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A DYNAMIC PROGRAMMING APPROACH TO OPTIMIZING STEM CONVERSION

University of Washington PH.D. 1980

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A Dynamic Programming Approach to Optimizing Stem Conversion

by

David George Briggs

A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

University of Washington

1980

Approved By ______________________________
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Program Authorized to Offer Degree ______ College of Forest Resources ______

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ACKNOWLEDGMENT

I wish to thank all those who have helped with this study. Members of my Supervisory Committee (B. Bruce Bare, James Bethel, Bruce Faaland, Frances Greulich, Gerard Schreuder and Kenneth J. Turnbull) and John Henley and Richard Woodfin of the U. S. Forest Service Pacific Northwest Experiment Station who provided the log diagrams and answers to many questions in the early stages of programming the log grading rules. Most of all, I wish to thank my wife Laurie for her loving support and generosity.

Chapter 1

STATEMENT OF THE PROBLEM

Introduction

This study begins by examining in Chapter 1 the importance of bucking tree stems into logs as a part of the overall process of converting trees into consumer products. It also evaluates the consequences of poor bucking including historic efforts to quantify the associated economic losses.

Chapter 2 reviews the operations research methods that have been used to find optimal bucking solutions and evaluates the strengths and weaknesses of these models.

Chapter 3 outlines the scope and objectives of this study and Chapter 4 develops a new dynamic programming model for the bucking problem. Existing models are generalized and extended to incorporate descriptions of internal and external defects in the tree, and shape abnormalities such as sweep and crook which are important factors in scaling and grading logs. The model also introduces predictions of end product and residue recovery that depend on these grading and scaling assessments.

Chapter 5 presents an example analysis for five Douglas-fir trees, demonstrates the importance of considering defects and end product information, and examines the sensitivity of solutions to changes in tree parameters, economic factors, and utilization standards.

The final chapters present extensions of the model to include coordination with long-log woods bucking policies, extensions to other areas of manufacture, and suggests future work that can be done to expand the applicability of this study.

Importance of Bucking in Wood Utilization

The operation of converting a tree into logs is the first in a series of manufacturing steps that ultimately result in a finished product such as plywood, lumber, or paper. Since each manufacturing step is dependent on actions taken previously, potential profits can be lost if each tree is cut without regard for end use. The standing tree has a potential value based on how it could best be used under given circumstances but the actual value realized depends in part upon how it is converted into logs by the cutting crew. The process of converting the tree into logs involves two steps, felling and bucking. Felling is the act of severing the tree from the stump and bucking is the conversion of the felled tree into log products. Both felling and bucking provide opportunities for making or losing profits. Conway (1973) states that "three quarters of the value lost in all woods operations is lost in felling and bucking." He adds that about half of this loss is due to felling through breakage and high stumps. These felling losses are mainly the result of practices that cause some part of the tree to be useless for further processing and can be minimized by proper supervision and care on the part of the cutter.

Unlike felling, bucking involves solving a very complicated problem. The felled stem has only potential value and bucking reduces it to log products which can be used in sawmills, veneer mills, pulp mills or for other purposes. Alternative solutions are likely to change the mix of products with a strong effect on value. The value of logs is generally determined by the market prices for logs, or prices for end products derived from them, and logging and milling costs; consequently, the end use and manufacturers' specifications for logs must be considered during bucking. These considerations combine to produce many possible log combinations that can be obtained from a stem. Discovering the best combination is a difficult problem to solve.

Historically, the principal objective of felling and bucking crews was to produce the greatest possible volume in a given time period. Soundness, which affects volume scale, was a major criterion (Petro, 1961) and little regard was given for end use except for prime lengths of sawlogs and veneer blocks (Conway, 1973). Since volume production is the basis for unit logging costs this is important. However, it has long been known that many perfectly sound logs will yield low value products because of scattered defects or improper sizing. Bucking, while often not considered as a direct profit generator, is a prime profit contributor since logs are not worth as much if they are not cut to specifications. Sometimes difficult work conditions impairing the buckers' ability to view the entire stem may be a reason for poor bucking but lack of instruction in fundamentals that affect bucking is the major reason why losses occur (Bryant, 1923; Petro, 1961). Loggers often assign the newest, most inexperienced laborer to the bucking job, apparently because it is perceived as requiring little skill compared to felling or operating heavy equipment (Carpenter, 1955; Wackerman et al., 1966). Consequently, quality control in bucking has lagged behind other areas of manufacture.

Palm (1973) suggests that there really are two aspects of the bucking problem. One is the question of where in the chain of operations it is best to do the cutting. This has given rise to several logging systems such as shortwood, tree length, and whole tree. By choosing among these systems, bucking may be performed at the felling site, a roadside landing, or at the mill. Landerud et al. (1973) compared bucking in the forest, at a roadside landing, and at a centralized landing and found considerable value differences. Blackman (1979) described a logging operation where tree length logging and bucking at the reload station was favored because better quality control was possible. This operation found that, with better control and supervision, fewer peeler blocks are bucked short and lost. The actual choice of a logging system involves considering all aspects of the timber and logging operation so the best choice from a bucking perspective may not be the best overall system to use.

The other aspects of the bucking problem is how to crosscut the stem. The bucker must consider the effects of his decisions on subsequent operations all the way to the consumer. Bucking a tree into logs has an important bearing on the end products it will produce and influences value realized by affecting both volume and quality (Simmons, 1960). This study will be concerned with this second aspect of the bucking problem--the determination of optimum solutions to the question of how to convert the stem into logs.

Penalties Associated with Poor Bucking

Reduction in profits due to improper stem conversion by buckers is attributable to several factors which can be grouped as those contributing to volume loss and those contributing to quality reduction. Taken together, these factors often commit portions of the stem to lesser valued end uses.

Volume Losses

One major source of profit loss occurs through inefficient stem volume utilization. Volume losses arise from

a. inaccurate length measurement resulting in logs that are shorter or longer than required;

b. excessive or insufficient jump-cutting or long-butting in attempting to remove cull segments;

c. leaving usable material in tops either through negligence or the selection of a combination of log lengths that does not efficiently utilize the stem;

d. losses due to producing logs with excessive sweep and crook;

e. improper removal of forks in forked trees.

Volume loss through inattention to length specififications is a critical problem. Ignorance of length specifications and improper trim allowance can result in a loss of log scale volume (Conway, 1973) and lumber trim losses in sawmills (Williston, 1976; Palm et al., 1973). In veneer plants overlength logs may be useless. Furthermore, ignoring length specifications may result in overproduction of products that have low market value. As examples, a log intended for peeling, if too short, may be processed into lower value lumber or chips; or a log intended for 16-foot lumber may be trimmed to lower value 14-foot lumber if it has insufficient trim allowance. Apparently, there has been little improvement in this aspect of bucking from the early days of logging to the present. Bryant (1923) mentioned a study in the Southern pines where it was found that only 42.5 percent of the logs were of proper length, while 33.3 percent were too long and 23 percent were too short. On the west coast, in conifer logging, it was found that only 20 percent of sampled logs were bucked to within 2 inches of specifications (Forbes, 1952). Lack of consideration of the end product was blamed for much of the loss. Fobes (1960) found that only 17 percent of California black oak logs had proper trim allowance. Dyson and Holemo (1973) found that only 18 percent of the saw logs brought to a southern pine sawmill were cut to proper length; 48 percent were too long and 34 percent were too short. Comparison with the study mentioned by Bryant (1923) suggests that bucking has worsened in the South.

Volume loss through excessive cull removal has often been found to be an important factor reducing profit potential of a tree (Conway, 1968, 1973; Petro, 1965, 1975; Tessier, 1974). In attempting to remove a cull segment buckers may include more sound material in the cull segment than is necessary or they may remove too little of the cull section and include this unusable material as part of a log. In the former case useful wood is left in the woods while in the latter case the cull portion must eventually be trimmed perhaps leading to a product different than originally intended with a lower value.

Buckers may not utilize merchantable material in the upper bole either through negligence or because a combination of log lengths was chosen that poorly matches the available bole. For example, suppose a bucker is confronted with a 19-foot long stem and can consider any combination of 12.5, 10.5, and 8.5 foot log lengths. If the bucker produces a 12.5 foot log, an unusable 6.5 foot length is created. Bucking two 8.5 foot logs leaving a 2 foot unusable segment, or bucking a combination of 10.5 foot and 8.5 foot logs leaving no unusable stem would be better choices, ignoring for the moment any economic factors that may dictate which choice is the most profitable.

Sweep and crook are defects that can contribute significantly to volume loss. Sweep is a gradual curvature or deviation of the longitudinal log axis from a straight line while crook is a sharp deviation (Petro, 1975). Including excessive sweep or crook in a log can reduce end product output in veneer or lumber operations. Williston (1976:29) shows a graph illustrating substantial lumber losses with increasing sweep in sawlogs and recommends that logs be bucked to the longest straight length. Church (1973) studied the distribution and influence of sweep in Appalachian hardwood logs and made suggestions to minimize volume losses by bucking shorter straighter logs. Similar recommendations have been made by Conway (1968, 1973) and

Petro (1975). Log scaling rules recognize the influence of these defects and make volume deductions for logs with excessive sweep (Dilworth, 1977).

Improper bucking near forks is another source contributing to volume losses (Sworder, 1978). Buckers may cut too far into a fork in an attempt to gain extra length only tc find that the mill must cut it back because of cross grain or they may buck out the fork but leave excessive amounts of usable wood attached to it.

Quality Reduction

Another major source of profit loss occurs through inattention to log and tree attributes that influence quality and their relationship to end product quality requirements. Grading is the process of grouping a product into classes or grades that reflect characteristics of quality or worth (Husch et al., 1972). Lockard (1959) indicates that log grades should accomplish two objectives: (1) separate desirable from undesirable logs and (2) segregate the desired logs into discrete groups that can be consistently recognized by trained personnel. When logs from these grade groups are converted, they should yield products with a reliable stipulated grade pattern or average value. Lockard also indicated that it is desirable for the grade system to produce information on the suitability of a grade for alternative products. Cobb (1957) suggested that log grading principles should be carried one step further and be applied <u>before</u> the logs are cut. He advocated applying these principles to the tree to predetermine log grade possibilities with the goal of obtaining the best possible mix of grades from the tree. He stated, "If buckers know the log grading rules and apply them, they can get the best possible yield from each tree. By considering the size, location, frequency, and nature of all defects, they can select bucking points that group these defects to best advantage" (Cobb, 1957).

Failure to consider grade characteristics is frequently mentioned as a cause of poor bucking practice. Bryant (1923) noted that a major source of loss is the buckers' failure to apportion the bole so the best and poorest quality portions are placed in separate logs. This is very costly since the value of a log is chiefly determined by its poorest section. Stenström (1969, 1970) compared two bucking methods where grade factors were considered with two methods where grade factors were ignored and found a 10 percent decrease in value when grade was ignored. He found that locating the grade limits had the greatest influence on where cross cuts should be located and that locating diameter limits for various kinds of logs was also important. He noted that locating diameter limits appeared to be very influential in smaller stems while the grade considerations were dominant in larger stems. Okhalnikov (1974) similarly found that considering rather than ignoring the pattern of stem defects in bucking improved value by 5 to 12 percent. Conway (1973) also discussed the importance of locating diameter limits as well as considering quality. Log grading rules often include diameter limits that are combined with limitations on permissible defects in determining log grade. In many situations, manufacturers may include diameter limits in their log specifications.

Influence of Volume and Quality Losses on Value

Several writers have demonstrated with diagramed hypothetical examples how improved bucking can affect the value obtained from an individual stem (Ostrander, 1956; Petro, 1975; Conway, 1968, 1973). The improvements in bucking translate into increased production of higher quality products in the mill. For example, Carpenter (1953) reported that a mill in the South, annually producing 4 million feet of gum lumber, averaged 57 percent No. 2 Common and Better lumber. This percentage jumped to 71 percent after a quality control program for bucking was initiated.

Several other writers have also examined trees felled by bucking crews, graded the logs as actually bucked, evaluated how they trees should have been bucked and noted the value differences. Randel (1955) found that lumber value could have been increased by $30 per MBF in red oak sawlogs. Whitmore and Jackson (1956) studied black oak in Southern Illinois and Cobb (1957) studied oak in the Tennessee Valley region and came to similar conclusions. These studies found that, with improved bucking, overall volume produced was increased (4.6 percent, 5.7 percent), value of lumber from the logs was increased (12.3 percent, 11.8 percent), the number of logs and number of cuts was increased, and the volume of 8, 10 and 16 foot log lengths was increased while the volume of other lengths (12, 14 and over 16 feet) was decreased. In a similar study of California black oak, Fobes (1960) found that careful bucking increased lumber value by 15 percent.

Petro (1965) conducted a more detailed study in yellow birch where two nearly identical test areas were laid out in a stand. One area was bucked without supervision while the other was supervised and maintained strict adherence to log quality specifications. Bucking was for sawlogs and pulpwood. On a per tree basis, the supervised area produced 89 percent more grade 1 sawlogs, 28 percent more grade 2 sawlogs and 6 percent more grade 3 sawlogs or 32 percent more sawlogs overall. Sawlog volume per tree was increased by 22 percent and pulpwood volume per tree was increased by 57 percent. Overall, volume utilized was increased by 26 percent and log value by 36.4 percent. Sawlogs in each grade cut in unsupervised area were generally one foot longer but the average lumber length produced from each sawlog grade was nearly the same. The poor performance in the unsupervised areas was due to a number of factors, principally failure to utilize upper portions of the tree, cutting high stumps, unnecessary jump butts, and a failure to consider defects to improve log grade.

In spite of these results, Petro (1961) found that loggers resisted and criticized the use of log grades as bucking aids in the belief that grading produced shorter length logs. This criticism does not appear to be justified according to the studies of Whitmore and Jackson (1956) and Cobb (1957). Whitmore and Jackson found no change in average log length while Cobb found that the average length when grading was performed was only one foot shorter. In Canada, Petro (1961) found that the average length decreased by only one foot and that the increased log value more than offset the extra bucking, skidding, and handling costs. This conclusion was further substantiated in his study of yellow birch (Petro, 1965). Using typical production costs, Whitmore and Jackson (1956) estimated that the profit margin on the logs in their study could be increased by 116 percent by improved bucking.

Few of these studies attempted to estimate in detail how much of the increased value from carefully conducted bucking was attributable to improved utilization of volume and how much was attributable to improved grade. In one study where this was done, Cobb (1957) estimated that

48 percent of the value increase was due to increased volume utilization and 52 percent was due to improved grade. He also pointed out that bucking for grade was least useful in very good or very poor quality trees and was most critical in average quality trees.

In summarizing results from the early studies, Lockard (1959) found that volume losses due to poor bucking are typically 6-20 percent while the average loss in value due to quality reduction is 10 percent. Assuming 10 percent as a conservative average volume loss, he estimated that the combined loss is easily 20 percent of the potential tree value. Similarly, Simmons (1960), in referring to the Appalachian region, indicated that more than half of the potentially high grade lumber in hardwood trees is not going into high grade uses. He attributed almost half of the loss to careless logging and the remaining to losses in milling, drying, storage and marketing operations. He showed a substantial redistribution of logs toward higher log grades when bucking was properly conducted and this, combined with the higher proportion of high grade lumber in high grade logs, had a very significant effect on value realized.

In spite of the many studies on bucking and the development of improved procedures and aids, obtaining good results remains a serious problem. Ek et al. (1972) compared fully mechanized and manual chain saw bucking of sawlogs and found that there was no significant difference between these methods. However, on the basis of theoretical analyses they also concluded that 45 percent of the volume in their study was misbucked. This may result in a significant economic loss to industry. For example, in British Columbia, Sworder (1978) reported that the potential log value lost to chippable residue because of misbucked logs is $23 million annually.

The Difficulty in Achieving Optimal Bucking Solutions in a Production Environment

The complexity involved in considering all of the log specifications, grading rules, and tree characteristics combined with price differentials for logs and end products puts great pressure on buckers by posing a very difficult decision problem. Even in the absence of quality considerations, selection of the most appropriate combination of log lengths to cut from a tree is itself a difficult problem whenever the bucker is confronted with even a few length choices.

When this complex decision problem is combined with pressure by management to achieve high productivity, it is not surprising that poor bucking often results. As examples of the productivity pressure, Harmon (1977) reported a situation where the operator of a centralized log merchandizing system is confronted with bucking 2000-2500 tree length stems per shift. This means that bucking decisions must be made for 4-5 trees per minute. Thornquist and Wallin (1977) describe a centralized merchandizer operation that has the objective of maximizing value of incoming wood in the form of tree lengths or long logs. They state that "each tree or bole is to be cut into that combination of end products (plywood, sawlogs, or pulpwood) yielding the highest monetary return." The operator, located in a control station, examines each stem for grade as it enters a holding or viewing station and feeds grade and cutting data into a computer. The operator must make choices as to the exact amount of butt trim, the placement of each cut and the length of each log. A series of activated lights are used to indicate his choices and he has the opportunity of changing his selections. Once satisfied with his choice, he instructs a computer to "remember" these choices. The computer keeps track of the stem as it enters the cutting station and uses the programmed instructions to activate the appropriate saws which buck the stem into the operator's selections. A single operator is expected to average making cutting decisions for at least six tree lengths or long logs per minute. Obviously it is unlikely that the operator can meet the stated value maximizing objective when he must solve a bucking problem every 10 seconds. These systems undoubtedly produce some improvements over less closely controlled bucking by reducing volume losses since the saws can be set to precisely match the length specifications and because the bucker is provided with a better environment where he can more easily observe all of the stem. Even though a bucker in the woods or at a roadside landing would not be subject to bucking this many trees per shift, he is still faced with pressure to achieve high productivity and must work in a less favorable environment.

Due to the complexity of the problem that must be solved and the pressure to achieve and maintain high production rates it is doubtful if human buckers can consistently meet optimizing objectives without some form of assistance. In a study of human fatigue factors, Kudinov (1967, 1969) and Leonov (1967) found, in typical Soviet production lines, that bucking station operators must be capable of comprehending 2.13 to 4.26 bits of knot defect information per second for conifers and about twice as much information for hardwoods. Since a human can only receive 0.7 to 4 bits of information per second, they concluded that the human brain is inadequate for making good unassisted decisions at production level speeds.

On the basis of these studies, it appears that the problem of optimally converting trees into logs has serious effects on economic returns, that in spite of new aids bucking continues to be an area of great concern, and that new decision making tools are needed to aid buckers. The field of operations research provides several optimization techniques that should be explored to provide these aids. These techniques may lead to bucking models that could be programmed on a computer to instantly consider all relevant factors and indicate the optimum solution. These computerized models could be valuable tools in training and aiding buckers.

Chapter 2

REVIEW OF OPERATIONS RESEARCH MODELS THAT OPTIMIZE INDIVIDUAL STEM BUCKING

Historically, the principal approaches for improving bucking have involved increased supervision and training of the bucking crew and shifting the point where bucking is accomplished in the tree harvest to mill conversion process. Increased supervision and training have relied on indoctrination of cutting crews with log scaling and grading rules, results of mill studies, and various felling and bucking manuals. Together these stress the need for careful measurement and consideration of quality and end use. Although these items plus close supervision make cutting crews more aware of the factors that must be considered to perform proper bucking and will eliminate some of the more glaring mistakes, they do not help the bucker determine what combination of logs should be cut from a stem to maximize profits. Movement of the act of bucking from the stump site to the roadside landing, concentration yard, mill yard, or log deck may improve the environment and yield better control but these shifts do not help solve the optimization problem.

One of the difficulties with traditional approaches to quality control of bucking is that they rely on rules-of-thumb or solution methods that do not guarantee an optimal solution. Therefore, there is uncertainty as to how "good" the solution obtained by these methods really is. Comparisons among proposed solutions can also be very misleading. For example, one proposed bucking solution for a stem may yield 50 percent greater dollar yield than another but both may be vastly inferior to the optimum. In other situations, one method may be superior to others in one set of circumstances but inferior in others. It is this kind of comparison and choice among limited and perhaps poorly selected alternatives that has been called optimization by some. Although the optimum choice among the alternatives considered may be discovered, many other alternatives are ignored, hence there is no assurance that the best alternative is contained in the set examined. Consequently there is no assurance that the global optimum to the problem will be discovered.

The forest products literature has many examples of new advancements in computerized "optimization" or "maximization" of bucking but on close inspection few of these studies have anything to do with the determination of global optima. For example, Ffolliot and Barger (1965) described a method for estimating multiproduct potential in standing timber that was designed to augment forest inventory procedures. This system only used a simple set of end product specifications and pre-defined bucking patterns. This essentially heuristic procedure would not guarantee that the best bucking solution is applied. Alm and Troedsson (1969) described a computerized otpimization of bucking which, in reality, is a search among a set of pre-defined patterns. There is no guarantee that the best pattern is included in the pre-defined set. Furthermore their technique does not solve for patterns but rather forces this burden on the analyst. Once the analyst's patterns are available, computerization simply allows fast calculations and comparisons. Murphy (1978) described a log merchandising system at a concentration yard that uses a small set of pre-defined bucking patterns. The merchandiser operator selects among these patterns based on his visual inspection of the stem. These patterns were empirically devised by management as reflecting their desires and notions of proper bucking. It is problematical whether the optimal pattern for a given stem is among these few patterns devised by management. The review in the following sections will not treat this literature on non-global optimum seeking techniques. The reader of the literature should be aware that this literature often uses terminology that confuses the distinction with global optimization techniques.

What is needed is a method that can determine the true global optimum solution to bucking individual trees. This can replace inferior methodologies or be used as the basis of comparison for other proposed methods. There have been some attempts toward this goal. Worley (1963) used break-even analysis in determining when one kind of log should be preferred to another. However, his analysis is presented for a very simple set of log length and product specifications. As this set of specifications becomes increasingly realistic and complex, the enumeration of all possible break-even points becomes unwieldy.

The field of operations research provides optimization techniques such as linear programming, integer programming, and dynamic programming that are concerned with finding the global optimum solution to problems. These techniques differ from simulation and heuristic programming which simply find a solution and from limited search techniques which find the best among a limited pre-defined set of alternatives. These latter techniques do not guarantee that the solution is the global optimum nor do they provide information as to how far from the global optimum the solution obtained from them is.

Linear Programming

The earliest operations research optimization method applied to the bucking problem used linear programming (Smith and Harrell, 1961). Their formulation was an adaptation of the paper trim problem (Eisman, 1957). Tree stems were placed in size categories. The decision variables represent the many alternative bucking patterns for each of the stem categories. The weakness in this formulation is the requirement that all possible alternative bucking patterns and their corresponding economic values must be known in advance by the analyst. This may not be easy to do if the mix of desired products and sizes is very complex and it can quickly lead to an extremely large number of decision variables. One possibility suggested by Smith and Harrell is to provide only a few alternatives for each tree category but this usually will lead to suboptimization. In the absence of constraints reflecting timber supplies, market demands or facility constraints, the task of developing the alternative patterns and their economic worth is tantamount to solving the problem as the pattern with the highest economic worth for each stem category would be chosen. Therefore, this formulation has potential usefulness only when constraints are present. Smith and Harrell considered constraints reflecting demands for the various kinds of logs and constraints reflecting the availability of trees in each category. Their objective was to select the set of cutting patterns and the number of times each is used in a way that satisfied these constraints and maximized profits.

In addition to the burden of knowing in advance all possible patterns and their returns, this formulation leads to other difficulties. First, the linear programming assumption of perfect divisibility can result in solutions that indicate that certain bucking patterns must be applied a fractional number of times. For example, the solution might specify that, for a particular category with say 11 trees, one bucking pattern should be used 5.4 times and another 6.6 times. Clearly a tree cannot be bucked by .4 of one method and .6 of another. Integer programming would resolve this difficulty but would not alleviate others.

The linear programming approach poses a number of technical difficulties in addition to the rapid increase in the problem size to handle more realistic problems. Within the linear programming formulation, there is no way to realistically treat the taper of the trees or calculations of log dimensions and volume based on taper. These calculations must be handled outside the linear program. Valuation of logs, which often incorporates unusual price premiums, would be difficult to handle and the influence of quality which, through the log grading systems, often involves the size, type, frequency and location of defects, would be impossible to handle within linear programming. Obviously, the Smith and Harrell linear programming formulation involves placing a heavy burden on the analyst who must consider the management log specifications, the scaling and grading rules and end products in defining all possible alternatives for each tree category. Since this is largely the problem for which a solution technique is sought and since it is unlikely that the analyst could determine all possiblities in a reasonable amount of time especially in realistic integrated utilization problems, other formulations are necessary.

Another linear programming formulation for bucking individual stems considers each tree to be divided into short equal length segments (Forster, 1967; Forster and Callahan, 1968). Tree description data include species, dbh, sawlog height, pulpwood height and the height of each degrading defect. A preliminary computer routine subdivides the tree into 2 foot segments, calculates the weight (for assessing transportation cost) and appropriate scaling measure for each potential sawlog, veneer log, pulp bolt and cooperage bolt. Defect heights are used to aid in ascertaining the grade of potential logs. The conversion surplus[1] of each potential log is calculated based on log prices and costs of bucking, loading and unloading and transport to alternative markets and a linear program matrix is formed to determine the optimal bucking and allocation. Allocation is based only on the log type and market location and is not constrained by facility demands, timber supplies or other factors.

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[1]Conversion surplus is the difference between the sales value of that amount and quality of the firm's end product that can be made from the tree and all of the variable costs of converting the tree into this product.

The linear programming model is as follows:

$$\text{MAX } P = \sum_{j=1}^{n} C_j X_j$$

$$\text{st} \sum_{i=1}^{m} a_{ij} X_j = b_i$$

X_j = the number of units of a particular log type from a particular portion of the stem to be produced for a particular mill location. j=1,...,n log to market activities

C_j = the conversion surplus associated with converting a particular portion of the stem into a log to be sent to a particular mill location

P = the conversion surplus of the tree

b_i = the amount of the i-th input available in the i-th 2-foot segement i = 1,2...,m segments in the tree

a_{ij} = the amount of the i-th input needed as part of one unit of output in the j-th log to market activity.

The m constraints in the linear program simply insure that each 2 foot stem length can only be used in one log to market activity. This model was solved for individual trees to determine the optimal conversion surplus when they were skidded in tree length form to a roadside landing for bucking. Conversion surplus calculations may have to be modified for other logging systems. The felling, limbing and skidding costs were deducted from the optimal bucking conversion surplus to determine if the tree itself was worth harvesting. The model was used to: (1) examine the influence on marginal log size of absolute distance from the bucking site to a mill; (2) to examine the influence on marginal log structure of the relative distance from the bucking site to different mills; and (3) to determine the effect of changing relative log prices.

Apparently, this model was limited to individual tree bucking because of the large linear programming matrix that developed when mature trees were considered. By dividing the tree into 2 foot segments, including several log type/size options, and including several mill locations this approach leads to a large number of log to market activities for a given stem and a large number of constraints. The model also has the disadvantage that all possible log to market activities and their associated conversion surplus values must be known in advance. These factors result in a large problem and a burden on the analyst. Also, since all of the log size possibilities must be an integer multiple of the stem segment size, different log length specifications could lead to a smaller stem interval. This would require substantial reformulation and would greatly increase the size of the linear program. In addition many of the proceeding comments regarding the assumptions involved in using linear programming apply to this formulation as well.

Dynamic Programming

Since the approaches using linear programming posed a number of difficulties, researchers began to examine alternative operations research methods. Dynamic programming is attractive because it does not contain the restrictive linear programming assumptions. Although some progress has been made, the use of dynamic programming is more difficult because of the lack of "canned" computer programs for routine solution of dynamic programming problems and the impression from the use of this technique in solving other problems that it would require excessive computing capabilities.

Dynamic programming is an optimization technique that is particularly adaptable to problems requiring a sequence of interrelated decisions. Each decision transforms the current situation into a new situation. A sequence of decisions which in turn yields a sequence of situations, is sought that maximizes or minimizes some measure of value. In contrast to linear programming, there does not exist a standard mathematical formulation for all dynamic programming problems nor does there exist a standard algorithm like the simplex method for the solution of dynamic programming problems. The only thread common to all dynamic programming problems is some form of recurrence relationship and the principle of optimality. Appendix A provides a brief description of the main concepts of dynamic programming for the reader unfamiliar with this technique.

The earliest reference to the use of dynamic programming for solving the bucking problem attempted to find the bucking points giving maximum total value for an individual tree within the framework of tree characteristics, log grade specifications and the market value of logs in each grade (Clemmons, 1966). Log specifications were given by management and included required dimensions and log value. Log grading was based on a simple system that included only the range of knot sizes and range of percent clear log surface area allowed in each grade. No details of the formulation were presented.

Strand (1967) applied dynamic programming in developing tables for Scots pine (*Pinus sylvestris*) showing the optimal value and number of logs according to tree dbh and height class. He later discussed the potential application of the model to bucking operations at mills (Strand, 1968). However, he did not present details of the formulation in either paper.

The first detailed presentation of dynamic programming applied to bucking was given by Pnevmaticos and Mann (1972). The optimization is based on considering log prices and the cost of bucking. Referring to Figure 1 and assuming that bucking proceeds from the large end of the stem toward its small end, define

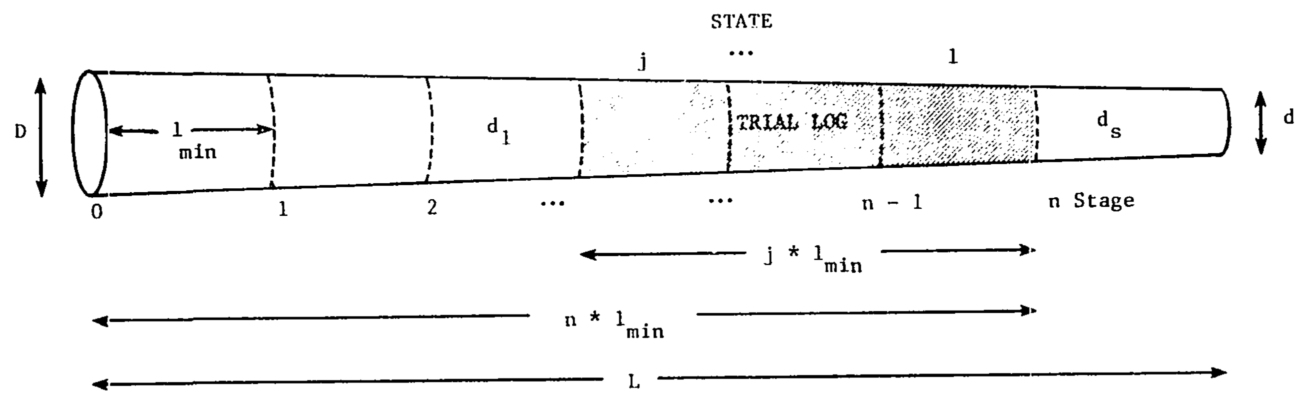


Figure 1. Notation for the Pnevmaticos and Mann (1972) dynamic programming bucking model.

D = large end diameter of stem

d = small end diameter of stem

L = stem length

l_i, P_i = log length desired by management and associated price per unit length

l_{min} = MIN $[l_i]$ smallest log length = dynamic programming stage interval

l_{max} = MAX $[l_i]$ largest log length

$n = 1, \ldots,$ INTEGER $(^{L/}l_{min})$ = stage number such that $n*l_{min}$ is the locus of a trial bucking point above the base of the stem

j = state (decision variable) = number of stage intervals to be combined into one log

$$1 \leq j \leq \text{MIN} \left[n, \frac{l_{max}}{l_{min}} \right]$$

This constraint insures that at least one minimum length log is removed and that the longest length that can be removed is the smaller of the distance from the stem base to the current stage or the maximum log length. This constraint can also be specified as

$$l_{min} \leq j*l_{min} \leq \min \left[n*l_{min}, l_{max} \right]$$

$j*l_{min}$ = length of a trial log; $j*l_{min} \; \varepsilon \; (l_i)$

d_l, d_s = large and small diameters of a log of length $j*l_{min}$, calculated using D, d, and L and assuming the stem is a truncated cone.

g = log grade

$$f_n\ (L,D,d) = \underset{J}{MAX} \left(\sum_g V_g \left[j*l_{min}, d_l, d_s \right] *Q \left[j*l_{min}, d_l, d_s \right] - C \left[j*l_{min}, d_s \right] + f_{n-j} \left[n*l_{min} - j*l_{min}, D, d_l \right] \right)$$

$V_g \left[j*l_{min}, d_l, d_s \right]$ = value of a trial log of grade g, length $j*l_{min}$, large diameter d_l and small diameter d_s

= l_i*p_i where l_i is the log length corresponding to $j*l_{min}$ and p_i is the corresponding unit price.

$Q \left[j*l_{min}, d_l, d_s \right]$ = probability that a trial log of length $j*l_{min}$, large diameter d_l, and small diameter d_s is of grade g.

$C \left[j*l_{min}, d_s \right]$ = cost of cutting through diameter d_s in removing a trial log of length $j*l_{min}$.

$$\frac{f_{n*l_{min} - j*l_{min}}}{l_{min}} \left[n*l_{min} - j*l_{min}, D, d_1\right]$$

$$= f_{n-j} \left[n*l_{min} - j*l_{min}, D, d_1\right]$$

= the optimal solution for bucking the portion of the stem between its base and the large end of the trial log of length $j*l_{min}$.

f_n (L, D, d) = value of the optimum solution for bucking the stem through the n-th stage.

They also show that it is a simple matter to formulate the model to consider bucking as proceeding from the small end of the stem toward its large end.

It may be instructive to illustrate this model with an intuitive example. Assume for illustration that only 8 and 16 foot logs are to be considered and assume bucking will proceed from the stump end toward the top of the stem. The following comments will however, be equally valid if bucking were to proceed from the top toward the stump.

Referring to Figure 2, it is obvious that the bucker can immediately move to a trial bucking point 8 feet from the stump end since neither log length is feasible at any point closer to the stump. At the 8 foot point the bucker has the option of bucking an 8' length or he could

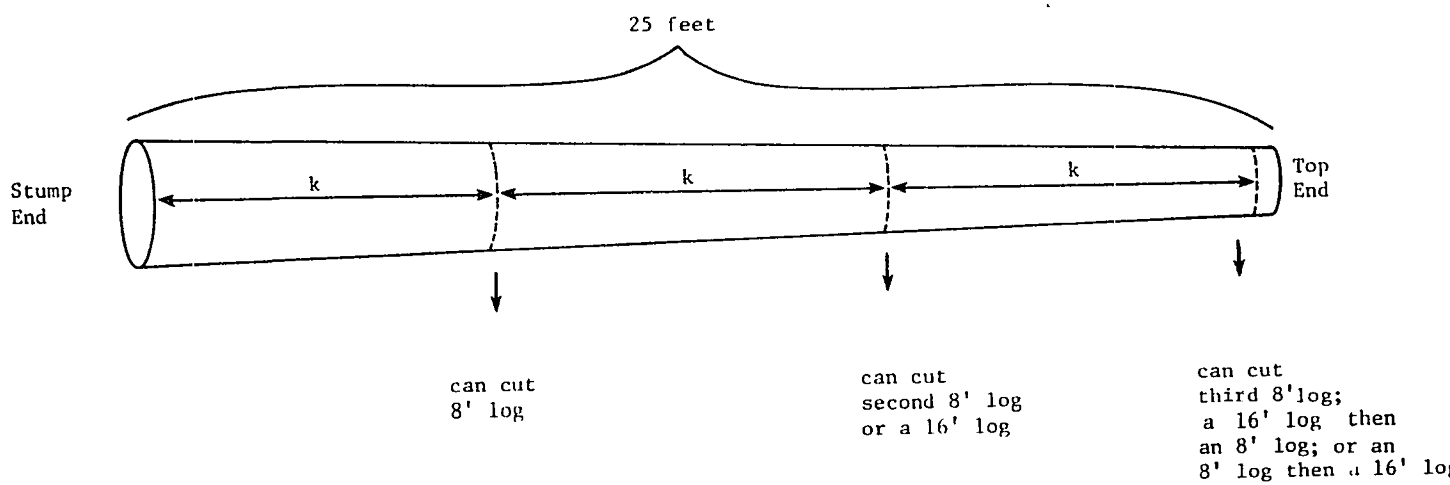


Figure 2. Illustration of the dynamic programming model when the stage interval equals the smallest log length.

move another 8 feet and consider cutting a 16' log or two 8 foot logs. Assume he records the value associated with bucking at the 8' point and moves on the the second trial bucking point located 16 feet along the stem. Here he can consider bucking a second 8 foot length to go with the one he already knows he could buck at the first trial bucking point or he could buck a 16 foot length. He could also do nothing at 16 feet because there is the possibility of moving another 8 feet and considering, among other alternatives, an 8 foot log followed by a 16 foot log. In this case no bucking would occur at the 16 foot point. Assume the bucker calculates the value associated with bucking a second 8 foot log (adding it to the value of the first one) and the value of one 16 foot log, compares the results and stores the better choice if he is to buck at 16 feet. The bucker then proceeds to a third trial point at 24 feet where he similarly evaluates and compares the alternatives of three 8 foot logs, an 8 foot log followed by a 16 foot log, and a 16 foot log followed by an 8 foot log. Since there is insufficient stem to proceed further, the optimum choice at this last trial bucking point leads to the optimum bucking for the entire stem.

In this form, Pnevmaticos and Mann have made a number of assumptions that greatly restrict use of the model. (1) By defining the stage interval as the minimum length log that is acceptable to management, they preclude many possible sets of log specifications since all log lengths must be an integer multiple of this stage interval. For example, if 8 feet is the minimum length log then other log lengths can only be the integer multiples 16, 24, etc. This definition prevents the model from being applied to many situations such as when a trim allowance must be added and when intermediate log lengths are desired. (2) Taper was oversimplified by assuming trees have the form of truncated cones. Many taper curves are available in the forestry literature that could replace this assumption. (3) Valuation was based only on log length while in actual practice valuation is more typically accomplished on a volume or weight basis. (4) Quality is unrealistically treated by assuming that the probability is known that a log of given dimensions is of a particular grade. Information of this nature is generally not available and this approach to quality fails to reflect the actual practice of applying log grading rules wherein factors such as minimum log diameter and the type, size, frequency and specific location of defects along the log are important. Log diameter limitations may also be specified by management because of facilities limitations. For example, a veneer lathe may not be able to accept a log larger than 48 or 60 inches. (5) They only consider that portion of the tree remaining after stump and top removal. The location of the stump and top cuts should be incorporated into the analysis. Taken together, these assumptions and limitations resulted in a model that is far removed from reality. Briggs (1977) has removed most of these restrictions by redefining the stage interval as the common denominator of whatever mix of log lengths is specified by management, by considering the entire tree from groundline to tip and providing for appropriate taper curve, stump height, and top limit information. He also revised the valuation to a volumetric basis and allowed for management log specifications to include diameter constraints. Referring to Figure 3 define

D = dbh of the tree

H = total height of the tree

S = stump height

l_i, p_i, $d_{min} \leq d_{si} \leq d_{max}$ = log dimension specifications of management for i-th log and assocated price per unit log volume

$l_{min} = \min[l_i]$ = smallest log length

$l_{max} = \max[l_i]$ = longest log length

k = an interval of stem length that is the common denominator of the log lengths, l_i, used as dynamic programming stage interval

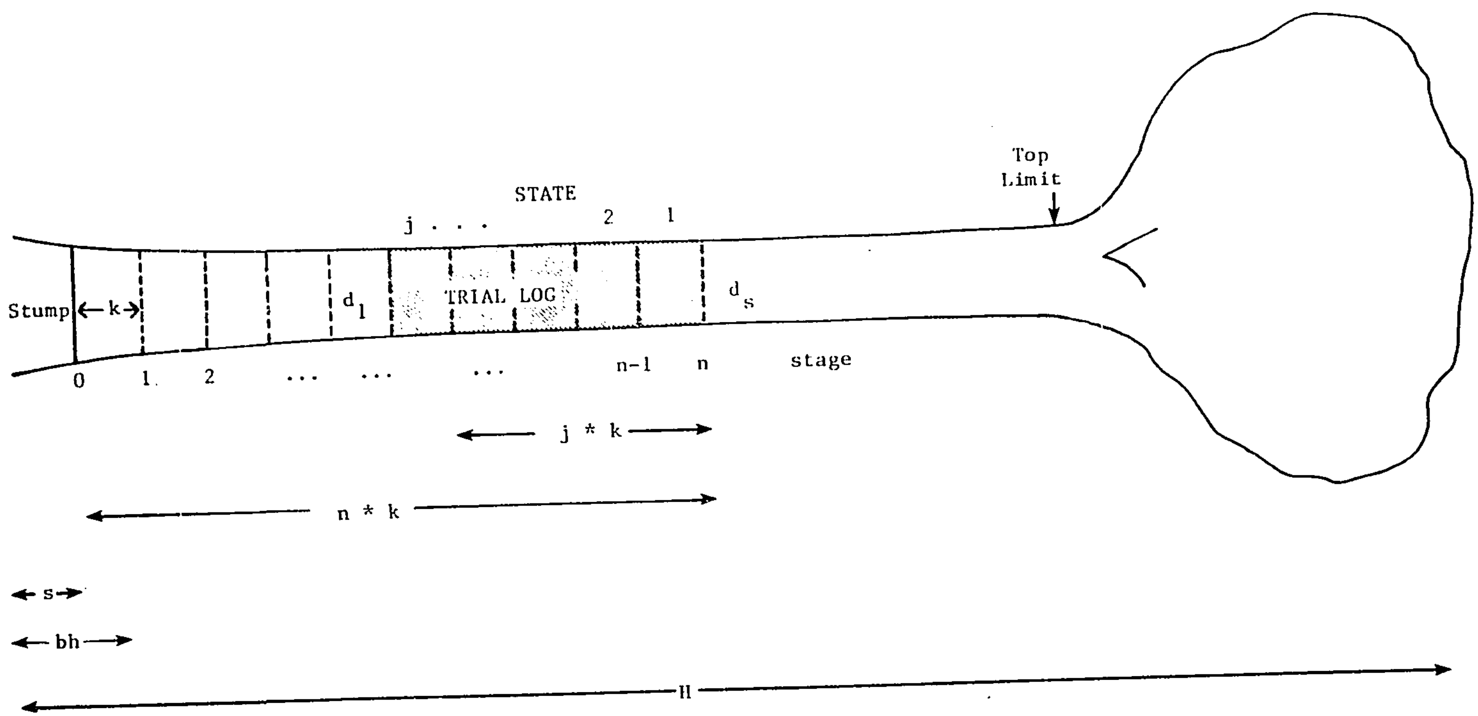


Figure 3. Notation for the Briggs (1977) dynamic programming bucking model.

n = 1,2,...,INTEGER [(H-S)/k)]

= stage number such that n*k+s is the height to a trail bucking point

j = state = number of stage intervals to be combined into one log where j is such that j*k, a trial log length, is in the range

$$l_{min} \leq j*k \leq \min(n*k, l_{max})$$

$$j*k \in (l_i)$$

This constraint insures that at least one minimum length log desired by management is removed and that the longest possible log length is the smaller of the distance above the stump of the maximum log length. Furthermore, logs can only be of the specific lengths desired by management.

d_l, d_s = large and small end diameters of a trial log of length j*k

These diameters are calculated on the basis of the taper curve appropriate for the species, the dbh and total height of the tree and the position of the log in the tree.

$$f_n(H, dbh, s) = \max_j (V[j*k, d_l, d_s] - C[j*k, d_s] + f_{n-j}[n*k - j*k, dbh, s])$$

$V[j*k, d_l, d_s]$ = value of a trial log of length $j*k$, large diameter d_l and small diameter d_s

$= v_i * p_i$ where v_i is the appropriate volume of the log and p_i its corresponding value per unit volume.

$C(j*k, d_s)$ = cost of cutting through diameter d_s in removing a trial log of length $j*k$

$f_{n-j}[n*k - j*k, dbh, s]$

= value of optimal solution for bucking the portion of the tree between the stump and large end of the trial log

$f_n(H, dbh, s)$

= value of optimal solution for bucking a tree, with a stump cut at height s, through the n-th stage.

A simple extension of this model allows consideration of a tree that has been broken during felling or a forked tree as a series of separate subproblems. This model has been incorporated into a systems approach for analyzing the utilization potential for tropical stands (Briggs, 1978). Geerts (1979) also produced a similar formulation.

A different dynamic programming approach to bucking was proposed by Gluck and Koch (1973) who regarded the stage variable as the number of cuts rather than the number of intervals along the stem. Referring to Figure 4, define

$\left.\begin{array}{l} D \\ d \\ L \end{array}\right\}$ Same as Pnevmaticos and Mann

l_i, p_i Same as Briggs' log dimension specifications for the i-th log and associated price per unit log volume

$\left.\begin{array}{l} l_{max} \\ l_{min} \end{array}\right\}$ Same as Pnevmaticos and Mann

k = buck cut number = stage

x_k = length of stem above its base that can be cut into k+1 logs with k cuts

This is the state variable

$$(k+1)*l_{min} \leq x_k \leq \text{MIN}\left[L,\ (k+1)*l_{max}\right]$$

This constraint says that for any k number of cuts, the height in the stem will be at least as great as the number of logs times the minimum log length and cannot exceed the smaller of the stem length or the number of logs times the maximum log length.

d_k = decision variable, length of log that can be taken with the k-th cut

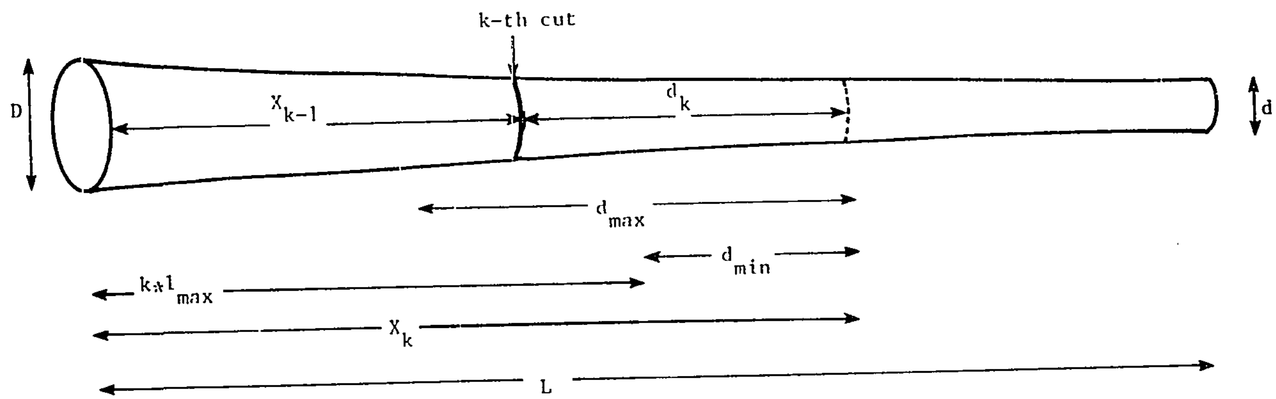


Figure 4. Notation for the Gluck and Koch (1973) dynamic programming bucking model.

$$\underbrace{\max\left[0, X_k - k^*l_{max}\right]}_{d\ min} \leq d_k \leq \underbrace{\text{MIN}\left[X_k,\ l_{max}\right]}_{d\ max}$$

This constraint says that the log length taken with the k-th cut must be at least as long as zero or the length of stem involved with k cuts minus k times the maximum log length. Also it cannot exceed the smaller of the length of stem involved in k cuts or the maximum log length. It should be obvious that also $d_k \ \varepsilon \ (l_i)$

$x_{k-1} = x_k - d_k$ = transformation between states

$$f_k(X_k) = \underset{d_k}{\text{MAX}} \left[r_k(X_k,\ d_k) + f_{k-1}\ (X_{k-1})\right]$$

$r_k(X_k,\ d_k)$ = return from deciding to cut the length d_k with the k-th cut based on log volume and per unit volume price

$f_{k-1}\ (X_{k-1})$ = optimal return for cutting stem length X_{k-1} with k-1 cuts

$f_k\ (X_k)$ = optimal return for cutting the length of stem X_k with k cuts

Philosophically the approach taken by Pnevmaticos and Mann, and Briggs optimizes with respect to the log lengths desired by management while, at any stage, holding constant the height position in the tree. The number of cuts required is a by-product of the solution. The Gluck and Koch approach optimizes with respect to the number of cuts. For a given number of cuts different height points in the tree are achieved depending on the combination of log lengths. The actual breakdown of the stem into logs and their sizes is a by-product of the solution. One potential difficulty with this formulation is that the accounting necessary to keep track of the solution may become tricky especially with more complex sets of log specifications. In the same article, Gluck and Koch reviewed the Pnevmaticos and Mann approach and concluded that it was more appealing. Although they introduced a taper curve and revised valuation to a volumetric basis, quality was not explicitly considered. In a comparison with the actual yield obtained from bucking 21 sample stems they found that the optimum would give returns averaging 17 percent greater.

