are presented in Table 9.

Table 9 . Results of predictions 9-10 vs. actual.

		Actual	Prediction 9		Prediction 10	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3	
CE	Saw Log	8	6		6	
	Gang	22	28		30	
	Chip & Saw	11	20		19	
	Utility	2	0		0	
	Pulp	14	7		8	
	Total CE	57	61	107%	63	111%
DF	Saw Log	281	254		264	
	Gang	106	113		123	
	Chip & Saw	20	0		11	
	Utility	9	6		24	
	Pulp	27	8		16	
	Total DF	443	381	86%	438	99%
HE	Saw Log	15	23		23	
	Gang	77	119		119	
	Chip & Saw	10	1		2	
	Utility	1	11		16	
	Pulp	27	12		20	
	Total HE	130	166	128%	180	138%
	VOLUME	630	608	97%	681	108%
	VALUE			99%		107%

As expected, the real scale value is between Predictions 8 and 9. Obviously, Prediction 10 yields a value greater than all preceding three values.

Fourth Group - Predictions 11-14: Results are presented in Table 10. Brief comments about each one of these predictions follow:

- Prediction 11: represents the actual values calculated by the MoF cruise compilation program from the operational cruise. It underestimates the total volume by 11%; an underestimation of 22% occurs in total volume of Douglas Fir, and an 21% overestimation of Hemlock. Since this prediction does not use company sorts, there are no data either for distribution of volume per sort or about values obtained.

- Prediction 12: is obtained by compiling the operational cruise with the model. Volumes per specie are less accurate than the previous prediction, but still comparable.
- Prediction 13: uses the FERIC cruise but takes only even number plots. Due to the small sample taken, the result is less accurate and overestimates volume and value for all species and consequently on a per hectare basis.
- Prediction 14: similar to the previous one, but using odd number plots. As expected, it results in an underestimation of volumes and values.

Table 10 . Results of predictions 11-14 vs. actual.

		Actual	Prediction 11		Prediction 12		Prediction 13		Prediction 14	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3		m^3	
CE	Saw Log	8			2		4		8	
	Gang	22			27		38		21	
	Chip & Saw	11			7		26		13	
	Utility	2			0		0		0	
	Pulp	14			6		5		10	
	Total CE	57	57	100%	42	74%	73	128%	52	91%
DF	Saw Log	281			217		322		191	
	Gang	106			104		116		122	
	Chip & Saw	20			0		27		18	
	Utility	9			3		11		5	
	Pulp	27			12		27		18	
	Total DF	443	347	78%	336	76%	503	114%	354	80%
HE	Saw Log	15			23		33		13	
	Gang	77			109		120		119	
	Chip & Saw	10			0		0		2	
	Utility	1			15		11		10	
	Pulp	27			25		21		20	
	Total HE	130	157	121%	172	132%	185	142%	164	126%
	VOLUME	630	561	89%	550	87%	761	121%	570	90%
	VALUE					86%		120%		86%

As one can see, these last predictions are quite different from the actual value, but this is due mostly to the fact that they are based on a much smaller sample size, about half of what was used in previous predictions.

7.2.2 Results for Okeover Block

The analysis was conducted in a manner similar to Stillwater; the fourteen different runs arranged in four groups are presented in the Table 11. In this study, cedar was eliminated and analysis was conducted only for Douglas-fir and Hemlock. This decision was taken because it was impossible to separate the logs produced from old-growth from those produced from second-growth trees. Another specific point for this block was that the main product that was supposed to be obtained from Douglas-fir, was peeler logs. This sort was not used in the first block, and its presence affected the analysis.

Unfortunately, actual values obtained in this second block were not disclosed (neither values per sort nor the total value). To run the analysis, some estimates have been made, based on values used for the other block. Since the real value was not available, the percentage between value of different runs is presented versus value produced by the model (Prediction No. 8). This is based on the observation that both volume per hectare and distribution of volume per species and sort produced by the model are close to actual numbers, therefore, predicted value should be close to the actual one, as well. The actual total volume obtained was 679 m^3/ha.

Table 11. Fourteen predictions of total volume and value for the Okeover block.

Prediction	Factors					Volume	Volume	Value
No.	Breakage	Fork	Sweep	Knot Diam.	Knot Sp.	m^3	(%)	(%)
1						684	101	120
2		x	x			684	101	120
3		x	x	x	x	681	100	102
4	x					658	97	116
5	x	x				659	97	116
6	x	x	x			659	97	116
7	x	x	x	x		658	97	100
8	**x**	**x**	**x**	**x**	**x**	**658**	**97**	**100**
9	Top Section Not Recoverable					615	91	98
10	Mechanical Falling					676	100	102
11	Company Cruise & MoF Compilation					565	83	-
12	Company Cruise Analyzed with the Model					552	81	92
13	Feric Cruise - even no. plots					543	80	82
14	Feric Cruise - odd no. plots					770	113	118

The four groups of predictions will be presented one by one (by species and by sort) in the rest of this chapter. Each table will contain also the actual scale result obtained at the log sortyard, for comparison.

First Group - Predictions 1-3: as one can see in the Table 12, the predicted total volume is almost identical to actual ; this should not be the case for these predictions since all of them are based on assumption that when breakage occurs, the top log is recoverable. Analyzing results per species, it is obvious that numbers obtained for Douglas-fir meet expectations, whereas values for hemlock, do not. As presented later, this was the case throughout the entire analysis, which suggests that hemlock was not uniformly spread in the block, and the cruise did not sample it properly.

Fork and sweep (there are 7 trees with fork and 3 trees with sweep) has almost no effect on value, but knots produced a great drop in value of 18%.

Table 12. Results of predictions 1-3 vs. actual, by species and sort.

		Actual	Prediction 1		Prediction 2		Prediction 3	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3	
DF	Saw Log	44	0		0		39	
	Peeler	259	430		430		302	
	Gang	90	8		8		66	
	Chip & Saw	64	81		80		96	
	Pulp	35	6		7		18	
	Total DF	492	525	107%	525	107%	521	106%
HE	Saw Log	5	0		0		9	
	Peeler	79	126		126		82	
	Gang	50	0		0		28	
	Chip & Saw	40	29		29		34	
	Pulp	13	4		4		7	
	Total HE	187	159	85%	159	85%	160	86%
	VOLUME	679	684	101%	684	101%	681	100%
	VALUE			120%		120%		102%

Also, to evaluate loss in value due to knots, from Tables 10 and 11 it is obvious that the value predicted when knots were considered but without considering breakage, was less than the value obtained when breakage, fork and sweep were examined.

Second Group - Predictions 4-8: values are presented in Table 13. Volume per hectare is about the same for these five predictions but, due to the lack of accuracy when computing the volume for hemlock, it is less than actual.

Similarly with the previous group, fork and sweep did not produce any significant changes, but value per hectare dropped 16% when knots were considered. In terms of distribution of volumes per sort within each species, as one can see in the Table 13 and Figure 7, for predictions No.4 - 8, by including more factors in the model, this distribution gets closer to the actual.

Table 13. Results of predictions 4-8 vs. actual.

		Actual	Prediction 4		Prediction 5		Prediction 6		Prediction 7		Prediction 8	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3		m^3		m^3	
DF	Saw Log	44	0		0		0		38		38	
	Peeler	259	414		413		413		300		300	
	Gang	90	10		10		10		63		63	
	Chip & Saw	64	59		61		61		67		67	
	Pulp	35	20		20		20		35		35	
	Total DF	492	503	102%	504	102%	504	102%	503	102%	503	102%
HE	Saw Log	5	0		0		0		9		9	
	Peeler	79	123		123		123		82		82	
	Gang	50	1		1		1		27		27	
	Chip & Saw	40	25		25		25		28		28	
	Pulp	13	6		6		6		9		9	
	Total HE	187	155	83%	155	83%	155	83%	155	83%	155	83%
	VOLUME	679	658	97%	659	97%	659	97%	658	97%	658	97%
	VALUE			116%		116%		116%		100%		100%

Figure 7. Results per Species Produced with the Model (Predictions No. 4 - 8)

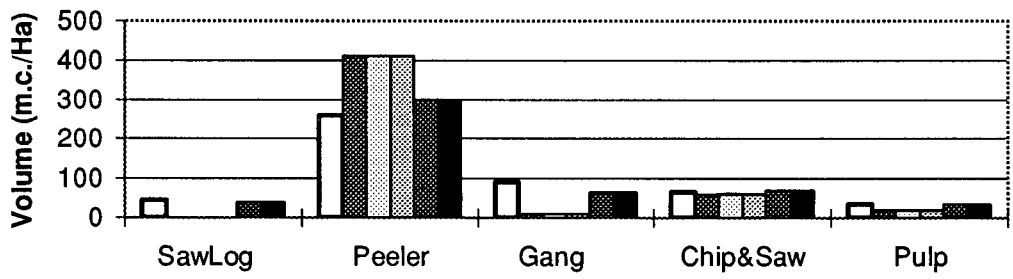

Figure 7a. Distribution of volume per sort for Douglas Fir.

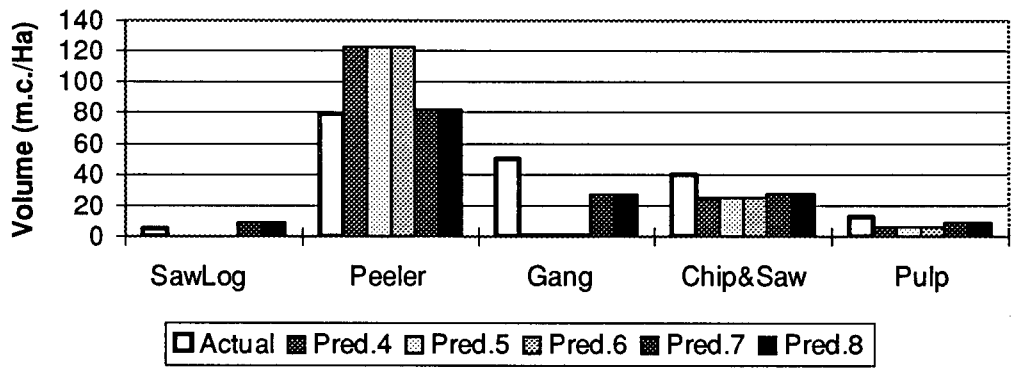

Figure 7b. Distribution of volume per sort for Western Hemlock.

Hemlock gang was the only sort for which predicted value was different from actual, as determined by the t-test (Prediction 8 vs. real values). This is due to the strict requirement on knots size, which in reality caused some downgrading from peeler to gang. The overall lack of accuracy in prediction of hemlock volume for this block, must have played a role. This problem was solved as part of another FERIC project, although results were not available at the time cruising was performed in this second block. The solution consisted of requiring the cruiser to estimate if the tree analyzed was appropriate for peeling (by assessing the uniformity of its cross section and lack of other surface defects), and record this in an additional field. The optimization algorithm has been modified to check if dimensional requirements were met, and in case of a peeler, the cruiser's call was used to override conditions related to knots. If available in time, this method would have assured a better distribution of volume between peeler and gang, and thus improve the overall accuracy of this prediction. Also, missing the real value of sorts, must have played a role in this analysis, by changing the log that maximized tree value at a given stage in the dynamic programming algorithm. It should be noted that the only significant difference occurred for the least representative species in the stand. For Douglas-fir, in all sorts, predicted and actual volumes, were statistically the same.

Prediction 8 represents the final version of the model. Overall, an underestimation of 3% in volume was achieved. No conclusion can be made about value.

Third Group - Predictions 9-10: results are presented in Table 14. Prediction 9 shows results of the model, assuming the top log of broken trees is not recoverable; Prediction 10 simulated a mechanically felled block. Results are good for Douglas fir, but overall results per hectare are affected by the imprecision related to hemlock.

Table 14 . Results of predictions 9-10 vs. actual.