Deadman and Goulding (1978) described an application of the Pnevmaticos and Mann formulation to *Pinus radiata*. They envision using the model as an aid in improving multiple product forest inventory assessments. Although no mathematical details were presented it is apparent that they redefined the stage interval in a fashion similar to Briggs. They similarly introduced a taper curve appropriate to the species and they explicitly considered the entire tree including the stump cut. They also introduced a stochastic component to treat breakage during felling. Each segment of a broken tree was treated as a problem requiring separate solution. Malformations such as large branches and forks were treated by estimating the "dbh" of each at 1.4 meters above its base and considering it to be a separate "tree." The influence of stem defects on quality was treated by partitioning the stem into variable length regions of uniform quality. This approach to quality is unrealistic in terms of log grading practices in the United States which involve the specific pattern, type, and sized defects. Judging a zone along the tree as being of a given quality makes little sense in bucking logs under these log grading systems because the log grade assigned to any log depends on where the log was located and bucked with respect to the pattern of defects on the stem.

Deadman and Goulding compared the predictions of their model with actual results of ten felling crews. The model predicted optimum bucking given log prices, log volume, a fixed cost percent, the log size specifications and the dimensions, malformations, breaks, and quality zones of the tree. They sampled 25 trees bucked by each crew and found that the model over-estimated the actual volume recovered by only 3.7 percent. Generally, the model, using a constant stump height, underpredicted the crew stump height and underpredicted other forms of waste. Although the total volume agreement was quite close they found that there were substantial volume differences between sawlogs and pulplogs and between long and short log lengths.

Generally, the model predicted more sawlogs and longer lengths. It is unfortunate that detailed comparisons with the objectives of individual crews were not provided along with the aggregate analysis. It is also unfortunate that they did not provide analyses on a value basis rather than in volumetric terms as comparisons on a value basis would undoubtedly be more revealing and meaningful.

Branch-and-Bound Method

As an alternative to dynamic programming, Ramalingham (1976) proposed the use of branch-and-bound methods which are enumerative schemes for solving optimization problems (Mitten, 1970). The utility of branch-and-bound methods derives from the fact that, in general, only a small fraction of the possible solutions need to actually be enumerated; the remaining solutions being eliminated through applying bounds which establish that such solutions cannot be optimal. The term branch-and-bound arises from the two basic operations: (1) branching, which consists of dividing collections of sets of solutions into subsets, and (2) bounding, which consists of establishing bounds on the value of the objective function over the subsets of solutions. The solution is found through recursive application of these operations with provision for deleting subsets known not to contain an optimal solution. The individual stem bucking problem is formulated (Ramalingham, 1976) as a branch-and-bound problem by considering the alternative log lengths to be branches. As the solution procedure moves along the stem, the upper bound on total profit for the whole tree is calculated as the sum of the returns from the logs bucked so far plus the maximum possible return for the remaining unbucked portion of the stem. Define

D, L, l_i, p_i, as in Pnevmaticos and Mann

UB [S(c, k)] = TR [S(c, k)] + MRU*(L-C)

where

TR [S(c, k)] = total return for a subset of total length c containing k logs

$= \sum_{j-1}^{k} b_j * p_j$ where b_j and p_j are the lengths of the specific bucked logs in the length c from the set l_i specified by management and their appropriate prices

MRU*(L-C) = maximum possible return for the unbucked remainder of the stem.

MRU = maximum possible return per unit length of stem over the section L/C

$= \underset{i}{MAX} \left[P_i / l_i \right]$

UB [S(c, k)] = upper bound on return for the subset of total length c containing k logs

Constraints

$0 \leq C \leq L$ i.e. the total length of a subset cannot exceed the stem length

$C = \sum_{j-1}^{k} b_j \quad b_j \varepsilon (l_i)$ i.e. the subset can only contain desired log lengths

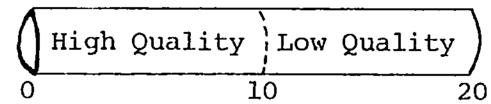
The upper bounds for each branch are compared and the largest selected as the alternative to continue examining.

Table 1 illustrates the branch-and-bound solution of the example previously solved by Pnevmaticos and Mann (1973) with dynamic programming. In the example, if any part of a log enters the 10-20 foot part of the stem, the entire log is downgraded to reflect the lower quality of the upper stem.

Ramalingham obtained the same solution with the branch-and-bound procedure as Pnevmaticos and Mann obtained with dynamic programming for this example. However, it is perplexing that Ramalingham's calculations use an MRU value that is known to be infeasible. For example, in level 1 for the 4 foot case, the MRU of 1.23 should apply only up to 10 feet rather than to all 20 feet. Also, since this MRU value is based on a 12 foot log which must be downgraded, because any 12 foot log enters the lower grade 10-20 foot section of the stem, use of $1.23 as the MRU appears to be illogical. Even with amendments to the procedure to remove the inconsistencies there is the question of whether the

Table 1

Branch-and-Bound Solution of the Pnevmaticos and Mann Stem Bucking Example



Stem length (TLS) = 20 feet where 0-10 feet is of higher quality than 10-20 feet

Desired log lengths (DL) = 4, 8, or 12 feet

Returns for the log lengths of cut from either quality sections of the stem

Location Along Stem	Log Length 4 feet	8 feet	12 feet
0-10 feet	$2.00	$9.00	$14.80
10-20 feet	$2.00	$6.00	$11.20

MRU for 0-10 feet = MAX{$2.00/4, $9.00/8, $14.80/12} = $1.23/foot
MRU for 10-20 feet = MAX{$2.00/4, $6.00/8, $11.20/12} = $.93/foot

cut(log) number k	sum of log lengths c	total return from the k logs TR $	remaining length of stem TLS-C	largest possible profit for the remaining stem MRU+(TLS-C) $	upper bound on total profit for the entire stem UB $	best prospective alternative
0	0	0	20	1.23*20 = 24.66	24.66	←
1	4	$ 2.00	16	1.23*16 = 19.73	21.73	
	8	$ 9.00	12	1.23*12 = 14.80	23.80	←
	12	$11.20[1]	8	.93*8 = 7.47	18.67	
2	4	9.00+2.00=11.00	8	.93*8 = 7.47	18.47	
	8	9.00+6.00=15.00	4	.93*4 = 3.73	18.73	←[2]
	12	9.00+11.20=20.20	0	.93*0 = 0	20.20	

[1] If any part of a prospective log enters the lower quality zone the log must be valued at the rate for the lower zone.

[2] Since the best prospective alternative for 2 cuts utilizes the entire log, the problem is solved. The solution is to cut an 8 foot log and a 12 foot log.

procedure will always find the optimum. In the case when all log lengths are perfect multiples of the smallest log length or when relative log value differentials are large enough, Ramalingham's branch-and-bound seems to work. However, Table 2 shows an example in which the optimum is not found by this procedure. In this case, the log lengths are not integer multiples of the minimum length and some combinations may not fully utilize the stem. Under these conditions and with specific relative price situations, the branch-and-bound procedure proposed by Ramalingham fails to determine the optimum solution (Bare et al., 1979).

Summary

This literature review suggests that dynamic programming may be the most useful and practical technique for determining the optimum solution to the bucking problem. This problem has several characteristics that influence the choice of solution technique. These are:

1. The discrete nature of many aspects of the problem

a. log lengths desired by management are expressed as a set of discrete lengths

b. diameter limits for logs technically suited for various manufacturing processes are often discrete. For example, veneer logs may be required to be no larger in diameter than the swing of the lathe and there may be a

Table 2

An Example Where Ramalingham's (1976) Branch-and-Bound Procedure Fails to Find the Optimal Solution to the Stem Bucking Problem

Stem Length (TLS) = 20 feet where 0-10 feet is of higher quality than 10-20 feet
Desired Log Lengths (DL) = 4, 7, or 12 feet
Returns for the log lengths if cut from either quality section of the stem:

Location Along Stem	Log Length 4 feet	7 feet	12 feet
0-10 feet	$2.00	$3.75	$7.00
10-20 feet	$2.00	$3.00	$5.00

MRU for 0-10 feet = MAX{$2.00/4, $3.80/7, $7.00/12} = $.58/foot
MRU for 10-20 feet = MAX{$2.00/4, $3.00/7, $5.00/12} = $.50/foot

cut(log) number k	sum of log lengths c	total return from the k logs TR $	remaining length of stem TLS-C	largest possible profit for the remaining stem MRU*(TLS-C) $	upper bound on total profit for the entire stem UB $	best prospective alternative
0	0	0	20	.58*20 = 11.60	11.60	←
1	4	2.00	16	.58*16 = 9.28	11.28	
	7	3.80	13	.58*13 = 7.54	11.34	←
	12	5.00	8	.50*8 = 4.00	9.00	
2	4	3.80+2.00 = 5.80	9	.50*9 = 4.50	10.30	←
	7	3.80+3.00 = 6.80	6	.50*6 = 3.00	9.80	
	12	3.80+5.00 = 8.80	1	.50*1 = .50	9.30	
3	4	5.80+2.00 = 7.80	5	.50*5 = 2.50	10.30	←
	7	5.80+3.00 = 8.80	2	.50*2 = 1.00	9.80	
	12	not feasible				
4	4	7.80+2.00 = 9.80	1	.50*1 = .50	10.30	←1
	7	not feasible				
	12	not feasible				

[1]Since no logs desired by management can be cut from the remaining stem, the best prospective alternative for 4 cuts is chosen as the solution. This says to cut a 7 foot log followed by three 4 foot logs. This would return $9.80. However, cutting five 4 foot logs is a better solution yielding a return of $10.00.

minimum diameter limit as well. Similar considerations may exist for other processes.

c. the systems for assigning log grades generally involve discrete log size intervals as well as the specific size, type, and patterns of defects.

2. The value functions are often discontinuous because of price premiums for certain sizes and qualities.

3. The procedure for cutting a stem into logs can be easily viewed as a multistage decision process.

When the assumptions and characteristics of operations research optimization techniques such as linear programming, integer programming and dynamic programming are compared to these characteristics of the bucking problem, all except dynamic programming have assumptions that violate the problem characteristics. In linear programming, all relationships are assumed to be linear and continuous while the bucking problem often involves discontinuous step functions. Furthermore linear programming assumes perfect divisibility of decision variables that can lead to illogical fractions. Although integer programming could treat this latter difficulty, it would not remedy the former and this technique imposes some computational obstacles. In order to overcome these differences between the linear programming technique and the bucking problem, linear programming formulations have forced a large amount of pre-calculation burden on the analyst. In addition to these difficulties, the linear programming formulations quickly lead to a very large number of decision variables and constraints. The use of linear programming to solve bucking problems has not gained significant practical use because of these limitations. The branch-and-bound method proposed by Ramalingham (1976) is not promising since examples have been found where it does not disclose the optimum solution.

Dynamic programming has been proposed by several authors for solving multistage decision problems and can easily treat the nonlinearities and discrete aspects of this problem. It is also easy to incorporate the calculations forced on the analyst by the linear programming approaches into the solution procedure. In spite of the advancements with the dynamic programming approach, there are three aspects of the bucking problem that must be incorporated before it can satisfactorily consider all the factors faced by a bucker. These needed features are:

1. introduction of tree defect data and log scaling and log grading rule requirements so that the solution process can determine the log grade and net scale of any trial log as well as its position in the tree, dimensions, and gross volume;

2. introduction of predictions of end product recovery alternative from graded logs; and

3. development and use of an appropriate decision criterion for valuation.

There are two principal disadvantages to using dynamic programming. First is the lack of general "canned" computer programs to solve dynamic programming problems. Each problem or class of closely written problems requires that a special program be written. This is because dynamic programming is more of a point of view towards solving a problem rather than the detailed mathematical process. The development of such a program for stem bucking will be one of the results of this study.

The second disadvantage of dynamic programming is the so called "curse of dimensionality." In the act of solving some problems through dynamic programming, the burden of storing information as the solution evolves may exceed any available or conceivable computer memory. Fortunately, the stem bucking problem is not afflicted with this limitation.

Chapter 3

SCOPE AND OBJECTIVES OF THE RESEARCH

It is apparent from the discussion in the preceding chapters that none of the approaches to optimizing the individual stem bucking problem is completely acceptable. It is also apparent that log buckers are faced with an almost insurmountable task in attempting to consider end product yield, stem quality factors, log grading and scaling rules, log dimension specifications, enumerate the large number of log combinations that fit the stem, and select the optimum, all while achieving a high production rate. Of the solutions proposed in the literature, none have been developed that incorporate in detail all of the factors the bucker must consider. Of the techniques used, dynamic programming appears to be the most promising and flexible for the task. However, several factors may be hindering the acceptance of the dynamic programming approach to solving the bucking problem. Outside of the general lack of "canned" computer programs are the practical concerns of the size of computing facility needed and the amount of time that it would take to establish a solution for a particular stem, and perhaps the impression gained from models previously formulated with dynamic programming that this method may be of limited applicability.

Given the rapid evolution of computing technology, concern over the size and speed of computing facilities needed to find solutions is not a valid reason for not examining and developing dynamic programming models for bucking. Computing capability has evolved to a state not even wildly imagined a decade ago and is likely to produce startling advancements in the future. This is especially true with the mini-computer which is affordable by almost any business and is rapidly outdistancing the speed, memory, and reliability capabilities of the large expensive systems of only a few years ago. It has been the experience of this writer that a dynamic programming bucking model (Briggs, 1977) written in BASIC for the DATA GENERAL NOVA 210 with 16 bit words and 32K of central memory can be easily solved for large size trees in less than 2 minutes and often in only a few seconds. As this is a fairly old and slow computer by present standards and since BASIC would undoubtedly not be the final language chosen for routine operational solutions, this solution time could be greatly reduced. Geerts (1979), for example, found that solution times for a formulation similar to that of Briggs using a DEC-System 10 32 bit word computer were about 6 CPU seconds in the most complex case (1 cm stage interval and 40 assortments) and about 1/3 of a CPU second in a simpler case (10 cm stage interval and 12 assortments). He also found that the memory space for solving various problems ranged up to 7K words depending on the stage interval. On this computer system the program instructions required another 8K of memory.

Even if a dynamic programming model for bucking was found to be operationally infeasible for direct usage in manufacturing facilities due to computing time restrictions, such a model could be very useful as a basis for providing a benchmark for evaluating operational procedures and training personnel.

The impression that dynamic programming can only be applied to bucking in limited cases is unwarranted. This attitude could have developed because published accounts have presented a dynamic programming formulation that is overly-restrictive and have either ignored quality, product recovery and other important considerations that affect bucking decisions or treated them in an unrealistic or grossly oversimplified way. Some of the restrictions and oversimplifactions have already been removed (Briggs, 1977).

The following aspects of the bucking problems defined in Chapters 1 and 2 are the objectives of this study.

1. To create a generalized formulation of the dynamic programming approach to solving the problem of bucking a tree into logs that is flexible enough to incorporate any set of log specifications and constraints, and utilize realistic stem quality characteristics, log grading and scaling rules, and product recovery information in guiding

the solution process. The model will also include flexibility to consider the location of bucking at any point between the tree site and mill and evaluate logs for roundwood scale and/or mill processing.

2. Since the quality factors and end product recoveries are usually specific to a particular species, the model will be developed for Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], and tested on a small set of sample trees.

3. To verify that the model operates as intended.

4. To examine the effect of including defect data on the optimal solution and solution time.

5. To evaluate the promise of the dynamic programming bucking model as an operational and analytical tool, suggest areas for refinement, and to suggest extensions and applications to similar manufacturing problems.

Accomplishment of these objectives requires progressive completion of the following phases of study:

1. Model development
   a. economic framework
   b. physical components
      i. tree shape and quality description
      ii. management specifications for logs
      iii. log scaling and grading procedures
      iv. product recovery
   c. integration of (a) and (b) into dynamic

programming form

d. design of input and output

2. Programming model logic

3. Verification and validation of the model

4. Selection of test trees, design of test problems, and analysis of results.

It is recognized that the individual tree bucking problem is only one of many steps involved in the system of activities that produce timber and processes and allocates wood to end uses. There is a danger that optimization of any single activity in the system may lead to suboptimization in a broader context. Ultimately, the individual tree bucking problem should be solved in the context of the problem of optimizing the production and allocation of the overall wood production system. The system may impose a variety of constraints that will influence the choice of optimal bucking. Bare et al. (1979) have reviewed the state of the art and concluded that much work remains to be done in this area. However it is important to recall that at present no realistic bucking optimization model exists. It is toward this end that this research is directed. Once such a model is developed, examination of how to interface it with the broader problem will be necessary.

Chapter 4

MODEL DEVELOPMENT

Introduction

Development of a realistic stem bucking model involves a number of factors that reflect the information a log bucker must consider in making decision. These factors are:

1. a description of the stem including
   a. dbh, total height, merchantable height and stump height
   b. taper
   c. bark thickness
   d. defects, external and internal, as well as sweep and crook, forks, and breaks caused by felling
2. log specifications and log scaling and grading rules
3. the recovery of end products from logs
4. the economic framework of the log production environment.

Careful consideration of all stem attributes is necessary to insure that unique features affecting proper bucking are included in the decision process. Knowledge of these attributes is necessary in order to properly apply log specifications and log scaling and grading practices in defining and measuring feasible alternative solutions. Knowledge of how various logs will process into end products is necessary especially when the bucker is producing logs that will enter his own firm's mills. Finally, it is important that the bucker realize the economic framework of the production system and utilize the relevant economic factors in establishing which alternative solution is best. This chapter deals with the organization of these factors into a dynamic programming model that will reveal optimum bucking solutions.

Criterion for Decision Making

To arrive at a best solution to the bucking problem, the log bucker, or a bucking model, must include a decision criterion. Although maximizing utilized tree volume or, conversely, minimization of unused tree volume may appeal to some, most firms are interested in optimizing some measure of economic value. One approach would be to maximize the revenue from selling logs or finished products after processing but this ignores costs. A valid measure of economic value for the bucking problem is the conversion surplus criterion which is the excess of product sales value over the direct or variable costs of production, exclusive or fixed charges (Guttenberg and Duerr, 1949). This criterion has been used in other studies of log bucking (Forster and Callahan, 1968; Pnevmaticos, 1974) and in other phases of forest product manufacture (Doyle and Calvert, 1961; Noreen and Hughes, 1968; Duerr and Guttenberg, 1968; Bousquet et al., 1972). In the context of bucking a stem into logs, conversion surplus is the difference between the final value of the products for which the logs in the tree are used and the variable costs of converting the tree into logs and these logs into products.

In developing this criterion there are two common cases that appear in log bucking. First is the situation in which logs are produced and sold on a log market. Here the final value of the products is simply the volume of logs multiplied by the appropriate log price which may include premiums for different log qualities, sizes, and uses. The variable costs of conversion are those variable costs incurred by the operator from the point in his logging operation where bucking occurs to the point of log sale.

In the second situation the logs do not enter a log market but instead are produced and processed into end products by a vertically integrated firm. It is in this setting where information on end product recovery is vital to the bucking decision process since the final value of the products is the sum of the end product items multiplied by their respective market prices. The variable cost of conversion is the sum of all variable costs from the bucking point through conversion to the point where the end product is sold.

This study will undertake to develop a model that will consider the production of sawlogs, veneer logs, pulp logs, and fuel bolts although other products could be introduced at a later time. It will be assumed that each of the products may be sold either in roundwood log form or they may be processed through manufacturing facilities into dry untrimmed veneer, surfaced lumber, unbleached kraft pulp, or fuel chips. These manufacturing end points are used because they reflect convenient end points for which product recovery data are available.

Although the revenue aspect of the conversion surplus criterion is relatively simple to estimate, the appropriate items to consider as components of the variable cost are more difficult because the location of bucking in the process of conversion in part determines which cost factors are relevant. Bucking can be accomplished at the felling site, roadside, intermediate landing, concentration yard, or mill site. Methods of payment, such as for stumpage, can determine whether a cost item is fixed or variable. Variable or direct costs are those expenses, principally for labor and supplies, that are directly chargeable to the log in question. Whether or not these costs are incurred depends on whether or not the log is produced. Costs that should not be charged to the log are fixed costs that occur regardless of whether or not the log is produced. Examples of fixed costs are the costs of locating, marking, and felling the tree. Since bucking occurs after the tree is felled, locating, marking, and felling are sunk costs and should be charged only to the tree as a whole. These are also joint costs in that they are shared by all logs produced in the tree. Guttenberg and Duerr (1949) illustrate how attempts to prorate joint costs among logs leads to erroneous decisions. Although locating, marking, and felling costs are not part of the direct cost included in bucking decision making, they would be part of the direct cost used in deciding whether or not the tree was profitable to cut.

It was mentioned that bucking can occur almost anywhere between the felling site and mill. Exactly where bucking occurs determines whether other logging costs items are fixed are variable. For instance, if bucking occurs at the stump site and the logs are subsequently skidded to a landing, skidding is a variable cost. However, if the tree is skidded to the landing before bucking, skidding is a sunk cost and is irrelevant to bucking decisions.

Cost items that may be relevant to the bucking decision depending on the location of bucking in the production process are limbing, bucking, skidding, loading, hauling and unloading, chipping, and milling. In addition to these cost items, stumpage may be a variable cost depending on the method of stumpage payment. If stumpage is bought on a log scale basis it should be treated as a variable cost since it will be paid only for each log removed. On the other hand if stumpage is paid lump sum, then it is jointly shared by all trees and hence all logs regardless of whether they are taken. In this case stumpage is an irrelevant sunk cost.

Formulation of a Generalized Dynamic Programming Stem Bucking Model

Referring to Figure 5 define

D = dbh of the tree

H = total height of the tree

MH = merchantable height of the tree

S = stump height

l_{ui} = target length of i-th log in u-th use desired by management

t_{ui} = trim allowance for i-th log in u-th use specified by management

$dmin_{ui} \leq ds_{ui} \leq dmax_{ui}$ constraint on the minimum and maximum small end diameter of i-th log in u-th use specified by management

P_{gui} = unit price for a log of grade g for i-th log in u-th use

$l_{min} = \min_{\{u,i\}} [l_{ui} + t_{ui}]$ = shortest log

$l_{max} = \max_{\{u,i\}} [l_{ui} + t_{ui}]$ = longest log

k = an interval of length on the stem that is the common denominator of the log lengths, $l_{ui} + t_{ui}$; used as stage interval in dynamic programming

n = 0,1,2,..., INTEGER [(MH-S)/k] stage number between the stump and merchantable height limit. The height in the tree to a trial bucking point (locus of the small end diameter of a trial log) is n*k+S

d_l = large end diameter of a trial log

d_s = small end diameter of a trial log

g = grade of a trial log

j = state; the number of stage intervals to be combined into one log where j is such that j*k, a trial log length, is in the range $l_{min} \leq j*k \leq \text{MIN}(n*k, l_{max})$

and

$$j*k \in (l_{ui} + t_{ui})$$

These constraints insure that the feasible logs considered are those in the set specified by management and that logs considered at any stage must have a length that fits between the stump and the locus of the current stage above the stump

r_{guz} = recovery of the z-th end product item from the net log scale of a trial log of grade g if placed into use u.

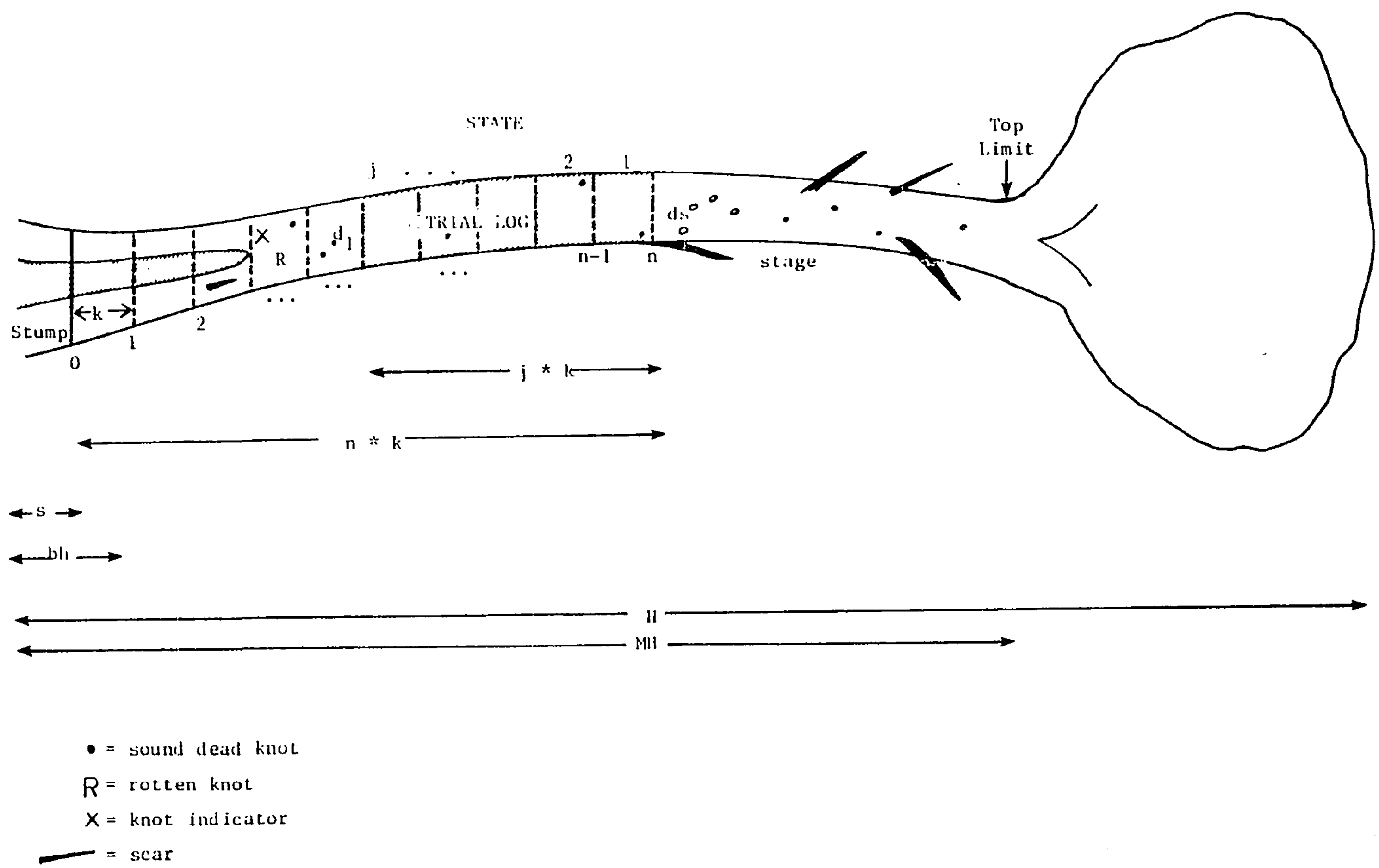


Figure 5. Notation for the generalized dynamic programming bucking model.

P_{uz} = price of the z-th end product item for use u.

NV_{gu} $(j*k, d_1, d_s)$ = net log scale of a trial log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

b = binary variable equal to zero to indicate that a cost item is to be excluded from conversion surplus calculations and equal to one when a cost item is to be included in conversion surplus

C_{1gu} $(j*k, d_1, d_s)$ = stumpage cost of a log grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{2gu} $(j*k, d_1, d_s)$ = bucking cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{3gu} $(j*k, d_1, d_s)$ = limbing cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{4gu} $(j*k, d_1, d_s)$ = skidding cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{5gu} $(j*k, d_1, d_s)$ = loading cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{6gu} $(j*k, d_1, d_s)$ = hauling and unloading cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{7gu} $(j*k, d_1, d_s)$ = chipping cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

C_{8gu} $(j*k, d_1, d_s)$ = manufacturing cost of a log of grade g for use u and of length j*k, large diameter d_1, and small diameter d_s

Then the dynamic programming model is

$$f_n(H, dbh, S) = \max_j (CS_{gu}[j*k, d_1, d_s] + f_{n-j}[n*k-j*k, dbh, S])$$

where

$f_{n-j}(n*k-j*k, dbh, S)$ = value of optimal solution for bucking the portion of the tree between the stump and the large end of the trial log

$CS_{gu}[j*k, d_1, d_s]$ = the conversion surplus associated with producing a log of grade g, length j*k, large diameter d_l and small diameter d_s for use u

$f_n(H, dbh, S)$ = value of optimal solution for bucking a tree with stump cut at height S through the n-th stage

(i) when logs are sold on a log market

$$CS_{gu}[j*k, d_l, d_s] = NV_{gu}(j*k, d_l, d_s) * P_{gu}(j*k, d_l, d_s) - \sum_{q=1}^{8} b_q C_{qgu}(j*k, d_l, d_s)$$

$$= \{\text{net log scale}\}\{\text{log price}\} - \begin{Bmatrix}\text{appropriate stem}\\ \text{conversion costs}\end{Bmatrix}$$

(ii) when logs are produced and processed by an integrated firm

$$CS_{gu}\ [j*k, d_l, d_s] = \sum_{z=1}^{m} r_{guz} * NV_{gu}(j*k, d_l, d_s) * p_{uz} - \sum_{q=1}^{8} b_q * C_{qgu}(j*k, d_l, d_s)$$

$$= \begin{Bmatrix}\text{total revenue from}\\ \text{end product items}\\ \text{manufactured from logs}\end{Bmatrix} - \begin{Bmatrix}\text{appropriate stem}\\ \text{and log}\\ \text{conversion costs}\end{Bmatrix}$$

In this formulation it is assumed that bucking will proceed from the base toward the top of the tree. Although the problem can be reformulated to proceed from the top toward the base, this viewpoint can be easily accomplished in the present formulation by simply viewing the tree as standing upside down. In solving the problem this way, the role of stump and merchantable height definitions are reversed and the accounting would be slightly modified.

In addition to the accounting constraints that a trial log, composed of a number of contiguous stage intervals, meet manufacturers' length restrictions and fit in the region between the stump and height to the current stage, other manufacturers' constraints may further limit log feasibility. For example, manufacturers may specify the range of log small end diameters and soundness acceptable for processing facilities and may even include practical restrictions on the amount of deviation from straightness. These and other constraints can be easily added to the basic formulation.

This formulation has been programmed in FORTAN IV for the University of Washington CDC 6400/CYBER 73 computer system using the University of Minnesota (MNF) 5.1 compiler. Although the formulation is general and applicable to any species, the programming of it for the solution of a particular problem is species dependent since many model details such as log scaling and grading practices and end product use and recovery data are species dependent. In the discussion of modeling details that follows, the discussion will focus on the solution of bucking problems for Douglas-fir [*Pseudostuga menziesii* (Mirb.) Franco]. This species was chosen for model development because of its significance in the forest industry and because of the availability of a wealth of reasonably compatible data from other studies describing nearly all of the factors needed to make bucking decisions. This allowed this study to focus on model development rather than the development of new data.

Before proceeding to the details of the Douglas-fir model an overview of the solution procedure and the relationship of the computer program components to the procedure will be given. Figure 6 presents a block diagram portraying the structural organization of the computer program routines. Figure 7 outlines the procedures for solving the dynamic programming formulation and indicates which computer program component performs the various steps. Appendix B contains a listing of the program and associated variable definitions.

Data Input

One function of the main program (BUCK) is to read in all of the data that will be used in reaching a solution. The input data that must be specified are basically of two types; information that describes the problem setting and information for each tree. These inputs, their FORTAN coding, and order expected are summarized in Table 3.

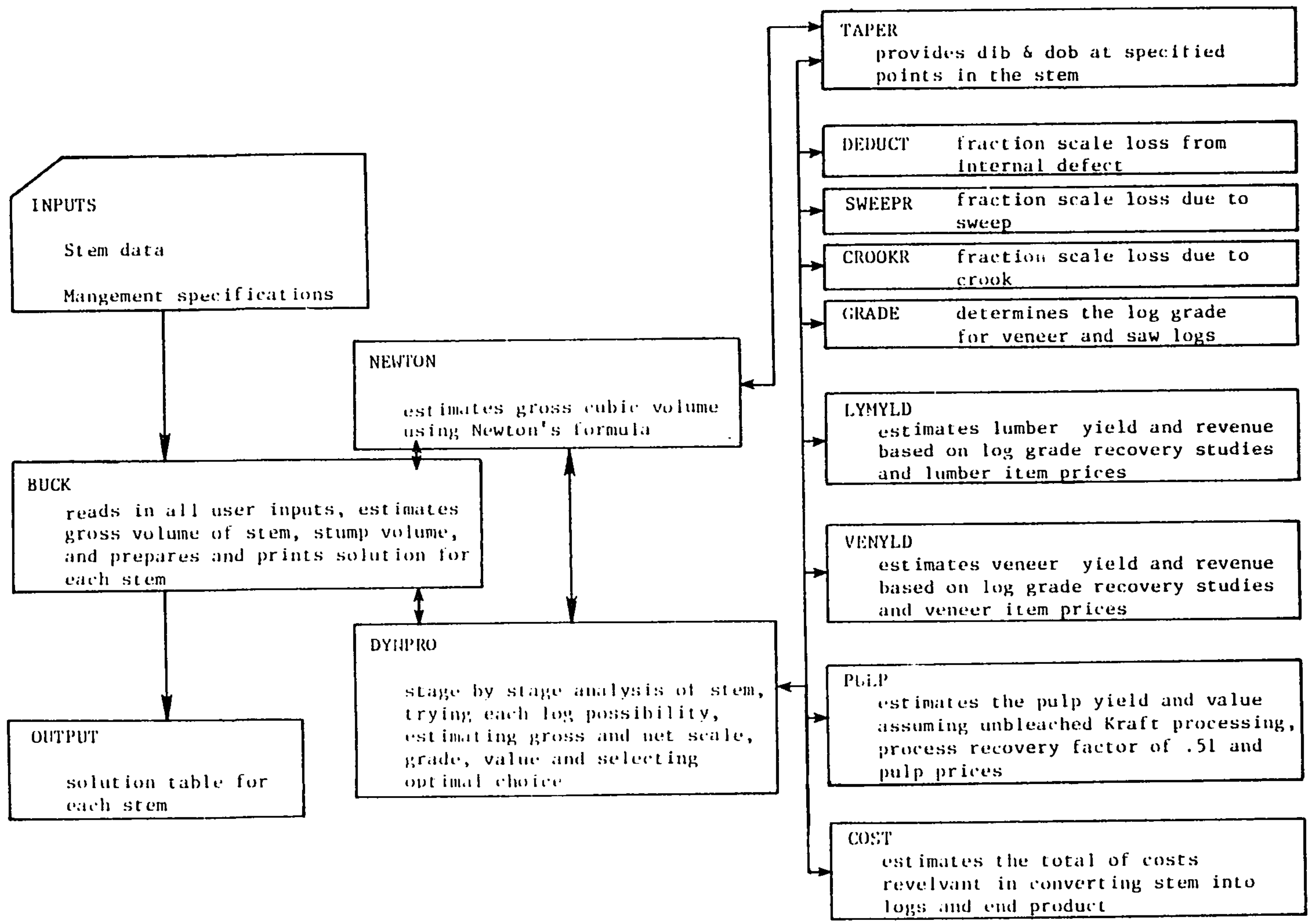


Figure 6. Flow diagram of the computer program components for solving the bucking problem.

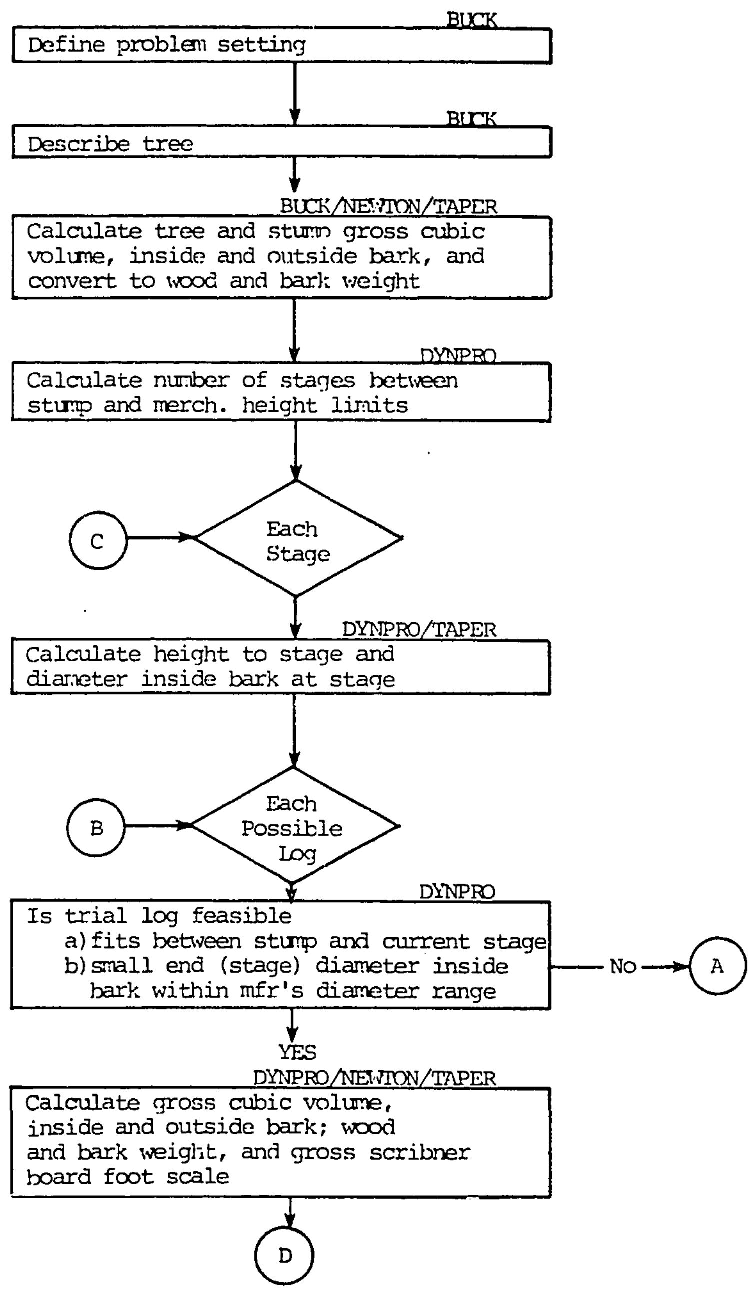


Figure 7. Procedure for dynamic programming solution of the bucking problem.

Figure 7. Continued

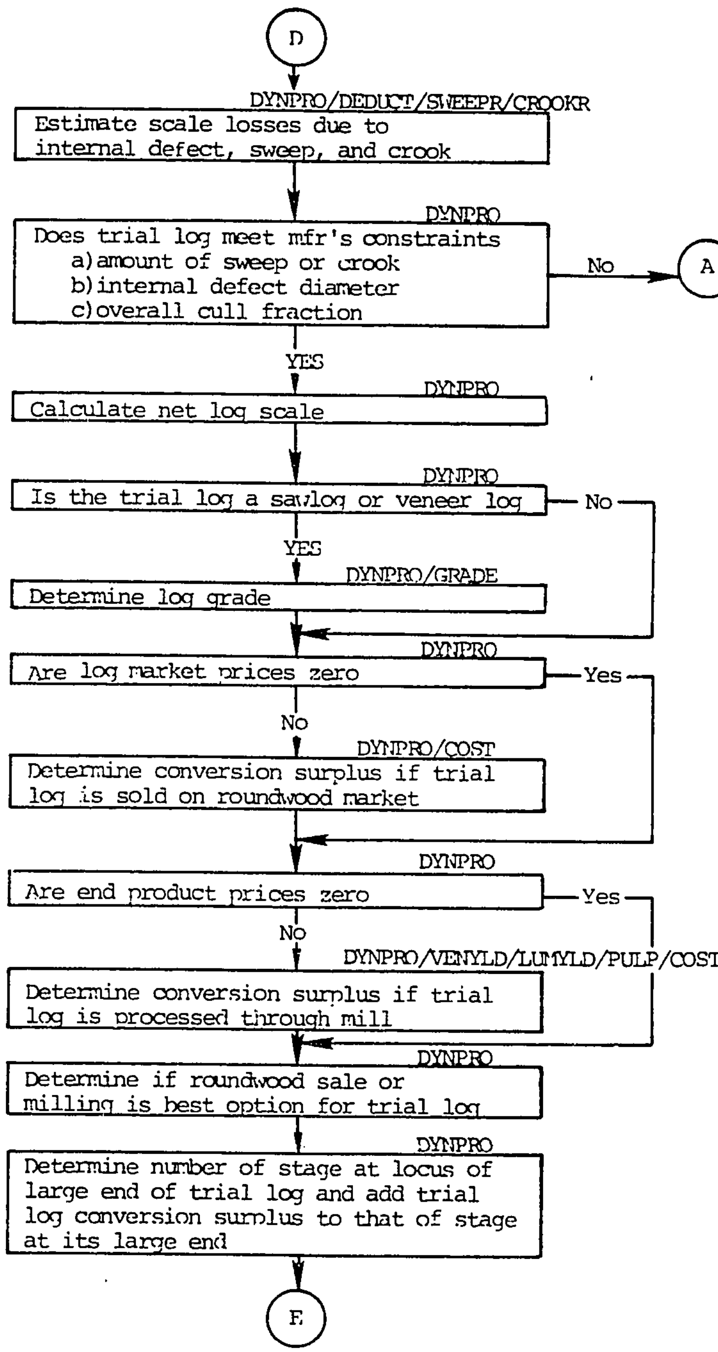


Figure 7. Continued

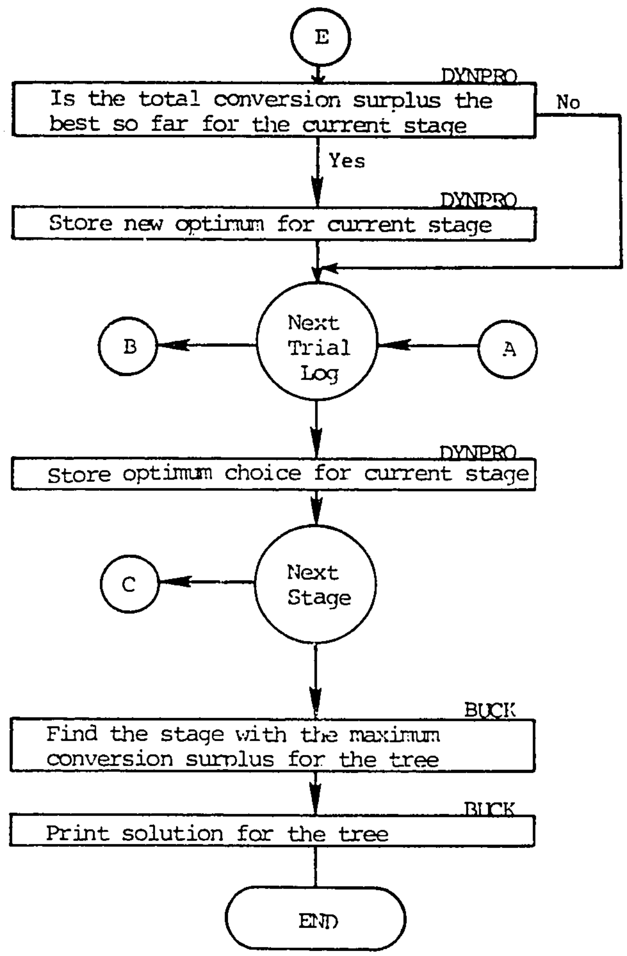


Table 3

Data Input

A. DESCRIPTION OF PROBLEM SETTING

ITEM	FORTRAN VARIABLE	FORMAT	COMMENTS
1. Number of trees to be analyzed	NTREES	I5	All items on one card.
Number of log possibilities ($\leq$ 20)	NOLOGS	I5	
Dynamic programming stage interval	STGL	F5.0	
Weight density of wood, O.D. lb/cu.ft.	WDENS	F5.0	
Weight density of bark, O.D. lb/cu.ft.	BDENS	F5.0	
Output code (0 = final solution only, 1 = stage optima and final solution, 2 = detailed calculations for each state and final solution, 3 = all of the above)	IOUT	I5	
2.(i) Specifications for each log possibility			
log product code (1 = veneer, 2 = saw, 3 = pulp, 4 = fuel)	DATAL(-,1)	F5.0	One card for each log possibility (NOLOGS). Enter zero roundwood price if the model is to evaluate a log possibility for milling only. If a price is given it must be consistent with the log scaling basis indicated in DATAL (-,2). A maximum of 20 log possibilities can be given of which up to 5 can be sawlogs.
log scaling basis (1 = cunit, 2 = MBF, 3 = lineal foot, 4 = OD ton)	DATAL(-,2)	F5.0	
log target length	DATAL(-,3)	F5.0	
log double end trim, zero if none	DATAL(-,4)	F5.0	
minimum acceptable small end dib	DATAL(-,5)	F5.0	
maximum acceptable small end dib	DATAL(-,6)	F5.0	
roundwood price for grade 1 veneer or sawlog, or for pulp log or fuel log	DATAL(-,7)	F10.0	
roundwood price for grade 2 veneer or sawlog	DATAL(-,8)	F10.0	

Table 3 (Cont.)

ITEM	FORTRAN VARIABLE	FORMAT	COMMENTS
roundwood price for grade 3 veneer or sawlog	DATAL(-,9)	F10.0	
roundwood price for grade 4 veneer or sawlog	DATAL(-,10)	F10.0	
(ii) prices of lumber items and associated residues	PRLUM(5,16)	16F5.0	One card for each sawlog possibility placed immediately after the sawlog DATAL(,) card. See Table 4 for a listing of the items and units.
3. Prices of veneer items and associated residues	VP(2,12)	12F5.0	One card. See Table 5 for a listing of the items and units.
4. Price of unbleached kraft pulp, $/ODT of pulp	PULPPR	F5.0	One card.
Price of fuel chips from roundwood $/ODT	FUELPR	F5.0	
5. Maximum internal defect diameter that can be chucked on veneer lathe, inches	CLIM	F5.0	All items on one card.
maximum allowed sweep of crook deviation in a veneer log	SLIM	F5.0	
maximum allowed cull fraction in a sawlog	DLIMS	F5.0	
maximum allowed cull fraction in a pulp log	DLIMP	F5.0	

Table 3 (Cont.)

ITEM	FORTRAN VARIABLE	FORMAT	COMMENTS
6. Binary list indicating which cost items are (1) or are not (0) variable costs in the bucking decision	VCOST(1,10)	10F5.0	One card. See Table 6 for a listing of items.
7. Dollar rate for each cost item	VCOST(2,10)	10F5.0	One card. See Table 6 for a listing of items and units.
B. DESCRIPTION OF INDIVIDUAL TREE			
8. Tree identification number	TREENO	F10.0	Last two items go on a second card.
dbh, outside bark, inches	DBH	F10.0	
Total height, feet	HEIGHT	F10.0	
Merchantable height, feet	HTMRCH	F10.0	
Stump height, feet	HSTMP	F10.0	
Height to the last measured external defect, feet	HTDEF	F10.0	
Number of external defects relevant to the log grading rules	NEXTNL	I5	
Number of internal defects enclosable in a cylinder or ellipsoid (< = 5)	NINTNL	I5	
Number of internal defects enclosable in a wedge section (< = 5)	NWEDGE	I5	
Number of crooks (< = 5)	NCROOK	I5	
Code indicating presence (1) or absence (0) of sweep	ISWP	I5	
Average number of rings per inch	RINGS	F5.0	

Table 3 (Cont.)

ITEM	FORTRAN VARIABLE	FORMAT	COMMENTS
9. Description of external defects relevant to the log grading rules	DEFECT(-,-)	10F10.2	Assumed stored in a file. See Table 7 for a listing of descriptors. Read only if NEXTNL > 0.
10. Internal defects enclosable in a cylinder or ellipsoid			
(i) number of measurement points for each (< = 10)	NPTSE	I5	Skip if NINTNL = 0.
(ii) description of each defect in the tree			One card for each point. Skip if NINTNL = 0.
height of measurement point, feet	DELLPS(-,1,-)	F10.0	
major diameter, inches	DELLPS(-,2,-)	F10.0	
minor diameter, inches	DELLPS(-,3,-)	F10.0	
11. Internal defects enclosable in a wedge section			
(i) number of measurement points for each (< = 10)	NPTSW	I5	Skip if NWEDGE = 0.
(ii) description of each defect point in the tree			One card for each point. Skip if NWEDGE = 0.
height of measurement point, feet	DWEDGE(-,1,-)	F10.0	
degrees of circumference from baseline to nearest part of defect	DWEDGE(-,2,-)	F10.0	
degrees of circumference from baseline to furthest part of defect	DWEDGE(-,3,-)	F10.0	
12. Description of each crook			One card for each crook. Skip if NCROOK = 0.
height to maximum crook deviation, feet	CROOK(-,1)	F10.0	

Table 3 (Cont.)