		Actual	Prediction 9		Prediction 10	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3	
DF	Saw Log	44	38		39	
	Peeler	259	299		302	
	Gang	90	61		66	
	Chip & Saw	64	47		86	
	Pulp	35	20		25	
	Total DF	492	465	95%	518	105%
HE	Saw Log	5	9		9	
	Peeler	79	82		82	
	Gang	50	27		27	
	Chip & Saw	40	24		33	
	Pulp	13	8		7	
	Total HE	187	150	80%	158	84%
	VOLUME	679	615	91%	676	100%
	VALUE			98%		102%

As expected, Prediction 9 yields a value less than No. 8, whereas value given by Prediction No. 10 is greater than the one produced by No.8. However, the differences between these three predictions are smaller than in the first block, due especially to the larger trees found in the first block.

Fourth Group - Predictions 11-14: results are presented in Table 15. Brief comments about each one of these predictions are given as follows:

- Prediction 11: represents the actual values calculated by the ministry cruise compilation program from the operational cruise. It underestimates the total volume by 17%; an underestimation of 25% occurs in total volume of Douglas Fir, and an 6% overestimation of Hemlock; since this prediction does not use company sorts, there is no data about distribution of volume by sort.
- Prediction 12: is obtained by compiling the ministry cruise with the model. Volumes per species are less accurate than the previous prediction produced, but still comparable.

- Prediction 13: uses the FERIC cruise but takes only even number plots. The result is less accurate. It underestimates volumes for most sorts and consequently on a per hectare basis, however, it seems to yield the best result for Hemlock.
- Prediction 14: similar to the previous, but using odd number plots. As expected, it results in an overestimation of total volume. In terms of distribution of volume by sort for hemlock, produced by the last two predictions, the only explanation found was that this species is spread non uniformly (in patches) in the stand and the cruise could not sample it properly.

Table 15 . Results of predictions 11-14 vs. actual.

		Actual	Prediction 11		Prediction 12		Prediction 13		Prediction 14	
Sp.	Sort	Vol/Ha	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%	Vol/Ha	%
		m^3	m^3		m^3		m^3		m^3	
DF	Saw Log	44			0		10		66	
	Peeler	259			297		242		358	
	Gang	90			15		45		81	
	Chip & Saw	64			59		46		88	
	Pulp	35			30		23		47	
	Total DF	492	367	75%	401	82%	366	74%	640	130%
HE	Saw Log	5			0		8		9	
	Peeler	79			126		87		76	
	Gang	50			0		31		23	
	Chip & Saw	40			15		38		17	
	Pulp	13			10		13		5	
	Total HE	187	198	106%	151	81%	177	95%	130	70%
	VOLUME	679	565	83%	552	81%	543	80%	770	113%
	VALUE					92%		82%		118%

As one can see, these last predictions are different from the actual values, but this is mainly due to the fact that all of them are based on a much smaller sample size.

For both blocks, another factor that may have affected predictions is the inaccuracy in measuring the total area of the block.

7.3 Results for Harvesting System Design

No formal validation was performed for the harvesting design section; however, this part of the model undergone detailed verification and testing. A detailed description of this module is given in the user manual. Since this part depends almost entirely on user's experience, an analysis will not be objective. The program will be given to people in industry to plan their costs when harvesting a block. The real cost of harvesting the block will be compared with what they predicted using the model.

People with more experience in this field, will be asked to take part in the analysis, and more information may be incorporated into the model, depending on findings.

8. MODEL SUMMARY AND DISCUSSION

The objective of this thesis was to develop a decision support tool that will predict economics of second-growth harvests. Primary input was chosen to be company sort descriptions and cruise data. Based on these, the model first computes volume by sort for each species and total volume and value for the entire block. Second, it allows forest planners to configure various harvesting systems and select the best one. Built-in productivities and costs, or input values can be used to compute the total cost for logging the block, and obtain an estimate of time necessary for each one of phases in the harvesting process. Total value of the block and the cost of logging can be then used to compute the net revenue.

An alternative (more detailed) cruise method was tested and it provided better results than the standard one. Various factors that may affect the accuracy of prediction were identified, analyzed and methods to account for them were developed and incorporated into the model. The tree characteristics included in the cruise were sweep, fork or crook and knot size. For the first two items their exact location was recorded. For knots, the distribution on the stem was estimated. All these factors proved to play a role in prediction of volume by sort and total value produced by a stand. The most important factor was knot distribution.

As part of this project, a dynamic programming algorithm that will theoretically buck each tree to its maximum value, was developed. Also, a breakage model was incorporated into the program for manual and mechanical felling. The amount of wood that is lost during harvesting and its impact on stand value was evaluated.

The model was tested at two sites. Overall, it can be considered that it performed well: an accurate distribution of volume by species and by sort was obtained. The predicted volume was within 5% and predicted value was within 3% compared to the actual numbers. The best prediction of volume by sort was achieved for those species that are the most dominant in the

stand. Considering the large variability existing in the B.C. forest industry, in terms of sort descriptions for each species, future validation will be very beneficial.

It is concluded that from the technical point of view, all the objectives set forth at the beginning of the study were fulfilled.

The model has the standard appearance of Microsoft products. For common tasks (new file, open file, print etc.) standard buttons, designed and used by Microsoft, were used. For jobs specific to this project, buttons have attached images suggesting the task they initiate. All buttons that appear on the start-up form, display tag tips (labels that explain what the button does) and in other instances the model displays different help messages.

Being a joint UBC - FERIC project, the model will be presented in both a Master of Forestry thesis and a FERIC report. The report plus the user manual will be submitted to Canadian Forest Service - Pacific Forestry Center, that provided partial funding for this project. It will summarize the findings of the model validation process.

During the elaboration of this project, people from industry had been contacted and asked their opinion about the model. This had a major impact on the model, especially on the part that addressed partial cuts. As a consequence, at the completion of the program, a detailed presentation will be made to the same people and the model will be discussed.

Depending on the input from the industry and other factors (especially funding) the items described in the next section of the paper will be considered for future development.

9. FUTURE DEVELOPMENT OF THE MODEL

The features that can be added, in further development of the model are:

- related to forestry specific problems.
- related to programming in general and to Visual Basic in particular.

The first class of improvements addresses primarily mensuration problems that aim at improving the methods used to predict the volume of second-growth stands using the B.C. Ministry of Forests cruise method:

- Include more details when predicting the best combination of logs for each tree. The current version of the model uses only dimensions (diameters and length), sweep, knot diameters and spacing. Other details collected when cruising (conk, blind conk, scar, frost crack, mistletoe, rotten branch, spiral grain) are used only as criteria for partial cutting. Although these defects are not very frequently found in second-growth, a method to assimilate them in the optimum bucking algorithm should be developed. This will increase the applicability of the model.
- Assign a B.C. Ministry of Forests grade to each log produced in the optimum bucking process and calculate a value for stumpage.
- Include other species in the model, especially hardwoods. A solution would be to include Alder and assimilate all hardwoods to this grouping. This should be done to improve accuracy of volume and value and for a better analysis of the cost of harvesting process.
- Offer a separate menu (plus icon) that will analyze the block as if no breakage occurs. This is the theoretical maximum value that should be obtained from the block and would serve as a target for the logging crew.
- Include a "t" table in the model. Currently, the model calculates the volume for each plot individually. These values can be displayed so experienced users can check if

the sampling error for the cruise is within the legal limit, or more plots have to be cruised.

- Include a knot distribution function. As a part of this project it was found that considering knots accounted for about 4% of the entire value of the stand. It may be of interest to try to develop an equation that will describe (per species) the diameter of knots on the stem as a function of DBH, total height and current height. By including this, it is expected that the model will perform as well as it does now, using standard cruise data.
- Make the model capable of accepting cruise data that are input for B. C. Ministry of Forests stumpage and appraisal purposes, thus avoiding inputting it twice.
- Attach a new field to cruise data that will record whether or not a tree is appropriate for peeling, and consider it in the optimum bucking algorithm. This was done as part of another FERIC project, because peelers were in fact the most important sorts in the operation. No final result is available so far, but is estimated that with minor effort, a significant improvement of prediction can be achieved in this type of situation. The modification was not available by the time the Okeover block was cruised, so it was not used in the analysis.

Further work on a more elaborate bucking and breakage model may not be very rewarding, as important influences include logging personnel and variability of ground conditions within the stand, neither of which may be predictable.

Apart from these improvements, which are all quantitative, the following qualitative improvements should be considered. All of them are driven by the extensivity of Visual Basic, i.e. by the modules that can be attached to this programming language. Once the final program is written, the setup kit will include the components it needs from these external modules and can be distributed royalty-free. So far, three products of this type have been used and the results were very good. They worked very well in conjunction with Visual Basic and dramatically

improved the quality of the overall performance of the program and of its user interface. Among these add-on tools advertised in the latest "Component Objects and Companion Products for VB" catalog, the following can be used to improve the model both quantitatively and qualitatively:

- Sylvan Maps - a powerful Geographic Mapping and Analysis custom control, which can be used to add sophisticated mapping functionality to VB programs.
- M.4 - a software package for adding intelligence to VB applications using a expert system language with English-like syntax, which makes knowledge system development easy. Previous research in this field (Linehan and Corcoran, 1994) proved the feasibility and utility of applying this type of tool in forestry.
- NeuroWindows - a Dynamic Link Library for VB that enables a programmer to solve using neural networks, applications that have previously defied solution with conventional programming. This may be used as a substitute for the dynamic programming procedure should the introduction of more detail make processing speed prohibitive.

All the above mentioned applications can be used to attach to the model information related to social, legal or environmental problems related to harvesting activities.

Apart from these ones, there are lots of VB add-ons that can assist the programmer in writing a professional "help" for the application and improve its graphic capabilities, making it more appealing to the user.

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Appendices:

1. Presentation of the program using pseudocode:

    1.A Computation of stand volume and value.

    1.B Harvest System Design and computation of net revenue.

2. Productivity equations and average productivities used in Harvest System Design.

    2.A Clear-cut.

    2.B Partial cut.

Appendix 1A. Presentation of the program using pseudocode: computation of stand volume and value.

There is no pseudocode description given on how to input bucking specifications and cruise data, because this is a straight forward procedure; more detailes are given in the user manual.