ITEM	FORTRAN VARIABLE	FORMAT	COMMENTS
maximum crook deviation, inches	CROOK(-,2)	F10.0	
total length affected by crook, feet	CROOK(-,3)	F10.0	
13. Description of sweep			
(i) number of sweep measurement points (< = 30)	NPTSS	I5	Skip if ISWP = 0.
(ii) height of measurement point, feet	SWEEP(-,1)	F10.0	One card for each point. Skip if ISWP = 0.
deviation of tree axis from chord from tip through center of base, inches	SWEEP(-,2)	F10.0	

Information Describing the Problem Setting

The information describing the problem setting consists of describing the environment in which bucking will take place for every tree. These are largely definitions and conditions provided by management. First, the number of trees to be analyzed, number of log possibilities, dynamic programming stage interval, oven dry weight density of wood and bark and output code are read. As explained earlier, the dynamic programming stage interval (STGL) is the common denominator of all the possible log lengths (target length plus trim). Another way to think of the stage interval is that all log lengths must be an integer multiple of it. Next, specifications for each log possibility are read into array DATAL. There is one card for each log possibility and the specifications include the log product code, basis for log scaling, target length, double end trim allowance if any, minimum and maximum acceptable small end diameter, and log price per unit of scale according to the scaling basis indicated by the second item on the card. The model can presently accept as many as 20 log possibilities. For sawlogs and veneer logs the log prices are for each of the four Pacific Northwest Forest and Range Experiment Station log grades (Lane et a., 1973). For other log products, for which log grades are not assigned, only the first log price entry is necessary. When a sawlog (product code 2) is read, the next card should present the appropriate prices of the 13 lumber items and 3 residue items listed in Table 4. The quantity of each of these items is estimated from a lumber recovery study of Douglas-fir (Plank and Henley, 1976). Lumber and residue prices must be given on the basis of the units in Table 4. This procedure allows the introduction of price premiums for various log grades and log lengths and for corresponding lumber lengths. After all of the sawlog and associated lumber and residue items are read, BUCK reads the prices in dollars per thousand square feet (1/8 basis) for the 5 veneer and 7 associated residue items listed in Table 5. The quantity of each of these items is estimated from equations from veneer recovery studies of Douglas-fir (Woodfin, 1973, 1974). Finally, the prices per ton of unbleached kraft pulp and fuel chips are read.

In specifying the roundwood log and end product prices, it is possible to set either the roundwood or end product prices equal to zero. The model is designed to test for these possibilities and if the roundwood price is zero, it assumes the corresponding log possibility is to be evaluated only for mill processing. If instead, end product prices are zero, the model assumes that the corresponding log possibility is to be evaluated only for roundwood sale. When both prices are nonzero, the model will compare the roundwood and milling options for the log and select the best one. Thus it is possible to use the model

Table 4

Lumber and Lumber Residue Items
Considered in the Model

Item		Valuation Basis
1.	B & Btr Select	$/MBF lumber tally
2.	C Select	$/MBF lumber tally
3.	D Select	$/MBF lumber tally
4.	Moulding	$/MBF lumber tally
5.	Factory Select	$/MBF lumber tally
6.	No. 1 Shop	$/MBF lumber tally
7.	No. 2 Shop	$/MBF lumber tally
8.	No. 3 Shop	$/MBF lumber tally
9.	Select Structural	$/MBF lumber tally
10.	Construction	$/MBF lumber tally
11.	Std	$/MBF lumber tally
12.	Util	$/MBF lumber tally
13.	Econ	$/MBF lumber tally
14.	Sawdust	$/ODT
15.	Other Woody Residues	$/ODT
16.	Bark	$/ODT

Table 5

Veneer and Veneer Residue Items

Item		Valuation Basis
1.	A	$/MSF 1/8"
2.	A patch	$/MSF 1/8"
3.	B	$/MSF 1/8"
4.	B patch	$/MSF 1/8"
5.	C	$/MSF 1/8"
6.	D	$/MSF 1/8"
7.	Core	$/cunit
8.	Below grade veneer	$/ODT
9.	Spur trim	$/ODT
10.	Round up	$/ODT
11.	Green clipping	$/ODT
12.	Bark	$/ODT

to evaluate the logs only for roundwood sale, only for milling, or compare these alternatives. A log possibility should not be given for which both the roundwood and end product prices are zero.

The last two cards describing the problem setting indicate which of the cost items discussed in section "Criterion for Decision Making" are relevant variable costs and the appropriate cost rate to be applied. Table 6 lists these cost items and the measurement basis for each expected by the model. To indicate whether a particular cost item should be considered or not enter on the first card a zero to exclude the cost item and a one to include it.

Information for Each Tree

After BUCK has received definitions of the setting for bucking analysis, it is ready to begin analyzing individual trees. This requires a description of each tree including its size, shape, and quality. The data input specifications for these descriptors are also contained in Table 3. The first of these cards indicates the outside bark diameter at breast height (dbh), total and merchantable heights, stump height, height in the tree to the last described external defect, the number of external defects, number of internal defects enclosed in a cylinder or ellipsoid, number of internal defects enclosed in a wedge section, number of crooks, presence or absence of sweep, and number of rings per inch. The merchantable height should

Table 6

Cost Items

Item		Valuation Basis
1.	Stumpage	$/cunit net log scale
2.	Bucking	$/log
3.	Limbing	$/log
4.	Skidding	$/log
5.	Loading	$/log
6.	Hauling and unloading	$/cunit net log scale
7.	Chipping	$/cunit net log scale
8.	Milling, lumber	$/cunit net log scale
9.	Milling, veneer	$/cunit net log scale
10.	Milling, pulp	$/OD ton of pulp

be given the same value as total height if no factor in the tree, such as deliquescent branching habit, prevents potential utilization. In this case, analysis will eventually stop before the top is reached because of the presence of minimum log small end diameter restrictions. The height to the last described external defect allows for the possibility that stem external defect data may be lacking in the upper portion of the tree. This height, if less than the total height, indicates where this occurs. Any logs entering a portion of the tree above this point are assumed to be of the lowest log grade.

If the number of externally visible defects (NEXTNL) relevant to the log grading rules is not zero, BUCK reads into array DEFECT the descriptions of the external stem defects which are maintained on a disk file. Each defect is read into array DEFECT which has the data structure shown in Table 7. The model is presently dimensioned to accept up to 250 external defect descriptions for a single tree. The details of external defect data acquisition are described in a later section titled "Log Grading."

Next BUCK reads in array DELLPS a description of each internal defect enclosable by an ellipsoid or cylinder. If NINTNL is zero, these cards are not necessary. Up to five such internal defects are allowed and each is assummed to be described by a series of measurements along its extent. These measurements include the height in the

Table 7

Data Input for External Stem Defects

DEFECT (,1)	defect code
DEFECT (,2)	defect diameter or width, inches
DEFECT (,3)	defect height or depth from surface of tree, inches
DEFECT (,4)	defect angle of inclination
DEFECT (,5)	height to base of the defect, feet
DEFECT (,6)	degrees from zero baseline to right edge of defect base
DEFECT (,7)	degrees from zero baseline to left edge of defect base
DEFECT (,8)	height to the top of the defect, feet
DEFECT (,9)	degrees from zero baseline to right edge of defect top
DEFECT (,10)	degrees from zero baseline to left edge of defect top

tree to the measurement point, and major and minor diameters of the defect at that height (Figure 8). The measurements should include the start and end point of the defect. It is presently assumed that each of these defects have the same number (not larger than 10) of measurements (NPTSE). After these defects are read in, BUCK determines if there are any internal defects enclosable in a wedge section by checking if NWEDGE exceeds zero. If so, the procedure used for internal defects enclosable in a cylinder or ellipsoid is repeated except that the diameter measurements are replaced by measurements of the circumference in degrees from an arbitrary zero line to the edges of the defect point (Figure 8). These data are stored in array DWEDGE. It is assumed that each of these defects has the same number (not exceeding 10) of measurements (NPTSW).

Next, if there are crooks, (NCROOK > 0), BUCK reads in three parameters for each (maximum of 5 allowed in one tree), the height to the maximum deviation point of the crook, the maximum deviation of the actual axis of the tree from normal condition and the length affected by the crook (Figure 8). It is assumed that the maximum deviation occurs at the midpoint of the affected length although this assumption can be easily modified.

Finally, if the tree contains sweep (ISWP = 1) BUCK reads two parameters for up to 30 points of measurement (NPTSS) along the tree. It is assumed that sweep is

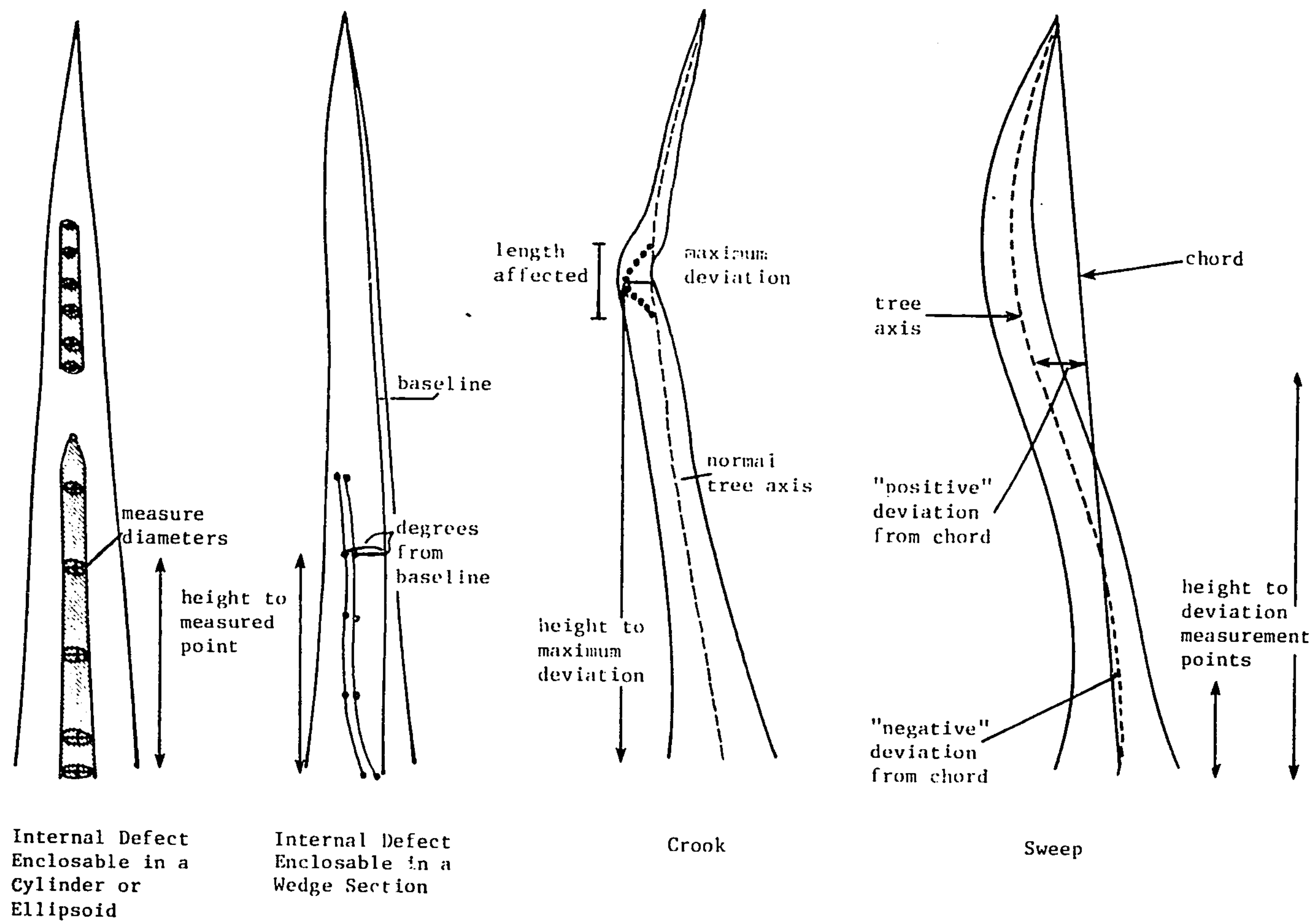


Figure 8. Method for describing internal defects, crook, and sweep.

measured by imagining a chord running from the tip through the center of the tree base and by measuring at various height points the deviation of the central axis of the stem from this chord. Deviations will be noted as "positive" on one side of the chord and "negative" on the other.

Modeling Details

Stem Taper and Bark Thickness

Quantification of the change in diameter with increasing height in a stem has been studied by foresters for at least a century and many approaches have evolved (Garay, 1979). Generally, most of the recent studies have attempted fitting an equation by regression to taper data. These equations usually involve the use of only dbh and total height as independent variables. Depending on the procedure used there has been mixed success in developing an equation that accurately portrays the diameter profile of the entire stem. Many of the equations developed have some bias in diameter prediction along the bole. This bias could seriously alter the mix of logs and location of bucking points especially when diameter restrictions for certain log products are specified.

A recently published taper equation developed for many western species is of the form (Kozak et al., 1969; Smith and Kozak, 1971):

$$d = D\sqrt{a + b\left(\frac{h}{H}\right) + c\left(\frac{h}{H}\right)^2}$$

where d = diameter inside bark, inches, at height h along the bole

D = diameter breast height, outside bark, inches

H = total height, feet

a, b, c = coefficients determined by regression subject to the condition that they sum to zero when h = H and d = 0.

Kozak et al. (1969) noted that this equation produced positive bias at 1 foot height, negative bias between 20 and 30 percent of the total height and positive bias above 30 percent of total height to near the tree top. It is worth noting that the degree of success achieved with this equation occurred only after all measurements below breast height were eliminated and dbh outside bark was substituted as the tree diameter at a height of one foot. In studying Douglas-fir in British Columbia, Kozak et al. (1969) estimated the coefficients for the taper curve as a = .85458, b = -1.29771, and c = .44313 for 97 coastal Douglas-fir trees. Later, Smith and Kozak (1971) presented revised coefficients a = .80747, b = - 1.39037, and c = .58290 for a sample of 640 mature Douglas-fir trees. This taper equation, based on this enlarged study, was selected for use in the model but with reservations due to the possibility that there may be biased diameters along the bole as noted by Kozak et al. Further research may be needed to produce a taper curve without this bias.

An alternative to the equation approach to depicting stem taper would be to utilize direct measurements from the stem. This could be easily accomplished in some settings, using dendrometer data measured in the field or using electronic scanners on centralized log merchandizers. Periodic diameter measurements along the stem would provide the basis for interpolating intervening diameters needed by the model.

The scanner approach has the advantage that if desired, eccentricity of the circumference could be considered. Recent scanners often collect several points around the stem circumference and are able to portray eccentric shape conditions. Provision for this kind of data acquisition will not be done in the present model. However, it would be a simple undertaking to revise the model to be based on this approach.

Since bucking trees into logs is primarily concerned with wood fiber, consideration of bark thickness in the calculations is important. Log diameter specifications are defined for the inside bark dimensions of the log but tree diameters are usually estimated outside bark hence bark must be accounted for. Furthermore, bark is becoming an increasingly important residue for fuel, mulch, and other uses so its content is worth estimating. One approach to estimating bark is to develop a separate bark thickness equation which predicts bark thickness along the bole. Wiant and Koch (1974) provide several alternative bark thickness equations. The calculated bark thickness is added to the inside bark diameter estimated from the taper equation. Another approach would be to develop two taper equations; one to estimate inside bark diameter and the other outside bark diameter. Given the inside and outside bark log diameters from either approach, log volume with and without bark may be calculated and bark volume estimated as the difference. Bark weight can be estimated from bark weight density. A search of the literature produced few bark thickness equations and none for Douglas-fir. Consequently, for the purposes of this study, double bark thickness was assumed to be a constant percentage of section diameter, in this case 10 percent.

The taper and bark thickness equations are contained in subroutine TAPER which is accessed by the other routines of the model and provides either diameter outside bark (ICODE = 1) or diameter inside bark (ICODE $\neq$ 1). The subroutine must be provided with the dbh (outside bark) of the tree, its total height, and the height point where the diameter estimate is desired. Figure 9 presents a simplified flow diagram of the logic of this subroutine.

<u>Stump Cutting Practice</u>

During felling, the decision locating the stump

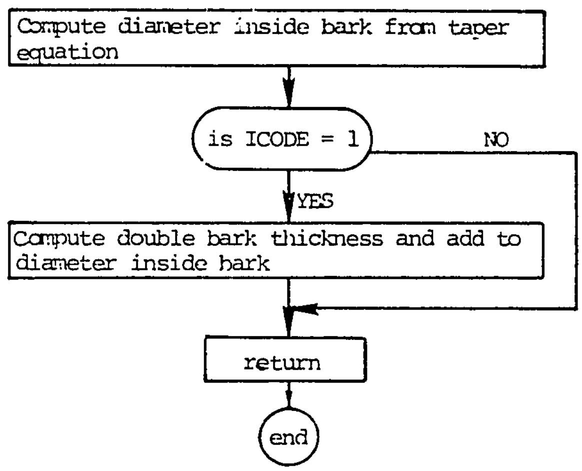


Figure 9. Flow diagram of subroutine TAPER.

height is actually the first manufacturing cut and will be taken as an externally given parameter. In the present version of the model, it is assumed that the actual stump height for each tree is known. However this could be easily replaced by a curve modeling stump cutting practice. Although the use of an externally given stump height can be criticized as constraining the model to finding the optimum bucking subject to this limitation, there may be overriding physical limitations in felling dictating placement of the stump cut. This does not mean that the model cannot find the optimum bucking for the tree including locating the optimal stump cut. This can be achieved by giving a stump height equal to zero and observing the location of the base of the butt log in the optimum solution. In fact, this is one part of the sensitivity analysis that can be achieved with the model since by varying stump height, the influence of this practice on the optimal solution can be observed.

Forks

Because of some accident or deliquescent species behavior, a tree may develop one or more forks, some of which may contain potentially useful logs. Trees exhibiting forks can be treated by considering the tree as a series of separate problems, one for the main bole and one for each potentially usable fork. To accomplish this, the original tree is described as usual but with the merchantable height limit no higher than the base of the first fork. Each potentially useful fork is considered to be a separate tree with the following definitions.

tree height = length from the base of the fork to its top

dbh = diameter of the fork 4.5 feet above its base

stump height = 0

merchantable height = length from the base of the fork to its top unless there is some reason, such as another fork, for limiting the length analyzed by the model.

Figure 10 presents the decomposition of a multiple forked tree into a series of problems.

<u>Breakage</u>

Occasionally during felling, the stem breaks into several segments. In this case, bucking is confined to each segment. The approach taken in this study is to treat each segment as a separate problem, by describing each as a separate "tree." The original tree dbh and total height are given for each subproblem but as shown in Figure 11 stump height and merchantable height are used to define the base and top of each segment. This is possible since the model only bucks the tree portion defined between stump and merchantable height. Thus these definitions can be altered from their conventional meaning to trick the model into

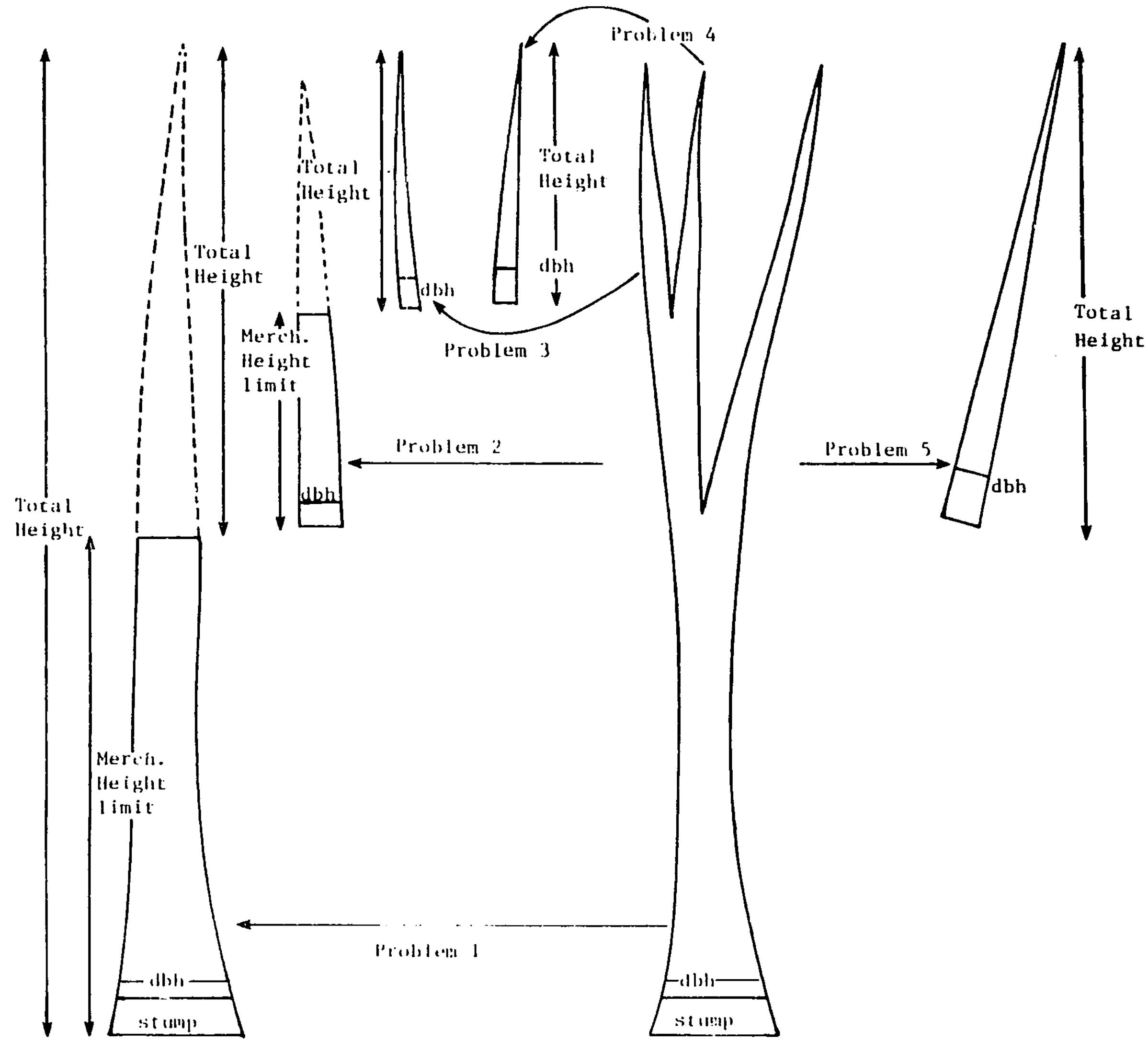


Figure 10. Decomposition of a forked tree into a series of separate problems.

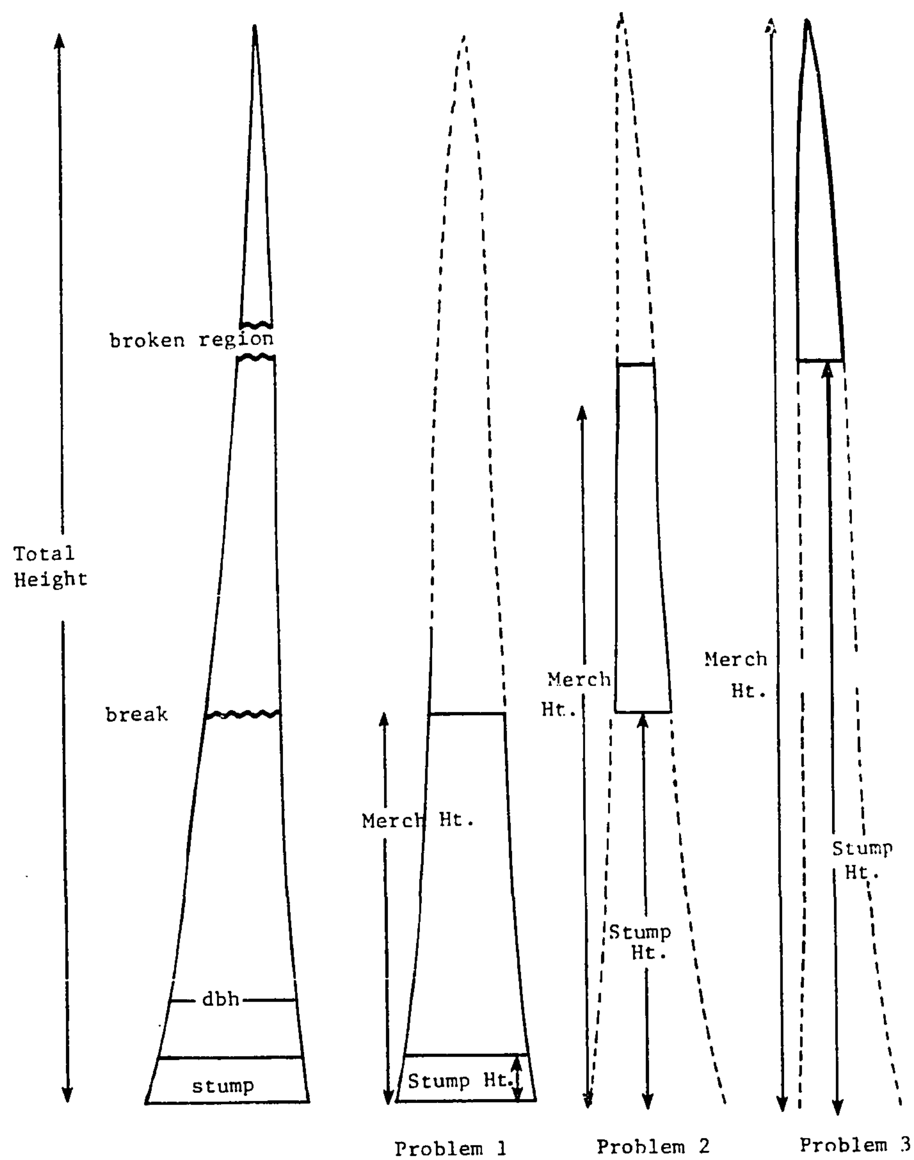


Figure 11. Decomposition of a broken stem into a series of separate problems.

analyzing any segment of the tree that is desired. This technique allows the model to use the proper taper and bark thickness parameters while analyzing only the portion of the tree between the "stump" height and "merchantable height" limits.

Log Scaling

Scaling is the process of measuring individual logs. Logs are generally scaled and sold in terms of board feet, cubic feet or meters, weight, or length. Frequently there are alternative scaling methods that can be used for estimating the scale of a log for an intended use. For example, sawlogs can be scaled and sold on a cubic foot, board foot or weight basis. Furthermore, weight can be estimated in the green or oven dry condition, board feet according to many log rules such as the Scribner, International, or Doyle rules, and cubic volume according to Huber's, Newton's or Smalian's formulas. Other products have a similar proliferation of scaling possibilities. In this study the following log scaling alternatives are available for each log: cubic foot volume, Scribner board foot volume, lineal foot, oven dry weight. These options were chosen because they reflect common practice in the Douglas-fir region. It would be relatively simple to change the scaling practices in the model. The selection of the appropriate scaling basis for each log possibility is made by management and is part of the data input [DATAL

(_,2)]. In analyzing a tree it is possible and appropriate for the model to encounter, consider, and compare sawlogs scaled in Scribner board feet, pulpwood scaled according to cubic volume, and fuel wood scaled in terms of oven dry weight.

In addition to distinguishing among scaling methods, the distinction between gross and net log scale must be made. Gross scale is the scale of the log if there are no defects that reduce the sound wood content or otherwise inhibit manufacture. Net scale is the gross log scale adjusted for these defects.

Estimating gross scale. The log scaling procedure in the model begins with the estimation of gross scale and the first step is the estimation of gross cubic volume on the basis of Newton's prismoidal formula (Husch et al., 1972). In the model, the stem portion for which volume is desired is assumed to be divided into an even number of equal length sections. The diameters inside or outside bark of each section are estimated by subroutine TAPER. These diameter estimates, combined with the section length, allow calculation of the gross cubic volume. In the model, this procedure appears in subroutine NEWTON. Details of Newton's formula and this subroutine are shown in Figure 12. This subroutine expects to receive a code indicating whether volume is desired inside or outside bark, the height in the tree to the base and to the top of the formula

volume = .5236* section length $\left[.5 \begin{pmatrix}\text{section 1} \\ \text{base diam.}\end{pmatrix} + 2 \begin{pmatrix}\text{section 1} \\ \text{top diam.}\end{pmatrix}^2 + \begin{pmatrix}\text{section 2} \\ \text{top diam}\end{pmatrix}^2 + \ldots +\right.$

section counter ⟶ 0 = even, 1 = odd, 2 = even, ...

$\left. 2 \begin{pmatrix}\text{section i} \\ \text{top diam.}\end{pmatrix}^2 + \begin{pmatrix}\text{section i + 1} \\ \text{top diam}\end{pmatrix}^2 + \ldots + .5 \begin{pmatrix}\text{section n} \\ \text{top diam.}\end{pmatrix}^2 \right]$

odd, even, ..., even

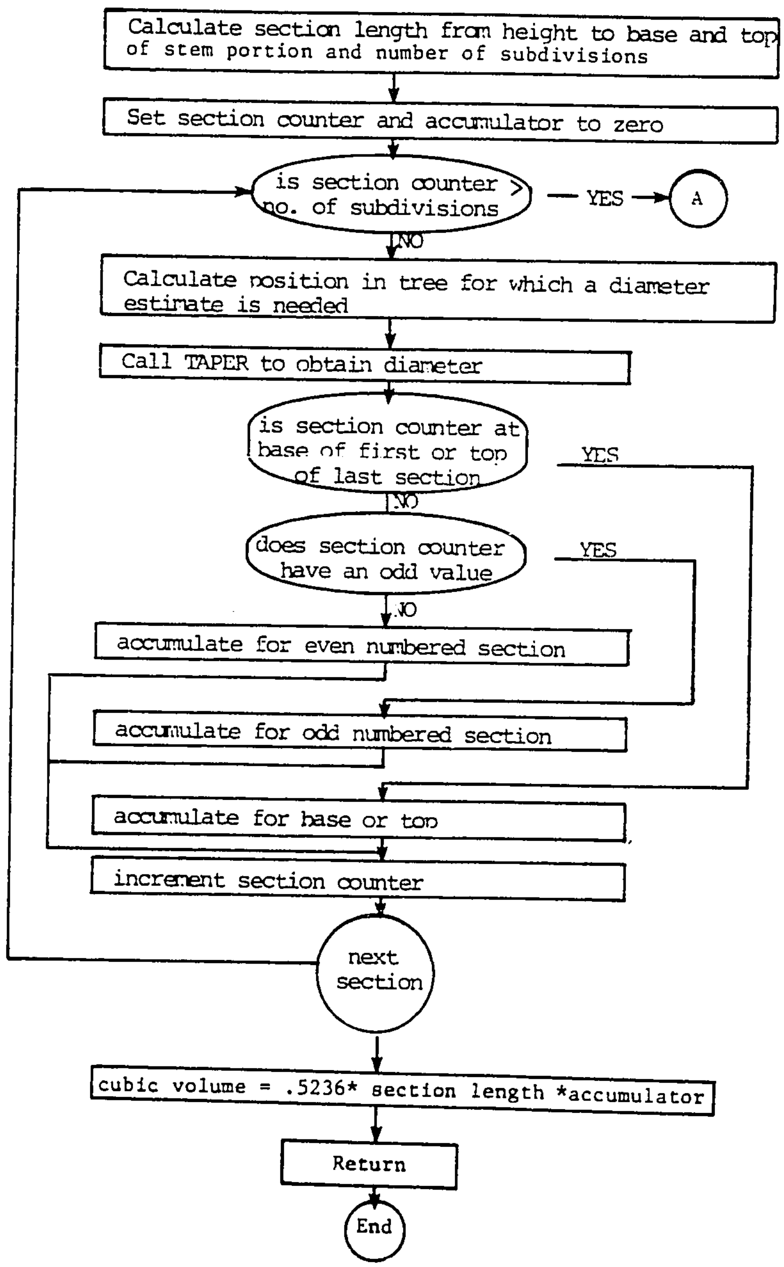


Figure 12. Newton's formula and flow diagram of subroutine NEWTON.

stem portion for which the volume estimate is desired, and the number of segments into which the portion of the stem will be subdivided in making the estimate. This subroutine can be used to estimate the gross cubic volume of any portion of the stem whether it is a log, the stump, or the entire tree.

Subroutine NEWTON is called upon by BUCK and by subroutine DYNPRO. When called upon by BUCK, it is used to estimate the gross cubic volume inside and outside bark of the entire stem and of the stump. When called upon by DYNPRO it is used to estimate the gross cubic volume inside and outside bark of a trial log. Except when an estimate is desired for the whole tree, a stem portion such as a log or stump is presently divided into four equal length sections. When an estimate is desired for the whole tree, it is presently divided into ten equal length sections.

Upon receiving these gross cubic volume estimates, BUCK or DYNPRO estimates bark volume by subtraction and converts these estimates to the gross weight scale of wood and bark in oven dry tons. DYNPRO also estimates the gross Scribner board foot volume of a log using Knouf's rule (Dilworth, 1977). This formula approximation to the Scribner rule is based on the small end diameter inside bark (with fraction dropped) and target length of the log.

Estimating NET SCALE. Once the gross scale is established, the log must be examined for scale reducing defects such as crook, sweep or internal defects such as rot. Although the taper and bark thickness curves provide an estimate of bole diameter anywhere along the stem, they convey no information concerning other shape-related aspects of the tree such as sweep or crook. In the model, sweep and crook are considered as scale reducing defects only for sawlogs and veneer logs. Crook and sweep reduce the scale of sawlogs and veneer logs since it is in the manufacture of product from such logs where these defects can significantly affect product yield. This generally would not be the case for pulp logs or fuel bolts.

In the present formulation of the model, sweep and each crook can only be described in a two-dimensional plane. This assumption may be inadequate in some cases and in the future it may be desirable to introduce changes to accommmodate a three-dimensional description. Although the approach taken toward measuring sweep and crook may seem impractical, such measurements would be readily obtainable by a scanner-computer system on the infeed of a log merchandizer deck. The technique for efficient collection of such data by scanner technology or in the field will not be considered in this study.

Internal defects such as rots and frost cracks that influence log scale reduction are considered by assuming that a description of the location and dimensions of each of these defects is present. The defect description varies depending on the scaling deduction method. Grosenbaugh (1952) provided two basic techniques for treating internal defect deductions; one for defects enclosable in a cylinder or ellipsoid and one for defects enclosable in a wedge section.

Subroutines DEDUCT, SWEEPR and CROOKR contain the technique for estimating the scale reduction for internal defects, sweep and crook. These subroutines accept the data describing the profile of the appropriate defect category, (refer to the section "Information for Each Tree" and Figure 8), examine each defect location with respect to the trial log under consideration by DYNPRO, interpolate the entry and exit points of the defect if necessary, and use the information on the location of these defects in the trial log to estimate the parameters of the defect leading to reduction estimates according to Grosenbaugh's (1952) formulas. Each subroutine returns to DYNPRO a fraction representing the total scale reduction due to defects found affecting the trial log. These fractions are accumulated for the different defect categories and the total is applied to the appropriate gross scale to determine the net scale basis for log valuation.

The loss fraction due to internal defect in an ellipsoid or a cylinder is estimated by scanning the data profile for each defect from its base toward its top until a point, if any, is found within the trial log. If this condition occurs, the model examines whether the defect extends only through the large end of the trial log, only through the small end, through both ends, or if it is entirely enclosed within the trial log. For each case, the length of the defect within the trial log is calculated, major and minor diameters interpolated if necessary where the defect exits the trial log, and the defect profile within the trial log is examined to determine the maximum major and minor diameters. The scale reduction fraction due to the defect is estimated from the following formula (Grosenbaugh, 1952).

$$\text{reduction fraction} = \frac{(\text{major diameter})(\text{minor diameter})}{(\text{small end diameter} - 1)^2} * \frac{\text{length of defect within log}}{\text{log length}}$$

The reduction fraction for each defect in the trial log enclosable in an ellipsoid or a cylinder is accumulated and the total is returned to DYNPRO. Figure 13 provides a flow diagram of subroutine DEDUCT which performs these steps.

The loss fraction due to internal defect enclosable in a wedge section follows nearly the same procedure as for defects enclosable in an ellipsoid or a cylinder. The principal difference is that instead of searching for the maximum major and minor defect diameters, the model searches for the maximum central angle within the trial log that is spanned by the defect. The scale reduction fraction due to

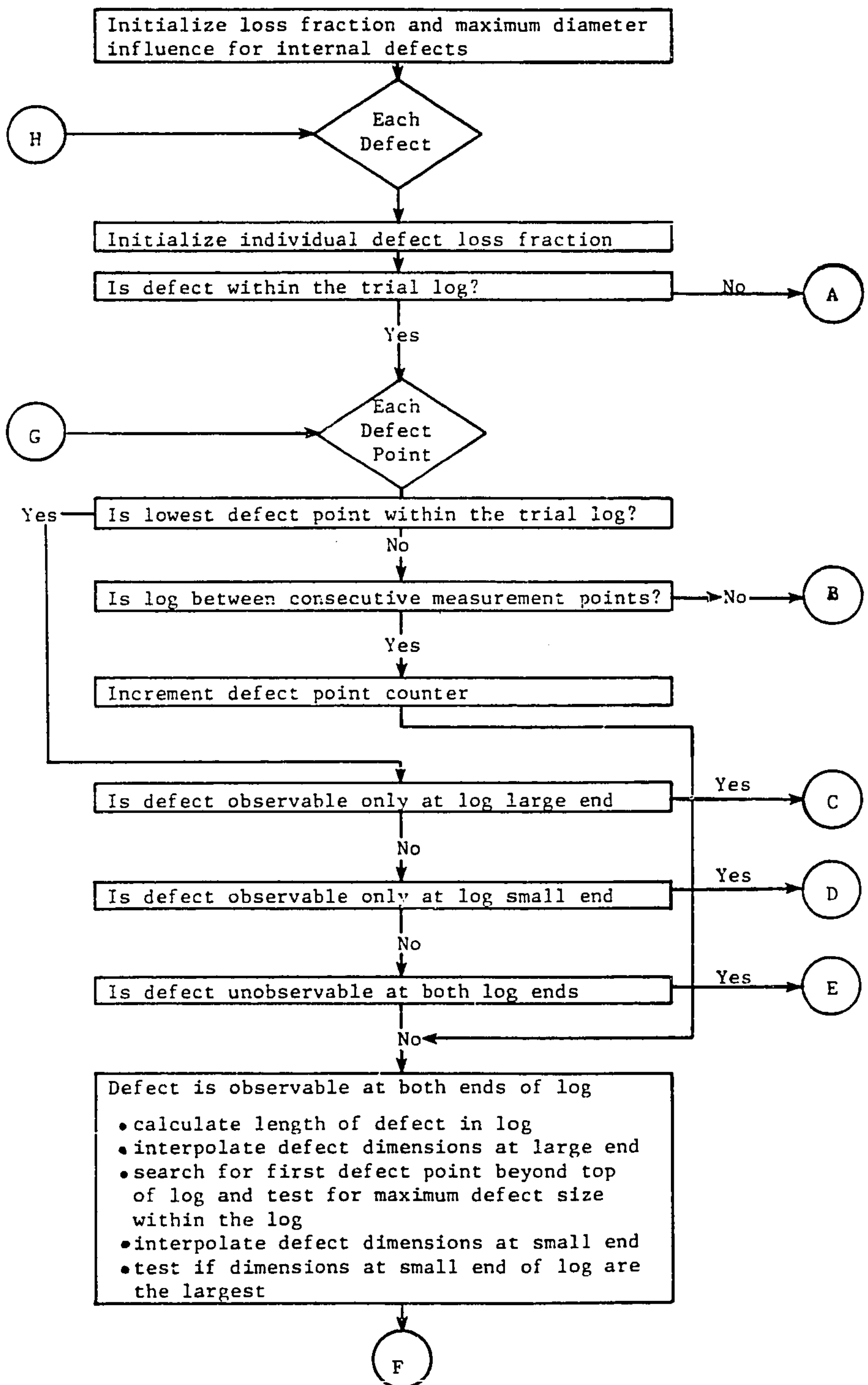
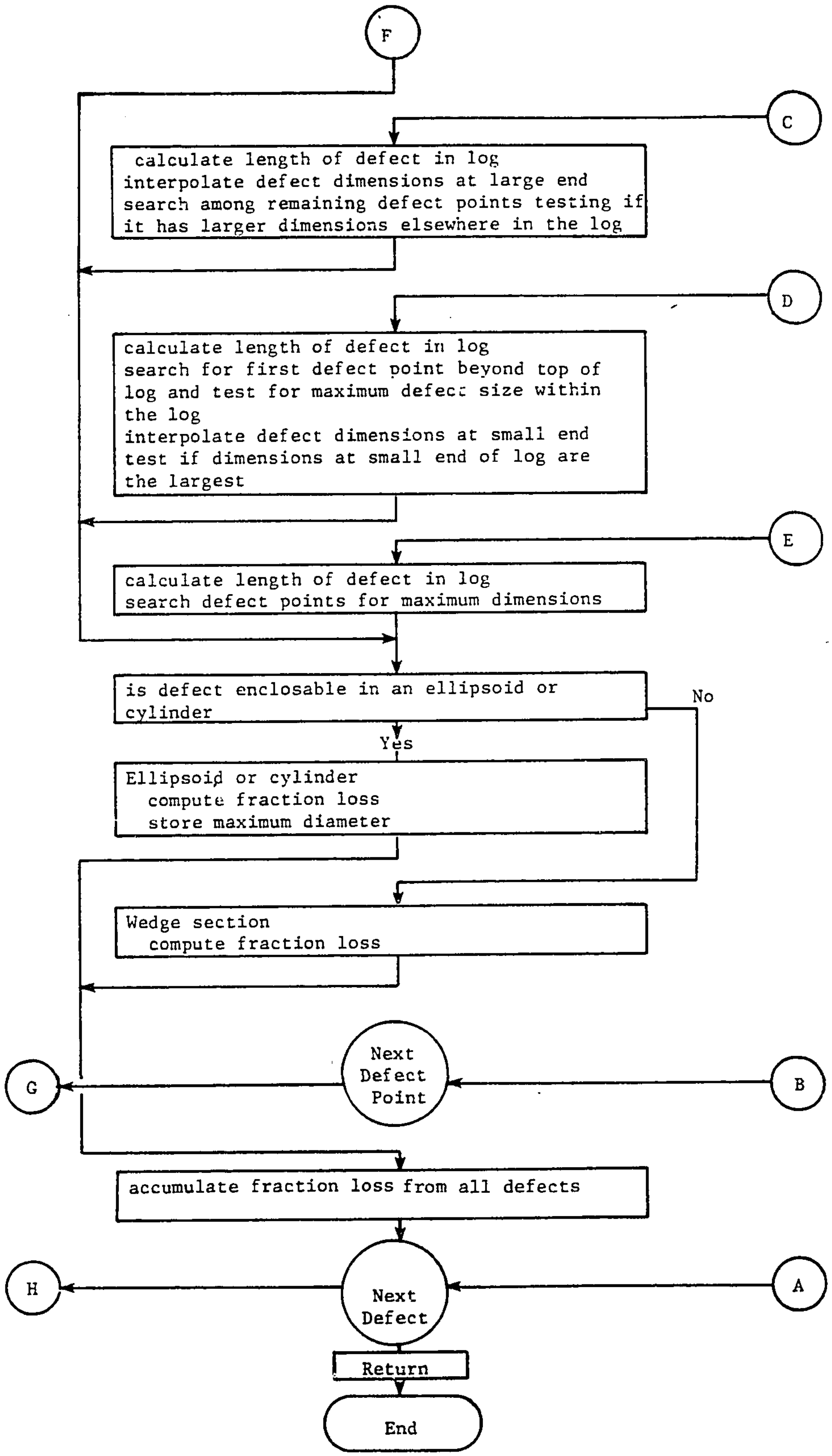


Figure 13. Flow diagram of subroutine DEDUCT.

Figure 13. Continued



the defect is estimated from the following formula (Grosenbaugh, 1952).

$$\text{reduction fraction} = \frac{\text{central angle of defect}}{360} * \frac{\text{length of defect within log}}{\text{log length}}$$

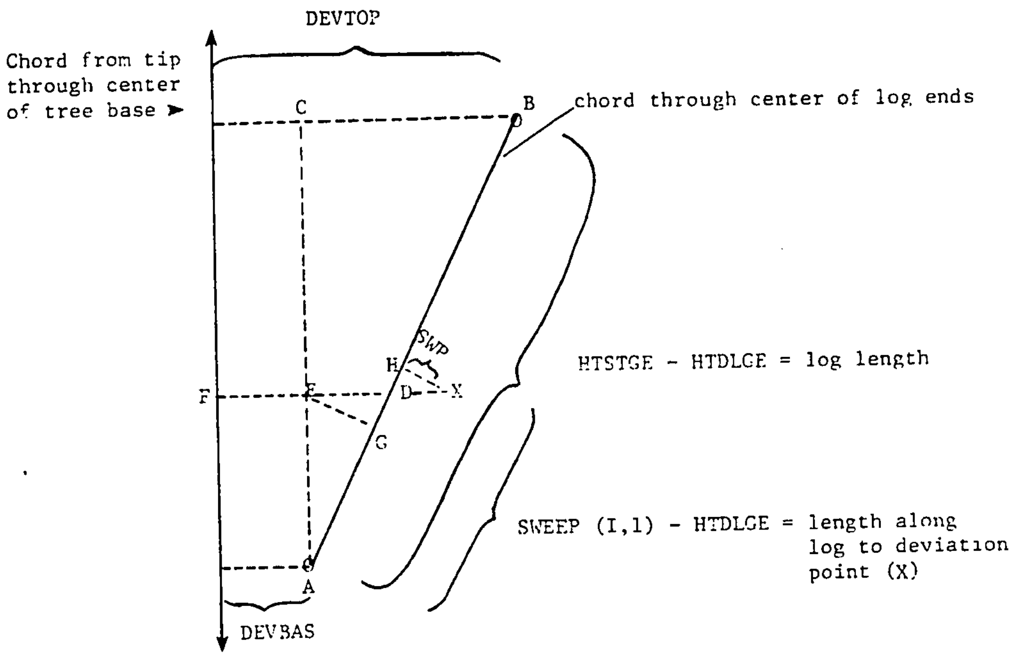
The reduction fraction for each defect in the trial log that is enclosable in a wedge section is accumulated and the total returned to DYNPRO. Subroutine DEDUCT also performs the steps that lead to the estimate of this reduction fraction.

Sweep in a log is modeled by first locating the log ends with respect to the measurements of sweep in the tree and interpolating the deviation of the top and the base of the log from the tree chord. If there is sufficient information to estimate sweep in the log, the deviations from the log central axis are calculated on the basis of similar triangles as shown in Figure 14. The maximum "positive" and "negative" sweep deviation in inches from the log axis are combined. The fraction loss due to sweep is estimated from the following formula (Grosenbaugh, 1952).

$$\text{reduction fraction} = \left(\frac{\text{maximum departure} - 2}{\text{small end diameter}}\right)$$

Figure 15 presents subroutine SWEEPR that deals with the reduction due to sweep.

Crooks are modeled by locating each crook with



DEVBAS = distance from center of log base to tree chord; from actual measurement or interpolation

DEVTOP = distance from center of log top to tree chord; from actual measurement or interpolation.

HTSTGE = stage height in tree, or height to small end of log

HTDLGE = height to large end of log

SWEEP (I,1) = height to deviation point X

SWEEP (I,2) = deviation of tree at point X from tree chord i.e. FX

SWP = sweep deviation in log, which by similar triangles can be derived as

$$AC * DX/ (HTSTGE - HTDLGE)$$

$$\text{where } AC = \sqrt{(HTSTGE - HTDLGE)^2 - \left(\frac{DEVTOP - DEVBAS}{12}\right)^2}$$

$$DX = DEVBAS + ED - SWEEP\ (I,2)$$

$$ED = (DEVTOP - DEVBAS)\left(\frac{SWEEP\ (I,1) - HTDLGE}{HTSTGE - HTDLGE}\right)$$

Figure 14. Procedure for estimating amount of log sweep from tree sweep measurements.