The first procedure that is used to process the data is the following:

```
SUBROUTINE DataInput

    Input general data about the block: Area, Silvicultural System, StageLength (used in
        DynamicProgramming), Falling Method, BAF, Min.Diam, Pulp Value, Min.Len.Pulp and
        if necessary Area of Corridors

    If Silvicultural System is clear cut Then
        Call CalcVolAndValue
        Exit Sub

    Else
        Display graph showing the actual structure of the stand (Stand Table)

        Do
            Do
                Display form CriteriaForPartialCut, where the user can input his criteria for each
                    species
                Validate user input for partial cut (see user manual for details)
            Loop Until a set of valid criteria is selected.

            Display graph showing the structure of the stand according to criteria set by the
                user
        Loop Until an acceptable stand structure is obtained

    End If

    Call CalcVolAndValue

END OF SUBROUTINE
```

```
SUBROUTINE CalcVolAndValue

    Call LoadBuckPrefs - this procedure will load in the memory, using dynamic arrays, all
        sorts grouped by species and arranged in ascending order with respect to length.
    Initialize data about breakage - read data from corresponding table and store it in
        memory
    Initialize the array that will store volume and value per plot/species/sort
    Initialize the array that will store volume and no. of stems per plot
    Initialize values (TotalVolume, TotalValue and other numbers used later in the model )

    If Silvicultural System is clear cut Then
        Assign Area = Total Area Block
        Set stringClearCut that selects all trees from Cruise Data table, ordered by plot and
            tree number
        Call CruiseData(stringClearCut)

    Else
        ' do the analysis for corridors as if it is a clear cut
        Assign Area = Area of Corridors
        Set stringClearCut that selects all trees from Cruise Data table, ordered by plot and
            tree number
        Call CruiseData(stringClearCut)

        ' do the analysis for the remaining area as a partial cut
        Assign Area = Area Block - Area Corridors
        Initialize arrays and values specific to Partial Cut
        Set stringPartialCut that selects trees from Cruise Data table, according to criteria
            established by the user, ordered by plot and tree number
        Call CruiseData(stringPartialCut)

    End If

    Compute AverageDBH, StandDensity
    Compute TotVolumePerHa, TotValuePerHa, VolPerSpeciesAndSortPerHa,
        ValuePerSpeciesAndSortPerHa, volume and value per total block, per species, per
        sort for the entire block
    Compute AverageTreeVolume and AveragePieceVolume

    If Silvicultural System is partial cut Then
        Compute all the above numbers corresponding to Partial Cut
    End If

    Save all the numbers computed above in the corresponding database

    Display results for the block analyzed

END OF SUBROUTINE
```

```
SUBROUTINE CruiseData(stringSql)

    Set DynaSet (set of records from Cruise Data) according to string passed to this
        procedure
    Do While Not End Of DynaSet
        Read fields from current record (Plot No., Tree No., Species, DBH, TotalHeight etc.)
        Assign new Plot No. to account for non sequential plots (if this is the case)
        Compute BasalArea, TreeFactor and other number that will be used in the program
        Compute MerchH (MerchantableHeight) for the tree analyzed
        Compute NoStages (used in the Dynamic Programming procedure)
            NoStages = TotalHeight / StageLength; correct NoStages with stump height
        Call MakeStemProfile
        Assign innitial values for LowerLim and UpperLim, i.e. the first and last stage used in
                DynamicProgramming; LowerLim = 0, UpperLim = NoStages
        Call CheckIfBreakage - this procedure will check if the current tree will break or not. If
                yes, then FlagBreakage will be set true and data will be available about where
                breakage occurs and the length of shatter

        If FlagBreakage = True Then
            Compute BreakH (height where breakage occurs)
            If MerchH > BreakH Then
                ' i.e. breakage occurs below merchantable height
                LowerLim = (MerchH - BreakH) / StageLength
                UpperLim = NoStages
            Else
                ' breakage is above merchantable height
                Set FlagBreakage = False
            End If
        End If

        Do
            ' if breakage is below merch. height analyze first the butt log
            Call DynamicProgramming(LowerLim, UpperLim)
            Call BackPass(LowerLim, UpperLim)

            ' check if there is a second log to be analyzed
            If FlagBreakage = True Then
                If MerchH > BreakH + LengthOfPulp Then
                    ' if the top log is long enough, analyze it
                    LowerLim = 0
                    UpperLim = (MerchH - BreakH) / StageLength
                Else
                    ' there is breakage but the top log is too short
                    FlagBreakage = False
                End If
            End If

            Assign FlagBreakage = Not(FlagBreakage)
        Loop Until FlagBreakage = True
        Move to next record in DynaSet
    Loop
END OF SUBROUTINE
```

```
SUBROUTINE MakeStemProfile

  For i = 0 To NoStages

    Compute diameter of each stage using Kozak's taper equation, based on Species,
        DBH, Current Height, Total Height
    Compute average taper based on Minimum Top Diameter, Diameter at inflection
        point, and (Total Height - Height of inflection point).
    Compute diameter for the last 2 m. (close to the stump) based on average taper
        calculated above
    Compute each diamter using BCMoF scaling manual conventions, i.e. round off
        diamteres to the nearest even number

  Next

  ' the following subroutines work in a similar way; each one reads information about the
      ' current tree in its record and assigns it to corresponding stages

  Call AssignSweep

  ' the next procedure will read if Fork or Crook is present on the stem and put it in the
  ' corresponding stage. Since none of the sorts will accept this deffect, the procedure will
  ' also set FlagBreakage=True that will impose that the tree be bucked at the stage where
      ' the deffect is
  Call AssignForkOrCrook

  Call AssignDiameterKnots

  Call AssignKnotsSpacing

END OF SUBROUTINE
```

```
SUBROUTINE DynamicProgramming(FirstStage,LastStage)

    Compute  N, which is the length of shortest sort for a species, converted to stage
       intervals  N = MinimumSortLength / StageLength

    For i = FirstStage + 1 To FirstStage + N
       Compute  Volume for each stage using Smalian's formula
       Assign  Value = Pulp Value  for each stage
       Assign SortName = Pulp for each stage
       ' Note: Logs resulted after applying this algorythm and that are shorter than Minimum
          ' Length of Pulp, will have a value and volume equal to 0 assigned in procedure
          ' BackPass
    Next

    ' let i be the current stage
    For i = FirstStage + N + 1 To LastStage
       Assign StageValue = 0
       Assign CurrentSort = 1
       ' N.B.  Sorts are already arranged in increasing order of length
       Assign BuckLength=length of CurrentSort converted to StageIntervals

       Do While (BuckLength <= i - FirstStage) And (CurrentSort <= No.Sorts For This Sp.)
          Call VerifyConditions (i, BuckLength)
          ' VerifyConditions will return ValueSort - the value of the sort that can
          '  be obtained at this stage
          '  TemporaryVal will store the value of current log + the value of the rest of the tree
          TemporaryVal = ValueSort + Value of Stage ( i - BuckLength )

             If TemporaryVal > StageValue Then
                ' Save the best decision  so far
                ' This is the highest value of the tree up to stage i
                StageValue = TemporaryVal
                ' These are the characteristics of log that has to be bucked at this stage
                ' to get the above value
                OptimumLength = BuckLength
                OptimumSort= Current Sort
                OptimumVolumeStage=VolumeSort
                OptimumValueStage=ValueSort
             End If

             Calculate BuckLength as the length in stages of next sort
       Loop

       ' When exit above loop have optimal decision for stage i
       Save solution for backward pass
    Next

END OF SUBROUTINE
```