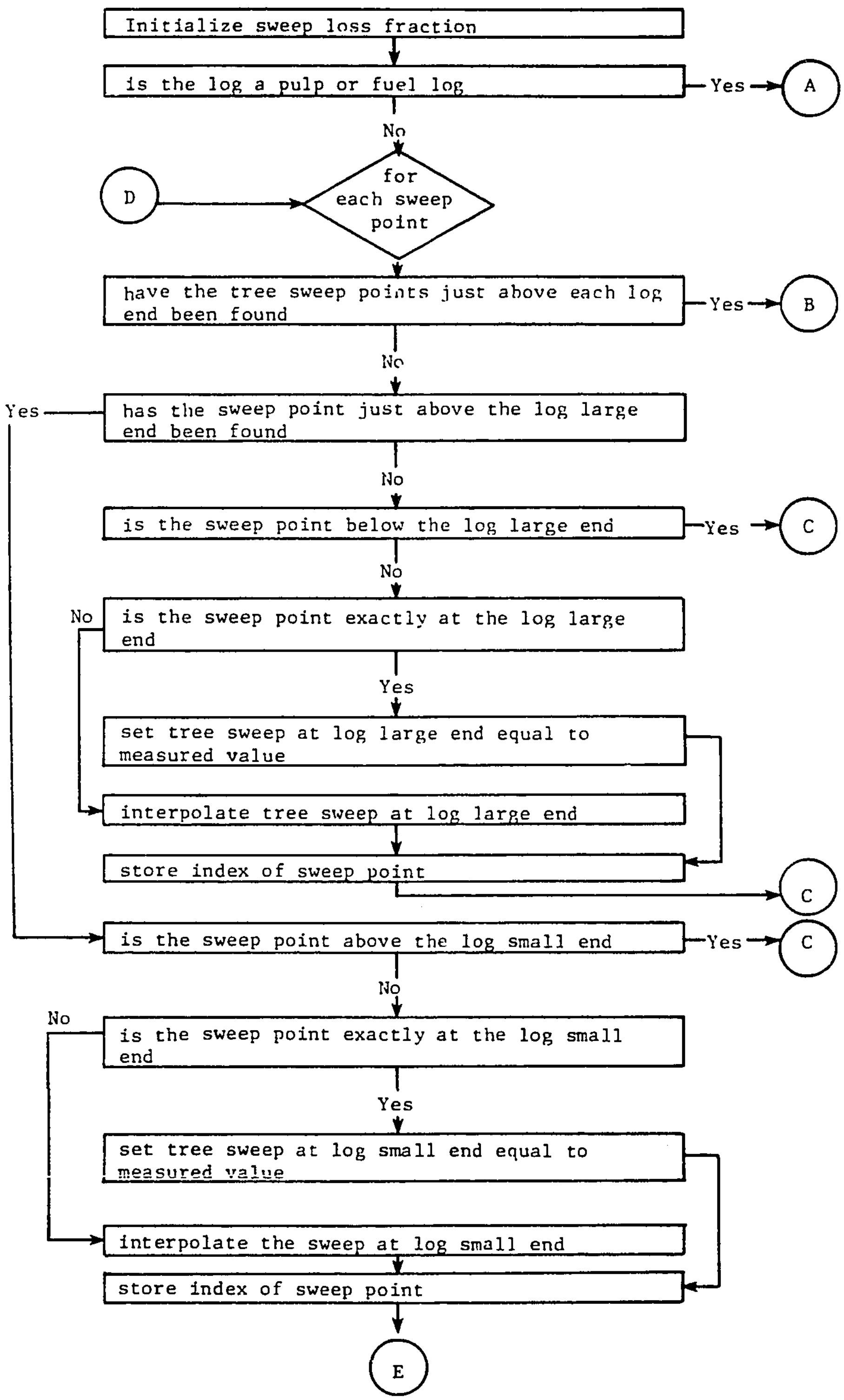
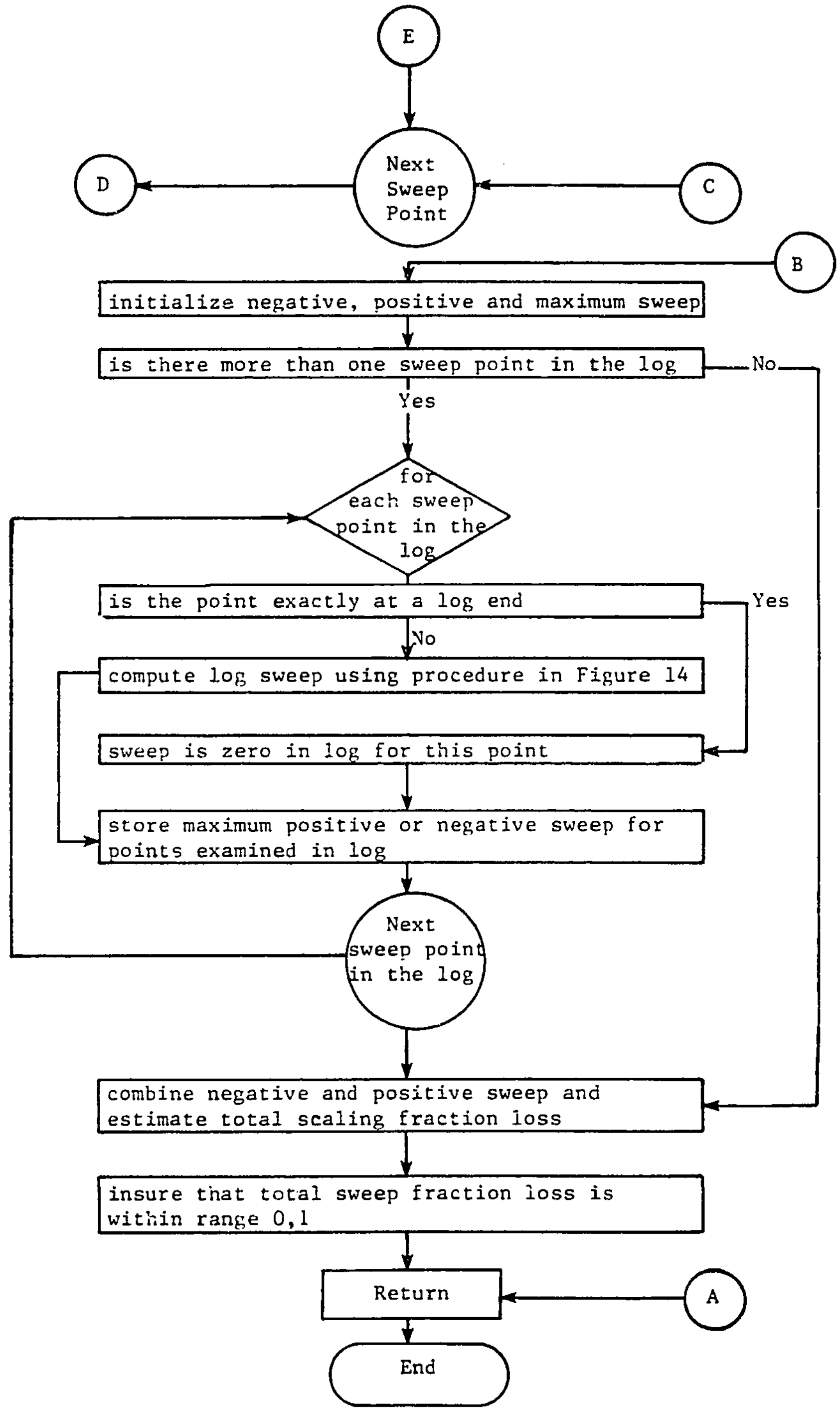


Figure 15. Flow diagram of subroutine SWEEPR.

Figure 15. Continued



respect to the locus of the trial log and ignoring those with no influence on it. If a crook influence extends into a trial log, a check is made to determine if the maximum deviation point occurs within the trial log. If not, a check is made to determine which log end is nearest to the crook and the deviation of that end is interpolated and taken to be the maximum deviation of that crook in the log. After the crook deviation influence is determined, the length of the trial log influenced by it is estimated. The deviation and length affected in the trial log is accumulated for each crook and the total fraction loss is estimated by the following formula (Grosenbaugh, 1952).

$$\text{reduction fraction} = \frac{\text{length of deviating section}}{\text{log length}} * \frac{\text{maximum deviation}}{\text{log small end diameter}}$$

Figure 16 presents the details of subroutine CROOKR which incorporates these steps in estimating the reduction fraction due to crook.

In considering these scaling defects it is assumed that the losses are additive. This could lead to a problem if overlapping internal defects are described. The model would estimate the total loss due to the full extent of each defect and add them together in arriving at a total reduction. This could overestimate the loss factor. To circumvent this difficulty, it is assumed that when two or

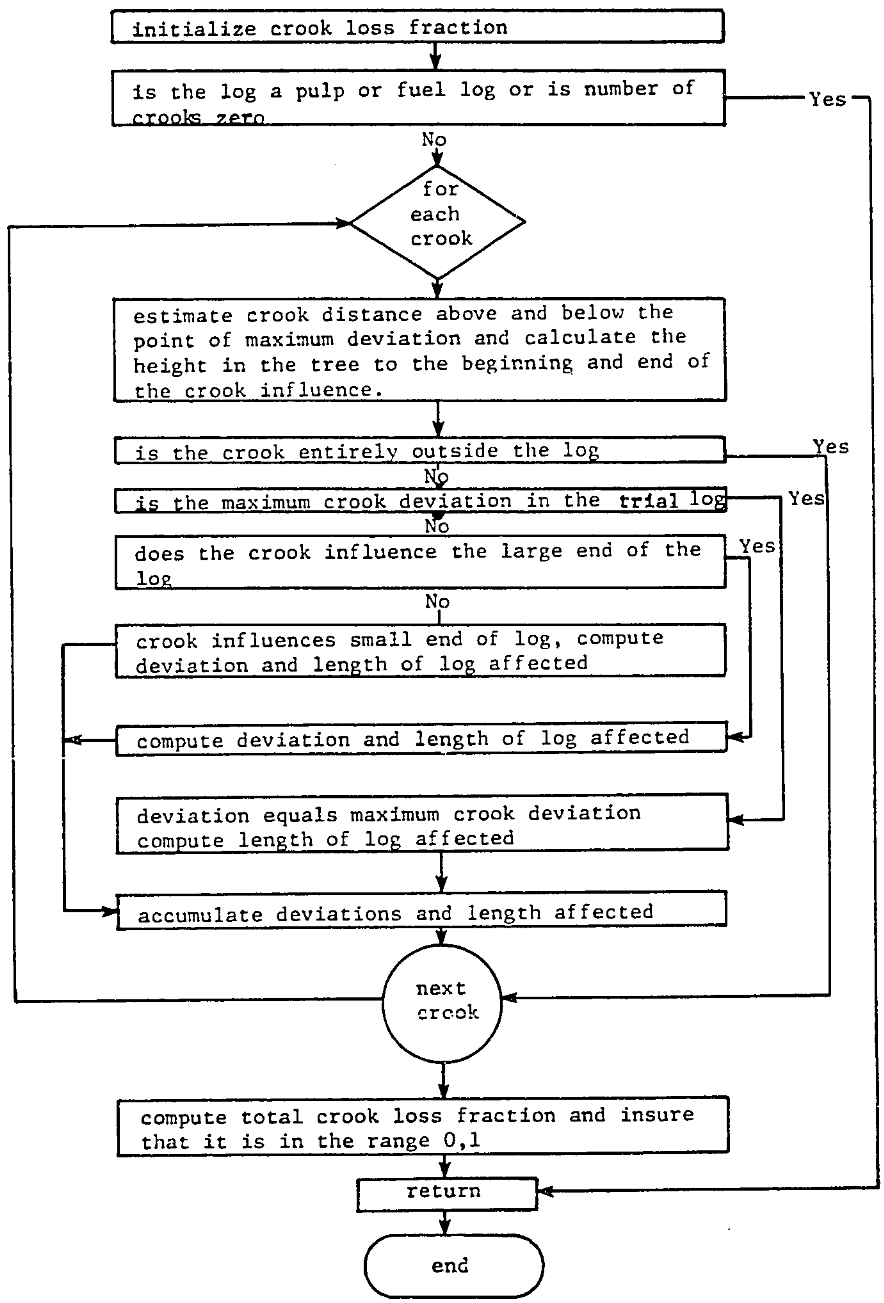


Figure 16. Flow diagram of subroutine CROOKR.

more such scaling defects overlap, the defect profiles in the overlap zone will not be repeated. It may be useful as experience is gained with the model to amend the procedures in DEDUCT, SWEEPR, and CROOKR so that the model estimates and compensates for the extent of overlap of scaling defects.

Log Grading

A critical factor involved in producing logs is the recognition of externally visible defects and their role in ascertaining the quality of a prospective log through the application of log grading rules. In this study a description of each externally visible stem defect and defect indicator relevant to the grading rules is available to the model. The description indicates the type of defect, its dimensions, and its location in the tree. This information, combined with the locus of a trial log in the tree and the provisions of the log grading rules, allows the model to inspect the defects in a trial log and assign a log grade to it. In this study, the log grading rules developed for Douglas-fir by the U.S.F.S. Pacific Northwest Forest and Range Experiment Station (Lane et al., 1973; Lane and Woodfin, 1977) for sawlogs and veneer logs will be used. The provisions of these rules are summarized in Table 8. Although designed to aid in timber cruising, these log grades can also be used in grading bucked logs. The rules are a four grade system in which a log in

Table 8

Summary of Log Grading Rules

DEFECT	GRADE 1	GRADE 2	GRADE 3	GRADE 4
Sound Burls	No limit < 6" diam. If > 6" diam. must be confined to 90° of circumference	No limit < 6" diam. If > 6" diam. must be confined to 270° of circumference	No limit < 6" diam. If > 6" diam. must be confined to 270° of circumference	No limit
Sound Knots	One allowed if < = 1" diam. or one larger if within 6" of ends of the log	Any number but must be confined to 2 faces and all > 2" diam. must be confined to upper or lower half of one face	Any number but sound (or rotten) > 3" must be confined to one face	No limit
Knot Indicators	No limit if < = 1" diam. If > 1" diam. must be confined to no more than 2 faces	No limit	No limit	No limit
Knot Clusters	None allowed	One allowed if confined to one face	No limit but all must be confined to 2 faces	No limit
Knot Indicator Clusters	One allowed if confined to one face	No limit	No limit	No limit

Table 8 (Cont.)

DEFECT	GRADE 1	GRADE 2	GRADE 3	GRADE 4
Bumps & Bulges	No limit above 8' in the tree. Below 8' none larger than 6" x 6" allowed	No limit	No limit	No limit
Epicormic Branches, Bird Peck Holes	No limit but all must be confined to one face	No limit	No limit	No limit
Rotten scars	None allowed	No limit but all must be confined to one face	No limit	No limit
Sound Scars	None allowed below 8' in tree. Above 8' those >6"x6" must all be on one face or no more than 2 faces in any 1/4 of the log length	No limit	No limit	No limit
Conks, Cankers, Unsound Burls Rotten Knots	None allowed	None allowed unless log is otherwise grade 1	No limit except for rotten knots > 3" diam. (See sound knots)	No limit
Log is Adjacent to cull log	Lose 1 grade	Lose 1 grade	Lose 1 grade	

any grade can be considered to be either a sawlog or veneer log. The selection of this log grading system was based on its compatibility with lumber and veneer recovery studies also developed by the Pacific Northwest Forest and Range Experiment Station. Together, these log grades and recovery studies provide a basis for performing bucking analyses that include quality and end product yield. There are no conceptual problems in changing the model to accommodate another log grading system and associated recovery studies. This change would involve revising program DFLE, and subroutines GRADE, LYMYLD, and VENYLD of program BUCK.

External defect data acquisition. Preparing descriptions of the externally visible defects and defect indicators involves acquiring this information from the tree and processing it into a form useful to the model. The typical procedure for collecting descriptions of external defects is through the use of log and tree diagrams (Figures 17 and 18) (Jackson et al., 1963) which portray the type, size, and location of external defects and defect indicators. Data are collected with reference to an arbitrary baseline along the bole corresponding to the bottom of the log diagram.

Data from the log diagrams were transferred to the computer by means of an Altek digitizer located at the University of Washington Academic Computer Center. The

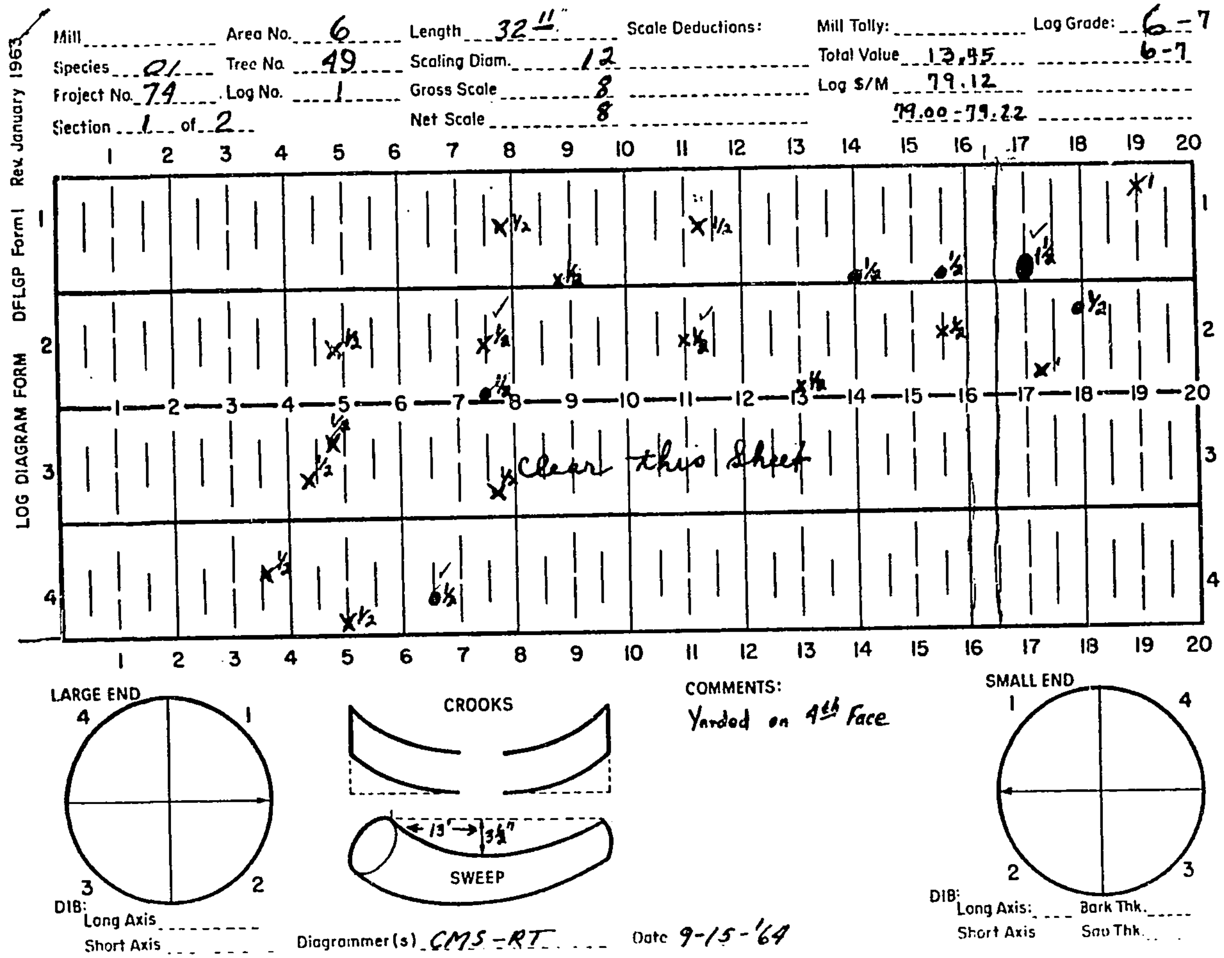


Figure 17. A portion of a typical log diagram for a Douglas-fir tree.

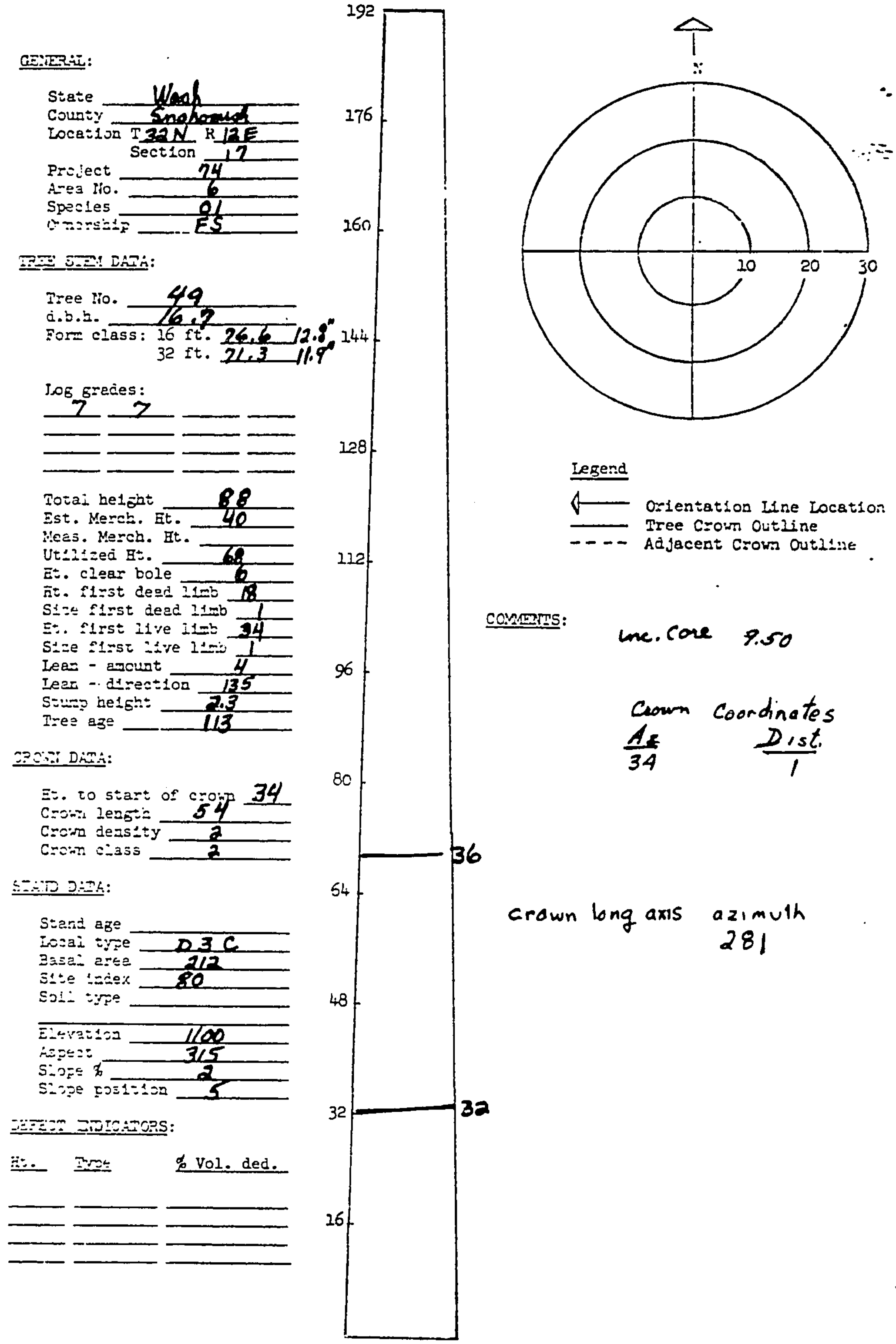


Figure 18. A tree data sheet and diagram for a Douglas-fir tree.

digitizer is a device that records x-y coordinates for subsequent processing by a computer program. It consists of a 42 x 60 inch digitizing table and cursor, a keyboard, a microprocessor based controller, a character buffer and tape drive for magnetic tape output, and an RS-232 output port for interactive digitizing. It is a manual system that relies on a human operator to decide which points are significant; the digitizer merely automates the recording of points, it does not select them. Further information concerning this system and its operation is contained in University of Washington Academic Computer Center document W00049 (1978).

The procedure for collecting defect data from the log diagrams of a tree began with taping the butt log diagram to the digitizing table with masking tape. If a log spanned more than one log diagram, the diagrams were taped together so that the entire log was on the digitizing table. Three lines of data were entered into the digitizer that consisted of information describing the tree and butt log and digitized coordinates of three corners of the log in the log diagram. After these three lines were completed, the cursor was placed over each defect, the defect type and dimension data entered, and its coordinates digitized. Table 9 and Figure 19 show the general procedure and Table 10 indicates the defect coding and measurements entered for each defect type. Defects that are typically

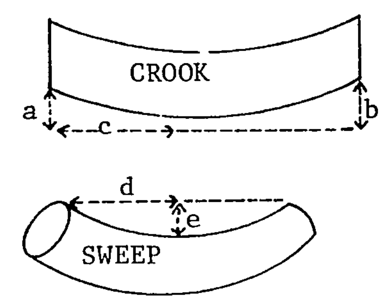
Table 9

General Procedure for Digitizing Log Diagrams for a Tree

	Text Information Typed and Separated by Commas[1]	Digitized Coordinates
Butt Log	T, tree number, dbh, total height, stump height	* bottom left corner of butt log
	L, log number, height to log base, log length	* top left corner of butt log
	L, a, b, c, d, e, (see crook and sweep diagrams below)	* top right corner of log
	D, defect code, width, depth or height from surface, angle of inclination	* center of defect base } defects such as scars entered as 2 records
	D	* center of defect top } defects such as scars entered as 2 records
	•	•
	•	•
	•	•
	D, defect code, diameter	* center of defect } defects such as knots entered as one record
	•	•
	•	•
Upper Logs	L	* bottom left corner of log
	L, log number, height to log base, log length	* top left corner of log
	L, a, b, c, d, e,	* top right corner of log
	D	•
	•	•
	•	•
	•	•

T = beginning of a new tree
L = log data to follow
D = defect data to follow

* digitize ... = place cursor over point to be digitized and press any keypunch key



[1]No comma separating the last text from the digitized point. The system inserts the * as a separator.

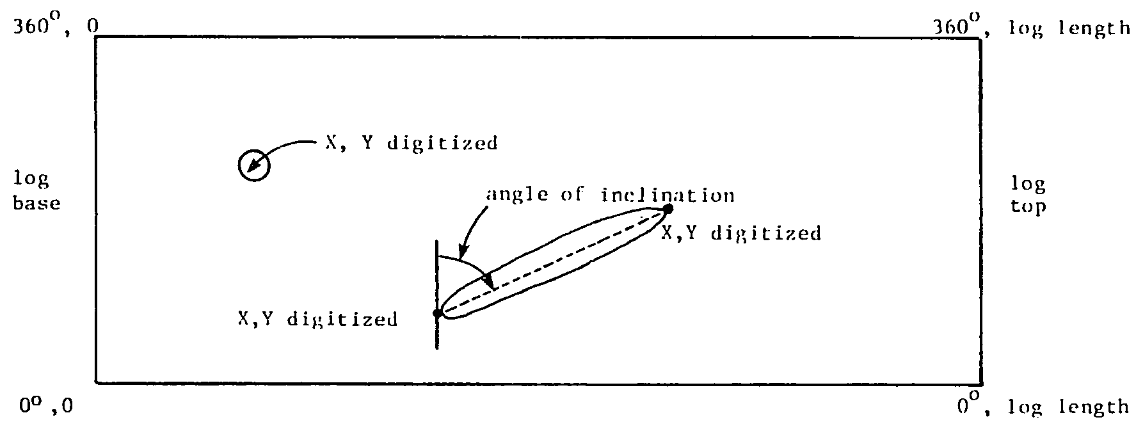


Figure 19. Method used for digitizing defects from log diagrams.

Table 10

Defect Codes and Measurement Procedures

Numeric Code	Abbreviation in Log Diagram	Definition	Measurements
1	BD or D	bark distortion	x-y at each end, width, depth or height
2	BPK-O	open bird peck	x-y at each end, width, depth or height
3	BPK-C	closed bird peck	x-y at each end, width, depth or height
4	Bulge	bulge	x-y at each end, width, depth or height
5	B	bump	x-y at each end, width, depth or height
6	BL	sound burl	x-y at each end, width, depth or height
7	BL-U	unsound burl	x-y at each end, width, depth or height
8	Swell	butt swell	x-y at each end
9	Cank	canker	x-y at each end, width, depth or height
10	C	conk	x-y at center, diameter
11	CR	crook	entered as part of log data
12	FLG	flange	x-y at each end, width, depth or height
13	FLT	flute	x-y at each end, width, depth or height
14	⊙ or O	sound live knot	x-y at center, diameter
15	•	sound dead knot	x-y at center, diameter
16	OR, ⊙R, or •R	rotten knot	x-y at center, diameter
17	X	overgrown knot	x-y at center, diameter
18	KCL	knot cluster	x-y at each end, width, depth or height
19	Sucker	sucker limb	x-y at center, diameter
20	EB	epicormic branch	x-y at center, diameter
21	MD	mechanical damage	x-y at each end, width, depth or height
22	SR	sap rot	x-y at each end, width, depth or height
23	SC	sound scars & seams	x-y at each end, width, depth or height, angle of inclination
24	SW	sweep	entered as part of log data
25	UC	undercut	x-y at each end, width, depth or height
26	WC	weather checks	x-y at each end, width, depth or height
27	RSC	rotten scars & seams	x-y at each end, width, depth or height, angle of inclination
28	KCLI	knot indicator cluster	x-y at each end, width, depth or height

circular in shape such as knots were entered in a single entry that included the defect code, its diameter and the digitized coordinate of its center. For other defects, two entries were made; the first indicating the defect code, its width in inches around the log circumference, its height or depth in inches from the log surface, for scars and seams the angle of inclination from the vertical log axis, and the digitized coordinate at the center of its base. The second entry consisted of the digitized coordinate at the center of the top of the defect. The length dimension of the defect was calculated in a subsequent program (DFLE). After all of the defects in the butt log were digitized, its diagram was removed and replaced by the next log in the tree. The procedure for the second and subsequent logs was basically the same as described for the butt log except that the first three descriptive lines only reflect log data. All data from the digitizing session were stored on magnetic tape for further processing.

After the digitizing session, the tape of digitizer coordinate values was converted to a coordinate system that reflects the scale of the tree. In this study, the coordinate system used to locate defects in a tree includes the height of the defect (x coordinate) in the tree and its circumferential distance in degrees (y coordinate). The bottom of the log diagrams was chosen as a convenient zero degree baseline for locating the circumferential position of defects. The program, DIG, converts the digitized data into this tree coordinate system. This program makes use of University of Washington Academic Computer Center supplied software (1978) that simplifies the task of digitizer data conversion. The details of program DIG are described in Appendix C. The result of this program is a permanent record of the tree in the form of a punched card deck with the structure shown in Table 11.

The defect data is processed through two additional steps by program DFLE. These steps reduce the calculation burden that would otherwise be borne by the bucking model and eliminates from further consideration all defects that have no influence in the log grading rules. The first step involves creating a simplified record of each defect in the form shown in Table 7 that is used as a data input to the bucking model. This involves calculating the height to the base and top of the defect and the circumference to the corners of a rectangle or trapezoid enclosing the defect as shown in Figure 20. By performing these calculations in a separate program and merging the two record digitizer descriptions of many defects into a single simplified record, many redundant calculations are removed from the bucking model which would repeat many of these steps for the same defect during dynamic programming stage iterations. As a further step in reducing the computational burden in the bucking model, DFLE screens out all defects that are not relevant to the log

Table 11

Structure of Card Deck Produced for Each Tree by Program DIG

		Format
Card 1	tree card indicator, T	A10
	tree number	F8.2
	tree dbh	F8.2
	total height	F8.2
	stump height	F8.2
	butt log number	F8.2
	height to the base of the butt log	F8.2
	length of the butt log	F8.2
Card 2	tree card indicator, T	A10
	3 crook measurements for butt log	3F8.2
	2 sweep measurements for butt log	2F8.2
M Defect Cards	defect card indicator, D	A10
	height to defect base, top or center	F8.2
	degrees of circumference to the center of the defect base, top, or midpoint	F8.2
	defect numeric code (Table 10)	F8.2
	defect dimension(s)	
	diameter of width	F8.2
	defect depth or height from surface	F8.2
	angle of inclination	F8.2
Card M+3	log card indicator, L	A10
	log number	F8.2
	height to base of the log	F8.2
	log length	F8.2
	3 crook measurements	F8.2
	2 sweep measurements	F8.2
Defect Cards		
	•	
	•	
	•	
Last Card	indicator = END	A10

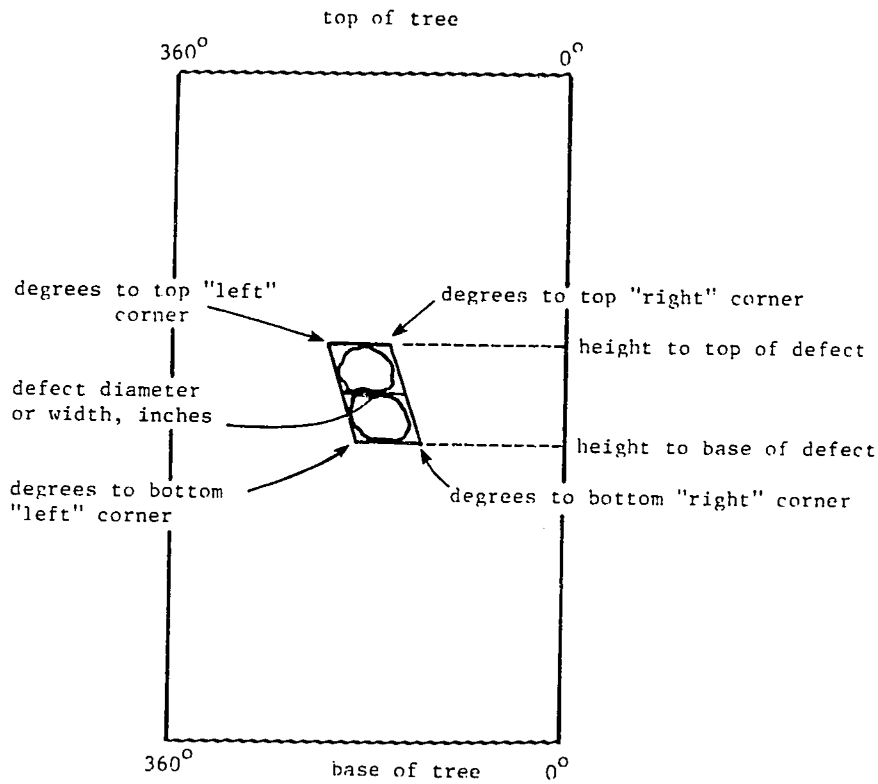


Figure 20. Defect measurements used as data input to the bucking model.

grading rules. This step generally greatly reduces both the defect storage and testing requirements in the bucking model. Although it is possible to screen out irrelevant defects during digitizing, this was found to be tedious and reduced the efficiency of the operator of the digitizer. It was easier to digitize all defects and remove irrelevant ones later by computer screening. It also allows the creation of a data base for the tree that includes all defects irrespective of the grading rules to be used. If another log grading system were to be used, the time consuming digitizing step would not need to be repeated. Program DFLE thus takes the card deck fully describing all defects in the tree and creates a disk file containing a simple descriptive record of only those defects relevant to the PNW log grades. This disk file is accessed by program BUCK and the data read into array DEFECT. Appendix D presents a more detailed description of program DFLE.

Log diagrams and tree data were made available by the U.S.F.S. Pacific Northwest Forest and Range Experiment Station for more than 1000 mature coast Douglas-fir trees. This information was collected during the 1960s as part of studies concerned with estimating veneer and lumber recovery from Douglas-fir. The log diagrams provided information on the type, size, and location of external defects on logs cut from these trees. Provision was also made for recording individual log features such as the presence and amount of crook, sweep, and internal defects. Although these diagrams provided a large potential data base, relatively few trees were suitable for this study.

Criteria for selection of test trees were completeness of log diagram coverage of the bole, legibility of the log diagrams, and obtaining a range of tree size and quality. Since log diagraming was performed only for the log segments between the stump and top of the last merchantable log, only trees with a high fraction (about 90 percent) of the total height included in the diagrams were sought. In many trees, zones of breakage or cull that were not diagramed produced relatively poor coverage. In searching through the diagrams many that were suitable were difficult to read through years of handling and storage. Xerox copies of these were often impossible to read. Trees with difficult to read diagrams were discarded. Of those trees that remained, five from study sites in Whatcom and Skagit counties in Washington were selected. Table 12 presents information on these trees. Trees 71 and 73 were located in Skagit County at about 600 feet elevation on site III (Dilworth, 1977:158) land. The remaining trees were located in Whatcom County at 500 feet elevation on site IV land. Generally, diagram coverage was close to 90 percent of the tree height. For these trees only 53-77 percent of the digitized defects were relevant to the log grading rules.

Table 12

Description of Test Douglas-fir Trees

Tree Number	Age	dbh Inches	Height, Feet			Percent Log Diagram Coverage	Number of External Defects		Percent of External Defects Relevant
			Total	Stump	Log Diagrammed[1]		Total	Relevant to Grading Rules	
73	87	17.1	110	1.5	96	87	264	140	53
71	88	24.3	131	2.1	114	87	435	269	62
59	445	38.2	138	2.0	128	93	183	123	67
60	438	40.5	156	2.0	143	92	325	231	71
55	422	42.0	138	2.0	120	87	198	152	77

[1] Includes stump height

Defect data from the log diagrams was digitized and processed by programs DIG and DFLE onto a disk file containing only information on those defects relevant to the log grading rules used in this study. The digitizer operation averaged one hour per tree which undoubtedly could be reduced by an experienced operator. Since log diagram coverage omitted the portion of the tree above the last log cut in the original study, it was assumed that, whenever a trial log in the model reached above this point, the log would be rated as the lowest log grade, grade 4. This is accomplished by a test within subroutine DYNPRO and could be easily modified.

The methods used in this study for the acquisition of internal and external defect data are fairly tedious and time consuming. This approach would prevent the model from having practical application in a production environment, although it may be a reasonable approach for analyzing selected trees for research, inventory, or training purposes. However, automated scanning technologies are evolving at a rapid rate and it is likely that breakthroughs will occur that will introduce defect scanning as a routine activity especially in the production environment. For example, Lakatosh (1970), McGinnes and Shigo (1975) and McDonald (1978) have explored techniques ranging from photographic to ultrasonics to x-rays that can be used to describe internal or extenal defect profiles in trees, logs, timbers and boards. It is interesting to note that a new sawmill is being built in Finland with the provision for later inclusion of x-ray scanning for internal defects at various processing stations (Anonymous, 1979). These advancements, coupled with the rapid evolution of computers adaptable to manufacturing process control may mean that computer based optimization of tree length or long log bucking using defect information automatically provided by scanners and an optimization model such as is being developed in this study will be a reality in the near future.

Grading veneer and sawlogs. The defects relevant to the grading system for the tree are read by BUCK and stored in array DEFECT. These data are transferred to subroutine GRADE which determines the highest grade that a trial sawlog or veneer log under consideration by DYNPRO can achieve.

The first step in GRADE is to scan the array (DEFECT) containing the defects along the bole and transfer into arrays TRLDF or BL those that occur between the base and top positions of the trial log. When a defect extends only partially into a trial log, exit point information is interpolated.

In grading a log, certain peculiarities of the rules help define procedural logic. As can be observed in Table 8, establishing the influence of most defect types on the log grade involves counting the number of grading faces that contain the particular kind of defects. Grading faces are established by dividing the log circumference into four equal quadrants. The objective is to find grading faces that concentrate defects on as few faces as possible thereby maximizing the log grade that can be assigned. In subroutine GRADE the grading faces are initially established so that the zero line along the bole established in log diagramming coincides with the break between grading faces 1 and 4. After ascertaining the grade with the initial locus of the faces, a 10 degree shift is made and the log regraded. This procedure is repeated up to a maximum of 9 times. The maximum grade found among the 9 examinations is returned to DYNPRO as the log grade. The procedure can terminate earlier if, for any set of grading faces, the highest log grade is established. The procedure for the 10 degree shift involves subtracting 10 degrees from the circumferential location of each defect in the trial log. This is like imagining holding the grading faces in a constant position while rotating the log counter clockwise 10 degrees between gradings. The 10 degree interval can be made smaller but at the expense of increased computing time. Use of this interval does increase the chance that the highest possible grade for a trial log will not be found. Reduction of this interval to one degree greatly reduces this possibility but greatly increases computing time.

Although most defects are considered with respect to these fixed grading faces, some, such as sound burls are considered differently. In the case of sound burls, the grading faces may be shifted to determine minimum number of faces that contain all of them. In the case of other defects, such as conks, cankers, unsound burls, and most rotten knots, their mere presence will, after the grade has been established without considering them, cause the grade to be lowered to the next lower grade. These considerations led to the following order in treating the defects.

1. Examine sound burl to assign a preliminary grade;

2. establish up to 9 sets of fixed grading faces and continue grading;

3. examine final grade reducers.

In grading, it is assumed that a log is of the highest grade until a degrading influence occurs. For this reason, it is generally more efficient to program rules for the more common defects early since, if they reduce the grade, the rules for less common defects in higher grades can be ignored. The order of the defects shown in Table 8 was used as the defect testing hierarchy in establishing the grade based on a particular set of grading faces.

The overall scheme of subroutine GRADE is portrayed in Figure 21. Sound burls within the confines of the trial log are placed in array BL and all other defects within the

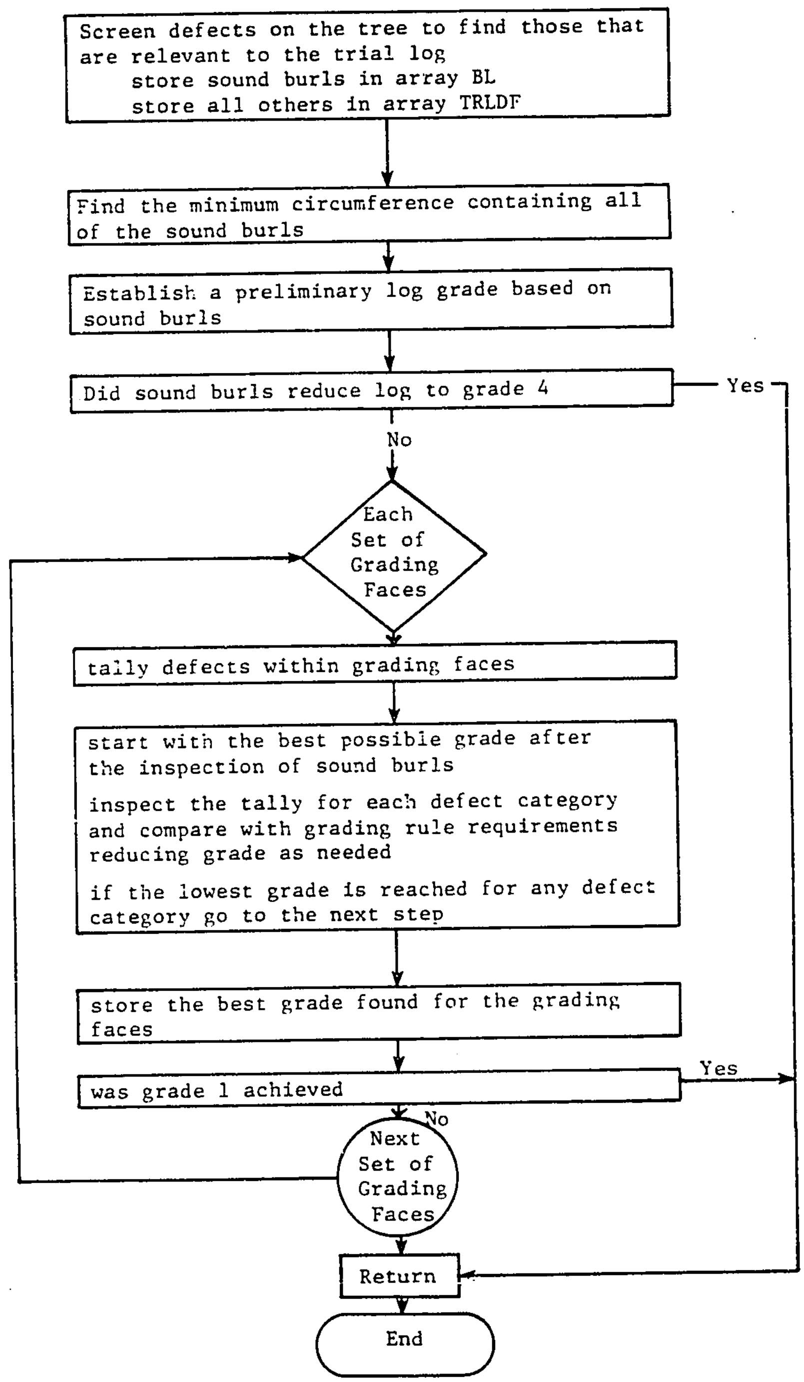


Figure 21. Procedure for grading veneer and sawlogs.

trial log are placed in array TRLDF. Next, the minimum circumference, in degrees, containing all of the sound burls is found and a log grade based on this information is assigned. If the sound burls cause the log to be graded as grade 4, grading is finished and this grade is transferred back to DYNPRO. Otherwise, the 9 sets of fixed grading faces are examined and the best grade for iterations examined so far is stored. In each iteration, array TRLDF is scanned for defects in each category and those found are tallied by grading face. The grading face tally is compared with the rule requirements and the highest possible grade allowed is noted. During an iteration, if the grade reduces to grade 4 the search for that iteration ends and the next iteration is stated. This process continues until all 9 possibilities have been examined and the best grade found among them is returned to DYNPRO. The procedure may terminate prematurely and return to DYNPRO if any iteration results in a log grade of 1.

Details of subroutine GRADE. Figures 22, 23 and 26-35 provide a detailed flow diagram of subroutine GRADE. The problem of converting this particular log grading system into computer instructions is not difficult but as the reader will notice, it does lead to a fairly lengthy computer code in order to incorporate all of the features and possibilities. In practice a relatively small portion of GRADE is executed for any given log since many provisions

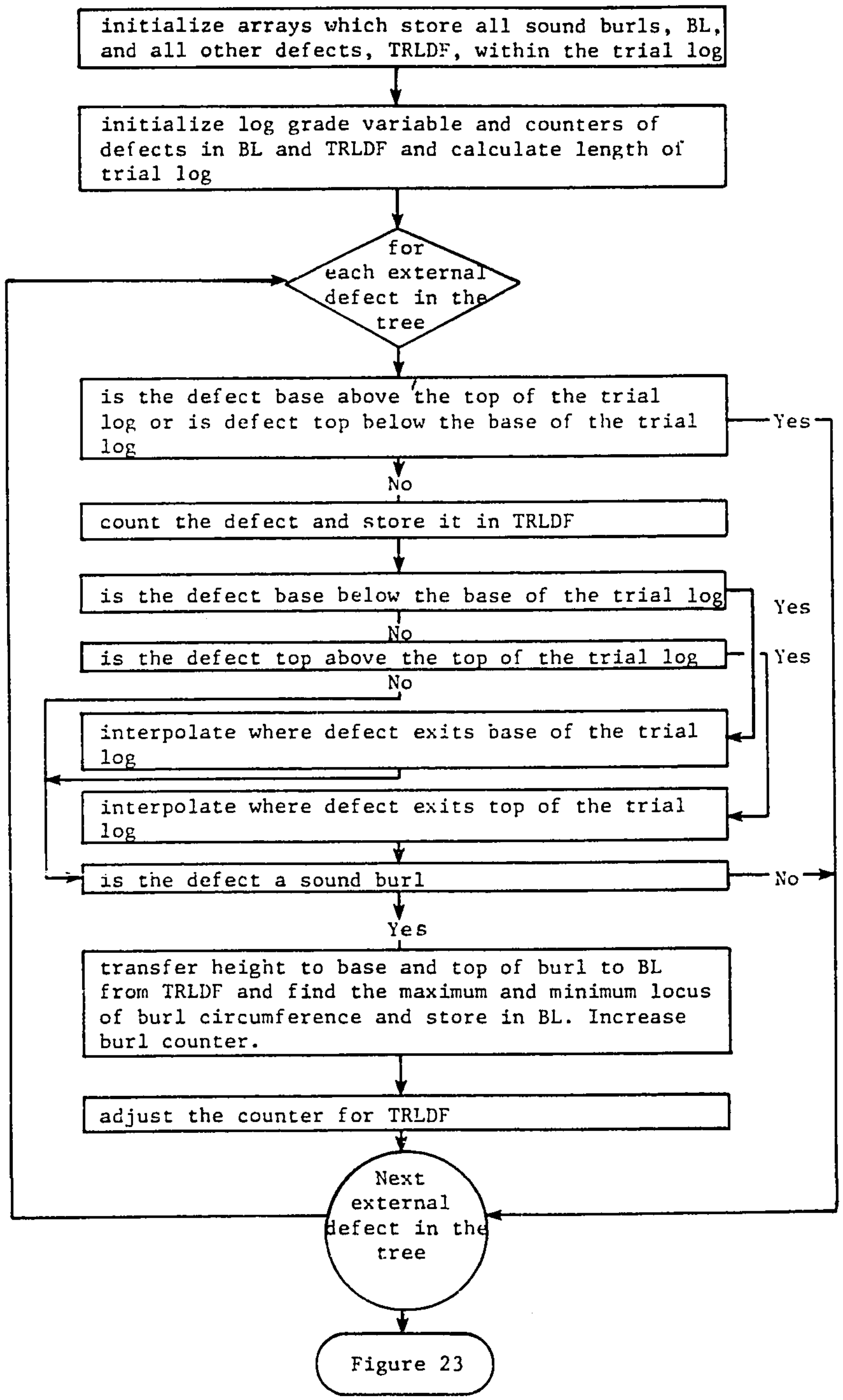


Figure 22. Flow diagram of subroutine GRADE - finding defects that are relevant to the trial log.