To make this procedure easy to follow, conditions are presented as if are tested together. In the program, conditions are tested separately and when one of them fails, the program skips a portion of code; this ensures optimum functionality for this procedure.

```
SUBROUTINE VerifyConditions (CurrentStage, BuckLength)

   Declare boolean variable Condition
   Initialize VolumeSort and ValueSort to zero
   Assign Small End Diameter   Sed = Diameter At Stage (CurrentStage - BuckLength)
   Assign Large End Diameter   Led = Diameter At CurrentStage

   'Check conditions about sort dimensions
   If ( Led  >=  MinButtDiam of Current Sort Or MinButtDiam  IsNull )  And
     ( Led  <=  MaxButtDiam of Current Sort Or MaxButtDiam  IsNull ) And
     ( Sed  >=  MinTopDiam of Current Sort Or MinTopDiam IsNull )    And
     ( Sed  <=  MaxTopDiam of Current Sort Or MaxTopDiam IsNull )   Then
      Condition = True
   Else
      Condition = False
      GoTo label
   End If

   ' Check for allowable defects

   For i = CurrentStage - BuckLength To CurrentStage

      If  (KnotsDiam at stage i <= KnotsDiam accepted  for Current Sort)  And
            ' KnotsSpacing  and Sweep are boolean values
         (KnotsSpacing at stage i >= KnotsSpacing accepted  for Current Sort) And
         (Sweep at stage i <= Sweep accepted  for Current Sort)     Then
         Condition = True
      Else
         Condition = False
      End If

      ' The Fork or Crook was already considered in AssignForkOrCrook
   Next

   label:
      Calculate VolumeSort with Smalian's formula (given Led, Sed and BuckLength)

      If  Condition = True Then
         ValueSort = VolumeSort * Unit Value of Current Sort
      Else
         ValueSort = VolumeSort * Unit Value of Pulp
      End If

END OF SUBROUTINE
```

```
SUBROUTINE BackPass (FirstStage,LastStage)
    ' This procedure picks-up the combination of logs that maximizes the value of the tree

    Assign CurrentStage = LastStage

    Do
        ' take sort name and length produced by DynamicProgramming
        CurrentSort = Sort Obtained at CurrentStage
        BuckLength = BuckLength at CurrentStage

        If ( CurrentSort = Pulp ) And (BuckLength < sngLengthPulp) Then
            ' the sort produced is Pulp but doesn't satisfy the minimum length condition
            CurrentVolume = 0
            CurrentValue = 0

        Else
            ' take values produced by DynamicProgramming
            CurrentVolume = VolumeSort
            CurrentValue = ValueSort

        End If

        Accumulate the CurrentVolume, CurrentValue into the corresponding plot/species/sort
        Increment the StandDensity in the array that stores it (only for the first log
            produced from a tree)
        Assign CurrentStage = CurrentStage - BuckLength

    Loop While CurrentStage > FirstStage

END OF SUBROUTINE
```

Appendix 1B. Presentation of the program using pseudocode: Harvest System Design and computation of net revenue.

The following procedures are attached to the Harvest System Design form.

SUBROUTINE HarvSystDesign

Select a system for the first stratum, according to indication displayed under the toolbar, i.e.: click on the item that you want to include in the system (only one item can be included in each phase). To deselect all items in a phase, double click on any of them. By default the first stratum is available and its percentage is 100%. If the block will be stratified in more than one stratum, then the percentage for the first one must be reduced. This principle holds also when the block includes more than one stratum and the user wants to include a new one, i.e. the sum of percentages for existing strata must be less than 100%.

```
Select Case the Button clicked by user

    Case NewStratum
        Call NewStratum_Click

    Case StratumNumber (one of the buttons in the Strata frame)
        Call StratumNumber_Click

    Case DeleteStratum
        Call DeleteStratum_Click

    Case Phases
        Call Phases_Click

    Case Results
        Call Results_Click

    Case Cancel/End
        Unload the form.

End Select
```

END OF SUBROUTINE

```
FUNCTION CheckStratum

    Calculate MaxPercentage = 100% - Sum of percentages for all other existing strata.

    If Percentage assigned to current stratum > MaxPercentage Then
        Display message about the range allowed for Percentage
        CheckStratum = False
        Exit Sub
    End If

    Update record for the last stratum analyzed

    If  system of current stratum <> system of current stratum that was assigned previously
            Then
        Update the system for current stratum
        Update machine names to "No Machine"
        Update the cost of harvesting the stratum to 0.
    End If

    If PercentageOfTotalVol of current stratum <> PercentageOfTotalVol of current stratum
        that was assigned previously Then
        Update the Volume of Current Stratum
        Update machine names to "No Machine"
        Update the cost of harvesting the stratum to 0.
    End If

    CheckStratum = True

END OF FUNCTION
```

```
SUBROUTINE NewStratum_Click

    If CheckStratum( ) = False Then Exit Sub

    If Not all existing strata have a system assigned Then
        Display message showing the user the situation that occured
        Exit Sub
    End If

    ' each block can include maximum 5 strata
    If  number of existing strata = 5 Then
        Display message showing the user the situation that occured
        Exit Sub
    End If

    ' all conditions are met, a new stratum can be added
    Add a new stratum, i.e. find the first available stratum and enable it. Make all its labels
        grey and make its percentage = 100% - sum of percentages for all other existing
        strata.

    Refresh foregrounds for strata buttons: make the active one red, and all the others
        grey.

END OF SUBROUTINE
```

```
SUBROUTINE StratumNumber_Click

    If CheckStratum( ) = False Then Exit Sub

    Activate the stratum corresponding to the button that was clicked: change the colour of
        labels (in green) according to the system previously set, and display its percentage.

    Refresh foregrounds for strata buttons: make the active one red, and all the others
        grey.

END OF SUBROUTINE
```

SUBROUTINE DeleteStratum_Click

Display message asking the user to confirm that he wants to delete that stratum

If the answer is No **Then Exit Sub**

Set to 0 the value associated to each label in the harvesting system (i.e. not selected).

Delete the name of all machines for that system.

Set to 0 the cost for each phase and for harvesting the entire stratum.

Disable the button corresponding to that stratum.

Activate the first stratum available in the block; if none is available, activate stratum number 1.

END OF SUBROUTINE

SUBROUTINE Phases_Click

If CheckStratum( ) = False Then Exit Sub

If none of existing strata has a system assigned **Then**
  Display message showing the user the situation that occured
  Exit Sub
End If

Call FormPhases_Show

END OF SUBROUTINE

SUBROUTINE Results_Click

If CheckStratum( ) = False Then Exit Sub

If none of existing strata has a system assigned **Then**
Display message showing the user the situation that occured
Exit Sub
End If

Call FormResults_Show

END OF SUBROUTINE

SUBROUTINE FormResults_Show

Show form Results.