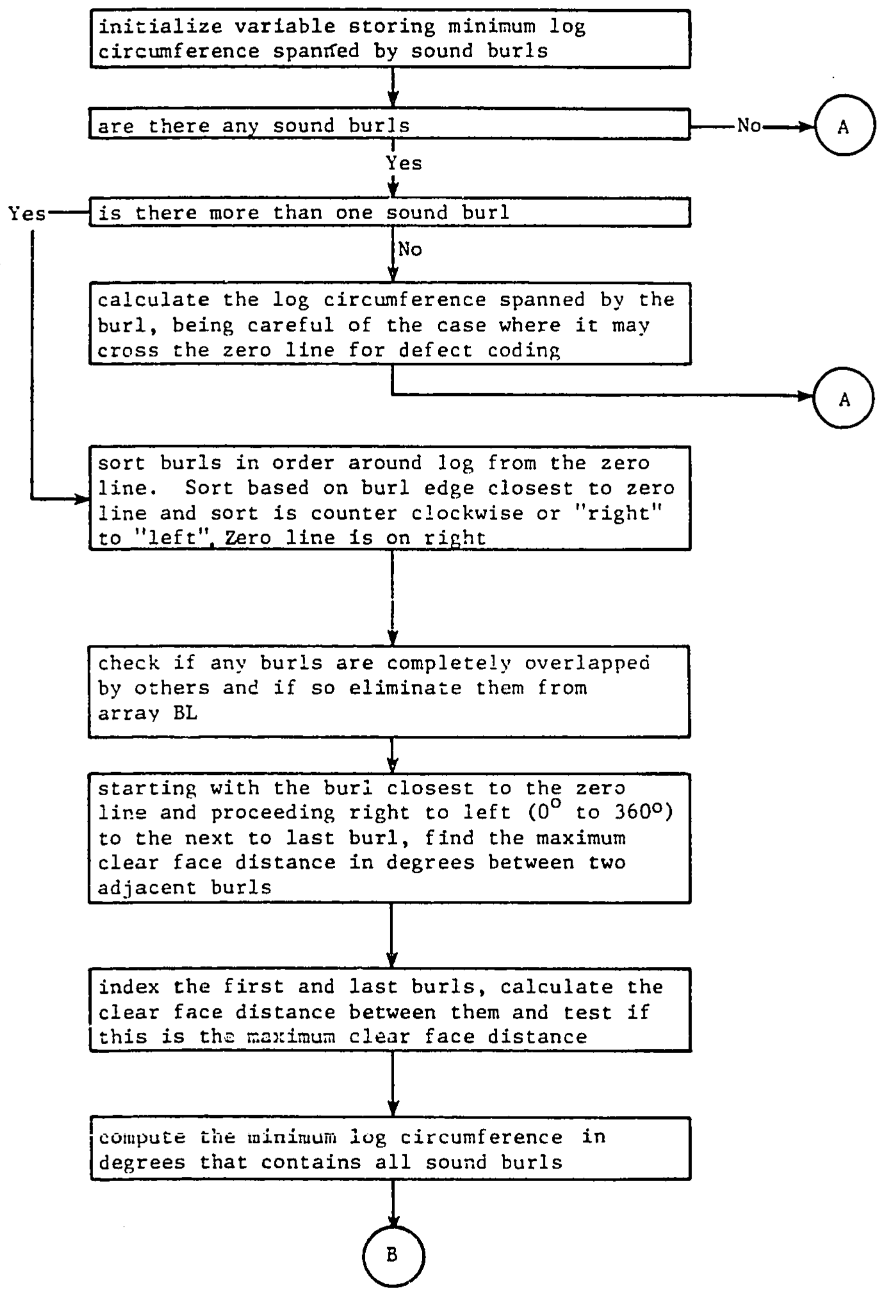
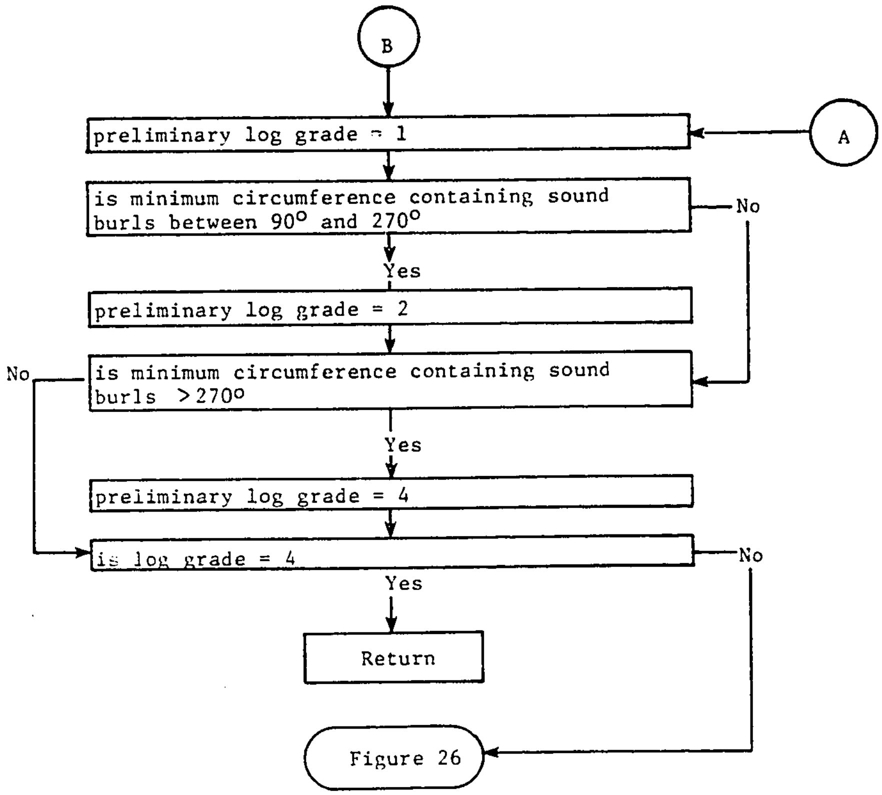


Figure 23. Flow diagram of subroutine GRADE - assigning a preliminary log grade based on sound burls.

Figure 23. Continued

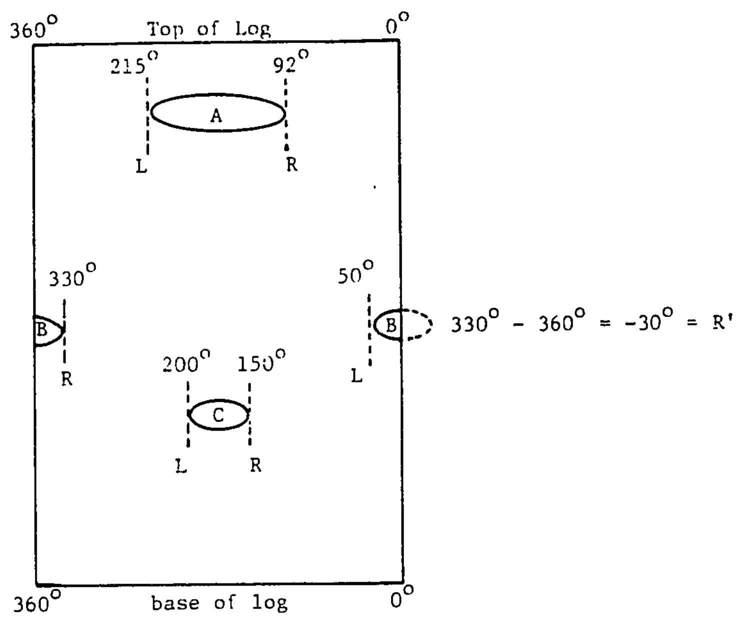


in the rules either do not occur because of the lack of certain kinds of defects or because other defects may have already degraded the log sufficiently to allow avoiding consideration of other features.

The subroutine begins by initializing arrays BL and TRLDF which respectively store the information on sound burls and all other defects that occur wholly or partially within the trial log. The first step in subroutine GRADE utilizes information from DYNPRO regarding the position in the tree of the trial log and examines the tree defect array (DEFECT) and transfers those involved in the trial log into arrays BL and TRLDF. As this is accomplished, GRADE determines if the defect is wholly or partially in the trial log and in the latter situation interpolates defect exit points from the trial log. This procedure is outlined in Figure 22.

The next phase (Figure 23) examines the effect of sound burls and assigns a preliminary grade to the log. GRADE first checks to determine if any sound burls are within the trial log and, if there are, whether or not more than one sound burl is present. If only one burl is present, the maximum log circumference in degrees affected by it is calculated by subtracting the burl circumference points closest to and further from the zero baseline. Care must be taken in distinguishing between the case when the burl does not span the zero baseline from situations when it does. As can be seen in Figure 24 burl A spans 123 degrees of log circumference. In the case of burl B which is split by the zero baseline one cannot simply subtract the two values. In subroutine GRADE, this is taken care of by subtracting 360 degrees from the left portion of the burl, effectively creating the dashed image. Another subtraction yields 50-(-30) = 80°, the correct result.

When multiple burls are present, GRADE must find the smallest log circumference that includes all of them. Referring again to Figure 24, this is done by first sorting the data in array BL on the basis of the burl edge (R) closest to the zero line. Then a check is made to determine if any burls are completely overlapped by others. If so these overlapped burls are zeroed from BL. Next GRADE compares each burl to the nearest neighbor on its left, calculates the clear log circumference between them. The maximum clear log circumference is retained. Finally the last burl is compared with the first burl and the clear distance is compared with the best of previous tests. When finished, the minimum circumference distance spanning these burls is 360 degrees minus the maximum log circumference not containing burls. This value if compared to the log grading requirements for sound burls. If the circumference containing the burls is less than 90 degrees the log is tentatively grade 1. If the circumference containing the burls is between 90 degrees and 270 degrees then the log is



Burl C can be eliminated since burl A spans it

Find the clear circumference between left edge of B and right edge of A, between left edge of A and right edge of B, etc., and store the maximum clear circumference.

Then minimum circumference containing all burls is 360° minus the maximum interburl clear circumference

Figure 24. Method for analyzing sound burls.

tentatively grade 2. Finally, if the circumference containing the burls is more than 270 degrees then the log is grade 4. If the log is found to be no better than grade 4 after testing burls then a return can be made to DYNPRO; otherwise examination of other defects is required.

After the sound burls, which do not utilize fixed grading faces, have been examined, GRADE sets up the first of 9 sets of fixed grading faces to examine the influence of other defects. First, the array TALLY which contains the count of various defect categories according to grading face is set to zero. Next, GRADE examines a defect in array TRLDF, computes its location on the log circumference with respect to the grading faces, and sets array IP to zero. Array IP contains four cells, one for each grading face. When the defect is found to influence a grading face, the corresponding cell in IP is set equal to 1. Thus IP is a flag indicating which faces are influenced by a defect. Another variable, IFLAG, is used to indicate whether any part of the defect crosses the zero baseline which also corresponds to the break between faces 1 and 4. It remains minus one if the defect spans the break between these faces and is set equal to plus one otherwise.

The next portion of GRADE determines the faces influenced by the defect. As shown in Figure 25, there are six possible cases that can occur, five of which involve the defect crossing the break between face 1 and face 4.

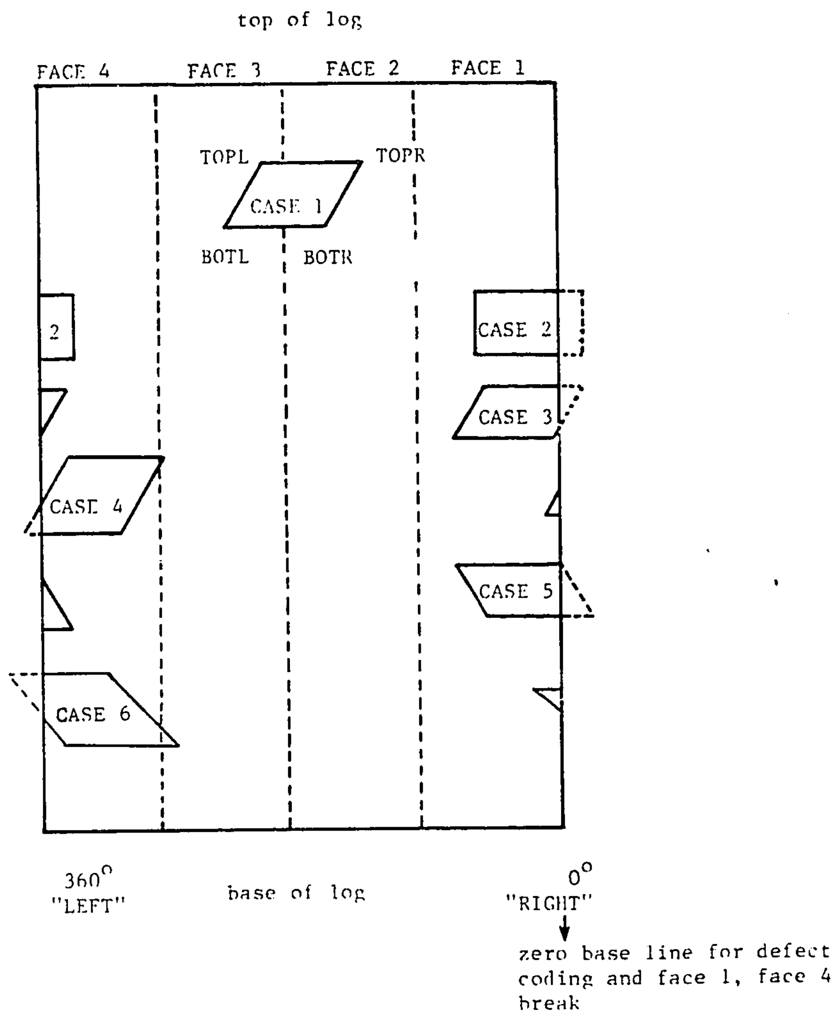


Figure 25. Possible relationships of defect enclosing trapezoids to log grading faces.

The defect circumference point furthest to the "right" and "left" is obtained and each is converted into the face code number. The appropriate cells in array IP corresponding to the faces influenced by the defect are set equal to 1. These procedures are outlined in the flow diagram in Figure 26. It should be noted that when a defect overlaps the division between two or more grading faces, it is counted as a defect on each face it affects.

After GRADE has determined which faces are influenced by the defect, defect must be tallied in accordance with grading rule requirement. This involves checking the defect type and incrementing the portion of array TALLY corresponding to the influenced faces. The array TALLY stratifies defects by size and type categories according to grading rule requirements. Table 13 outlines the entries in TALLY and Figure 26 also shows the detailed flow diagram of this portion of subroutine GRADE.

After the array TALLY is completed for the current set of grading faces on the trial log, subroutine GRADE compares the entries in TALLY with the log grading rule requirements and assigns the highest grade possible. If, when this comparison is completed for all defect categories, the best grade assigned is grade 1, an immediate return to DYNPRO is possible. Otherwise, the best grade achieved among the grading face sets examined thus far is stored, a new set of grading faces is defined and the procedure is

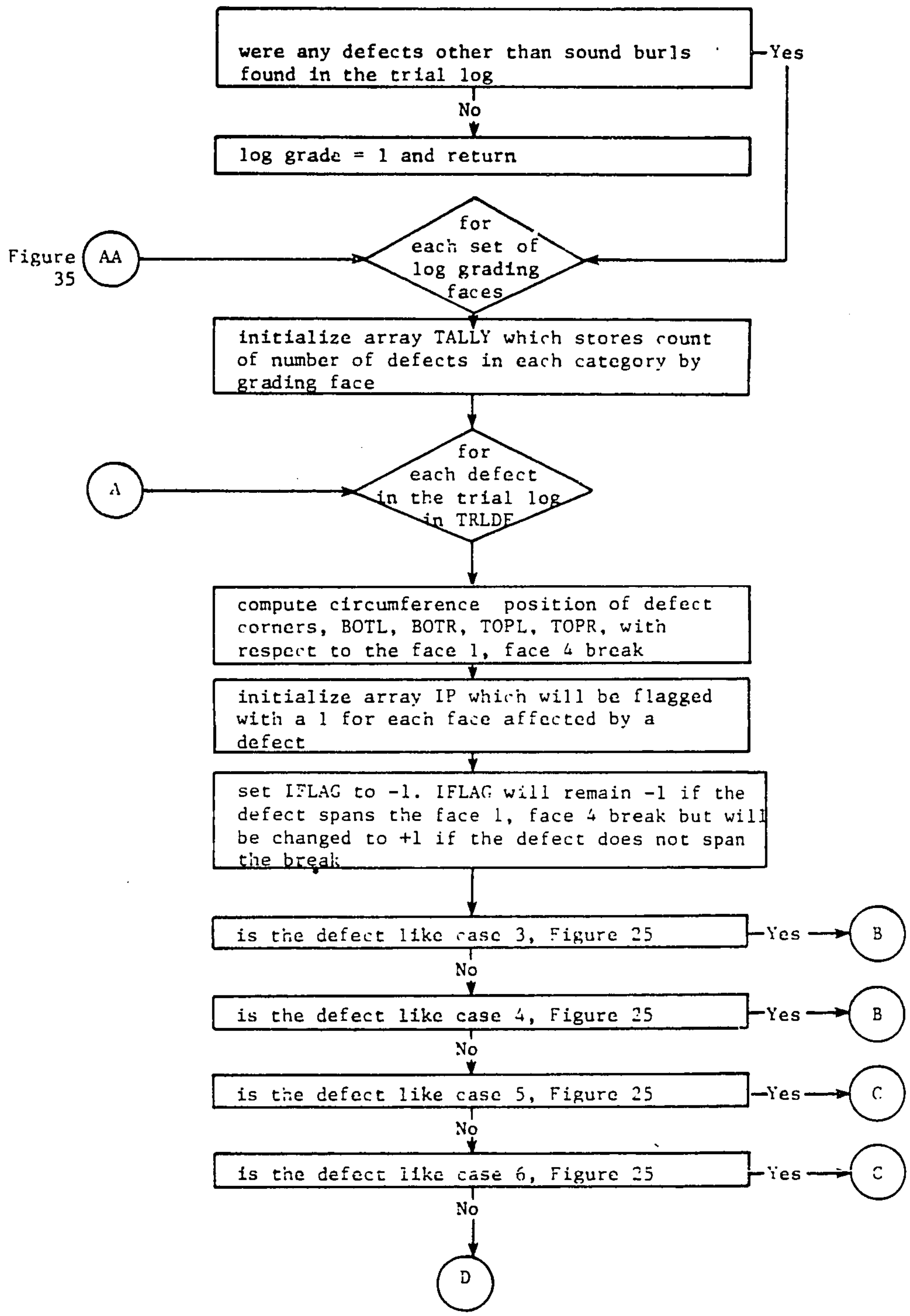


Figure 26. Flow diagram of subroutine GRADE - establishment of a set of log grading faces and tallying defects by defect type on each face.

Figure 26. Continued

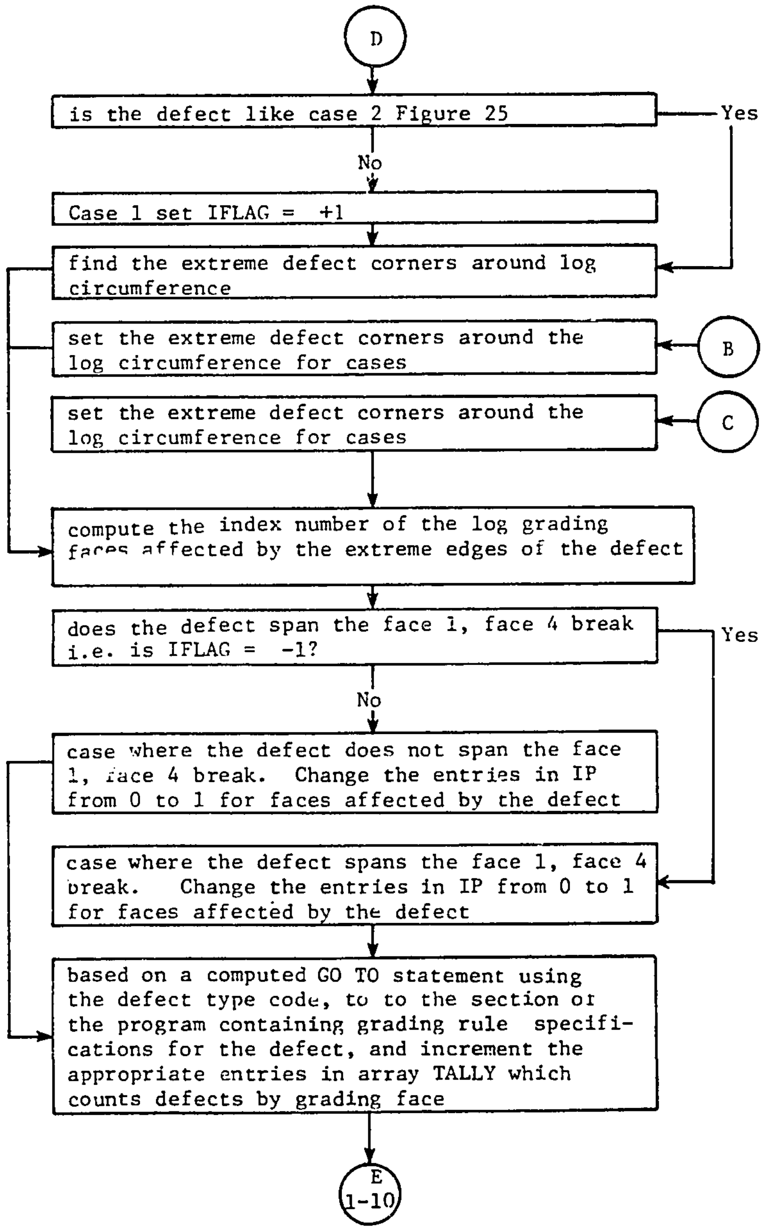


Figure 26. Continued

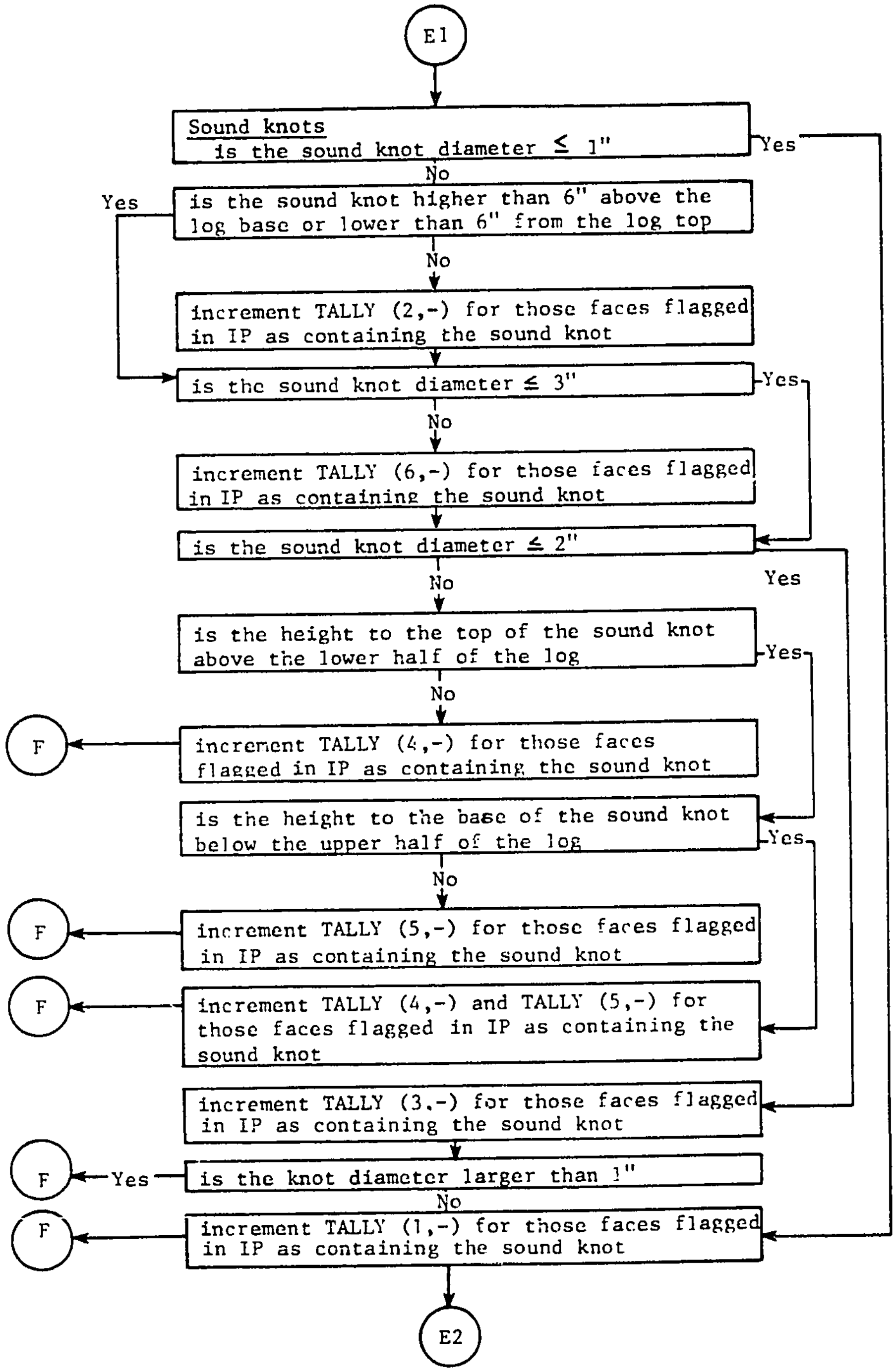


Figure 26. Continued

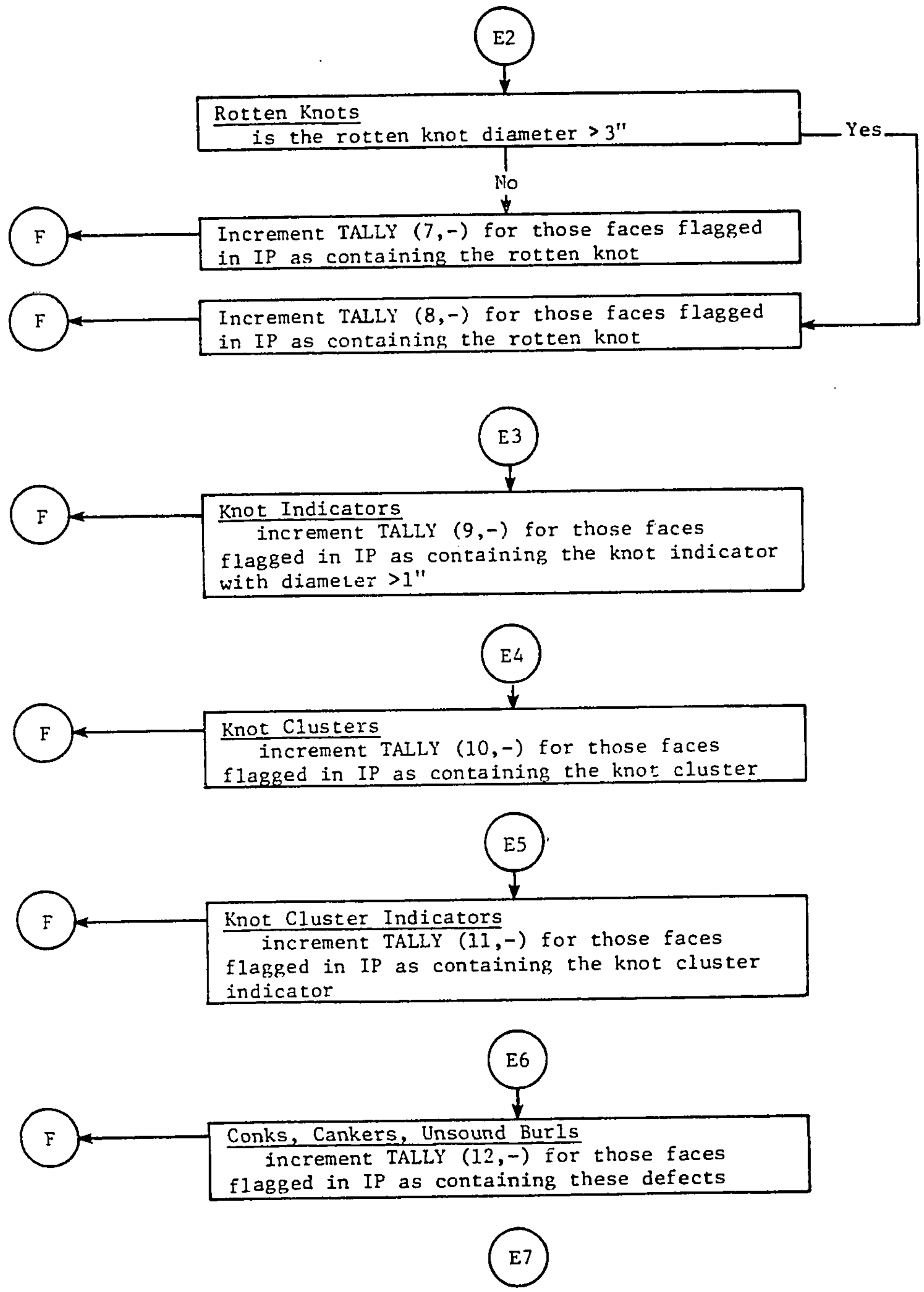


Figure 26. Continued

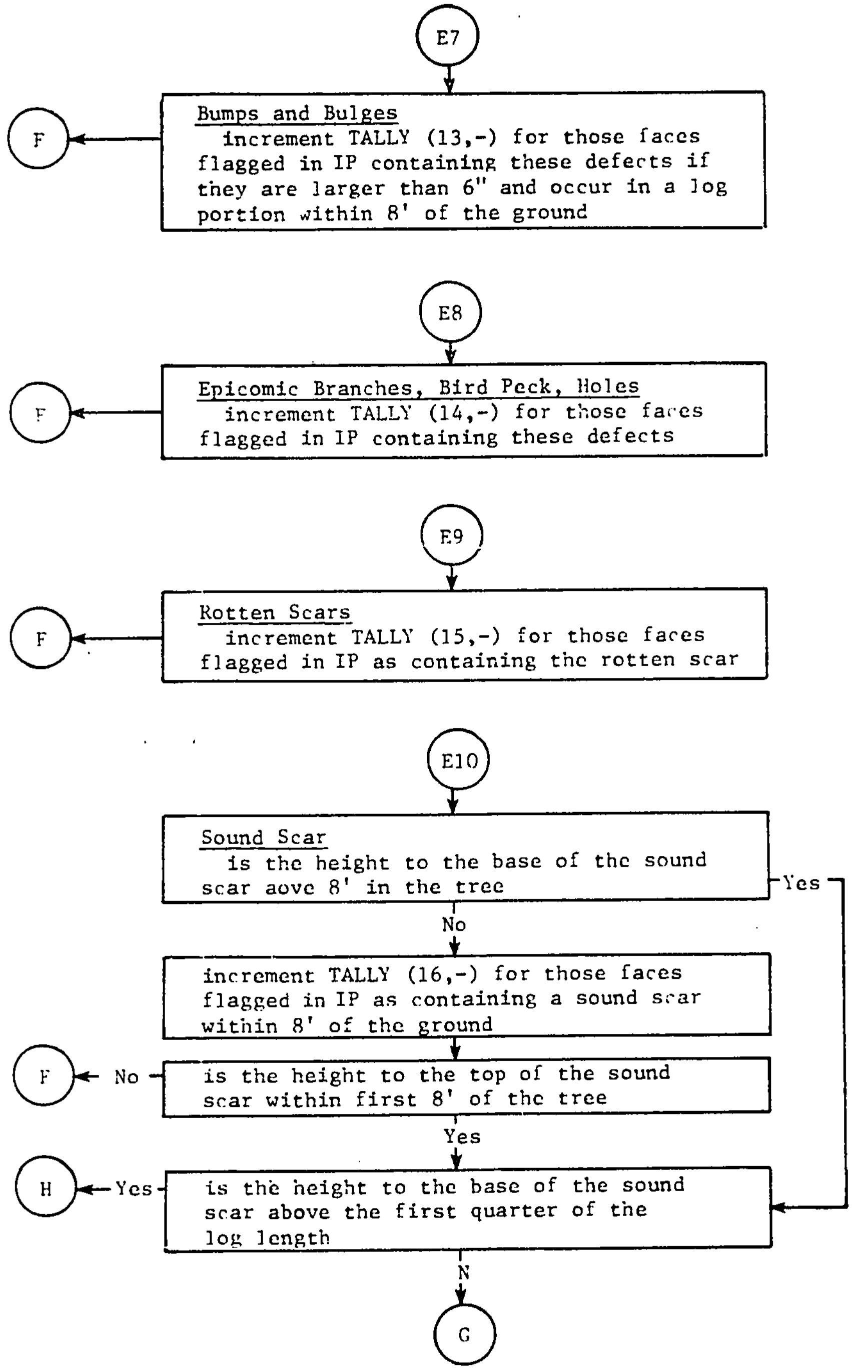


Figure 26. Continued

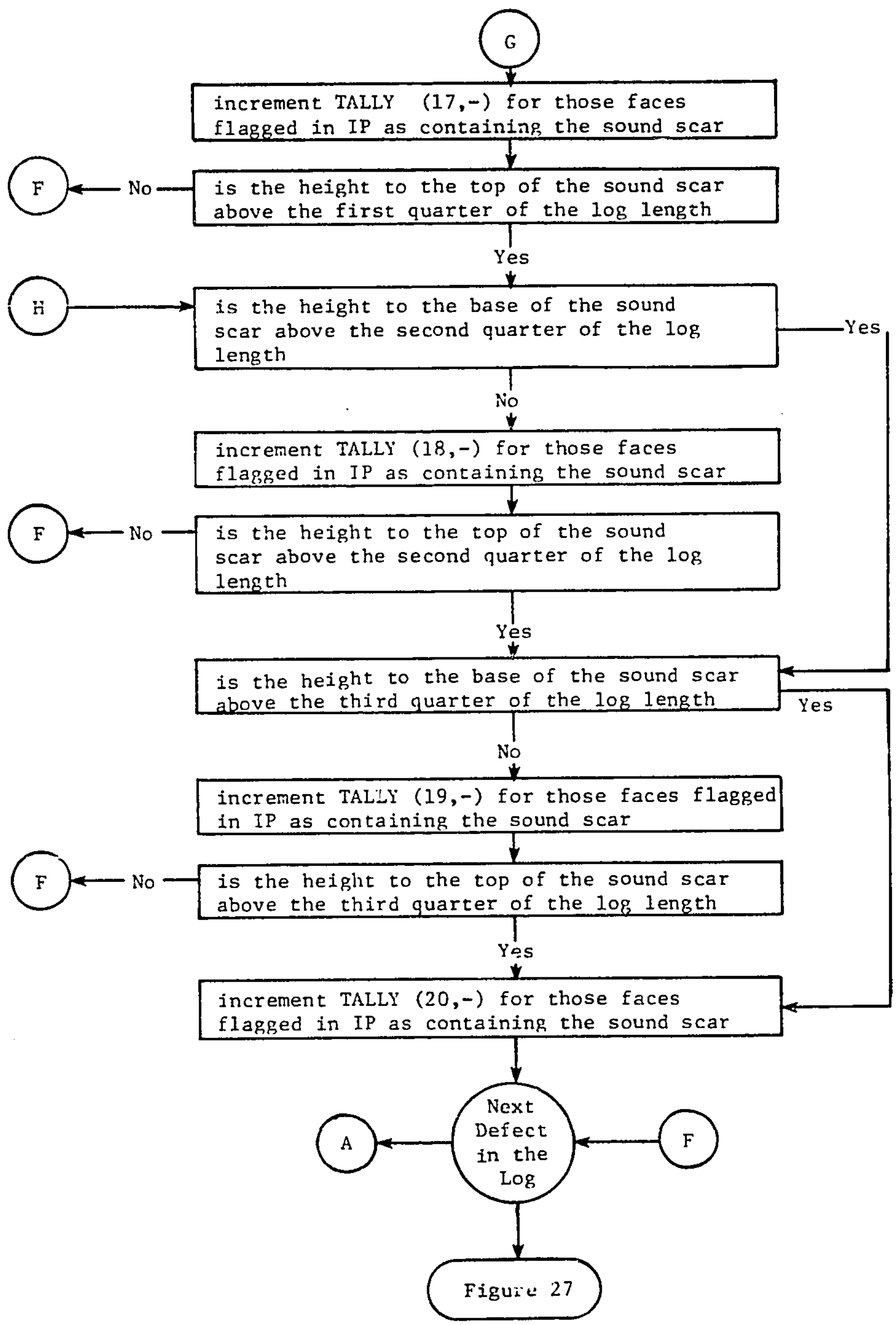


Table 13

Structure of Array TALLY

ROW	
1.	number of sound knots $0'' \le \text{diameter} \le 1''$
2.	number of sound knots within 6" of log ends $1'' < \text{diameter} < \infty$
3.	number of sound knots $1'' < \text{diameter} \le 2''$
4.	number of sound knots on lower half of face $2'' < \text{diameter} < \infty$
5.	number of sound knots in upper half of face $2'' < \text{diameter} < \infty$
6.	number of sound knots $3'' \le \text{diameter} < \infty$
7.	number of rotten knots $0'' < \text{diameter} \le 3''$
8.	number of rotten knots $3'' < \text{diameter} < \infty$
9.	number of knot indicators $1'' < \text{diameter} < \infty$
10.	number of knot clusters
11.	number of knot indicator clusters
12.	number of conks, cankers, and unsound burls
13.	number of bumps and bulges at least 6" diameter and on log portion within 8' of ground
14.	number of epicormic branches, bird pecks and holes
15.	number of rotten scars
16.	number of sound scars on log portion within 8' of the ground
17.	number of sound scars within first 25% of log length
18.	number of sound scars within second 25% of log length
19.	number of sound scars within third 25% of log length
20.	number of sound scars within fourth 25% of log length

COLUMN	
1.	grading face 1
2.	grading face 2
3.	grading face 3
4.	grading face 4

repeated. The entire procedure for defining grading faces, creating array TALLY, and comparing the results stored in TALLY with the log grading rules is outlined in the flow diagrams in Figure 27 to 35.

The details of the individual comparisons for each defect category are carried out in the following format. Initially, the log has a preliminary grade assigned on the basis of inspecting sound burls. This preliminary grade is used as the basis for entering the defect category tests. It was mentioned that the order for testing defect categories is the order of defects listed in Table 8. When a defect category is tested, obviously there is no need to check grade conditions higher than the preliminary grade assigned to the log. The conditions for the current preliminary grade serve as the entry point in testing each defect category. If a log has been assigned a grade of 2 because of previous defect tests, then conditions for grade 2 will be the starting point for testing the current defect. If the log meets grade 2 conditions for the current category of defect, grade 2 is retained, otherwise conditions for lower grades are checked until the conditions of a grade are met. The new grade is returned and the next defect category is examined. This continues until all defect categories have been inspected. If the lowest log grade, grade 4, is assigned the testing of defect categories for the current set of grading faces is terminated. When the

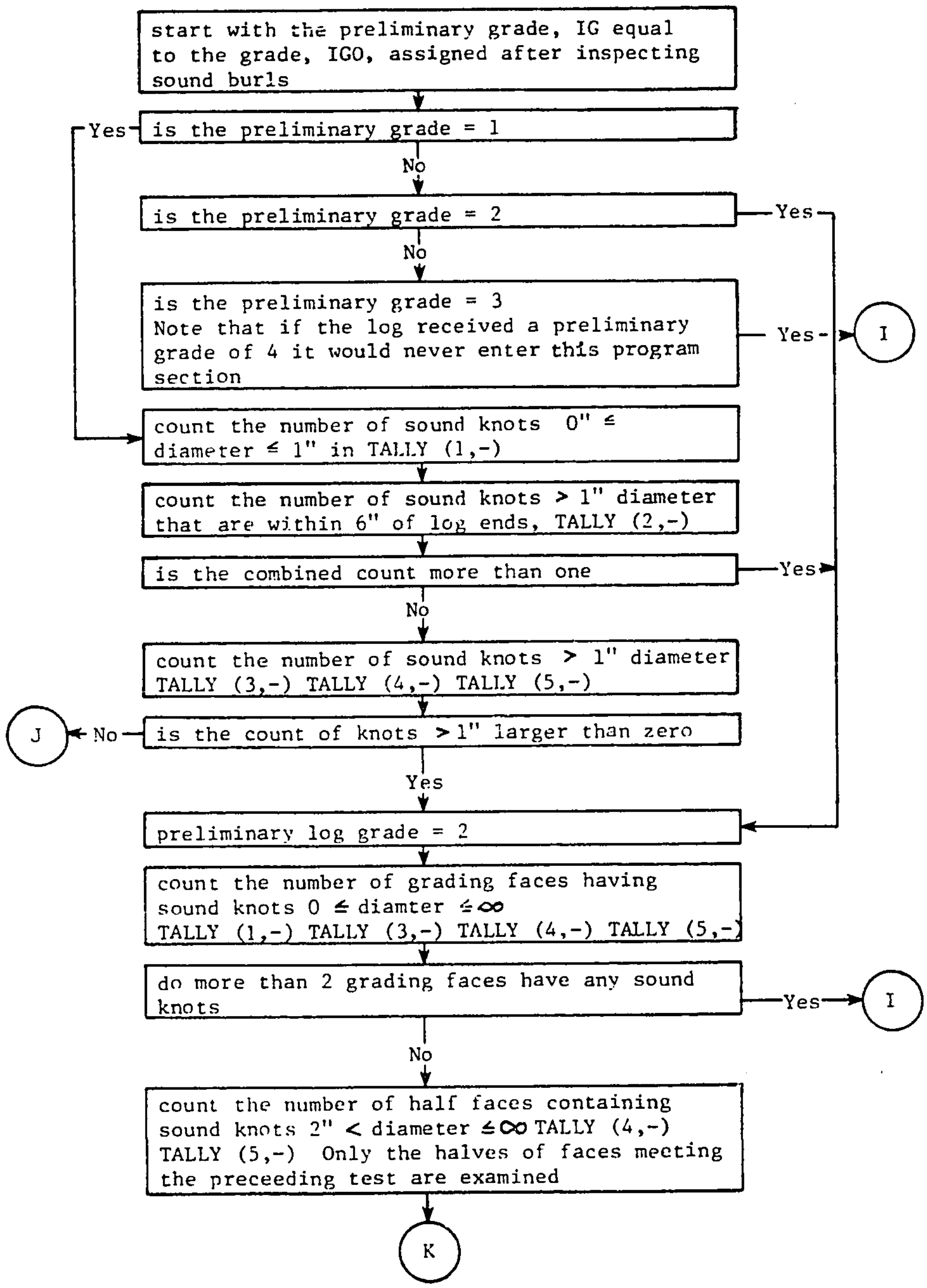
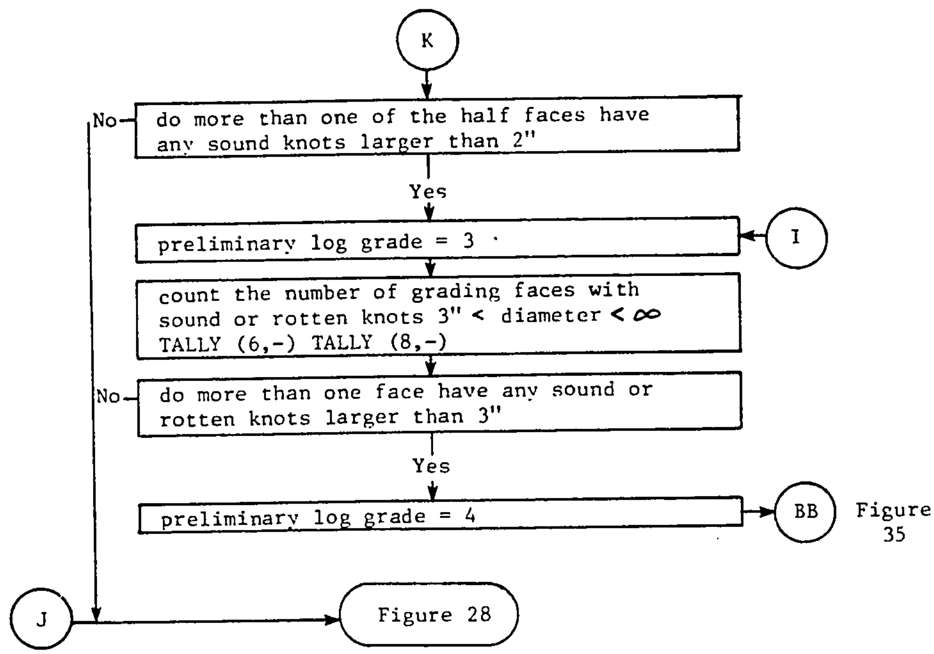


Figure 27. Flow diagram of subroutine GRADE - grading knots.

Figure 27. Continued



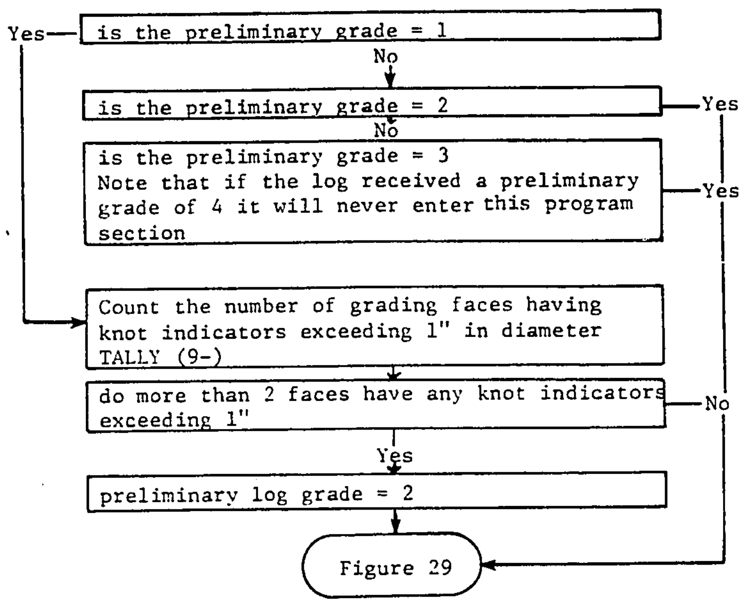


Figure 28. Flow diagram of subroutine GRADE - grading knot indicators.

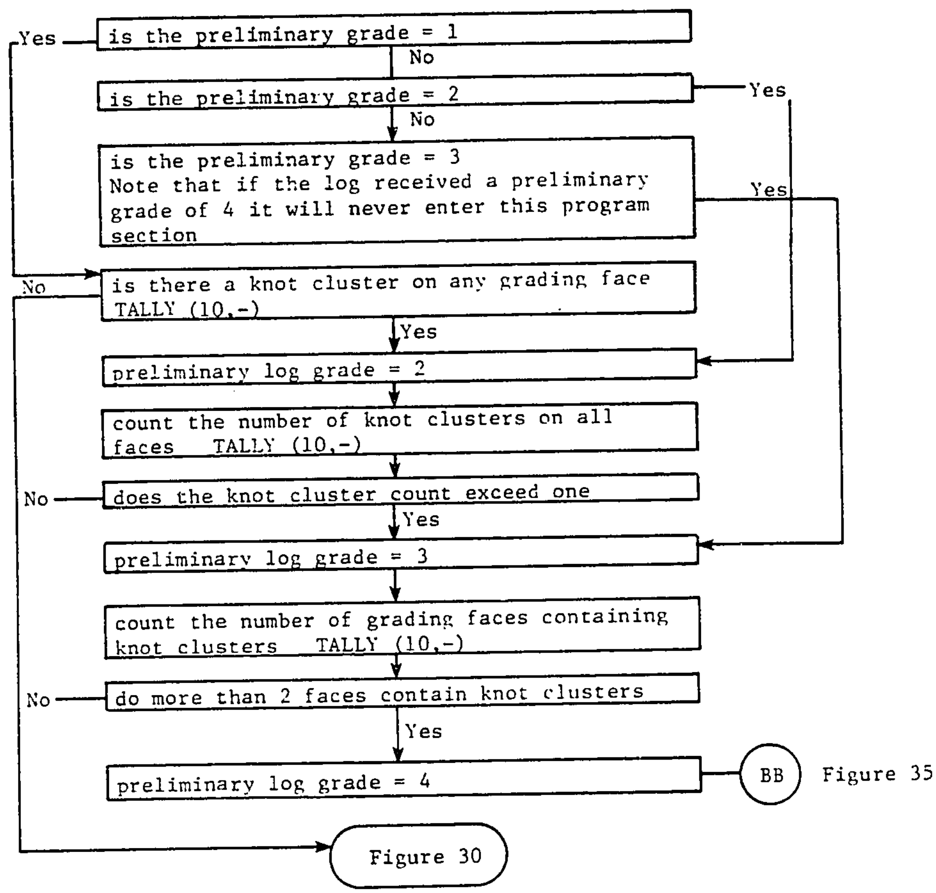


Figure 29. Flow diagram of subroutine GRADE - grading knot clusters.

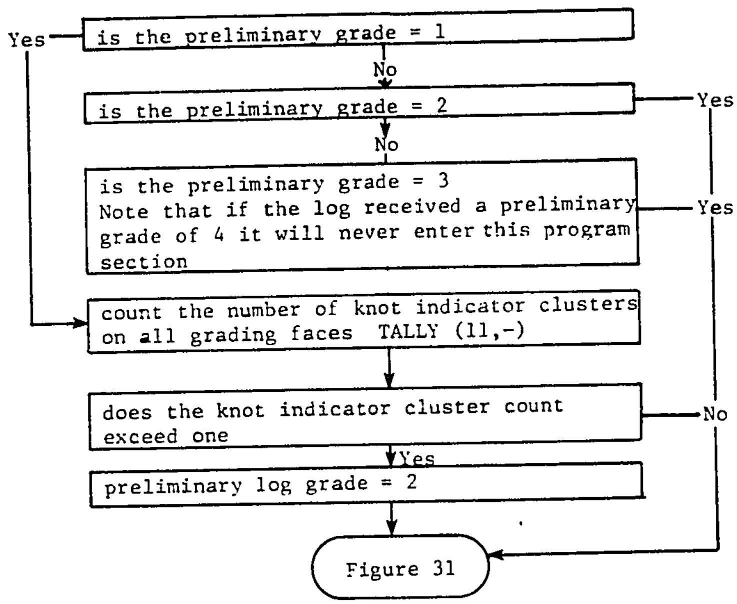


Figure 30. Flow diagram of subroutine GRADE - grading knot indicator clusters.