Display percentage of block analyzed summing up percetages for all strata.

Display information about each stratum (in the grid).

Calculate and **Display** the total cost of harvesting and net revenue generated by the entire block.

END OF SUBROUTINE

SUBROUTINE FormPhases_Show

Show form Equipment Productivity and Cost.

Enable only buttons that correspond to strata that have a system assigned.

Activate the first stratum that has a system assigned.

Display the volume of the active stratum.

Configure tabs of the active stratum according to the harvesting system chosen (each tab corresponds to a phase in the system).

Activate the first tab (phase) in the system; display in the grid data related to the first phase.

END OF SUBROUTINE

The following procedures are attached to the Equipment Productivity and Cost form.

```
SUBROUTINE EquipProdAndCost

    If  a new tab in the same system is selected Then
        Call SwitchTab
    End If

    Select Case the Button clicked by user

        Case StratumNumber (one of the buttons in the Strata frame)
            Call StratumEquipment_Click

        Case Design
            Call Design_Click

        Case Results
            If CheckMachines( ) = False Then Exit Sub
            Call FormResults_Show

        Case End
            If CheckMachines( ) = False Then Exit Sub
            Unload the form.

    End Select

END OF SUBROUTINE
```

```
SUBROUTINE SwitchTab

    If CheckMachines( ) = True  Then
        Update the new tab; refresh information in the grid according to the new tab
            (phase) that was selected.

    End If

END OF SUBROUTINE
```

```
FUNCTION CheckMachines

    Select Case NoOfMachinesSelected

        Case 0
            Update values in the previous tab; set machine name to "No Machine", for
                that phase, and make cost equal to 0.

        Case 1
            Update the name of machine used and cost for previous phase, according to
                user selection.

        Case Else
            Display message box to warn the user that he is not allowed to select more
                than one machine.
            CheckMachines = False
            Exit Function

    End Select

    CheckMachines = True

END FUNCTION
```

SUBROUTINE StratumEquipment_Click

If CheckMachines( ) = False Then Exit Sub

Activate New Stratum; change foreground to gray for the other strata and red for the active one.

Display the volume of active stratum.

Configure the tabs for the active stratum according to system selected.

Select the first tab which corresponds to the first phase in the system.

Update data in the grid as per new stratum.

END OF SUBROUTINE

SUBROUTINE Design_Click

If CheckMachines( ) = False Then Exit Sub

Unload form EquipmentProductivityAndCost

Call FormDesign_Show

END OF SUBROUTINE

SUBROUTINE FormDesign_Show

Show form HarvestSystemDesign

Enable buttons for strata that have a system assigned

Activate the first stratum available; change the colour of labels (in green) according to the system previously set, and display its percentage.

Refresh foregrounds for strata buttons: make the active one red, and all the others grey.

END OF SUBROUTINE

The following procedure is attached to the Results form.

```
SUBROUTINE Results

    Select Case the Button clicked by user

        Case Design
            Unload form Results
            Call FormDesign_Show

        Case Phasses
            Unload form Results
            Call FormPhases_Show

        Case End
            Unload form Results

    End Select

END OF SUBROUTINE
```

Appendix 2.A Productivities for clear cut.

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$/h]
1A	FALLING		MEDIUM MACHINES			
1	Feller-Buncher	Std.Feller-Buncher	Prod[m^3/h]=60*TreeVol[m^3]	0.6 - 1.1	Andersson - 1996	115
2	Feller-Processor	Valmet 500 T	22.5 [m^3/h]	-	Andersson - 1996	135
3	Felling Only	Std. Power Saw	Prod[m^3/h] = TreeVol[m^3]*60 / (1.037 + 0.548*TreeVol [m^3])	-	Andersson - 1996	58
4	Fell and Buck	Std. Power Saw	Prod [m^3/h] = TreeVol [m^3] * 60 / (1.633 + 1.327 * TreeVol [m^3])	-	Andersson - 1996	58
1B	FALLING		LARGE MACHINES			
1	Feller-Buncher	ACL 771 B	Prod [m^3/h] = 86 * TreeVol [m^3]	0.8-1.7 m^3	Andersson - 1996	155
2	Feller-Processor	same as 1A2				
2A	AT-STUMP	PROCESSING	MEDIUM MACHINES			
1	Delimber		Prod [m^3/h] =60		Assumption	135
2	Processor	same as 5A3				
2B	AT-STUMP	PROCESSING	LARGE MACHINES			
1	Processor	same as 5A3				
3	LOG	ALIGNMENT				
1	Exc.Log Align.	JD 992 D	Prod [m^3/h] = 87.9		Jukes 1995	156

Appendix 2.A Productivities for clear cut (cont.).

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$ / h]
4A I	PRIMARY	EXTRACTION	MED. MACHINES - NON ALIGNED WOOD			
1	Grapple Yarder	Madill 122	TurnTime[min] = 0.82 + 0.00581 * d [m] ; TurnVol= 1.1 m^3	def. d=80	MacDonald - 1987	164
2	High Lead Yard.	West Coast Falcon	Prod [m^3/h] = 18		Howard and Dodic - 1989	175
3	Super Snorkel	Madill 075	TurnTime[min] = 0.3880 + 0.000269 * d^2 [m] ; TurnVol=1.2	def. d=40	Jukes - 1995	160
4	Chocker Skidder	Caterpillar 518	TurnTime[min] = 7.49 + 0.0166 * d [m] ; TurnVol = 4.9 m^3	def. d=200	Rogers and MacDonald 1988	159
5	Grapple Skidder	same as 4AII 5				
6	Short Wood For.	same as 4A6 {PC}				
7	Hoe Chucking	same as 4BI 7				
4B I	PRIMARY	EXTRACTION	LARGE MACHINES - NON ALIGNED WOOD			
1	Grapple Yarder	Cypress 7280 B	TurnTime[min] = 0.52 + 0.00167*d[m] ; TurnVol=1.2 m^3	def. d=80	Peterson - 1988	453
2	High Lead Yard.	same as 4AI 2				
3	Chocker Skidder	same as 4AI 4				
4	Grapple Skidder	same as 4AII 5				
5	Short Wood For.	same as 4A6 {PC}				
6	Hoe Chucking	JD 992 (serpentine)	Prod [m^3/h] = 50 ; AvgTreeVol=1.5m^3 ; ForwDist=150 m		Jukes - 1995	196

Appendix 2.A Productivities for clear cut (cont.).