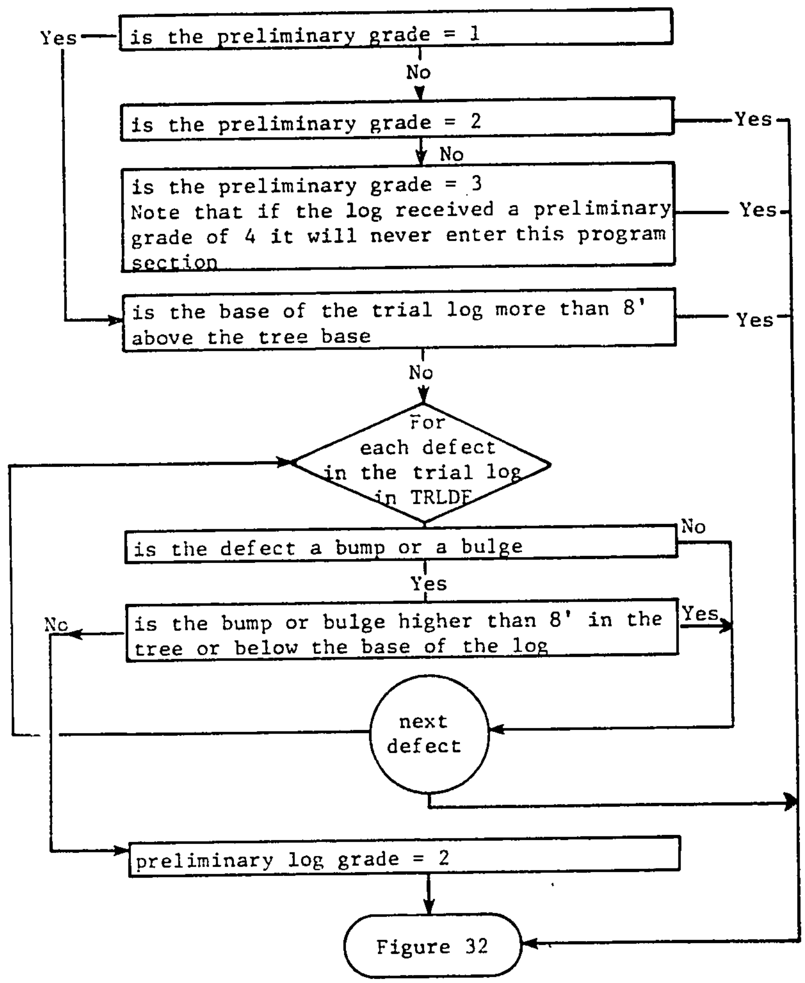


Figure 31. Flow diagram of subroutine GRADE - grading bumps and bulges.

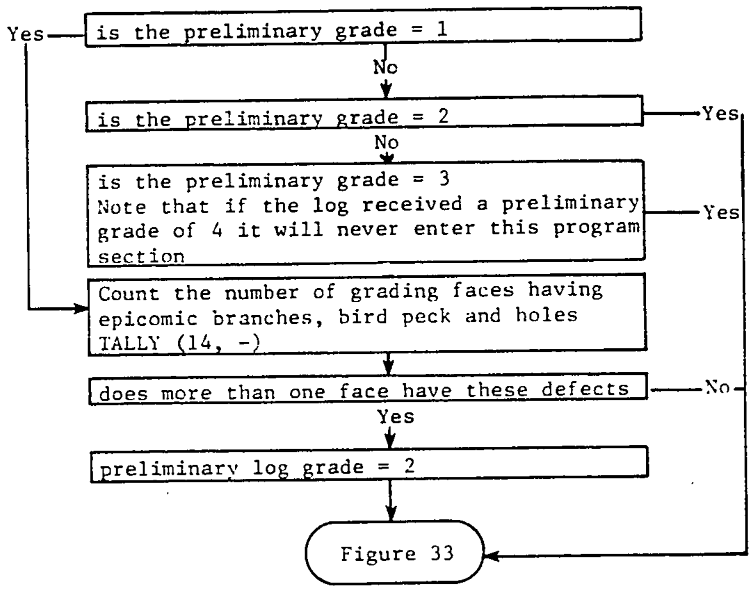


Figure 32. Flow diagram of subroutine GRADE - grading epicormic branches, bird pecks and holes.

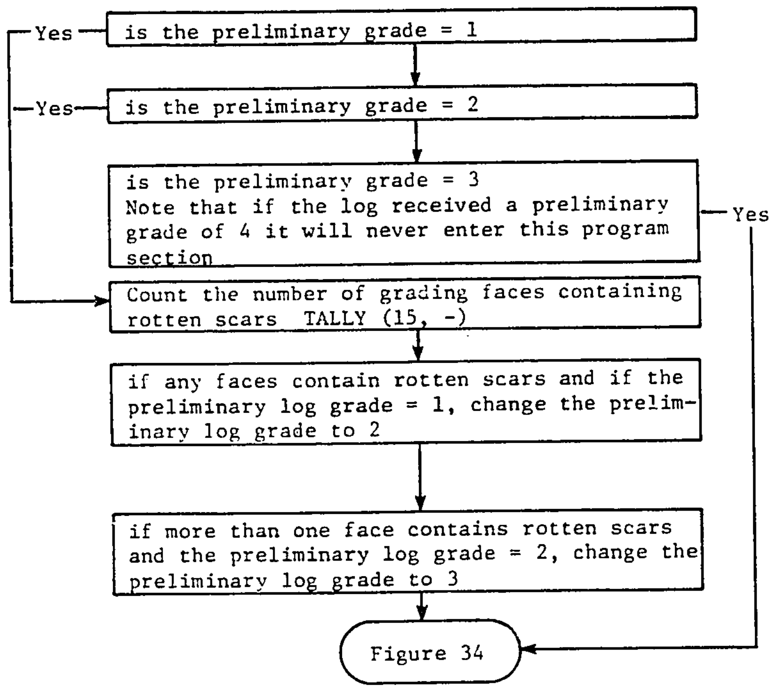


Figure 33. Flow diagram of subroutine GRADE - grading rotten scars.

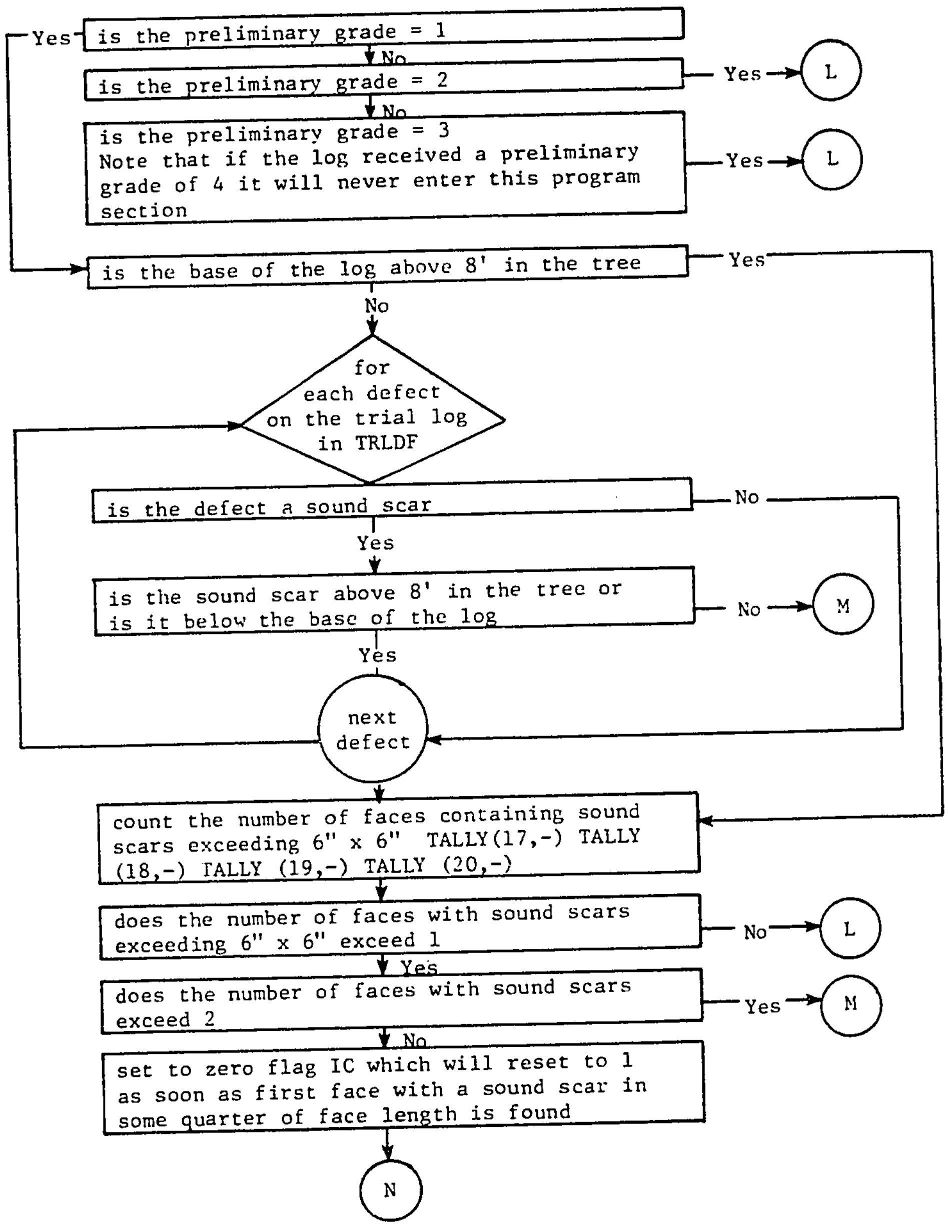
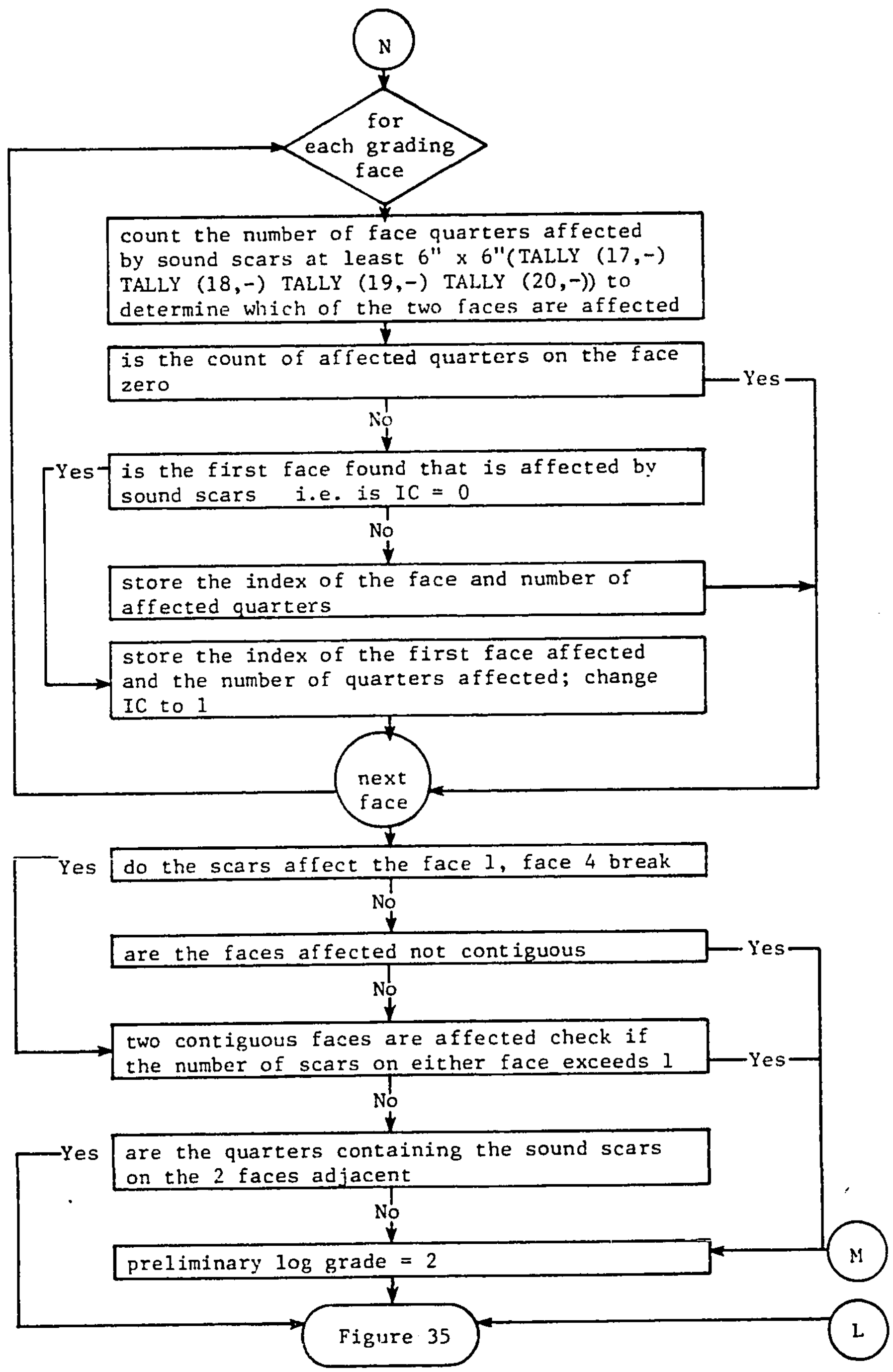


Figure 34. Flow diagram of subroutine GRADE - grading sound scars.

Figure 34. Continued



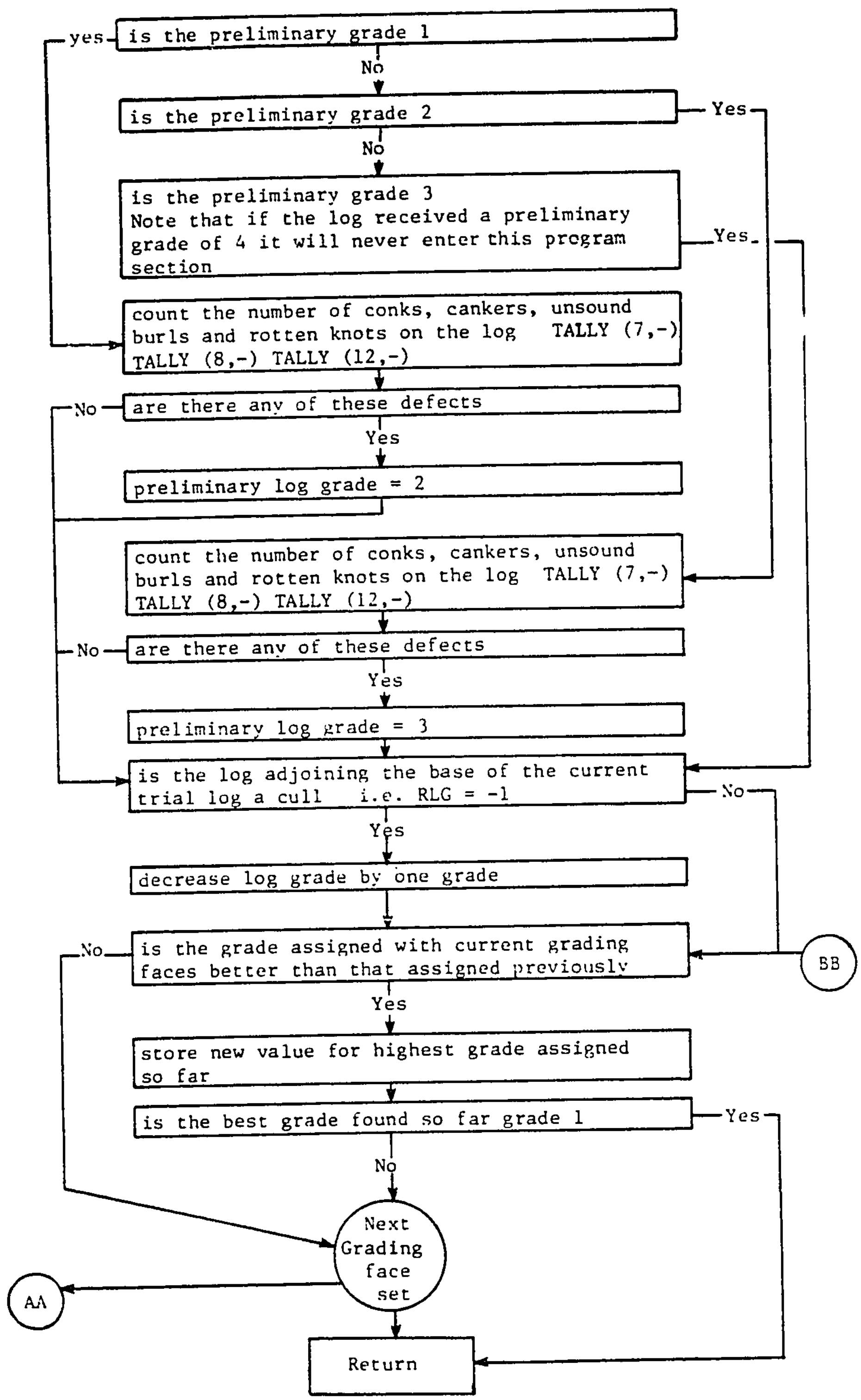


Figure 35. Flow diagram of subroutine GRADE - grading conks, cankers, unsound burls, rotten knots, and adjusting for adjacency to a cull log.

testing is completed, the grade assigned based on the current grading face is compared with the best grade assigned among all preceding grading face sets and the best result stored. Then another set of grading faces is defined and the procedure is repeated.

1. Sound knot conditions. Starting with the prelininary log grade assigned on the basis of examining sound burls, the conditions for sound knots are tested. If the preliminary log grade = 1, the grading rules (Table 8) specify that the log can have only one sound knot which either can be larger than one inch in diameter if it is within six inches of the ends of the log or can be no larger than one inch in diameter if located elsewhere in the log. These conditions are tested by examining the combined count of sound knots less than or equal to one inch diameter, TALLY (1,_), and sound knots larger than one inch diameter within six inches of the ends of the log, TALLY (2,_), and testing if the combined count exceeds one knot. A second test examines if there are any sound knots larger than one inch diameter, TALLY (3,_), TALLY (4,_), TALLY (5,_), other than the one permitted within six inches of the log ends, if it exists. If either of these tests are true, then the log cannot be grade 1 and the requirements of the next lower grade must be inspected. If both of these tests are false, then a log grade of 1 may be retained and

control transfers to testing the next defect category.

If the log cannot be grade 1 or if the preliminary grade based on sound burls is grade 2, then the grade 2 sound knot conditions are tested. The grading rules specify that for grade 2 a log may have an unlimited number of sound knots provided that they are confined to two faces and provided that, if there are any knots larger than two inches diameter, these be confined to the lower or upper half of one of these faces. The first of these conditions is tested by counting the number of faces having sound knots in TALLY (1,_), TALLY (3,_), TALLY (4,_), TALLY (5,_), and testing if more than two faces were counted. If so, the log cannot be grade 2 and control transfers to testing grade 3 sound knot conditions. Otherwise, a further check must be made to determine if there are sound knots larger than two inches in diameter on these two faces and if these are confined to half of one face. This is done by counting the number of lower, TALLY (4,_), and upper, TALLY (5,_), half faces with sound knots exceeding two inches diameter and testing if the count exceeds one. If so, the log cannot be grade 2 and control transfers to testing grade 3 sound knot conditions. Otherwise the log grade of 2 can be retained and control transfers to the next type of defect in the testing hierarchy.

If the log cannot be grade 2 or if the preliminary grade based on sound burls is grade 3, then the grade 3 knot conditions are tested. In this grade the sound and rotten knot conditions are identical and are combined into a single procedure. The grading rules specify that this grade can have an unlimited number of sound or rotten knots but those exceeding three inches diameter must be confined to one face. This provision is examined by counting the number of faces with sound, TALLY (6,_), or rotten, TALLY (8,_), knots larger than three inches diameter and testing if the count exceeds one. If so, the log must be reduced to grade 4, the lowest grade. If this occurs, the testing of the defect categories is terminated, the current grade and all previous grades assigned through testing other sets of grading faces is stored and the procedure involving filling out array TALLY and testing the grade rule provisions is repeated with a new set of grading faces. If the grade 3 may be retained, control transfers to testing the next defect category. The procedure for testing these knot conditions is outlined in the flow diagram in Figure 27.

2. Knot indicator conditions. Knot indicators are a log grade defect only in grade 1 and are allowed in unlimited numbers in grades 2, 3, and 4. Starting with the preliminary log grade based on examining sound knots, transfer is routed to the next defect in the testing hierarchy if the preliminary grade is already 2 or lower.

Otherwise the preliminary log grade is 1 and the knot indicator conditions must be tested. Grade 1 permits an unlimited number of knot indicators but those larger than one inch diameter must be confined to two faces. This condition is tested by counting the number of faces with knot indicators larger than one inch diameter, TALLY (9,_). If this count exceeds two, the log cannot be grade 1 and is reassigned a preliminary grade of 2 before transferring to testing the next defect category. Otherwise the log grade of 1 can be retained and control transfers to testing the next defect category. The procedure for testing knot indicator conditions is outlined in the flow diagram in Figure 28.

3. Knot cluster conditions. Starting with the preliminary log grade based on examining knot indicators, the conditions for knot clusters are examined. If the preliminary log grade is 1, the grading rules specify that no knot clusters are allowed for the log to retain this grade. This is tested by checking if any face has a knot cluster, TALLY (10,_). If so, the log cannot be grade 1 and the requirement for the next lower grade is inspected. Otherwise, the grade 1 may be retained and control transfers to testing the next defect category.

If the log cannot be grade 1 or if the prelminary log grade based on preceding defects is grade 2 then grade 2 knot cluster conditions are tested. This grade permits only one knot cluster provided it is confined to one face. This is tested by counting the total number of knot clusters, TALLY (10,_), and checking if the count exceeds one. If the count exceeds one, then the log cannot be grade 2 and control transfers to inspection of the requirement for the next lower grade. Otherwise the grade 2 may be retained and control transfers to testing the next defect category.

If the log cannot be grade 2 or if the preliminary log grade based on preceding defects in the testing hierarchy is grade 3, then grade 3 knot cluster conditions are tested. This grade permits any number of knot clusters provided they occupy no more than two faces. This is tested by counting the number of faces, TALLY (10,_), containing knot clusters and checking if the count exceeds two. If so, the log cannot be grade 3 and is reduced to grade 4, the lowest grade. If this occurs, the testing of defect categories is terminated, the best of the current and all previous grades assigned to the log by testing other sites of grading faces is stored, and the procedure involving filling out array TALLY and testing the grading rule provisions is repeated with a new set of grading faces. If the grade 3 may be retained, control transfers to testing the next type of defect category. The procedure for testing these knot cluster conditions is outlined in the flow diagram in Figure 29.

4. Knot indicator cluster conditions. Knot indicator clusters are a grade defect only in grade 1 and are allowed in unlimited numbers in grades 2, 3, and 4. Starting with the prelminary log grade based on examining preceding defect categories transfer is routed to testing the next defect category if the preliminary grade is already 2 or lower. Otherwise, the prelminary log grade is 1 and knot indicator cluster conditions must be tested. Grade 1 permits only one knot indicator cluster and it must be confined to one face. This is tested by counting the number of knot indicator clusters, TALLY (11,_), and testing if the count exceeds one. If so, a preliminary log grade of 2 is assigned and control is transferred to testing the next defect category. Otherwise, grade 1 may be retained and control is transferred to testing the next defect category. The procedure for testing knot indicator cluster conditions is outlined in the flow diagram in Figure 30.

5. Bump and bulge conditions. Bumps and bulges are a grade defect only in grade 1 and are allowed in unlimited numbers in grades 2, 3, and 4. Starting with the preliminary grade based on examining preceding defect categories, transfer is routed to testing the next defect category if the preliminary grade is already 2 or lower. Otherwise, the preliminary log grade is 1 and bump and bulge conditions must be tested. Grade 1 allows an unlimited number of these defects in logs or portions of logs located above

eight feet height in the tree but allows none in any part of the log occurring in the first eight feet of the tree. This is tested by first checking if the base of the trial log is above eight feet in the tree in which case transfer is routed to testing the next defect category. If the base of the trial log is below eight feet in the tree, the array containing description of defects in the trial log (TRLDF) is screened to find if any bumps or bulges occur between the base of the trial log and eight feet height. If any of these defects are found in this region, the log is degraded to grade 2 and control transfers to testing the next defect catetory. Otherwise grade 1 may be retained and control is transferred to testing the next defect category. This procedure is outlined in the flow diagram in Figure 31.

6. Epicormic branches, bird peck, and hole conditions. These are grade defects only in grade 1 and are allowed in unlimited numbers in grades 2, 3, and 4. Starting with the prelminary grade based on examining preceding defect categories, transfer is routed to testing the next defect category if the preliminary grade is already 2 or lower. Otherwise the preliminary log grade is 1 and conditions for these defects must be tested. Grade 1 allows an unlimited number of these defects but they must all be confined to one face. This is tested by counting the number of faces containing any of these defects, TALLY (14,_), and

checking if the number of faces exceeds one. If so, the log is reassigned a log grade of 2 and control transfers to testing the next defect category. Otherwise, grade 1 may be retained and control is transferred to testing the next defect category. This procedure is outlined in the flow diagram in Figure 32.

7. Rotten scar conditions. Rotten scars are grade defects in grades 1 and 2 and are allowed in unlimited numbers in grades 3 and 4. If the preliminary log grade is 1 the grading rules specify that the log cannot have any rotten scars. This is tested by counting the number of faces with rotten scars and checking if the count exceeds zero. If so, the log cannot be grade 1 and the requirements of the next lower grade are tested. If the log cannot be grade 1 or if the prelminary grade based on examining preceding defect categories is 2, the grade 2 rotten scar requirements are checked. Grade 2 allows any number of rotten scars as long as they are all confined to one face. This is checked by counting the number of faces with rotten scars and testing if the count exceeds one. If so, the log is reduced to grade 3. After these tests, control is transferred to testing the next defect category. This procedure is outlined in the flow diagram in Figure 33.

8. Sound scar conditions. Sound scars are a

grading defect only in grade 1 and are allowed in unlimited number in grades 2, 3, and 4. If the preliminary grade from preceding tests is lower than grade 1 control is transferred to testing the next defect category. Otherwise, the grade 1 conditions must be tested. Grade 1 permits no sound scars of any size in any portion of the log within the first eight feet of the tree. Above eight feet sound scars larger than 6 inches by 6 inches in size must be all on one face or no more than two faces in any quarter of the log length. The first check in testing these conditions is to determine if the base of the log occurs below eight feet in the tree. If so, the array storing the defects in the trial log (TRLDF) are screened to determine if any sound scars exist between the log base and eight feet. If so, the log is reassigned a grade of 2 and control is transferred to testing the next defect category. Otherwise, further testing to determine if sound scars larger than 6 inches by 6 inches occur. First, a count is made of the number of faces containing these sound scars, TALLY (17,_), TALLY (18,_), TALLY (19,_), TALLY (20,_). If the count exceeds two faces than the log must be degraded to grade 2. If the count is zero or one the log can remain grade 1. In either event control then transfers to testing the next defect category.

However, if the count indicates that two faces contain sound scars, further testing is necessary to determine if the condition that sound scars cannot occur on more than 2 faces in any quarter of the log length is met. This is accomplished by counting the number of sound scars in each face, flagging the faces that have these defects, and storing the number of quarters associated with each face having these scars. Next, a check is made to determine if the faces containing the sound scars are contiguous. If they are not, the log is reassigned a grade of 2 and control is transferred to testing the next defect category. Otherwise, the faces are contiguous and a check is made to determine if the number of quarters of each face with sound scars exceeds one. If so, the log is reassigned a grade of 2 and control is transferred to testing the next defect category. If not, then only one quarter in each face has sound scars and a final test is made to determine if these quarters are contiguous. If not the log is reassigned a grade of 2, otherwise it remains grade 1. In any event control then transfers to testing the next defect category. The procedure in testing sound scars is outlined in the flow diagram in Figure 34.

9. Conk, canker, unsound burl, and rotten knot conditions. None of these defects are allowed in grade 1 or in grade 2 unless the log was rated as grade 1 based on considering all other defects. They are allowed in unlimited

quantity in grade 3 with the exception of rotten knots larger than three inches that must all be confined to one face. This grade 3 condition was tested in conjunction with sound knots. Finally, grade 4 has no restrictions on these defects.

If the preliminary grade based on testing prior defects is grade 1 or 2, a count is made of the number of these defects, TALLY (7,_), TALLY (8,_), TALLY (12,_). If the count is zero, the log retains its current grade; otherwise, it is degraded to the next lower grade. In either event control then transfers to testing adjacency to a cull log. The procedure for testing these defects is outlined in the flow diagram in Figure 35.

10. Adjacency to a cull log. The last log grading test involves checking if the trial log is adjacent to a cull log. If so, and the log is not already grade 4, the log is reduced by 1 grade. This is checked by means of a flag (RLG) which is set equal to minus one in DYNPRO if the top log in the optimal solution adjoining the base of the current trial log is a cull. A cull log is defined as a log having a scaling loss fraction of more than two thirds. This is a technical definition of a cull log and differs from a log that is a cull in an economic sense because it can only be produced at a loss.

After completion of all tests, the final grade for the current grading face set is compared to the best grade obtained in checking all previous sets of grading faces and the highest grade achieved is stored. If this grade is the highest grade, an immediate return to DYNPRO can occur. Otherwise, another set of grading faces is examined. The procedure continues until all grading face sets are examined or until grade 1 is reached after examining a particular set.

These final steps of subroutine GRADE are also outlined in Figure 35.

End Product Recovery

One of the objectives of this study is to allow the bucking model to take into consideration end product and residue recovery and their values. This is appropriate when a firm engages in producing logs and manufacturing them into products rather than selling them on a log market. In this situation it is the total revenue derived from the sale of the end products combined with all of the variable costs of producing and milling the log that determines whether or not a log should be produced for a given mill.

Lumber and residue manufacture from sawlogs. The most recent lumber recovery study for Douglas-fir allows prediction of cubic foot or board foot recovery based on the log scaling diameter and the log grading system used in this study (Plank and Henley, 1976). Plank and Henley (1976) published prediction equations only for the cubic recovery ratio and board foot cubic volume ratio. The cubic recovery equation predicts the percentage of log net volume that becomes lumber on the basis of log scaling diameter. Given the net log volume, its grade, its scaling diameter, and the predicted lumber percentage, the cubic volume of lumber in the log is estimated; the remainder of the log is residue. The lumber tally in board feet can be estimated from the log cubic foot volume and another regression equation which predicts the board foot cubic foot ratio for each log grade as a function of log scaling diameter. Multiplication of the log cubic foot volume and this ratio yields the estimated quantity of lumber in board feet. Plank and Henley (1976) also published tables providing, for each log grade, the mean quantity of sawdust, other woody residue, and lumber grade yield according to log scaling diameter. Rather than incorporate these lengthy tables of raw data means into the model, smoothed curves (Table 14) were fitted to these diameter class means. The lumber grade yield equations predict the percentage of each lumber grade of the total lumber produced in a log of a particular scaling diameter and log grade.

Residues produced in the conversion of a log into lumber include bark, sawdust, and green and dry scrap items. In this study bark residue for every trial log is determined in DYNPRO by subtracting the log volumes calculated from NEWTON and TAPER using diameter insidue and

Table 14

Lumber Recovery Prediction Equations

Equation Form: $Y = a + bX + cX^2$ where X = log scaling diameter, inches.

Y	Log Grade 1			Log Grade 2			Log Grade 3			Log Grade 4		
	a	b	c	a	b	c	a	b	c	a	b	c
Cubic feet of lumber as a % of log volume	51.81	.714	-.010	49.66	.928	-.147	33.33	2.465	-.0421	33.78	2.086	-.0349
Board foot cubic foot ratio	6.41	.0657	-.00101	6.22	.0866	-.00157	4.18	.288	-.00512	4.23	.241	-.00423
Sawdust as a % of residue volume	9.58	1.177	-.0160	14.09	.999	-.0152	6.62	1.899	-.0293	12.24	1.078	-.0156
Other woody residue as a % of residue volume	85.05	-.900	.0128	86.04	-.993	.0147	93.40	-1.900	.0243	88.26	1.160	.0172
Lumber grade yields as a % of lumber volume												
B & Btr Select	5.60	.00369	---	-1.43	---	.00897	-2.13	.210	-.00148	-.632	.0547	---
C Select	-7.14	.927	-.00798	-6.15	.614	-.00295	-3.86	.330	---	-2.61	.273	-.00313
D Select	-1.54	.352	-.00444	-4.15	.526	-.00697	-1.58	.170	---	.126	.000124	---
Moulding	-3.42	.406	-.00525	-5.48	.570	-.00773	-.774	.107	---	.307	-.338	.00884
Factory Select	-3.68	.317	-.00324	-4.27	---	.00248	-.268	.032	---	-1.50	.142	-.00184
No. 1 Shop	-3.91	.330	-.00370	-3.42	.293	-.00262	-4.39	.437	-.00597	-.219	---	.00278
No. 2 Shop	-4.12	.369	-.00447	-4.25	.412	-.00452	-5.55	.600	-.00832	-2.95	.297	---
No. 3 Shop	.52	---	---	-.760	.090	-.00104	-.877	.108	-.00148	.738	.0788	---
Select Structural[1]	66.83	-1.786	.0119	41.53	-.707	---	11.86	.231	-.00842	.851	.236	-.00500
Construction	55.47	-1.804	.0159	53.54	-1.286	.00829	64.34	-1.420	.00694	40.54	-.705	---
Standard	7.41	---	-.00131	22.06	-.580	.00519	22.93	---	-.00502	2.76	.00202	---
Utility	5.74	---	---	7.20	---	.00133	13.82	-.383	.0127	19.21	.279	---
Economy	1.34	---	.000738	2.71	---	.000567	7.34	-.497	.0123	1.62	---	.0000001

[1]Includes 1-inch Select Merchantable lumber.

outside bark. Plank and Henley (1976) provided tabular data indicating the mean quantity of sawdust and other residue derived from converting logs of various scaling diameters and log grades. These data were converted to reflect percentages of total woody residue and were fitted to equations that are also shown in Table 14. In the model, the percentage of each residue is estimated and the percentages, multiplied by the difference between log net volume and lumber volume, provide the estimate of each residue volume.

After the quantity of each lumber grade in board feet and each residue of a log is estimated, the quantity is multiplied by the appropriate lumber or residue price. The sum total is the gross return from the sawlog. The lumber and residue recovery equations and calculation of total revenue derived from processing a log into lumber are incorporated into subroutine LUMYLD. Figure 36 is a flow diagram of LUMYLD.

Veneer and residue manufactured from veneer logs. With minor differences, the procedure used to predict the yield of lumber, lumber grades and associated residues was used in estimating the yield of dry untrimmed veneer, veneer grades, and associated residues. Veneer yield and veneer grade yields from Douglas-fir are based on equations published by Woodfin (1974) and are summarized in Table 15. These equations estimate the percentage of veneer recovery according to log grade and scaling diameter and estimate

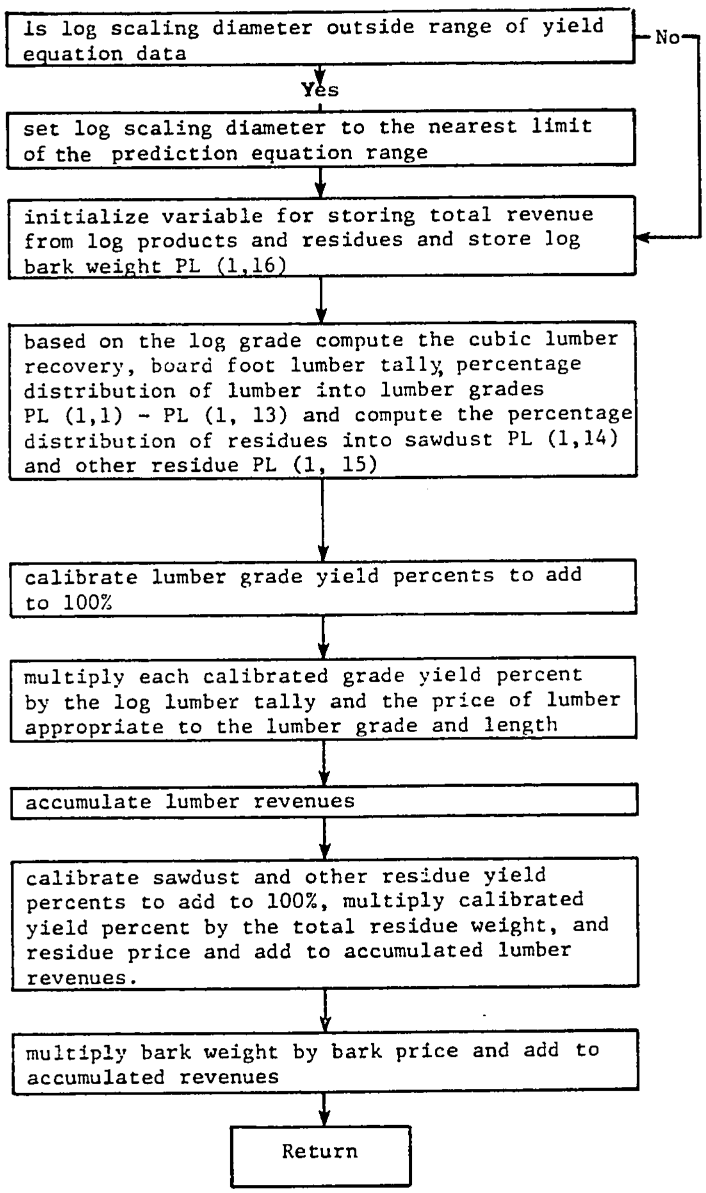


Figure 36. Flow diagram of subroutine LUMYLD.

Table 15

Veneer Recovery Prediction Equations

Equation Form: $Y = a + bX + cX^2$ where X = log scaling diameter, inches.

Y	Log Grade 1 a	Log Grade 1 b	Log Grade 1 c	Log Grade 2 a	Log Grade 2 b	Log Grade 2 c	Log Grade 3 a	Log Grade 3 b	Log Grade 3 c	Log Grade 4 a	Log Grade 4 b	Log Grade 4 c
Veneer fraction of log cubic foot volume	.2493	.0229	-.0004	.2246	.0212	-.0003	.1198	.0293	-.0005	.36	---	---
Square feet of veneer per cubic foot of log volume	8.0083	.7672	-.0121	7.4973	.6965	-.0099	4.5025	.9124	-.0149	11.6	---	---
Veneer shrinkage as a % of non veneer log volume				All grades combined			-1.59	.488	-.00678			
Core shrinkage as a % of non veneer log volume							82.50	-3.06	.0322			
Below grade veneer as a % of non veneer log volume							-7.18	1.19	-.0163			
Spur trim as a % of non veneer log volume							.718	.176	-.00187			
Roundup as a % of non veneer log volume							12.43	---	---			
Green clipping as a % of non veneer log volume							13.96	1.37	-.0116			
Veneer grade yield as a % of veneer volume												
A	-4.3970	.3076	---	-3.411	.2264	---	1.4894	-.1643	.0053	4.6437	-.3976	.0097
A patch	3.9789	.3596	---	-5.6803	.5702	---	4.6036	-.5733	.0178	.7599	-.1870	.0095
B	-1.4637	.2706	---	-1.5941	.2036	---	2.1044	-.1819	.0057	-2.7078	.2050	-.0008
B patch	11.4281	.0981	---	1.6300	.4154	---	-7.1942	.6403	-.0026	-4.8265	.3912	-.0008
C	69.4019	-.9505	---	74.5566	-1.2536	---	82.5624	-3.8282	.0548	13.4055	-.0111	-.0008
D	21.0518	-.0853	---	34.5799	-.1619	---	16.4393	4.0564	-.0810	88.7251	-.0005	-.0014

veneer grade yield as a percentage of total veneer according to log grade and scaling diameter. Woodfin (1973) also published mean residue yields and shrinkage loss for all log grades combined according to log scaling diameter. These yields were converted to reflect percentages of the log volume that did not become veneer and were fit to equations that are also summarized in Table 15.

The estimated veneer grade and residue yields, multiplied by log net volume and appropriate veneer grade and residue prices reflect the gross return from the veneer log. The veneer and residue recovery equations, and calculation of total revenue derived from processing a log into veneer are incorporated into subroutine VENYLD. Figure 37 is a flow diagram of VENYLD.

Pulp recovery. In the model, it is assumed that pulp logs may be processed by a pulpmill that produces unbleached Kraft pulp. Assuming the midpoint of the range of kraft pulp production from softwoods of 48 to 51 percent by weight (Hartman et al., 1974), the following equation was used to predict pulp yield.

$$P = .51*W$$

P = pulp yield, OD tons

W = wood furnish weight, OD tons

This equation is incorporated in subroutine PULP. Revenue is estimated by multiplying the pulp yield estimated by the

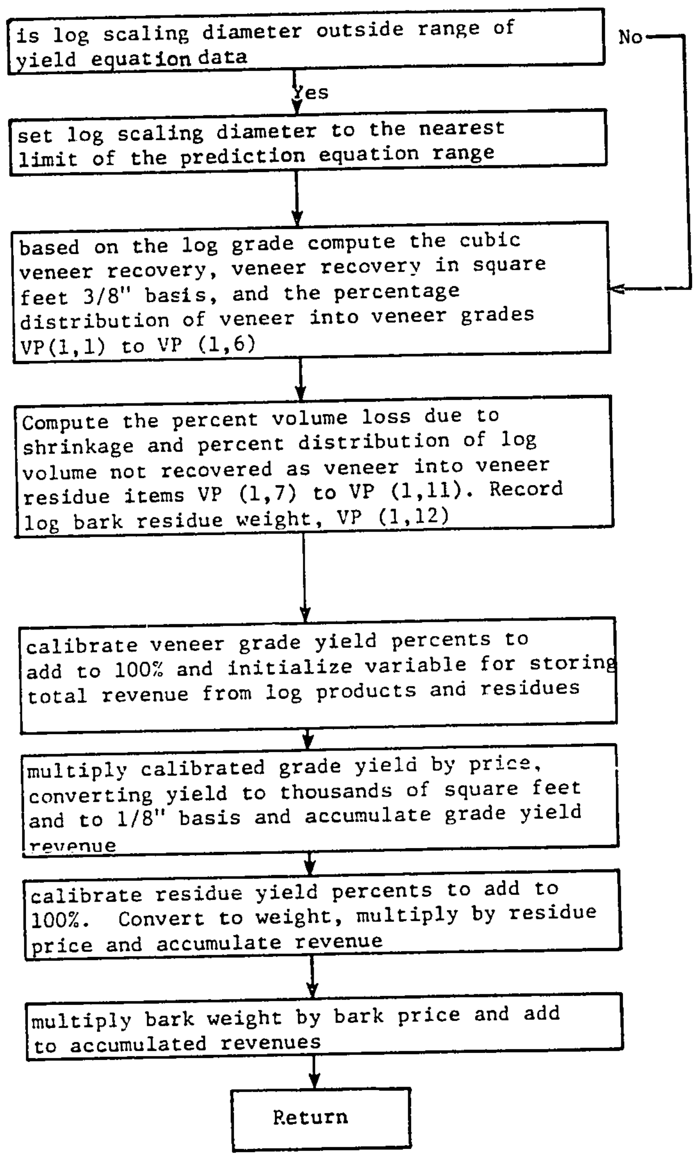


Figure 37. Flow diagram of subroutine VENYLD.

kraft pulp price per oven dry ton.

Chips from fuelwood. If roundwood is to be processed into chips for fuel, it is assumed that the entire log including bark is chipped. Revenue is estimated by multiplying the total weight in oven dry tons by the chip price per oven dry ton.

Process residues. During the calculations of end product recovery from roundwood, the model keeps a tally of process residues in the form of bark, sawdust, and chips. The model does not allow for process interactions whereby residues from one process are transferred to another for further processing. Thus veneer cores produced by VENYLD are not submitted to LUMYLD for processing into lumber. Presently the model only allows the user to enter prices (positive or negative) for each residue item in each process. These prices can be used to indicate differences between processes in creating and disposing of residues.

Estimation of Variable Costs Associated with Bucking and the Calculation of Conversion Surplus

As described in the section "Criterion for Decision Making," the model uses the conversion surplus criterion as the basis for optimization. This criterion expresses the difference between end product sales revenue and the variable production costs. The model has been designed to provide a great flexibility in defining the framework of this criterion. The model provides for selling logs in log form on the basis of log scale, selling finished products after processing logs through manufacturing facilities, or comparing these alternatives. Which of these choices is used depends on whether log price entries in array DATAL or the end product prices are zero. If the price entry for a particular log type and grade is zero the model assumes that the log will only be processed through the appropriate mill. If nonzero log prices are given, then it is assumed that one alternative is to sell the log in roundwood form. Similarly, if zero end product prices are given, the model assumes the log will only be sold in roundwood form. If nonzero end product prices are given, the model assumes that one alternative is to mill the log. When sold in log form, DYNPRO estimates the sales revenue for a log of particular grade, end use, and dimension by multiplying the net log scale in cunits (units of 100 cubic feet) by the appropriate log price. When logs are to be processed through a firm's mill, the end product gross revenue is estimated by LUMYLD, VENYLD or PULP based on lumber, veneer and pulp recovery yields and appropriate prices for these items and associated residues. Premiums for certain types, lengths, and grades of logs are allowed since log prices are entered for every log option and lumber prices entered for every sawlog size. The remaining step in deriving the conversion surplus value for a particular log is the estimation of the variable costs of log production and conversion.

Subroutine COST determines the variable cost associated with the bucking decision. DYNPRO subtracts the variable cost from the gross revenues of either log or end product to obtain the log conversion surplus value. However, the items to be included in the variable cost calculation depend on where bucking is performed in the stream of manufacturing activities and at what point the log or end products are sold. To provide flexibility, all cost items that could be considered as variable costs are included in subroutine COST. These items include stumpage, bucking, limbing, skidding, loading, hauling and unloading, and milling. The model user is provided a means through data input for selecting which of this list of cost items are to be considered as variable costs. To do this, the user must supply two pieces of information for each of these items.

1. A binary variable indicating whether the cost item is a variable (binary variable = 1) or a fixed cost (binary variable = 0). With this technique, all cost equations are multiplied by the binary variable entry provided by the user. If the cost item is a fixed cost in a particular situation, the binary variable is zero hence cost item is zeroed out of the conversion surplus criterion. If it is a variable cost, the binary variable is one and the

cost item remains part of the criterion.

2. For each cost item with binary variable equal to one, the appropriate cost rate. For cost items with the binary variable equal to zero the cost rate may be entered or left blank.

This technique was chosen because it allows flexibility in applying the model to different situations such as bucking at the stumpsite, at the roadside landing, at a centralized merchandiser, or at the mill. The user simply designs the system through the binary variables and specifications of the appropriate cost rates.

The total variable cost is based on the formula

$$TVC = \sum_i B_i C_i U_i$$

TVC = total variable cost

B_i = binary variable associated with the i-th cost item (= 0 to exclude, = 1 to include)

C_i = the cost per unit of the i-th cost item

U_i = the number of units produced

Since the bucking model proceeds by analyzing each individual log possibility at each stage, the unit of valuation for log production and conversion costs should be based on log and individual tree parameters that influence the cost of producing and processing a given log. This is not always possible because published studies generally do not provide information at the level of detail that would be desired for some of the cost items.

Stumpage. Stumpage may or may not be a variable cost depending on the method of stumpage payment. If stumpage is paid on a log scale basis it should be treated as a variable cost since it is paid only for the volume in each log that is removed. The model is presently designed to deal with this situation when stumpage is paid on the basis of net log volume expressed in cunits (units of 100 cubic feet). If stumpage is paid on a lump sum basis it is shared by all trees and is incurred regardless of how many logs or how much log volume is actually removed. In this case stumpage is a sunk cost and is irrelevant to the bucking decision. The user must decide if stumpage payment is relevant to the bucking decision. If so, the binary variable is entered as a one and the stumpage price is entered in dollars per cunit.

Bucking and limbing. In many published studies, the activities of bucking and limbing are aggregated with other actions such as time spent locating and walking to the tree, clearing obstacles from the felling site and felling. In such an aggregation some of these items are associated with sunk costs and some with variable costs. As a result studies of this type are not useful in making bucking decisions.

Theoretically, bucking and limbing should be considered as separate activities. Limbing may not be a variable cost of log production if it is conducted on the whole tree prior to bucking. This would occur in logging systems where mechanical tree length limbing is conducted or if the entire tree were power saw limbed before the commencement of bucking. In these cases limbing is a sunk cost borne by the tree and is incurred regardless of the number of logs that are produced from it.

In cases where bucking and limbing activities are conducted simultaneously, these items are incurred only if the decision is made to produce the log and hence they are variable costs. In theory, the total time incurred involves three major time elements. First, a time element associated with walking along the log, measuring, and clearing obstacles such as brush. This element would depend principally on the log length and is likely to be fairly constant per lineal foot of log length in a given stand. Another time element is associated with the branchiness of the log and influences limbing time. This element would depend on the log length and number and size of branches encountered. This element may perhaps be simplified to a description of the relative position of the log along the stem and the log length. The third time element is the time spent in making the bucking cut and depends on the stem diameter at the cut point.

This approach would be ideal in the model because it would allow associating higher costs with those logs that are more difficult to limb and buck. Generally bucking time per cut would be expected to decrease with decreasing diameter. Thus the cost of making a cut would tend to diminish as smaller diameter upper stem logs were produced. On the other hand, limbing time and cost would tend to be small near the base of the tree and high toward the top. The interaction of these cost items would have an influence in determining the number of cuts to make in a tree and in locating the marginal log. Although the writer is aware of proprietary studies that treat bucking and limbing from this detailed point of view, a review of published bucking studies and an extensive survey of delimbing (Dunfield, 1971) produced no information that could be used to quantify these bucking and delimbing parameters. Research should be undertaken to quantify these and other factors that may be important in limbing and bucking and to determine the influence of differences in the logging environment such as species, brushiness, terrain, time of year, method of payment, and type and condition of equipment used.

Since no studies of this nature were found, an attempt was made to adapt existing studies of felling, bucking and limbing which predict the overall time per tree or per unit of volume. Adams (1967), the Bureau of Land Management (B.L.M., 1974) and Sessions (1979) work with a bucking and limbing time equation where time per tree is based on the tree dbh and the number of bucking cuts after felling. Unfortunately, this equation cannot be used or adapted to the model because its use depends on knowing in advance the total number of bucking cuts in the tree while this is what the model is attempting to determine. Furthermore there is no meaningful way to segregate bucking from limbing such that the model user could have the model consider limbing as a sunk cost and bucking as a variable cost. In another study, Forster and Callahan (1968) expressed limbing time per tree as a function of stump basal area and merchantable height. However their equation cannot be used since it was derived for hardwoods and it does not provide a basis for associating limbing cost with individual logs.

Since no satisfactory detailed approach was found, one alternative is to use average bucking and limbing cost per cunit of net log scale. Since bucking and limbing are generally combined on this basis (B.L.M., 1974) and would be impossible to segregate, it would be possible to set the binary variable for limbing equal to zero and to interpret the bucking item to mean the combination of bucking and limbing. One criticism of this approach is that it does not allow for distinguishing between large logs near the base of trees with low unit costs and small branchy logs near the top with high unit costs. It also fails to take into account the higher cost of bucking more short logs as opposed to few long logs from a tree.

One method that incorporates sensitivity to the number of logs is to assume under a given set of stand conditions that a bucker will produce a relatively stable number of logs per day. Dividing the bucker's daily cost by an estimate of this piece rate yields a constant cost per log. In this approach, bucking cost increases in direct relationship to the number of bucking cuts or logs produced in a tree. In the model it is presently assumed that this is a valid approach to the combined bucking and limbing cost. The user must enter a binary variable of one for either bucking or limbing and associate with it an estimated cost per log. This cost per log could be varied to reflect general differences between stands or buckers.

Skidding. Although it is known that small logs are more costly to skid than large logs, most studies have produced equations that relate skidding time and cost to the volume per turn, distance, method of logging, terrain, stand conditions plus other human and environmental factors. There is no way to meaningfully convert equations from these studies to reflect individual log differences. The use of an average skidding cost per unit is not sensitive enough to differences in log size that are important in determining break-even and unprofitable logs.

An alternative method for assigning skidding cost is to assume that the number of logs skidded per day is relatively constant. This assumption would lead to a constant skidding cost per log, regardless of its size. This assumption is reasonably valid since a skidder or yarder will often handle nearly the same number of pieces per turn and produce nearly the same number of turns per day. For example, grapple yarders normally handle one log per cycle and choker equipped equipment normally handle one log per choker. For a given crew organization, method of payment, and timber conditions the "piece count" is quite stable. This can be observed in the frequency distributions for several logging systems presented by Dykstra (1975). These distributions indicate that predominantly the same number of logs per turn were produced by each system. Nott (1976) in a study of cable yarding machines concluded "yarding production varied primarily as a function of a comparatively stable parameter--piece count per day. Regardless of piece size, this variable remained relatively constant." In the model it is assumed that the appropriate skidding cost per log will be entered when skidding is a variable cost item in making the bucking decision.

Loading. Studies by Briggs (1973) and Marcellus (1973) of hydraulic log loader operations in Western Washington found that longer time is required to load a truck with smaller size logs. This conclusion was also reached by Smith and Tse (1977). Marcellus (1973) expressed pure loading time for in-woods loading by a contract logger of standard eight-foot bunk on-highway trucks as

$$\text{time, minutes} = 77.35 - 24.25\ \ln(P) + .55(B) + .00012\ (S)(P)$$

where P = average diameter of logs in the load

B = number of sorting set asides during loading

S = load scale, Scribner board feet

Other activities while the truck was on the loading stand such as truck preparation and personal and operational delays averaged 10.6 minutes. The average time the loader spent waiting for the next truck was 12.7 minutes (Briggs, 1973). Combining the equation estimates of pure loading time with these estimates reflects the total loader cycle time per load. This time, expressed in hours and combined with the typical load volumes represents the loader productivity in volume per hour. Dividing the loader machine rate per hour by the estimate of hourly productivity gives an estimate of loading cost per unit of log volume which is applied to the net scale of log in the model. The net log scale used in the Marcellus equation is expressed in cunits hence the user must convert from Scribner to cunits (Hartman et al., 1974). Unfortunately, this approach does not adequately reflect the changes in loading cost that should be associated with changing log size in a tree.

Loading by most log loaders is a single piece handling system. In a given type of timber, production is largely dependent on loading cycle time which includes the time to load a truck to capacity with logs of a particular overall average diameter and the time between trucks. Under these circumstances, number of loads per day, number of logs loaded per day and loading cost per piece would be fairly constant. In the model, it is assumed that, if loading is a variable cost item, the user will enter the appropriate cost per log.

Hauling and unloading. These two activities were combined since unloading generally occupies a small fraction of the total truck cycle time and no references were found that provided details on unloading operations. Generally, in the Pacific Northwest, the entire load is removed by mill yard machinery in one single operation which usually requires only a few minutes. In this study, it is assumed that the user will input the cost per cunit of net log scale appropriate to the truck size and haul conditions. Since hauling and unloading involve all logs simultaneously, differences due to individual log dimensions are relatively unimportant.

Chipping. In the model, if pulp logs and fuel bolts are not sold in roundwood form, they are assumed to be processed through a chipping operation. Fuel chips are sold on the basis of oven dry weight in tons while it is assumed that pulp chips enter a kraft process and are pulped. The chipping cost per cunit of log scale must be entered if either of these log types are to be chipped.

Milling. If milling of logs into end products is considered, the cost of milling must also be entered. In the model, it is assumed that a veneer mill and sawmill cost, including all activities from log yard through marketing, is entered. It is assumed that these costs are entered per cunit of net log scale. In processing pulp and fuel logs it is assumed that chipping cost is entered per cunit of net log scale. Pulping cost is entered per ton of pulp produced on an oven dry basis.

Details for entering into the model the binary codes and cost rate data for each cost item are described in section "Data Input." The basis for estimating the cost associated for each production activity could be easily changed by substituting the appropriate statement in subroutine COST and redefining the unit cost basis for cost data input.

In summary, it will pay to buck and use any section of the tree for which the gross revenue will at least cover the variable costs of conversion. Logs having a surplus above direct or variable costs will help defray fixed costs and contribute to profit. The most profitable use of a particular log will be to place it in the end use providing the highest conversion surplus. Whether or not the conversion surplus indicated enables the firm to cover the fixed costs and provide a suitable profit depends on the magnitude of the fixed costs and the level of profit desired by the owners of the firm.

Chapter 5

A HYPOTHETICAL APPLICATION OF THE MODEL

Log Constraints

Previously, it was noted that the model utilizes two forms of data, a description of the tree and a description of the physical and economic setting in which bucking occurs. Except for dbh, total height, stump height and a few other tree descriptors, most of the tree data is in the form of descriptions of external defects that are read from a data file and descriptions of scaling defects submitted on punched cards when these defects are present.

The description of the physical and economic setting of the problem must be provided by management. This information involves a description of each log possibility including the log target length, double end trim, range of acceptable small end diameter, and acceptable amount of sweep, crook or rot. Management must also provide information on end product recovery for logs processed through its mills, log and end product prices and costs. It will be assumed in this example that the end product recovery data based on the Douglas-fir studies conducted by the U. S. Forest Service Pacific Northwest Forest and Range Experiment Station are appropriate to the hypothetical firm. Data from these studies is programmed into subroutines LUMYLD and VENYLD. It will be assumed that management is interested in producing logs for veneer, lumber, kraft pulp and fuel markets. Veneer logs have a target length of 8 feet and a 6 inch trim allowance on each end. The smallest veneer log diameter acceptable is 18 inches and the largest diameter, limited by the lathe capacity, is 48 inches. Logs will not be accepted for veneer production if the diameter of internal rot exceeds 14 inches, the maximum rot diameter that can be held by the lathe chucks, or if they contain a deviation from sweep or crook exceeding 4 inches.

Sawlogs are acceptable for sawmilling in lengths of 8, 10, 12, 14, and 16 feet. They must have a 3 inch trim allowance on each end, must be at least 10 inches in diameter and cannot have a total scaling loss due to internal defects, sweep, and crooks exceeding 70 percent. Pulplogs are desired in 8 foot lengths, must be at least 6 inches in diameter and cannot have a scaling loss due to internal defects exceeding 90 percent. Fuel logs are desired in 4 foot lengths and must be at least 4 inches in diameter.

Considering these specifications, the largest value for which all final lengths, including trim, are an integer multiple is 0.5 feet. This value will be entered in the model as the dynamic programming stage interval, STGL.

Economic Data

Prices

In this example, assume that the manufacturer wishes to consider the option of selling logs in roundwood form as well as processing them through the appropriate manufacturing facility.

Prices for each lumber grade were derived from data developed by Westercamp (1973) in a log allocation study. Lumber prices, which he expressed in dollars per cunit of log input, were converted back to the original prices per thousand board feet lumber tally. These were obtained from the July 1973 report of the Western Wood Products Association (1973). These prices were arbitrarily adjusted to reflect length differentials. The prices derived from Westercamp's data are assumed to represent the prices for 16 foot length lumber. Prices for 14, 12, 10, and 8 foot lumber were arbitrarily assumed to be 85, 95, 90, and 99 percent, respectively, of the price for 16 foot lumber. Prices for sawdust and chip residue from lumber manufacturing were \$7.25 per oven dry ton and \$18.00 per oven dry ton (Austin, 1973; Westercamp, 1973). For purposes of this example, bark residue is assumed to have a price of \$1.00 per oven dry ton in 1973.

Prices for each veneer grade were also derived from data presented by Westercamp (1973) who converted prices reported by Crows' publications (Crows, 1973) into dollars per cunit of log input. His values were converted back to price per thousand square feet of veneer on a 1/8 inch thickness basis. Prices for the A and B patch grades of veneer are assumed to be the same as the prices for grades A and B. All veneer process residues except cores and bark are assumed to be sold in chip form at a price of $18.00 per oven dry ton (Westercamp, 1973), cores are assumed to be sold to a stud mill for $8.00 per cunit, and bark is assumed to have a price of $1.00 per oven dry ton.

Unbleached kraft pulp is assumed to have a price of $150.00 per ton (Holt, 1972) and chips from fuel logs are assumed to have a price of $15.00 per oven dry ton in 1973.

Roundwood log prices for veneer and sawlogs in each of the log grades in the four grade system used in this study were estimated from average prices reported by the Washington State Cooperative Extension Service (1973) for Douglas-fir logs graded under the peeler-sawlog grading system. The peeler-sawlog grading system prices were converted to prices for the four grade system by means of a frequency distribution comparison of these log grading systems (Burck, 1974). These prices were assumed to be the prices for 16 foot sawlogs and were arbitrarily adjusted to reflect a differential between veneer and sawlogs and to reflect differentials between sawlog lengths. Veneer roundwood log prices were assumed to be 5 percent greater than the 16 foot sawlog price. Prices for shorter sawlog lengths were based on the same arbitrary percentages used in creating lumber price length differentials. The 1973 prices for pulp logs is assumed to be $30.00 per cunit and for fuel logs $20.00 per cunit.

<u>Costs</u>

In the example, stumpage is considered as a fixed rather than a variable cost. The cost for bucking and limbing is based on an average bucker rate of $150.00 per day, including overhead and chainsaw (Sauder and Nagy, 1977). This was converted to $2.06 per log assuming production of 32 cunits per day and 0.44 cunits per log. This cost was adjusted to a value of $1.34 per log in 1973 dollars by means of the wholesale price index for all industrial commodities. The cost of skidding is based on a highlead yarding rate of $923.52 per day including laborers and overhead (Sauder and Nagy, 1977). Assuming production of 250 logs per day this translates into $3.69 per log or $2.40 per log in 1973 dollars. Loading cost is based on a rate of $72.15 per hour including operator and overhead (Sauder and Nagy, 1977). Using average values of 22.5 logs per load on standard 8 foot bunk highway trucks and 34 minutes loader cycle time including loading time, delays and wait time between trucks (Briggs, 1973; Marcellus, 1973), the cost per log is $1.82 or $1.18 in 1973 dollars.

Estimation of the cost of hauling logs by truck involves consideration of the truck cycle which includes time spent loading, travel full and empty, unloading time, delays due to loading and unloading queues, and personal and operational delays. The total time at the loader landing was estimated from an average "pure" loading time for standard 8 foot bunk highway trucks of 10.7 minutes plus estimates of average truck preparation and landing delay time of 10.6 minutes (Marcellus, 1973). Travel time can be estimated by multiplying the following average empty and loaded travel speeds for each road type (Smith and Tse, 1977) by the mileage of the road type.

	Minutes per mile	
Road type	empty	loaded
on sale	2.67	3.77
secondary (incl. dump)	2.27	2.48
main haul	1.37	1.60

Assuming a one way trip consisting of 3 miles of on sale travel, 10 miles of travel on secondary roads and 30 miles on main haul roads, round trip travel time is 155.9 minutes. Smith and Tse (1977) found that operational delays and delays in queues took another 44.0 minutes. An unloading time of 18.0 minutes was imputed from Smith and Tse's data by subtracting all other time elements from their total time estimates. Combining these estimates, the truck cycle is 239.2 minutes or about 4 hours. It is assumed that a log truck will make 3 such trips per day and averages 10 cunits per load (Marcellus, 1973). Under these conditions the truck rate including the driver and overhead is \$100.90 per trip (Smith and Tse, 1977) which converts to \$10.09 per cunit or \$6.51 per cunit in 1973 dollars.

Manufacturing costs for sawmilling, veneer manufacturing, chipping and kraft pulping are taken from Westercamp's (1974) study. He estimated a 1973 sawmilling cost of \$16.70 per cunit of log input (BLM, 1973), a veneer manufacturing cost of \$20.00 per cunit of log input (American Plywood Association, 1972), a kraft pulping cost of \$27.00 per ton of pulp produced (Guthrie, 1972) and assumed a log chipping cost of \$8.00 per cunit of log input. Table 16 presents the complete data deck submitted to the model for tree number 59. The external defect data are read from a disk file.

Model Verification

Verification, the process of determining if the model is producing the desired behavior, involved verifying the model structure and logic and the data base inputs. Successful verification ultimately depends on the programmer's familiarity with the system being modeled and his thoroughness in examining the details of the model's behavior and response. Verifying the model structure and logic involved carefully flow charting model steps, checking that the FORTRAN statements properly translated these steps into

Table 16

Sample Data Deck for Tree 59 Considering External Defects and Comparing the Sale of Logs for Roundwood with Processing them through the Firm's Mills

```
  1    8   .5   28   31    1
  1    1   8.   1.  18.  48.         91.        84.        72.       67.
  2    1  16.   .5  10.1000.         87.        90.        69.       64.
327  288  242  230  200  200   200  200   197  172   162  130   62 7.25   18.   1.
  2    1  14.   .5  10.1000.         74.        68.        59.       51.
278  245  206  196  170  170   170  170   167  146   138  110   53 7.25   18.   1.
  2    1  12.   .5  10.1000.         83.        75.        66.       61.
311  274  230  218  190  190   190  190   187  163   154  124   60 7.25   18.   1.
  2    1  10.   .5  10.1000.         78.        72.        62.       58.
294  259  218  207  180  180   180  180   177  155   146  117   56 7.25   18.   1.
  2    1   8.   .5  10.1000.         86.        79.        68.       63.
324  285  240  228  198  198   198  198   195  170   160  129   61 7.25   18.   1.
  3    1   8.    0   6.1000.         30.
  4    1   4.    0   4.1000.         20.
 35   35   30   30   15   10     8   18    18   18    18    1
150
 15
14.   4.  .70  .90
  C    1    0    1    1    1     1    1     1    1
  0 1.34 1.34 2.40 1.18 6.51 8.0016.7020.0027.00
      59      38.2      138        138         2          128  123
  1  10.
```

computer form, and printing out (IOUT = 2 or 3) very detailed stage by stage calculations and checking the results with a pocket calculator. This procedure, combined with the error check and tracing features of the MNF compiler (Schofield, 1977) isolated conceptual logic errors and programming errors.

The best technique devised for verification involved starting with a very simple tree description and simple set of log specifications and systematically increasing the problem complexity in a way that allowed testing a new subroutine after others used by the simpler case were checked. Comparing detailed printouts by the model with hand solutions was about the only way to discover and identify the causes of errors and check if subsequent changes were correctly incorporated. This is a time consuming and costly process but is the best insurance against mistakes in the model.

The structure of the model should be considered verified on the basis of the detailed checks performed. This judgment is reserved for the trees tested in this study. In spite of the extensive checking performed it is possible that a tree may be found in the future with unforeseen conditions that will cause an error. As a larger number of trees are successfully processed by the model, confidence that all components and conditions are performing correctly will be gained. A larger scale study is needed to collect information for a wider variety of trees to further verify the model. It should be pointed out that the use of the detailed printout options (IOUT = 2 or 3) should not be routinely requested. These options produced 10000-15000 lines of output for the larger trees. Normally, IOUT = 0 or IOUT = 1 should be used.

Data base verification involved checking the acquisition of external defect descriptions from the digitizer. This was accomplished by comparing the defect descriptions produced by program DIG with the original log diagram sheets, recording any errors and replacing the appropriate defect card with corrected information.

Validation and Results for the Hypothetical Example

Validation

Validation consists of comparing the model results with actual performance of log buckers. This cannot be accomplished for several reasons. First, there is no background information on the test trees indicating the instructions given for bucking them. According to Lane et al. (1973) the study trees were felled and bucked according to normal practice of each study mill and these practices were not recorded. Another difficulty arises from the fact that the log diagrams provide no useful basis for reconstructing crook, sweep, or internal defect in the tree. In many instances, sweep may have been eliminated by bucking short straight logs. The only data on these scaling defects is the quantity of defect remaining in the finished log and this is insufficient to reconstruct how the tree appeared before bucking. Even if the bucking instructions and complete defect data were available, validation of the model would be difficult since the model would undoubtedly yield a different bucking pattern than that produced by the original bucker unless the bucker accidentally stumbled upon the optimal pattern. In actual comparisons, the model is more likely to point out discrepancies in actual performance than it is to agree. It is for this reason that verification of the model is critical.

With the group of test trees there is no way to reach meaningful conclusions concerning validation except to encourage well designed field studies comparing the model with actual practice where reasons for discrepancies can be uncovered and either attributed to some factor(s) not yet included in the model or to poor work by buckers.

Results for the Test Trees

Results for the trees are presented in order of increasing dbh. The smaller trees tend to have simpler solutions due in part to the complete lack of feasibility of some log possibilities and the relatively short portion of stem length where others were feasible.

The results in the solution summary tables were prepared from more detailed solution tables printed by the model. Table 17 presents the solution table printed for tree number 59 when analyzed with the data portrayed in Table 16. Proceeding from left to right, this table portrays the log type (1 = veneer log, 2 = sawlog, 3 = pulp log, 4 = fuel log), the log grade, large end and small end inside bark diameters of the log, the target and trim length of the log, the gross log volume inside bark in cubic feet and board feet, the gross weight of the wood and bark, the total percent loss due to internal defect, sweep, and crook to be applied in deriving net volume, the conversion surplus of the log and its allocation to the roundwood market or to the firm's own mill. The optimum mix of logs portrayed in the list are ordered from the top to the base of the tree. The solution also prints the total conversion surplus of this optimal solution and indicates the stage number corresponding to the location of the small end of the top log.

Another more detailed table portraying stage-by-stage optima can also be obtained. This table will be discussed in a later section on sensitivity analysis.

Results from tables such as Table 17 have been summarized further into a few key parameters: the pattern of logs obtained and their grades and use, their total conversion surplus, and their total cubic volume. This allows compression of results from many tables into smaller tables facilitating comparisons.

Table 17

Optimal Solution Table for Tree 59 Using the Data Portrayed in Table 16

TREE NO.	CUBIC VOL. TREE	CUBIC VOL. STUMP	O.D. TONS TREE	O.D. TONS STUMP	
59.	407.	15.	5.61	.22	INCLUDING BARK
	337.	13.	4.71	.18	WITHOUT BARK

OPTIMUM TREE VALUE OF 338.99STARTS AT STAGE 215

LOG TYPE CODE	LOG GRADE	DIAMETER IB LARGE	DIAMETER IB SMALL	LENGTH TARGET	LENGTH TRIM	GROSS VOLUME CF	GROSS VOLUME BF	GROSS WEIGHT WOOD	GROSS WEIGHT BARK	PERCENT CULL	TOTAL VALUE DOLLARS	LOG MARKET=1 GR MILL=0
2.	4.	14.0	10.2	16.0	.5	13.4	56.0	.19	.04	0	3.68	0
2.	4.	17.7	14.0	16.0	.5	22.9	123.2	.32	.07	0	10.60	0
2.	3.	21.4	17.7	16.0	.5	34.6	190.4	.48	.11	0	29.96	0
2.	3.	25.0	21.4	16.0	.5	48.4	302.4	.68	.16	0	48.41	0
2.	1.	28.5	25.0	15.0	.5	64.5	403.2	.90	.21	0	78.93	0
2.	2.	30.4	26.5	8.0	.5	40.2	250.0	.56	.13	0	45.67	0
2.	1.	33.9	30.4	16.0	.5	93.0	648.0	1.30	.30	0	121.74	0

<u>Tree 73</u>. This tree is 87 years of age, 110 feet tall and 17.1 inches in dbh. It was cut with a 1.5 foot stump and the log diagrams indicate a lack of internal defect. It has 140 defects that are relevant to the log grading rules. Table 18 presents a volume summary plus four solutions for this tree. According to the model, it contains 54 cubic feet of wood, of which 2 cubic feet is in the stump. It also is sheathed in 11 cubic feet of bark. The left portion of Table 18 shows optimal solutions obtained when the model was instructed to ignore defects. These solutions rely entirely on the interaction of stem geometry expressed in the taper curve, the log specifications and the economic data. This is the type of solution obtainable with current dynamic programming models. In this solution process, the stem is considered to be perfect and, in these runs of the model, all logs were assumed to have the highest grade possible. This assumption could be changed with the possibility of achieving different solution patterns and a different tree value but this would not change the approach of comparing a model that assumes some constant level of quality with a model recognizing quality variation. The right portion of Table 18 shows two optimal solutions obtained when defects were considered during the solution process.

When instructed to examine bucking this tree assuming no defects and assuming the firm only produces and sells roundwood logs, the optimal solution is to produce two 16.5

Table 18

Summary of Solutions for Tree 73 with Initial Economic Data

	cubic volume
Bark	11
Wood	54
Stump Wood	2

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	31.6	36.8	36.8	36.8
% utilization of tree volume, excluding bark	59	68	68	68
Conversion surplus, ignoring defects	15.57	27.23	---	---
Conversion surplus, considering defects[1]	(9.89)	(21.05)	9.98	21.05
Log pattern[1,2]	SAW 16.5 (3) R SAW 16.5 (3) R	SAW 8.5 (1) M SAW 16.5 (3) M SAW 16.5 (3) M	SAW 8.5 1 R SAW 16.5 3 R SAW 16.5 3 R	SAW 8.5 1 M SAW 16.5 3 M SAW 16.5 3 M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

foot sawlogs which have a conversion surplus of $15.57. However, if these logs are subsequently graded, it is found that they both really are grade 3 and their true conversion surplus is $9.89, nearly 36 percent less than originally estimated. In contrast, when the model was instructed to consider defects as part of the solution process, it found a different log pattern involving producing an 8.5 foot grade 1 butt log followed by two grade 3 16.5 foot sawlogs. This increases the optimal conversion surplus by about 1 percent to $9.98 and increases overall tree volume utilization from 59 to 68 percent. Consideration of defects allowed the model to take advantage of a short high grade section near the base of the tree and improve the solution over the case when defects were ignored.

The other two solutions compare the results of excluding or including the defect information when the model considered a firm that can either sell roundwood logs or process them through its own mills. Here the patterns with and without defects are identical although the solution without defects overestimated the conversion surplus by $6.18 or 23 percent. Since these solutions are also identical to the solution obtained when the model considered logs only for roundwood sale, it is apparent that, under the initial set of economic conditions, it is advantageous to be a vertically integrated firm that produces and mills logs rather than a firm that only produces and sells logs.

Veneer logs, which must be at least 18 inches in diameter, do not appear in any solutions for this tree since it is too small to produce them. Pulp and fuel bolts are feasible but are inferior to sawlogs over the portion of the tree where sawlogs can be produced and have a negative conversion surplus toward the top where sawlogs become infeasible. This was observed when detailed calculations for each stage were printed for this tree. These details, obtained by setting IOUT equal to 2 or 3, are not reproduced here because they are voluminous.

<u>Tree 71</u>. This tree is 88 years old, 131 feet in height and 24.3 inches dbh and was cut with a 2.1 foot stump. The log diagrams indicate no presence of internal rot, but the tree has 269 defects relevant to the grading rules. This tree is estimated by the model, Table 19, to contain 129 cubic feet of wood of which 5 cubic feet is in the stump. It was also estimated that bark volume is 28 cubic feet. All log possibilities are feasible in this tree, however, the optimal solutions include only sawlogs.

When the model examined this tree assuming roundwood sale as the only marketing option and ignored defects, it produced four 16.5 foot sawlogs followed by a 12.5 foot sawlog. These logs, produced under the assumption that they all are grade 1, were estimated to have a conversion surplus of $65.44. However, when these logs were graded, the conversion surplus dropped to $39.70. Also, the 12.5

Table 19

Summary of Solutions for Tree 71 with Initial Economic Data

Cubic Volume: Bark, 28; Wood, 129; Stump Wood, 5.

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	112.3	112.3	104.0	112.3
% Utilization of tree volume inside bark	87	87	81	87
Conversion surplus ignoring defects	65.44	108.83	---	---
Conversion surplus considering defects[1]	(39.70)	(59.36)	40.09	59.36
Log pattern[1,2]	SAW 16.5 (4) R SAW 16.5 (4) R SAW 16.5 (4) R SAW 16.5 (4) R SAW 12.5 (4) R	SAW 16.5 (4) M SAW 16.5 (4) M SAW 16.5 (4) M SAW 16.5 (4) M SAW 12.5 (4) M	SAW 16.5 4 R SAW 16.5 4 R SAW 16.5 4 R SAW 16.5 4 R	SAW 16.5 4 M SAW 16.5 4 M SAW 16.5 4 M SAW 16.5 4 M SAW 12.5 4 M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

foot sawlog was found to have a negative conversion surplus when graded. Consequently the value of this solution is inferior to that obtained when the model considered the defects as it developed the solution. In this case the negative value of the top log was noted and it was not produced. The optimal conversion surplus is 1 percent greater than that produced when defects were ignored. This improvement occurs in spite of a drop in tree volume utilization from 87 to 81 percent.

When milling is considered as an option, two identical log patterns emerge although the solution based on ignoring the defects overestimated the actual conversion surplus by 83 percent. Like tree 73, the analysis indicates that there are advantages associated with an integrated firm: the conversion surplus is much greater and this allows the 12.5 foot top sawlog to be produced at a profit. Under these economic conditions, an integrated firm is able to improve the overall tree utilization.

The analysis of this tree is limited because of the large number of external defects present. In examining the original log diagrams for this tree, many large knots were noted. The detailed stage-by-stage printout for this tree indicated that no graded log could be rated higher than grade 4, the lowest grade. This poor quality undoubtedly has a strong effect on the results.

Tree 59. Tree 59 is 445 years old, 138 feet in height, 38.2 inches dbh and was cut with a 2 foot stump. The log diagrams indicate no presence of internal defects but the tree has 123 external defects that are relevant to the log grading rules. According to the model, this tree is estimated to contain 337 cubic feet of wood of which 13 cubic feet are in the stump. The bark sheath in this tree is estimated to contain 70 cubic feet.

When the model was instructed to buck this tree for roundwood sale and to ignore defects in making bucking decisions, it produced a 9 foot butt log to be sold for veneer use followed by six 16.5 foot sawlogs. The model, assuming all logs could be grade 1, estimated the total conversion surplus as $222.99. However, when the logs were subsequently graded and revalued, the true conversion surplus was found to be $194.25. When the model was instructed to consider defects during the solution process, the optimal conversion surplus was $198.40. This was achieved by a much different pattern which took advantage of the defect information to improve log grade and value. This pattern change involves changes in the type and length of logs. It begins with a 16.5 foot grade 1 sawlog, followed by a grade 2 veneer log, another 16.5 foot grade 1 sawlog, two more grade 2 veneer logs, two 16.5 foot sawlogs of grade 3 and 4 and finally a grade 4 12.5 foot sawlog. This improved bucking pattern is achieved while using slightly less tree volume.

When counterpart solutions are derived under

Table 20

Summary of Solutions for Tree 59 with Initial Economic Data

Cubic Volume: Bark, 70; Wood, 337; Stump Wood, 13.

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	317.3	317.0	315.7	317.0
% Utilization of tree volume	94	94	94	94
Conversion surplus ignoring defects	222.99	372.34	---	---
Conversion surplus considering defects[1]	(194.25)	(335.59)	198.40	338.99
Log pattern[1,2]	Veneer 9.0 (1) R	SAW 16.5 (1) M	SAW 16.5 1 R	SAW 16.5 1 M
	SAW 16.5 (2) R	SAW 16.5 (2) M	Veneer 9.0 2 R	SAW 8.5 2 M
	SAW 16.5 (1) R	SAW 8.5 (1) M	SAW 16.5 1 R	SAW 16.5 1 M
	SAW 16.5 (3) R	SAW 16.5 (3) M	Veneer 9.0 2 R	SAW 16.5 3 M
	SAW 16.5 (3) R	SAW 16.5 (3) M	Veneer 9.0 2 R	SAW 16.5 3 M
	SAW 16.5 (4) R	SAW 16.5 (4) M	SAW 16.5 3 R	SAW 16.5 4 M
	SAW 16.5 (4) R	SAW 16.5 (4) M	SAW 16.5 4 R	SAW 16.5 4 M
			SAW 12.5 4 R	

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

conditions where milling logs in the firm's own mills is an alternative to roundwood sale, the patterns are similar with the exception of a switch of the second and third sawlogs which take better advantage of log grading opportunities and increase the overall conversion surplus by $3.40. As noted in the previous trees, the solutions obtained when milling is an alternative produce only sawlogs.

In this tree, consideration of defects allowed an improvement in the optimal conversion surplus of 1-2 percent and this was achieved through a restructuring of log positions and reallocation of logs to end uses.

Tree 60. Tree 60 was 438 years old, 156 feet in height, 40.5 inches dbh and was cut with a 2 foot stump. It is the tallest of the test trees and next to the largest in dbh. According to the log diagrams it had no internal defects but it has 231 external defects relevant to the grading rules. The model, Table 21, estimated that it contained 428 cubic feet of wood, 14 cubic feet of which are in the stump. It is also sheathed in 90 cubic feet of bark.

When this tree was bucked by the model for the roundwood market under the condition where the external defects were ignored and all logs were assumed to be grade 1 during the solution process, the solution indicated cutting a veneer log followed by seven 16.5 foot sawlogs. Under these circumstances the model estimated a conversion surplus of $289.98. However, when these solution logs were

Table 21

Summary of Solutions for Tree 60 with Initial Economic Conditions

	cubic volume
Bark	90
Wood	428
Stump Wood	14

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	406.1	406.0	402.2	400.9
% Utilization of tree volume	95	95	94	94
Conversion surplus ignoring defects	289.96	489.92	---	---
Conversion surplus considering defects[1]	(250.04)	(416.72)	261.44	442.59
Log pattern[1,2]	Veneer 9.0 (2) R SAW 16.5 (1) R SAW 16.5 (2) R SAW 16.5 (2) R SAW 16.5 (4) R SAW 16.5 (4) R	SAW 16.5 (2) M SAW 16.5 (2) M SAW 8.5 (1) M SAW 16.5 (2) M SAW 16.5 (4) M SAW 16.5 (4) M	Veneer 9.0 2 R Veneer 9.0 1 R Veneer 9.0 1 R SAW 16.5 1 R Veneer 9.0 1 R SAW 16.5 2 R	SAW 8.5 1 M SAW 8.5 1 M SAW 8.5 1 M SAW 8.5 1 M SAW 16.5 1 M SAW 16.5 2 M

Table 21 (continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]	SAW 16.5 (4) R SAW 16.5 (4) R	SAW 16.5 (4) M SAW 16.5 (4) M	SAW 16.5 4 R SAW 16.5 4 R SAW 16.5 4 R	SAW 8.5 4 M SAW 12.5 3 M SAW 16.5 4 M SAW 16.5 3 M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

subsequently graded and revalued, the conversion surplus estimate dropped to $250.04. When the external defects were considered in obtaining the solution, the optimal conversion surplus was $261.44, roughly 5 percent greater. This was achieved by a substantially different pattern of logs that started with a grade 2 veneer log, two grade 1 veneer logs, a grade 1 16.5 foot sawlog, another grade 1 veneer log and four 16.5 foot sawlogs, one of grade 2 and the others rated as grade 4. This 5 percent improvement in conversion surplus was achieved with a slight drop in volume utilization of the tree from 95 to 94 percent.

When the model also included milling logs as an alternative only sawlogs were produced but the pattern of sawlogs was markedly different when defects were ignored or included during the solution process. When defects were ignored all but one log was 16.5 feet in length. When these logs were graded and revalued the conversion surplus estimate dropped from $489.92 to $416.72 and only one log remained grade 1. When the external defects were considered by the model, four grade 1 8.5 foot sawlogs were produced, followed by a grade 1 16.5 foot sawlog, a grade 2 16.5 foot sawlog, a grade 4 8.5 foot sawlog, a grade 3 12.5 foot sawlog, a grade 4 16.5 foot sawlog and finally a grade 3 16.5 foot sawlog. The optimal conversion surplus was $442.59, an improvement of about 7 percent. Comparison of the log patterns and grades reveals that the use of defect information during the solution process substantially revised the pattern to take better advantage of higher valued higher grade sections of the stem. This improvement also was obtained with a slight drop in utilization of the tree.

In comparing the solutions obtained when defects are considered by the model, it is curious that the 9 foot veneer log that would be produced if logs are sold as roundwood is grade 2 while the 8.5 foot sawlog that would be produced if the milling alternative is also considered is grade 1. In checking the defect file obtained from the log diagrams, these grade assignments by the model are correct. In the first 8.5 feet above the stump only one relevant defect is present: a half inch sound knot that is permissible in grade 1. However, lengthening the log to 9 feet includes a second of these knots. This violates the grade 1 conditions but not grade 2.

<u>Tree 55</u>. Tree 55 was 422 years old, 138 feet tall, 42 inches dbh and was cut with a 2 foot stump. According to the log diagrams, it has no internal defects but it does have 152 external defects that are relevant to the log grading rules. The model estimated that it contained 407 cubic feet of wood of which 15 cubic feet are in the stump. It is sheathed in 86 cubic feet of bark.

When bucked for roundwood sale under the condition where the external defects were ignored and replaced by the

Table 22

Summary of Solutions for Tree 55 with Initial Economic Conditions

	cubic volume
Bark	86
Wood	407
Stump Wood	15

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	384.6	385.6	385.5	383.1
% Utilization of tree volume	94	95	95	94
Conversion surplus ignoring defects	276.90	465.52	---	---
Conversion surplus considering defects[1]	(225.70)	(415.20)	235.94	417.05
Log pattern[1,2]	Veneer 9.0 (1) R Veneer 9.0 (3) R Veneer 9.0 (1) R SAW 16.5 (3) R SAW 16.5 (3) R SAW 16.5 (3) R	SAW 16.5 (2) M SAW 16.5 (3) M SAW 16.5 (2) M SAW 16.5 (3) M SAW 16.5 (3) M SAW 16.5 (4) M	Veneer 9.0 1 R Veneer 9.0 3 R Veneer 9.0 1 R Veneer 9.0 2 R SAW 16.5 2 R Veneer 9.0 3 R	SAW 8.5 1 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 4 M

Table 22 (Continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]	SAW 16.5 (4) R SAW 16.5 (4) R	SAW 16.5 (4) M	SAW 16.5 3 R SAW 16.5 4 R SAW 16.5 4 R	SAW 16.5 4 M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

assumption that all logs were grade 1, the optimal pattern produced three veneer logs followed by five 16.5 foot sawlogs. The conversion surplus was originally estimated to be $276.90 but this was reduced to $225.70 when the solution logs were graded and revalued. When the external defects were considered in obtaining the optimal solution, the conversion surplus was about 5 percent greater, $235.94, and the optimal pattern of logs included more veneer logs and fewer sawlogs. Utilization of the tree increased slightly when defects were considered by the model.

When milling was also considered by the model, only sawlogs were produced but the mix of lengths was changed when defects were included in the solution process rather than ignored. Considering defects allowed the model to recognize and produce a short grade 1 first sawlog that was not produced when defects were ignored. This restructuring of the solution to take advantage of quality reduced tree utilization slightly and increased the conversion surplus slightly.

Summary of analyses with initial economic data. A few tentative conclusions can be reached from these comparisons of bucking optimizations that include and ignore external defect information.

1. Consideration of external defects and log grading rules can have an important influence on bucking decisions. This influence involves improving the economic value

of logs produced from a tree, the structure of the bucking pattern and the allocation of logs to end uses. The nature of the influence of defect consideration varies from tree to tree. It will be important to study a large sample of trees with a wide range of size and quality before firm statements can be made concerning the importance of using defect information in solving bucking problems for various size and quality classes of trees.

2. Ignoring defects in the solution process implies an assumption of constant quality along the stem. In the set of analyses produced here, the highest log grade was always assumed in the absence of defect information. The assumption of constant quality can lead to an improper assessment of the conversion surplus of a log and may lead to the production of uneconomic logs. This happened in tree 71 when analyzed for roundwood sale. An uneconomic 12.5 foot top sawlog was produced when defects were ignored. This was the only case where this happened in these test trees under the utilization and economic conditions imposed. It could occur more frequently under other circumstances. The assumption that all logs are grade 1 if no defect data are used by the model overestimates total conversion surplus but appears to give reasonable patterns in these trees, especially in the lower bole. The pattern with and without defects is often similar and individual log grades and values were often close or identical. More divergence

occurred toward the tops of trees where actual quality was further from the grade 1 assumption. This may only be a result of the quality patterns in these trees and the utilization and economic conditions imposed. Further experimentation with a larger sample of trees is needed to test these effects and to test the influence of other constant quality assumptions.

3. It is fallacious to evaluate bucking solutions on the basis of the percent of the tree utilized. The percent utilization of the tree is often strikingly similar for a variety of dissimilar bucking patterns. Percent tree volume utilization sometimes improved and sometimes decreased when defects were considered as part of the solution process.

4. Under the specific set of economic conditions in these analyses, sawlogs are preferred, especially when the model considered an integrated firm that has the option of milling logs or selling them in roundwood form. When the integrated firm option was analyzed, all logs were milled rather than sold on the roundwood market. This suggests that an integrated firm under the finished product price and milling cost structure used in these analyses has an economic advantage. The dominance of lumber and sawlog manufacture in the solutions is not surprising since the new housing construction market experienced a period of peak activity from 1971-1973 (Phelps and Hair, 1974) and

the economic data used in these analyses are based on this period. Softwood lumber prices were very high in this period and this may explain the reason why lumber and sawlogs dominate these solutions.

Within sawlogs, the 16.5 foot length has an economic advantage and is generally preferred by the model. This length has the highest roundwood and lumber price per unit of volume and since several of the cost items are constant, per log, this large size has a relatively large profit potential.

Fuel and pulp logs never appeared in any of the solutions. Based on the economic values used in this series of runs, trial fuel logs almost always had a negative conversion surplus except near the stump in the largest trees. Pulp logs usually had a positive conversion surplus near the base of these trees, but pulp and fuel logs were superseded by more valuable veneer and sawlogs. Toward the top when veneer and sawlogs became infeasible fuel and pulp logs always had a negative conversion surplus and were not produced.

Sensitivity Analysis

Variation of Economic Conditions

Since the initial series of runs with the model included economic conditions strongly favoring sawlogs, a second series of runs was performed in which the prices of veneer, pulp, and fuel products were increased while the sawlog and lumber prices were unchanged. In this example, veneer roundwood prices are assumed to be \$95, \$88, \$75, and \$70 per cunit for log grades 1, 2, 3, and 4 respectively. Veneer grade item prices were increased by \$5.00 per thousand square feet. Pulp log roundwood price was increased to \$60 per cunit and the kraft pulp price to \$200 per ton. The price of roundwood for fuel was increased to \$40 per cunit and the price for roundwood chips for fuel to \$30 per oven dry ton.

The results for each tree for this second set of economic conditions are portrayed in Tables 23-27. No change occurred in any of the solutions for tree 73 (Tables 18, 23). Veneer logs are not feasible in this tree and pulp and fuel are uneconomical in the portion of the tree where higher valued sawlogs are not feasible.

In the next larger tree, tree 71, two of the solutions are changed (Tables 19, 24). The solution obtained when defects are ignored and logs are produced for roundwood now includes a veneer log and four 16.5 foot sawlogs rather than four 16.5 foot sawlogs and a 12.5 foot sawlog. However, when defects are included during the analyses, the same solution consisting of four 16.5 foot grade 4 sawlogs is obtained. When milling is considered as an alternative along with roundwood sale, all logs are milled and the solution obtained when defects are ignored is identical to

Table 23

Summary of Solutions for Tree 73 with Revised Economic Conditions

	cubic volume
Bark	11
Wood	54
Stump Wood	2

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	31.6	36.8	36.8	36.8
% Utilization of tree volume	59	68	68	68
Conversion surplus ignoring defects	15.57	27.23	---	---
Conversion surplus considering defects[1]	(9.89)	(21.05)	9.98	21.05
Log pattern[1,2]	SAW 16.5 (3) R SAW 16.5 (3) R	SAW 8.5 (1) M SAW 16.5 (3) M SAW 16.5 (3) M	SAW 8.5 1 R SAW 16.5 3 R SAW 16.5 3 R	SAW 8.5 1 M SAW 16.5 3 M SAW 16.5 3 M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 24

Summary of Solutions for Tree 71 with Revised Economic Conditions

	cubic volume
Bark	28
Wood	129
Stump Wood	5

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	110.3	112.3	104.0	113.2
% Utilization of tree volume	86	87	81	88
Conversion surplus ignoring defects	65.84	108.83	---	---
Conversion surplus considering defects[1]	(40.06)	(59.36)	40.09	74.09
Log pattern[1,2]	Veneer 9.0 (4) R SAW 16.5 (4) R SAW 16.5 (4) R SAW 16.5 (4) R SAW 16.5 (4) R	SAW 16.5 (4) M SAW 16.5 (4) M SAW 16.5 (4) M SAW 16.5 (4) M SAW 12.5 (4) M	SAW 16.5 4 R SAW 16.5 4 R SAW 16.5 4 R SAW 16.5 4 R	Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M

Table 24 (Continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]				Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 25

Summary of Solutions for Tree 59 with Revised Economic Conditions

	cubic volume
Bark	70
Wood	337
Stump Wood	13

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	314.4	317.3	315.4	316.1
% Utilization of tree volume	93	94	94	94
Conversion surplus ignoring defects	227.65	372.64	---	---
Conversion surplus considering defects[1]	(206.28)	(335.85)	207.38	343.90
Log pattern[1,2]	Veneer 9.0 (1) R Veneer 9.0 (2) R Veneer 9.0 (1) R Veneer 9.0 (1) R Veneer 9.0 (1) R Veneer 9.0 (2) R SAW 16.5 (3) R	Veneer 9.0 (1) M SAW 16.5 (2) M SAW 16.5 (1) M SAW 16.5 (3) M SAW 16.5 (3) M SAW 16.5 (4) M SAW 16.5 (4) M	Veneer 9.0 1 R Veneer 9.0 2 R Veneer 9.0 1 R Veneer 9.0 1 R Veneer 9.0 1 R Veneer 9.0 2 R Veneer 9.0 2 R	SAW 16.5 1 M SAW 8.5 2 M SAW 16.5 1 M SAW 16.5 3 M SAW 16.5 3 M Pulp 8.0 - M Pulp 8.0 - M

Table 25 (Continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]	SAW 16.5 (4) R SAW 16.5 (4) R		Veneer 9.0 3 R SAW 16.5 4 R SAW 16.5 4 R	Pulp 8.0 - M Pulp 8.0 - M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 26

Summary of Solutions for Tree 60 with Revised Economic Conditions

	cubic volume
Bark	90
Wood	428
Stump Wood	14

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	404.4	406.1	402.2	405.5
& Utilization of tree volume	94	95	94	95
Conversion surplus ignoring defects	297.80	491.01	---	---
Conversion surplus considering defects[1]	(267.98)	(418.09)	269.34	453.01
Log pattern[1,2]	Veneer 9.0 (2) R	Veneer 9.0 (2) M	Veneer 9.0 2 R	SAW 8.5 1 M
	Veneer 9.0 (1) R	SAW 16.5 (1) M	Veneer 9.0 1 R	SAW 8.5 1 M
	Veneer 9.0 (1) R	SAW 16.5 (2) M	Veneer 9.0 1 R	SAW 8.5 1 M
	Veneer 9.0 (1) R	SAW 16.5 (2) M	SAW 16.5 1 R	SAW 8.5 1 M
	Veneer 9.0 (1) R	SAW 16.5 (4) M	Veneer 9.0 1 R	SAW 16.5 1 M
	Veneer 9.0 (2) R	SAW 16.5 (4) M	SAW 16.5 2 R	SAW 16.5 2 M
	Veneer 9.0 (2) R	SAW 16.5 (4) M	SAW 16.5 4 R	Pulp 8.0 - M

Table 26 (Continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]	Veneer 9.0 (4) R SAW 16.5 (3) R SAW 16.5 (4) R SAW 16.5 (4) R	SAW 16.5 (4) M	SAW 16.5 4 R SAW 16.5 4 R	SAW 8.5 3 M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 27

Summary of Solutions for Tree 55 with Revised Economic Conditions

	cubic volume
Bark	86
Wood	407
Stump Wood	15

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Cubic volume of logs	385.5	383.5	383.8	387.3
& Utilization of tree volume	95	94	94	95
Conversion surplus ignoring defects	286.07	466.07	---	---
Conversion surplus considering defects[1]	(243.19)	(419.99)	244.90	427.37
Log pattern[1,2]	Veneer 9.0 (1) R	Veneer 9.0 (1) M	Veneer 9.0 1 R	Veneer 9.0 1 M
	Veneer 9.0 (3) R	SAW 16.5 (3) M	Veneer 9.0 3 R	SAW 16.5 3 M
	Veneer 9.0 (1) R	SAW 16.5 (3) M	Veneer 9.0 1 R	SAW 16.5 3 M
	Veneer 9.0 (2) R	SAW 16.5 (3) M	Veneer 9.0 2 R	SAW 16.5 3 M
	Veneer 9.0 (2) R	SAW 16.5 (3) M	Veneer 9.0 2 R	SAW 16.5 3 M
	SAW 16.5 (3) R	SAW 16.5 (4) M	Veneer 9.0 2 R	Pulp 8.0 - M
	SAW 16.5 (3) R	SAW 16.5 (4) M	Veneer 9.0 3 R	Pulp 8.0 - M

Table 27 (Continued)

	Defects ignored during solution process		Defects considered during solution process	
	Roundwood sale	Roundwood sale or milling	Roundwood sale	Roundwood sale or milling
Log pattern[1,2]	SAW 16.5 (4) R SAW 16.5 (4) R		SAW 16.5 3 R SAW 16.5 4 R SAW 16.5 4 R	Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M

[1]Values in parentheses reflect conversion surplus and grade assigned to logs after the optimal solution was obtained by ignoring defects.

[2]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

that obtained with the initial economic conditions. The solution obtained when defects are considered is radically changed and indicates that only pulp logs should be produced for the pulp mill. It is preferable under the new economic conditions to produce pulp logs for pulping rather than low grade sawlogs for the sawmill from this tree. This change only occurs because the model was allowed to be sensitive to the impact of external defects on the grade and value of potential logs.

As illustrated in the earlier analysis, introducing defect information into the solution process can result in improvements in the solution. Even though the revised economic conditions resulted in some solutions for this tree with higher economic value and altered the log composition, overall stem utilization hardly changed.