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$/H]
4A I I	PRIMARY	EXTRACTION	MEDIUM MACHINES - ALIGNED WOOD			
1	Grapple Yarder	Washington 118 A	TurnTime[min] = 1.6 + 0.00548*d [m] ; TurnVol= 3.1	def. d=80	MacDonald - 1988	229
2	High Lead Yard.	same as 4AI 2				
3	Super Snorkel	Madill 075	TurnTime[min] = 0.3161 + 0.000326 * d^2 [m] ; TurnVol=1.2	def. d=40	Jukes - 1995	138
4	Chocker Skidder	same as 4AI 4				
5	Grapple Skidder	Clarke 667	Prod [m^3/h] = 23 ; TurnVol = 3.7 m^3	def. d=200	Peterson - 1986	62
6	Short Wood For.	same as 4A6 {PC}				
7	Hoe Chucking	same as 4BI 7				
4B II	PRIMARY	EXTRACTION	LARGE MACHINES - ALIGNED WOOD			
1	Grapple Yarder		all eq. similar to previous ones			
2	High Lead Yard.					
3	Chocker Skidder					
4	Grapple Skidder					
5	Short Wood For.					
6	Hoe Chucking					

Appendix 2.A Productivities for clearcut (cont.).

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$/H]
5A	ROADSIDE	PROCESSING	MEDIUM MACHINES			
1	Manual	Std. Power Saw	Prod [m^3/h] = 18		Peterson - 1986	58
2	Delimber		Prod [m^3/h] = 60		Assumption	
3	Processor	Hahn II	Prod [m^3/h] = 22		Peterson - 1986	142
5B	ROADSIDE	PROCESSING -	LARGE MACHINES			
1	Processor	Hahn	Prod [m^3/h] = 58		Peterson - 1986	94
6	LOADING					
1	Front End	Poclain	Prod [m^3/h] = 38		Peterson - 1986	156
2	Hydraulic	Barko	Prod [m^3/h] = 69		Peterson - 1986	78

Appendix 2.B Productivities for partial cut.

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$/h]
1A	FALLING		MEDIUM MACHINES			
1	Feller-Buncher	Std.Feller-Buncher {CC}	Prod[m^3/h]=60*TreeVol[m^3]	0.6 - 1.1	Andersson - 1996	115
2	Feller-Processor	Timberjack 1270	10.2 [m^3/h]	-	Hunt - 1995	135
3	Felling Only	Std. Power Saw	Prod[m^3/h] = 23	-	Hedin - 1994	58
4	Fell and Buck	Std. Power Saw {CC}	Prod [m^3/h] = TreeVol [m^3] * 60 / (1.633 + 1.327 * TreeVol [m^3])	-	Andersson - 1996	58
1B	FALLING		LARGE MACHINES			
1	Feller-Buncher	ACL 771 B {CC}	Prod [m^3/h] = 86 * TreeVol [m^3]	0.8-1.7 m^3	Andersson - 1996	155
2	Feller-Processor	same as 1A2				
2A	AT-STUMP	PROCESSING	MEDIUM MACHINES			
1	Delimber	{CC}	Prod [m^3/h] =60		Assumption	135
2	Processor	Hahn II {CC}	Prod [m^3/h] =22			
2B	AT-STUMP	PROCESSING	LARGE MACHINES			
1	Processor	Hahn II {CC}	Prod [m^3/h] =22			
3	LOG	ALIGNMENT				
1	Exc.Log Align.	JD 992 D {CC}	Prod [m^3/h] = 87.9		Jukes 1995	156

Appendisx 2.B Productivities for patial cut (cont.).

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$ / h]
4A	PRIMARY	EXTRACTION	MED. MACHINES			
1	Grapple Yarder	Washington 7840	TurnTime[min] = 5.505 + 0.01 * d [m] ; LatD=10m	LgsTrn=2.7	Rutherford - 1996	164
2	High Lead Yard.	West Coast Falcon {CC}	Prod [m^3/h] = 18		Howard and Dodic - 1989	175
3	Super Snorkel	Madill 075 {CC}	TurnTime[min] = 0.3880 + 0.000269 * d^2 [m]		Jukes - 1995	160
4	Chocker Skidder	JD 450	Prod [m^3/h] = 6		Benett - 1993	52
5	Grapple Skidder	Clarke 667 {CC}	Prod [m^3/h] = 23		Peterson - 1986	62
6	Short Wood For.	Timberjack 910	Prod [m^3/h] = 10.1		Hunt - 1995	92
7	Hoe Chucking	JD 992 (serpentine) {CC}	Prod [m^3/h] = 50		Jukes - 1995	196
4B	PRIMARY	EXTRACTION	LARGE MACHINES			
1	Grapple Yarder	same as 4A 1				
2	High Lead Yard.	same as 4A 2				
3	Chocker Skidder	same as 4A 4				
4	Grapple Skidder	same as 4A 5				
5	Short Wood For.	same as 4A 6				
6	Hoe Chucking	same as 4A 7				

Appendix 2.B Productivities for partial cut (cont.).

No.	Phase	Machine	Productivity Equation	Range for variables	Source	Cost [$/H]
5A	ROADSIDE	PROCESSING	MEDIUM MACHINES			
1	Manual	Std. Power Saw {CC}	Prod [m^3/h] = 18		Peterson - 1986	58
2	Delimber	{CC}	Prod [m^3/h] = 60			
3	Processor	Hahn II {CC}	Prod [m^3/h] = 22		Peterson - 1986	142
5B	ROADSIDE	PROCESSING	LARGE MACHINES			
1	Processor	Hahn {CC}	Prod [m^3/h] = 58		Peterson - 1986	94
6	LOADING					
1	Front End	Poclain {CC}	Prod [m^3/h] = 38		Peterson - 1986	156
2	Hydraulic	Prentice 625	Prod [m^3/h] = 23		Hedin - 1994	69