In trees 59, 60, and 55 all solutions change to some degree and in a similar fashion. (Compare Tables 20-22 with Tables 25-27). The changes in the solutions when defects were ignored and roundwood sale was considered involved production of veneer logs rather than sawlogs at the base of the tree. Inclusion of defects during the solution process also increased the substitution of veneer logs for sawlogs and reduced conversion surplus slightly. The changes in conversion surplus were larger when milling was considered as an option. When defects were ignored solutions indicated one veneer log followed by six or seven sawlogs depending on the tree. When defects were considered during the solution, trees 59 and 60 did not contain any veneer logs but instead contained sawlogs and pulp logs. Tree 55, the largest in dbh, was similar except that one veneer log was produced. These new solutions were produced with little change in the percent utilization of the tree.

Changing the value of veneer, pulp and fuel products relative to sawlogs and lumber did have the expected effect of altering the solutions. The changes were not enough to allow production of fuel although it was observed in detailed printouts that fuel had a positive conversion surplus over a greater length of each tree. However, fuel was at a competitive disadvantage compared to other products at these points and had a negative conversion surplus in the upper stem where other products eventually became infeasible. The economic changes did not alter the advantage of an integrated firm that produces and mills logs. When this alternative was available, all logs were milled.

This analysis indicates that changes in economic factors are likely to produce entirely new bucking patterns and log allocations even though utilization of the tree may not change. Variations in the prices for one type of product to another, variations in prices for roundwood compared to finished products, and variations in variable costs individually or in combination will produce different solutions. These preliminary results suggest that use of volume or percent utilization as a criterion for evaluating and comparing log buckers or bucking method is inappropriate and could be misleading; only comparisons based on economic criteria will give a meaningful comparison.

Effect of Changing Log Specifications

Another group of factors that may cause the solution to change are the size and quality constraints provided by management. Changes in any of these constraints may alter the region of feasibility of any log possibility in a particular tree and feasibility from tree to tree. To illustrate this effect, the veneer log minimum diameter was changed from 18 inches to 12 inches and the sawlog minimum diameter was changed from 10 inches to 6 inches. All other factors remained the same as the preceding analyses with the revised economic values. Analysis was performed only for the situation where both roundwood log sale and milling options were considered and with consideration of external defects.

Table 28 presents the results for the test trees which when compared with the counterpart for each tree in Tables 23-27 show changes in the solution. These changes occur in the top of each tree and add a sawlog in tree 73 and trade one or more pulp logs for a grade 4 sawlog in each of the other trees. In these trees, pulp logs suffer a piece size penalty due to their short length. This is

Table 28

Summary of Solutions for Test Trees Under Revised Economic Conditions When Veneer Log and Sawlog Specifications are Changed

Solutions are for conditions where defects are considered during the solution process when an integrated firm produces logs for roundwood sale or processing in its mills. These solutions should be compared to counterparts in Tables 23-27.

Tree	73	71	59	60	55
Cubic volume of logs	44.4	117.1	320.5	409.6	387.6
% Utilization of tree volume	82	91	95	96	95
Conversion surplus	22.32	74.48	344.02	453.16	427.38
Log pattern[1]	SAW 8.5 1 M	Pulp 8.0 - M	SAW 16.5 1 M	SAW 8.5 1 M	Veneer 9.0 1 M
	SAW 16.5 3 M	Pulp 8.0 - M	SAW 8.5 2 M	SAW 8.5 1 M	SAW 16.5 3 M
	SAW 16.5 3 M	Pulp 8.0 - M	SAW 16.5 1 M	SAW 8.5 1 M	SAW 16.5 3 M
	SAW 16.5 3 M	Pulp 8.0 - M	SAW 16.5 3 M	SAW 8.5 1 M	SAW 16.5 3 M
		Pulp 8.0 - M	SAW 16.5 3 M	SAW 16.5 1 M	SAW 16.5 3 M
		Pulp 8.0 - M	Pulp 8.0 - M	SAW 16.5 2 M	Pulp 8.0 - M
		Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
		Pulp 8.0 - M	Pulp 8.0 - M	SAW 8.5 3 M	Pulp 8.0 - M
		Pulp 8.0 - M	SAW 16.5 4 M	Pulp 8.0 - M	SAW 16.5 4 M
		SAW 16.5 4 M		Pulp 8.0 - M	
				Pulp 8.0 - M	
				Pulp 8.0 - M	
				SAW 16.5 4 M	

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

overcome by a longer sawlog near the top. The changed utilization specifications for sawlogs allow this unusual situation to occur. This indicates the difficulty that log buckers face in comprehending subtle changes in the factors affecting their decisions and in correctly integrating the information revisions into their thinking.

Effect of Variations in Stump Height

The solutions presented in the preceding analyses are all based on a stump height constraint which was set equal to the actual stump height cut for each tree (Table 12). The optimal solutions developed by the model are dependent on the height of the stump cut. One question to be raised is the sensitivity of the solutions to the stump height. Cutting crews are often asked to cut low stumps under the premise that this eliminates the waste of valuable wood. Low stumps may also be desirable because they offer less hindrance to logging operations and to future forest culture. Tables 29-33 portray the optimal solutions obtained by the model when given a stump height of zero feet, the actual stump height, and a four foot stump height. These solutions were obtained under the revised economic conditions using the defect information during the solution process and assuming that the firm can either sell roundwood or mill the logs it produces. The results for the actual stump height analyses were also given in Tables 23-27 and are shown here for convenient comparison.

Table 29

Summary of Solutions for Tree 73 with Revised Economic Data and Changes in Stump Height

Solutions were obtained under conditions where defects are considered and for a firm that produces logs either for roundwood sale or for its mills.

		Actual	
Stump height, feet	0	1.5	4
Cubic volume of logs	39.0	36.8	34.9
% Utilization of tree volume	72	68	65
Conversion surplus	22.22	2.105	17.29
Log pattern[1]	SAW 10.5 1 M SAW 16.5 3 M SAW 16.5 3 M	SAW 8.5 1 M SAW 16.5 3 M SAW 16.5 3 M	SAW 16.5 3 M SAW 16.5 3 M Pulp 8.0 - M

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 30

Summary of Solutions for Tree 71 with Revised Economic Data and Changes in Stump Height

Solutions were obtained under conditions where defects are considered and for a firm that produces logs either for roundwood sale or for its mills.

		Actual	
Stump height, feet	0	2.1	4
Cubic volume of logs	117.7	113.2	109.5
% Utilization of tree volume	91	88	85
Conversion surplus	78.72	74.09	69.99
Log pattern[1]	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	SAW 16.5 4 M	Pulp 8.0 - M	Pulp 8.0 - M
		Pulp 8.0 - M	Pulp 8.0 - M

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 31

Summary of Solutions for Tree 59 with Revised Economic Data and Changes in Stump Height

Solutions were obtained under conditions where defects are considered and for a firm that produces logs either for roundwood sale or for its mills.

		Actual	
Stump height	0	2.0	4
Cubic volume of logs	327.8	316.1	305.3
% Utilization of tree volume	97	94	91
Conversion surplus	361.33	343.90	324.09
Log pattern[1]	SAW 16.5 1 M	SAW 16.5 1 M	SAW 8.5 1 M
	SAW 8.5 2 M	SAW 8.5 2 M	SAW 8.5 2 M
	SAW 16.5 1 M	SAW 16.5 1 M	SAW 8.5 1 M
	SAW 16.5 2 M	SAW 16.5 3 M	SAW 16.5 1 M
	SAW 16.5 3 M	SAW 16.5 3 M	SAW 8.5 2 M
	Pulp 8.0 - M	Pulp 8.0 - M	SAW 16.5 3 M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
			Pulp 8.0 - M

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 32

Summary of Solutions for Tree 60 with Revised Economic Data and Changes in Stump Height

Solutions were obtained under conditions where defects are considered and for a firm that produces logs either for roundwood sale or for its mills.

		Actual	
Stump height	0	2.0	4
Cubic volume of logs	421.7	405.5	392.6
% Utilization of tree volume	99	95	92
Conversion surplus	474.66	453.01	432.46
Log pattern[1]	Veneer 9.0 1 M	SAW 8.5 1 M	SAW 16.5 2 M
	Veneer 9.0 1 M	SAW 8.5 1 M	SAW 8.5 1 M
	SAW 8.5 1 M	SAW 8.5 1 M	SAW 16.5 1 M
	SAW 16.5 1 M	SAW 8.5 1 M	SAW 8.5 1 M
	SAW 8.5 1 M	SAW 16.5 1 M	SAW 16.5 2 M
	SAW 12.5 2 M	SAW 16.5 2 M	Pulp 8.0 - M
	SAW 8.5 3 M	Pulp 8.0 - M	SAW 8.5 3 M
	SAW 16.5 3 M	SAW 8.5 3 M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	Pulp 8.0 - M
	Pulp 8.0 - M	Pulp 8.0 - M	
	Pulp 8.0 - M	Pulp 8.0 - M	

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

Table 33

Summary of Solutions for Tree 55 with Revised Economic Data and Changes in Stump Height

Solutions were obtained under conditions where defects are considered and for a firm that produces logs either for roundwood sale or for its mills.

		Actual	
Stump height	0	2.0	4
Cubic volume of logs	401.3	387.3	368.8
% Utilization of tree volume	99	95	91
Conversion surplus	449.43	427.37	406.85
Log pattern[1]	SAW 16.5 1 M SAW 16.5 2 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M	Veneer 9.0 1 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M	SAW 8.5 1 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M SAW 16.5 3 M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M Pulp 8.0 - M

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

In all cases, increasing the stump height lowered the percent utilization of the tree and lowered the conversion surplus. In tree 73 (Table 29) the change from a zero foot to a 1.5 foot stump is fairly small and does not affect the mix or pattern of logs. The higher stump simply means each log is slightly smaller in diameter and this translates into a corresponding reduction in conversion surplus. When the stump height is raised to four feet, the conversion surplus drops more sharply since the grade 1 8.5 foot sawlog is eliminated. Instead two 16.5 foot sawlogs and a pulp log are produced. This tree has a very limited length over which sawlogs are feasible and raising the stump height curtailed the production of a high quality sawlog but left room at the top for a pulp log. The loss of a quality high value sawlog was not made up for by the small pulp log.

In tree 71 generally only pulp logs were produced for the pulp mill except for one grade 4 sawlog when a zero foot stump height was used. This top sawlog apparently is a reflection of the piece size effect on small logs. As the stump height is raised from zero to 2.1 feet, the solution changes from nine pulp logs and one sawlog to ten pulp logs. Raising the stump to four feet retains the same number of pulp logs but, because of their smaller size and the loss of volume in the larger stump, conversion surplus continues to decline.

Similar reductions in tree utilization and larger losses in conversion surplus are observable in the trees 59, 60, and 55 (Tables 31-33) which are much larger and contain high quality wood in the lower bole. The mix of logs and their allocation is also affected by shifts in the stump height.

Considering the number of trees that a crew cuts in a day, a tendency to cut high stumps could lead to a significant economic loss, even in small or low quality trees.

Effect of Changing the Utilizable Height or Diameter Top Limit in a Tree

One advantage of dynamic programming is that it solves a whole series of problems along the way to arriving at the solution of the original problem. In the bucking problem, the optimal solution for the tree at each stage corresponds to the optimal solution for a tree of identical dbh and total height but with varying merchantable height. Thus, if one wished to examine the influence of variations in merchantable height on the optimal solution, solutions for all merchantable heights less than that originally given are known. Here merchantable height can be converted to a stage number by subtracting stump height and dividing by the stage interval. This stage number corresponds to the maximum utilizable point in the tree and one merely examines those stage optima at or below this point to find the one with the greatest economic value.

Stage by stage optima for the tree are stored as part of the solution process and in the model are retained in array A. This array can be obtained as part of the printed output. Table 34 presents this table for tree 60 when analyzed with defects for sale of logs on a roundwood market. In the original analysis, merchantable height was set equal to total height, so the only limiting physical factors are the log size and quality constraints. The optimum solution occurred at stage 237 (see Table 26). This corresponds to a height in the tree of 120.5 feet. At any merchantable height limit between this point and the top, this is the optimum. However, what would happen if during felling the tree shattered above 86 feet? This point corresponds to stage 168. Looking this stage up in the table, the optimum value is $248.02. However, scanning optima at lower stages it is better to go to stage 166 or stage 163. Bucking according to patterns based on either of these stages would yield $249.69. Examining the solution at stage 166 first, the bucking pattern produces a 12.5 foot grade 3 sawlog, at its base (stage 141) is a grade 3 veneer log, next (stage 123) a grade 2 veneer log, next (stage 105) a grade 1 veneer log, then (stage 87) a grade 1 16.5 foot sawlog, then (stage 54 and stage 36) two grade 1 veneer logs, and finally (stage 18) a grade 2 veneer log. Examining the solution at stage 163 produces a different sequence. The bucking pattern differs from the previous

Table 34

Stage by Stage Optima for Tree 60 When Analyzed to Consider External Defects for Sale of Logs for Roundwood Only

ARRAY A

TOTAL VALUE	PROD CODE	BASE STAGE	GRADE	DLGEIB	DSMLIB	TARG LEN	TRIM LEN	--GROSS--VOLUME CFWOB	--GROSS--VOLUME BDFT	--GROSS--WEIGHT WOOD	--GROSS--WEIGHT BARK	CULL	LOG VALUE	MKT=1 MILL=0	STAGE
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7
4.33	4.00	0	0	35.99	35.19	4.00	0	27.63	224.00	.39	.09	0	4.33	1.00	8
4.28	4.00	1.00	0	35.89	35.09	4.00	0	27.48	224.00	.38	.09	0	4.28	1.00	9
4.23	4.00	2.00	0	35.79	34.99	4.00	0	27.32	210.80	.38	.09	0	4.23	1.00	10
4.18	4.00	3.00	0	35.69	34.89	4.00	0	27.17	210.80	.38	.09	0	4.18	1.00	11
4.13	4.00	4.00	0	35.59	34.79	4.00	0	27.01	210.80	.38	.09	0	4.13	1.00	12
4.08	4.00	5.00	0	35.49	34.68	4.00	0	26.86	210.80	.38	.09	0	4.08	1.00	13
4.02	4.00	6.00	0	35.39	34.58	4.00	0	26.71	210.80	.37	.09	0	4.02	1.00	14
3.97	4.00	7.00	0	35.29	34.48	4.00	0	26.55	210.80	.37	.09	0	3.97	1.00	15
23.98	3.00	0	0	35.99	34.38	8.00	0	54.03	421.60	.76	.18	0	23.98	1.00	16
40.59	2.00	0	1.00	35.99	34.28	8.00	.50	57.25	421.60	.80	.19	0	40.59	1.00	17
44.34	1.00	0	2.00	35.99	34.18	8.00	1.00	60.44	421.60	.85	.20	0	44.34	1.00	18
44.05	1.00	1.00	2.00	35.89	34.08	8.00	1.00	60.10	421.60	.84	.20	0	44.05	1.00	19
43.77	1.00	2.00	2.00	35.79	33.98	8.00	1.00	59.75	396.00	.84	.19	0	43.77	1.00	20
43.49	1.00	3.00	2.00	35.69	33.88	8.00	1.00	59.41	396.00	.83	.19	0	43.49	1.00	21
43.21	1.00	4.00	2.00	35.59	33.78	8.00	1.00	59.07	396.00	.83	.19	0	43.21	1.00	22
42.93	1.00	5.00	2.00	35.49	33.68	8.00	1.00	58.72	396.00	.82	.19	0	42.93	1.00	23
42.66	1.00	6.00	2.00	35.39	33.58	8.00	1.00	58.38	396.00	.82	.19	0	42.66	1.00	24
52.26	2.00	0	2.00	35.99	33.48	12.00	.50	82.29	594.00	1.15	.27	0	52.26	1.00	25
51.93	2.00	1.00	2.00	35.89	33.38	12.00	.50	81.82	594.00	1.15	.27	0	51.93	1.00	26
51.60	2.00	2.00	2.00	35.79	33.28	12.00	.50	81.34	594.00	1.14	.26	0	51.60	1.00	27
51.28	2.00	3.00	2.00	35.69	33.18	12.00	.50	80.87	594.00	1.13	.26	0	51.28	1.00	28
53.11	2.00	0	2.00	35.99	33.07	14.00	.50	94.37	693.00	1.32	.31	0	53.11	1.00	29
52.77	2.00	1.00	2.00	35.89	32.97	14.00	.50	93.82	649.60	1.31	.31	0	52.77	1.00	30
52.43	2.00	2.00	2.00	35.79	32.87	14.00	.50	93.28	649.60	1.31	.30	0	52.43	1.00	31
52.10	2.00	3.00	2.00	35.69	32.77	14.00	.50	92.73	649.60	1.30	.30	0	52.10	1.00	32
73.10	2.00	0	2.00	35.99	32.67	16.00	.50	106.16	742.40	1.49	.35	0	73.10	1.00	33
76.85	2.00	17.00	1.00	34.28	32.57	8.00	.50	51.81	371.20	.73	.17	0	36.27	1.00	34
80.35	2.00	18.00	1.00	34.18	32.47	8.00	.50	51.50	371.20	.72	.17	0	36.02	1.00	35
87.53	1.00	18.00	1.00	34.18	32.37	8.00	1.00	54.37	371.20	.76	.18	0	43.19	1.00	36
86.95	1.00	19.00	1.00	34.08	32.27	8.00	1.00	54.04	371.20	.76	.18	0	42.90	1.00	37
86.38	1.00	20.00	1.00	33.98	32.17	8.00	1.00	53.71	371.20	.75	.17	0	42.61	1.00	38
85.81	1.00	21.00	1.00	33.88	32.07	8.00	1.00	53.39	371.20	.75	.17	0	42.32	1.00	39
85.25	1.00	22.00	1.00	33.78	31.97	8.00	1.00	53.06	347.20	.74	.17	0	42.03	1.00	40
84.68	1.00	23.00	1.00	33.68	31.87	8.00	1.00	52.74	347.20	.74	.17	0	41.75	1.00	41
87.36	2.00	17.00	2.00	34.28	31.76	12.00	.50	74.39	520.80	1.04	.24	0	46.77	1.00	42
95.97	2.00	18.00	1.00	34.18	31.66	12.00	.50	73.94	520.80	1.04	.24	0	51.63	1.00	43
95.34	2.00	19.00	1.00	34.08	31.56	12.00	.50	73.49	520.80	1.03	.24	0	51.29	1.00	44
94.72	2.00	20.00	1.00	33.98	31.46	12.00	.50	73.03	520.80	1.02	.24	0	50.94	1.00	45
94.09	2.00	21.00	1.00	33.88	31.36	12.00	.50	72.59	520.80	1.02	.24	0	50.60	1.00	46
96.60	2.00	18.00	1.00	34.18	31.26	14.00	.50	84.73	607.60	1.19	.28	0	52.27	1.00	47
95.97	2.00	17.00	1.00	34.08	31.16	14.00	.50	84.21	607.60	1.18	.27	0	51.92	1.00	48

Table 34. Continued

95.34	2.00	20.00	1.00	33.98	31.06	14.00	.50	83.69	607.60	1.17	.27	0	51.57	1.00	49
106.11	2.00	17.00	2.00	34.20	30.96	16.00	.50	95.85	648.00	1.34	.31	0	65.52	1.00	50
116.09	2.00	18.00	1.00	34.10	30.86	16.00	.50	95.26	648.00	1.33	.31	0	71.75	1.00	51
115.49	1.00	34.00	1.00	32.57	30.76	8.00	1.00	49.23	324.00	.69	.16	0	38.64	1.00	52
119.21	2.00	36.00	1.00	32.37	30.65	8.00	.50	46.05	324.00	.64	.15	0	31.68	1.00	53
125.61	1.00	36.00	1.00	32.37	30.55	8.00	1.00	48.60	324.00	.68	.16	0	38.09	1.00	54
124.77	1.00	37.00	1.00	32.27	30.45	8.00	1.00	48.29	324.00	.68	.16	0	37.81	1.00	55
123.92	1.00	38.00	1.00	32.17	30.35	8.00	1.00	47.98	324.00	.67	.16	0	37.54	1.00	56
123.08	1.00	37.00	1.00	32.07	30.25	8.00	1.00	47.67	324.00	.67	.16	0	37.27	1.00	57
122.24	1.00	40.00	1.00	31.97	30.15	8.00	1.00	47.36	324.00	.66	.15	0	36.99	1.00	58
121.40	1.00	41.00	1.00	31.87	30.05	8.00	1.00	47.06	324.00	.66	.15	0	36.72	1.00	59
126.03	2.00	43.00	1.00	31.66	29.95	8.00	.50	44.01	301.60	.62	.14	0	30.06	1.00	60
133.10	2.00	36.00	1.00	32.37	29.85	12.00	.50	66.02	452.40	.92	.21	0	45.57	1.00	61
132.20	2.00	37.00	1.00	32.27	29.75	12.00	.50	65.59	452.40	.92	.21	0	45.25	1.00	62
131.30	2.00	38.00	1.00	32.17	29.64	12.00	.50	65.16	452.40	.91	.21	0	44.92	1.00	63
130.41	2.00	37.00	1.00	32.07	29.54	12.00	.50	64.74	452.40	.91	.21	0	44.60	1.00	64
133.63	2.00	36.00	1.00	32.37	29.44	14.00	.50	75.60	527.80	1.06	.25	0	46.10	1.00	65
132.72	2.00	37.00	1.00	32.27	29.34	14.00	.50	75.11	527.80	1.05	.24	0	45.77	1.00	66
135.17	2.00	34.00	2.00	32.57	29.24	16.00	.50	86.05	603.20	1.20	.28	0	58.32	1.00	67
144.34	2.00	51.00	1.00	30.86	29.14	8.00	.50	41.73	301.60	.58	.14	0	28.25	1.00	68
150.96	2.00	36.00	1.00	32.37	29.04	16.00	.50	84.93	603.20	1.19	.28	0	63.44	1.00	69
149.94	2.00	37.00	1.00	32.27	28.94	16.00	.50	84.37	560.00	1.18	.27	0	62.99	1.00	70
153.20	2.00	54.00	1.00	30.55	28.84	8.00	.50	40.89	280.00	.57	.13	0	27.59	1.00	71
158.88	1.00	54.00	1.00	30.55	28.73	8.00	1.00	43.15	280.00	.60	.14	0	33.26	1.00	72
157.77	1.00	55.00	1.00	30.45	28.63	8.00	1.00	42.86	280.00	.60	.14	0	33.00	1.00	73
156.67	1.00	56.00	1.00	30.35	28.53	8.00	1.00	42.57	280.00	.60	.14	0	32.75	1.00	74
156.32	2.00	54.00	1.00	30.55	28.43	10.00	.50	49.84	350.00	.70	.16	0	30.71	1.00	75
156.87	2.00	51.00	1.00	30.86	28.33	12.00	.50	59.75	420.00	.84	.19	0	40.78	1.00	76
155.96	2.00	52.00	1.00	30.76	28.23	12.00	.50	59.34	420.00	.83	.19	0	40.47	1.00	77
159.37	2.00	53.00	1.00	30.65	28.13	12.00	.50	58.93	420.00	.83	.19	0	40.16	1.00	78
165.46	2.00	54.00	1.00	30.55	28.03	12.00	.50	58.53	420.00	.82	.19	0	39.85	1.00	79
164.31	2.00	55.00	1.00	30.45	27.92	12.00	.50	58.12	388.80	.81	.19	0	39.54	1.00	80
163.15	2.00	56.00	1.00	30.35	27.82	12.00	.50	57.72	388.80	.81	.19	0	39.23	1.00	81
162.12	2.00	61.00	1.00	29.85	27.72	10.00	.50	47.47	324.00	.66	.15	0	29.02	1.00	82
165.89	2.00	54.00	1.00	30.55	27.62	14.00	.50	66.97	453.60	.94	.22	0	40.28	1.00	83
167.58	2.00	51.00	2.00	30.86	27.52	16.00	.50	76.76	518.40	1.07	.25	0	51.49	1.00	84
168.90	2.00	68.00	1.00	29.14	27.42	8.00	.50	37.08	259.20	.52	.12	0	24.56	1.00	85
175.31	2.00	69.00	1.00	29.04	27.32	8.00	.50	36.82	259.20	.52	.12	0	24.35	1.00	86
181.20	2.00	54.00	1.00	30.55	27.21	16.00	.50	75.17	518.40	1.05	.24	0	55.59	1.00	87
179.93	2.00	55.00	1.00	30.45	27.11	16.00	.50	74.65	518.40	1.05	.24	0	55.16	1.00	88
182.60	2.00	72.00	1.00	28.73	27.01	8.00	.50	36.03	259.20	.50	.12	0	23.72	1.00	89
187.60	1.00	72.00	1.00	28.73	26.91	8.00	1.00	38.01	239.20	.53	.12	0	28.72	1.00	90
186.24	1.00	73.00	1.00	28.63	26.81	8.00	1.00	37.74	239.20	.53	.12	0	28.47	1.00	91
184.90	1.00	74.00	1.00	28.53	26.71	8.00	1.00	37.46	239.20	.52	.12	0	28.23	1.00	92
185.32	2.00	72.00	1.00	28.73	26.61	10.00	.50	43.87	299.00	.61	.14	0	26.44	1.00	93
186.29	2.00	69.00	1.00	29.04	26.50	12.00	.50	52.62	358.80	.74	.17	0	35.33	1.00	94
184.98	2.00	70.00	1.00	28.94	26.40	12.00	.50	52.24	358.80	.73	.17	0	35.04	1.00	95
187.94	2.00	71.00	1.00	28.84	26.30	12.00	.50	51.85	358.80	.73	.17	0	34.74	1.00	96
193.33	2.00	72.00	1.00	28.73	26.20	12.00	.50	51.47	358.80	.72	.17	0	34.45	1.00	97
191.93	2.00	73.00	1.00	28.63	26.10	12.00	.50	51.09	358.80	.72	.17	0	34.16	1.00	98
190.54	2.00	74.00	1.00	28.53	26.00	12.00	.50	50.72	330.00	.71	.17	0	33.87	1.00	99
190.32	2.00	77.00	1.00	28.03	25.89	10.00	.50	41.65	275.00	.58	.14	0	24.85	1.00	100

Table 34. Continued

194.14	2.00	68.00	1.00	29.14	25.79	16.00	.50	67.98	440.00	.95	.22	0	49.80	1.00	101
195.64	2.00	67.00	2.00	29.04	25.69	16.00	.50	67.48	440.00	.94	.22	0	44.67	1.00	102
196.19	2.00	86.00	1.00	27.32	25.59	8.00	.50	32.45	220.00	.45	.11	0	20.88	1.00	103
201.88	2.00	87.00	1.00	27.21	25.49	8.00	.50	32.20	220.00	.45	.10	0	20.68	1.00	104
206.34	1.00	87.00	1.00	27.21	25.39	8.00	1.00	33.97	220.00	.48	.11	0	25.14	1.00	105
204.84	1.00	88.00	1.00	27.11	25.28	8.00	1.00	33.71	220.00	.47	.11	0	24.91	1.00	106
205.48	2.00	70.00	2.00	26.91	25.18	8.00	.50	31.46	220.00	.44	.10	0	17.89	1.00	107
209.72	1.00	70.00	2.00	26.91	25.08	8.00	1.00	33.19	220.00	.46	.11	0	22.12	1.00	108
208.16	1.00	71.00	2.00	26.81	24.98	8.00	1.00	32.93	201.60	.46	.11	0	21.91	1.00	109
206.60	1.00	72.00	2.00	26.71	24.88	8.00	1.00	32.67	201.60	.46	.11	0	21.70	1.00	110
207.74	2.00	70.00	2.00	26.91	24.77	10.00	.50	38.27	252.00	.54	.12	0	20.14	1.00	111
208.20	2.00	87.00	2.00	27.21	24.67	12.00	.50	45.93	302.40	.64	.15	0	26.99	1.00	112
206.68	2.00	88.00	2.00	27.11	24.57	12.00	.50	45.57	302.40	.64	.15	0	26.75	1.00	113
209.99	2.00	77.00	2.00	26.20	24.47	8.00	.50	29.77	201.60	.42	.10	0	16.66	1.00	114
213.99	1.00	77.00	2.00	26.20	24.37	8.00	1.00	31.39	201.60	.44	.10	0	20.66	1.00	115
212.39	1.00	78.00	2.00	26.10	24.26	8.00	1.00	31.14	201.60	.44	.10	0	20.46	1.00	116
210.79	1.00	79.00	2.00	26.00	24.16	8.00	1.00	30.89	201.60	.43	.10	0	20.25	1.00	117
212.11	2.00	77.00	2.00	26.20	24.06	10.00	.50	36.19	252.00	.51	.12	0	18.78	1.00	118
214.17	2.00	70.00	2.00	26.91	23.96	14.00	.50	51.22	322.00	.72	.17	0	26.58	1.00	119
219.47	2.00	87.00	2.00	27.21	23.86	16.00	.50	58.77	368.00	.82	.19	0	38.27	1.00	120
217.86	2.00	88.00	2.00	27.11	23.75	16.00	.50	58.31	368.00	.82	.19	0	37.93	1.00	121
221.63	2.00	105.00	2.00	25.39	23.65	8.00	.50	27.88	184.00	.39	.09	0	15.29	1.00	122
225.38	1.00	105.00	2.00	25.39	23.55	8.00	1.00	29.40	184.00	.41	.10	0	19.04	1.00	123
223.68	1.00	106.00	2.00	25.28	23.45	8.00	1.00	29.16	184.00	.41	.09	0	18.84	1.00	124
224.51	2.00	108.00	2.00	25.08	23.34	8.00	.50	27.19	184.00	.38	.09	0	14.79	1.00	125
228.16	1.00	108.00	2.00	25.08	23.24	8.00	1.00	28.67	184.00	.40	.09	0	18.44	1.00	126
226.40	1.00	107.00	2.00	24.98	23.14	8.00	1.00	28.43	184.00	.40	.09	0	18.25	1.00	127
226.62	1.00	110.00	1.00	24.88	23.04	8.00	1.00	28.19	184.00	.39	.09	0	20.02	1.00	128
227.55	1.00	111.00	1.00	24.77	22.94	8.00	1.00	27.95	167.20	.39	.09	0	19.81	1.00	129
228.99	2.00	105.00	2.00	25.39	22.83	12.00	.50	39.67	250.80	.56	.13	0	22.65	1.00	130
227.25	2.00	106.00	2.00	25.28	22.73	12.00	.50	39.33	250.80	.55	.13	0	22.41	1.00	131
227.67	2.00	107.00	2.00	25.18	22.63	12.00	.50	39.00	250.80	.55	.13	0	22.18	1.00	132
231.67	2.00	108.00	2.00	25.08	22.53	12.00	.50	38.67	250.80	.54	.13	0	21.95	1.00	133
229.88	2.00	107.00	2.00	24.98	22.42	12.00	.50	38.34	250.80	.54	.12	0	21.72	1.00	134
228.90	2.00	102.00	2.00	25.69	22.32	16.00	.50	51.96	334.40	.73	.17	0	33.26	1.00	135
229.44	2.00	115.00	2.00	24.37	22.22	10.00	.50	31.09	209.00	.44	.10	0	15.44	1.00	136
234.50	2.00	104.00	2.00	25.49	22.12	16.00	.50	51.08	334.40	.72	.17	0	32.62	1.00	137
238.63	2.00	105.00	2.00	25.39	22.01	16.00	.50	50.64	334.40	.71	.16	0	32.30	1.00	138
232.52	3.00	123.00	0	23.55	21.91	8.00	0	22.55	151.20	.32	.07	0	7.14	1.00	139
235.13	2.00	123.00	3.00	23.55	21.81	8.00	.50	23.86	151.20	.33	.08	0	9.75	1.00	140
237.68	1.00	123.00	3.00	23.55	21.70	8.00	1.00	25.15	151.20	.35	.08	0	12.30	1.00	141
235.82	1.00	124.00	3.00	23.45	21.60	8.00	1.00	24.92	151.20	.35	.08	0	12.15	1.00	142
236.36	2.00	126.00	4.00	23.24	21.50	8.00	.50	23.21	151.20	.32	.08	0	8.19	1.00	143
238.78	1.00	126.00	4.00	23.24	21.40	8.00	1.00	24.47	151.20	.34	.08	0	10.62	1.00	144
236.88	1.00	127.00	4.00	23.14	21.29	8.00	1.00	24.24	151.20	.34	.08	0	10.47	1.00	145
237.12	4.00	138.00	0	22.01	21.19	4.00	0	10.18	75.60	.14	.03	0	-1.51	1.00	146
237.74	2.00	126.00	4.00	23.24	21.09	10.00	.50	28.16	189.00	.39	.09	0	9.58	1.00	147
239.03	1.00	130.00	4.00	22.83	20.98	8.00	1.00	23.58	136.00	.33	.08	0	10.05	1.00	148
237.75	3.00	133.00	0	22.53	20.88	8.00	0	20.56	136.00	.29	.07	0	6.08	1.00	149
239.04	2.00	133.00	4.00	22.53	20.78	8.00	.50	21.75	136.00	.30	.07	0	7.37	1.00	150
241.30	1.00	133.00	4.00	22.53	20.68	8.00	1.00	22.92	136.00	.32	.07	0	9.63	1.00	151
239.37	1.00	134.00	4.00	22.42	20.57	8.00	1.00	22.70	136.00	.32	.07	0	9.49	1.00	152

Table 34. Continued

240.16	3.00	137.00	0	22.12	20.47	8.00	0	19.79	136.00	.28	.06	0	5.67	1.00	153
244.20	3.00	138.00	0	22.01	20.37	8.00	0	19.60	136.00	.27	.06	0	5.56	1.00	154
245.42	2.00	138.00	4.00	22.01	20.26	8.00	.50	20.73	136.00	.29	.07	0	6.79	1.00	155
247.58	1.00	138.00	4.00	22.01	20.16	8.00	1.00	21.04	136.00	.31	.07	0	8.95	1.00	156
243.29	2.00	124.00	4.00	23.45	20.06	16.00	.50	42.68	272.00	.60	.14	0	19.61	1.00	157
245.14	2.00	141.00	3.00	21.70	19.95	8.00	.50	20.13	121.60	.28	.07	0	7.46	1.00	158
247.32	2.00	126.00	4.00	23.24	19.85	16.00	.50	41.87	243.20	.59	.14	0	19.15	1.00	159
245.33	2.00	127.00	4.00	23.14	19.75	16.00	.50	41.48	243.20	.58	.14	0	18.92	1.00	160
245.87	2.00	144.00	3.00	21.40	19.64	8.00	.50	19.53	121.60	.27	.06	0	7.09	1.00	161
247.95	1.00	144.00	3.00	21.40	19.54	8.00	1.00	20.58	121.60	.29	.07	0	9.17	1.00	162
249.69	2.00	138.00	4.00	22.01	19.43	12.00	.50	29.32	182.40	.41	.10	0	11.06	1.00	163
246.02	1.00	146.00	3.00	21.19	19.33	8.00	1.00	20.17	121.60	.28	.07	0	8.89	1.00	164
246.98	2.00	144.00	3.00	21.40	19.23	10.00	.50	23.65	152.00	.33	.08	0	8.20	1.00	165
249.69	2.00	141.00	3.00	21.70	19.12	12.00	.50	28.45	182.40	.40	.09	0	12.01	1.00	166
248.55	2.00	138.00	4.00	22.01	19.02	14.00	.50	33.36	212.80	.47	.11	0	9.92	1.00	167
248.02	2.00	143.00	3.00	21.50	18.92	12.00	.50	27.88	162.00	.39	.09	0	11.67	1.00	168
250.28	2.00	144.00	3.00	21.40	18.81	12.00	.50	27.60	162.00	.39	.09	0	11.50	1.00	169
251.19	2.00	137.00	4.00	22.12	18.71	16.00	.50	37.59	216.00	.53	.12	0	16.69	1.00	170
255.11	2.00	138.00	4.00	22.01	18.60	16.00	.50	37.22	216.00	.52	.12	0	16.48	1.00	171
251.99	1.00	154.00	3.00	20.37	18.50	8.00	1.00	18.55	108.00	.26	.06	0	7.79	1.00	172
253.26	2.00	156.00	3.00	20.16	18.40	8.00	.50	17.24	108.00	.24	.06	0	5.68	1.00	173
255.32	2.00	141.00	3.00	21.70	18.29	16.00	.50	36.09	216.00	.51	.12	0	17.63	1.00	174
253.23	2.00	142.00	3.00	21.60	18.19	16.00	.50	35.72	216.00	.50	.12	0	17.40	1.00	175
253.53	2.00	143.00	3.00	21.50	18.08	16.00	.50	35.35	216.00	.49	.12	0	17.17	1.00	176
255.72	2.00	144.00	3.00	21.40	17.98	16.00	.50	34.98	190.40	.49	.11	0	16.94	1.00	177
253.59	2.00	145.00	3.00	21.29	17.87	16.00	.50	34.62	190.40	.48	.11	0	16.71	1.00	178
254.05	2.00	154.00	3.00	20.37	17.77	12.00	.50	24.83	142.80	.35	.08	0	9.85	1.00	179
255.12	2.00	155.00	3.00	20.26	17.66	12.00	.50	24.56	142.80	.34	.08	0	9.69	1.00	180
255.90	2.00	156.00	4.00	20.16	17.56	12.00	.50	24.29	142.80	.34	.08	0	8.32	1.00	181
252.73	4.00	174.00	0	18.29	17.46	4.00	0	6.97	47.60	.10	.02	0	-2.59	1.00	182
253.49	2.00	166.00	4.00	19.12	17.35	8.00	.50	15.43	95.20	.22	.05	0	3.80	1.00	183
255.20	2.00	157.00	4.00	19.85	17.25	12.00	.50	23.50	142.80	.33	.08	0	7.88	1.00	184
254.93	2.00	156.00	4.00	20.16	17.14	14.00	.50	27.58	166.60	.39	.09	0	7.35	1.00	185
253.78	2.00	167.00	4.00	18.81	17.04	8.00	.50	14.91	95.20	.21	.05	0	3.50	1.00	186
257.56	3.00	171.00	0	18.60	16.93	8.00	0	13.79	83.20	.19	.04	0	2.45	1.00	187
258.42	2.00	171.00	4.00	18.60	16.83	8.00	.50	14.56	83.20	.20	.05	0	3.31	1.00	188
260.31	2.00	156.00	4.00	20.16	16.72	16.00	.50	30.71	166.40	.43	.10	0	12.73	1.00	189
257.51	3.00	174.00	0	18.29	16.62	8.00	0	13.30	83.20	.19	.04	0	2.20	1.00	190
258.33	2.00	174.00	4.00	18.29	16.51	8.00	.50	14.05	83.20	.20	.05	0	3.02	1.00	191
259.46	2.00	157.00	4.00	19.85	16.40	16.00	.50	29.68	166.40	.42	.10	0	12.14	1.00	192
257.66	3.00	177.00	0	17.98	16.30	8.00	0	12.83	83.20	.18	.04	0	1.94	1.00	193
258.45	2.00	177.00	4.00	17.98	16.19	8.00	.50	13.55	83.20	.19	.04	0	2.73	1.00	194
259.51	2.00	162.00	4.00	19.54	16.09	16.00	.50	28.66	166.40	.40	.09	0	11.56	1.00	195
261.32	2.00	171.00	4.00	18.60	15.98	12.00	.50	20.44	108.00	.29	.07	0	6.22	1.00	196
258.07	2.00	172.00	4.00	18.50	15.88	12.00	.50	20.19	108.00	.28	.07	0	6.08	1.00	197
259.21	2.00	173.00	4.00	18.40	15.77	12.00	.50	19.94	108.00	.28	.06	0	5.95	1.00	198
261.13	2.00	174.00	4.00	18.29	15.66	12.00	.50	19.70	108.00	.28	.06	0	5.81	1.00	199
260.49	2.00	171.00	4.00	18.60	15.56	14.00	.50	23.15	126.00	.32	.08	0	5.38	1.00	200
259.08	2.00	176.00	4.00	18.08	15.45	12.00	.50	19.22	108.00	.27	.06	0	5.55	1.00	201
261.14	2.00	177.00	4.00	17.98	15.35	12.00	.50	18.98	108.00	.27	.06	0	5.42	1.00	202
261.24	2.00	170.00	4.00	18.71	15.24	16.00	.50	26.04	144.00	.36	.08	0	10.05	1.00	203
264.97	2.00	171.00	4.00	18.60	15.13	16.00	.50	25.72	144.00	.36	.08	0	9.87	1.00	204

Table 34. Continued

261.67	2.00	172.00	4.00	18.50	15.03	16.00	.50	25.40	144.00	36	.08	0	9.68	1.00	205
262.76	2.00	173.00	4.00	18.40	14.92	16.00	.50	25.08	123.20	.35	08	0	9.50	1.00	206
264.63	2.00	174.00	4.00	18.29	14.81	16.00	.50	24.77	123.20	35	08	0	9.32	1.00	207
262.36	2.00	175.00	4.00	18.19	14.71	16.00	.50	24.45	123.20	.34	.08	0	9.14	1.00	208
262.49	2.00	176.00	4.00	18.08	14.60	16.00	.50	24.14	123.20	34	08	0	8.96	1.00	209
264.50	2.00	177.00	4.00	17.98	14.49	16.00	.50	23.83	123.20	33	08	0	8.78	1.00	210
262.19	2.00	178.00	4.00	17.87	14.39	16.00	.50	23.53	123.20	.33	08	0	8.61	1.00	211
262.48	2.00	179.00	4.00	17.77	14.28	16.00	.50	23.22	123.20	33	.08	0	8.43	1.00	212
263.37	2.00	180.00	4.00	17.66	14.17	16.00	.50	22.92	123.20	.32	.07	0	8.25	1.00	213
264.22	2.00	187.00	4.00	16.72	14.06	12.00	.50	16.20	92.40	.23	.05	0	3.91	1.00	214
261.34	3.00	177.00	0	15.66	13.96	8.00	0	9.58	52.00	.13	.03	0	.21	1.00	215
262.00	2.00	171.00	4.00	16.51	13.85	12.00	.50	15.76	78.00	22	.05	0	3.67	1.00	216
263.00	2.00	172.00	4.00	16.40	13.74	12.00	.50	15.54	78.00	22	05	0	3.55	1.00	217
263.53	2.00	187.00	4.00	16.72	13.63	14.00	.50	18.29	91.00	26	.06	0	3.22	1.00	218
261.76	2.00	174.00	4.00	16.19	13.52	12.00	.50	15.10	78.00	21	.05	0	3.31	1.00	219
264.82	3.00	204.00	0	15.13	13.41	8.00	0	8.90	52.00	.12	03	0	-.16	1.00	220
265.83	2.00	204.00	3.00	15.13	13.31	8.00	.50	9.39	52.00	13	.03	0	.85	1.00	221
267.04	2.00	187.00	4.00	16.72	13.20	16.00	.50	20.26	104.00	.28	.07	0	6.73	1.00	222
264.26	3.00	207.00	0	14.81	13.09	8.00	0	8.51	52.00	.12	.03	0	-.37	1.00	223
265.23	2.00	207.00	3.00	14.81	12.98	8.00	.50	8.97	43.20	.13	.03	0	.60	1.00	224
266.30	2.00	204.00	3.00	15.13	12.87	10.00	.50	11.26	54.00	16	.04	0	1.33	1.00	225
263.92	3.00	210.00	0	14.49	12.76	8.00	0	8.12	43.20	.11	.03	0	-.58	1.00	226
264.84	2.00	210.00	3.00	14.49	12.65	8.00	.50	8.56	43.20	.12	.03	0	.34	1.00	227
265.68	2.00	207.00	3.00	14.81	12.54	10.00	.50	10.75	54.00	.15	.03	0	1.04	1.00	228
267.79	2.00	204.00	3.00	15.13	12.43	12.00	.50	13.01	64.80	.18	.04	0	2.82	1.00	229
264.37	2.00	205.00	3.00	15.03	12.32	12.00	.50	12.80	64.80	.18	.04	0	2.70	1.00	230
265.34	2.00	206.00	3.00	14.92	12.21	12.00	.50	12.60	64.80	.18	.04	0	2.58	1.00	231
267.09	2.00	207.00	3.00	14.81	12.10	12.00	.50	12.40	64.80	.17	.04	0	2.46	1.00	232
266.57	2.00	204.00	4.00	15.13	11.99	14.00	.50	14.63	61.60	.20	.05	0	1.59	1.00	233
264.71	2.00	207.00	3.00	14.60	11.88	12.00	.50	12.01	52.80	.17	.04	0	2.22	1.00	234
266.61	2.00	210.00	3.00	14.49	11.77	12.00	.50	11.81	52.80	.17	.04	0	2.11	1.00	235
265.92	2.00	207.00	4.00	14.81	11.66	14.00	.50	13.94	61.60	.20	.05	0	1.28	1.00	236
269.34	2.00	204.00	4.00	15.13	11.55	16.00	.50	16.14	70.40	.23	.05	0	4.36	1.00	237
265.88	2.00	205.00	4.00	15.03	11.44	16.00	.50	15.88	70.40	.22	.05	0	4.21	1.00	238
266.83	2.00	206.00	4.00	14.92	11.32	16.00	.50	15.63	70.40	.22	.05	0	4.06	1.00	239
268.55	2.00	207.00	4.00	14.81	11.21	16.00	.50	15.37	70.40	.22	.05	0	3.92	1.00	240
266.13	2.00	208.00	4.00	14.71	11.10	16.00	.50	15.11	70.40	.21	05	0	3.77	1.00	241
266.11	2.00	209.00	4.00	14.60	10.99	16.00	.50	14.86	56.00	.21	.05	0	3.62	1.00	242
267.98	2.00	210.00	4.00	14.49	10.87	16.00	.50	14.61	56.00	.20	.05	0	3.48	1.00	243
265.53	2.00	211.00	4.00	14.39	10.76	16.00	.50	14.36	56.00	.20	.05	0	3.34	1.00	244
265.99	3.00	227.00	0	12.43	10.65	8.00	0	5.83	28.00	.08	.02	0	-1.80	1.00	245
266.42	2.00	213.00	4.00	14.17	10.53	16.00	.50	13.87	56.00	.19	.05	0	3.05	1.00	246
267.33	2.00	222.00	4.00	13.20	10.42	12.00	.50	9.57	42.00	.13	.03	0	.29	1.00	247
265.11	3.00	232.00	0	12.10	10.31	8.00	0	5.49	28.00	.08	.02	0	-1.98	1.00	248
265.44	2.00	232.00	4.00	12.10	10.19	8.00	.50	5.78	28.00	.08	.02	0	-1.65	1.00	249
266.63	2.00	227.00	4.00	12.43	10.08	10.00	.50	7.29	35.00	.10	.02	0	-1.17	1.00	250
264.45	3.00	235.00	0	11.77	9.96	8.00	0	5.17	21.60	.07	.02	0	-2.16	1.00	251
263.70	3.00	236.00	0	11.66	9.84	8.00	0	5.06	21.60	.07	.02	0	-2.21	1.00	252
267.07	3.00	237.00	0	11.55	9.73	8.00	0	4.96	21.60	.07	.02	0	-2.27	1.00	253
263.55	3.00	238.00	0	11.44	9.61	8.00	0	4.85	21.60	07	.02	0	-2.33	1.00	254
264.45	3.00	239.00	0	11.32	9.50	8.00	0	4.75	21.60	.07	02	0	-2.38	1.00	255
266.11	3.00	240.00	0	11.21	9.38	8.00	0	4.64	21.60	06	02	0	-2.44	1.00	256
263.64	3.00	241.00	0	11.10	9.26	8.00	0	4.54	21.60	06	01	0	-2.49	1.00	257
263.57	3.00	242.00	0	10.99	9.14	8.00	0	4.44	21.60	06	01	0	-2.55	1.00	258

Table 34. Continued

265.38	3.00	243.00	0	10.87	9.02	8.00	0	4.34	21.60	.06	.01	0	-2.60	1.00	259
262.88	3.00	244.00	0	10.76	8.90	8.00	0	4.24	16.00	.06	.01	0	-2.65	1.00	260
263.28	3.00	245.00	0	10.65	8.79	8.00	0	4.14	16.00	.06	.01	0	-2.71	1.00	261
263.66	3.00	246.00	0	10.53	8.67	8.00	0	4.04	16.00	.06	.01	0	-2.76	1.00	262
264.52	3.00	247.00	0	10.42	8.54	8.00	0	3.94	16.00	.06	.01	0	-2.81	1.00	263
262.25	3.00	248.00	0	10.31	8.42	8.00	0	3.85	16.00	.05	.01	0	-2.86	1.00	264
262.52	3.00	249.00	0	10.19	8.30	8.00	0	3.75	16.00	.05	.01	0	-2.91	1.00	265
263.66	3.00	250.00	0	10.08	8.18	8.00	0	3.66	16.00	.05	.01	0	-2.96	1.00	266
261.44	3.00	251.00	0	9.96	8.06	8.00	0	3.56	16.00	.05	.01	0	-3.01	1.00	267
260.64	3.00	252.00	0	9.84	7.93	8.00	0	3.47	11.20	.05	.01	0	-3.06	1.00	268
263.95	3.00	253.00	0	9.73	7.81	8.00	0	3.38	11.20	.05	.01	0	-3.11	1.00	269
260.39	3.00	254.00	0	9.61	7.68	8.00	0	3.29	11.20	.05	.01	0	-3.16	1.00	270
261.23	3.00	255.00	0	9.50	7.56	8.00	0	3.20	11.20	.04	.01	0	-3.21	1.00	271
262.85	3.00	256.00	0	9.38	7.43	8.00	0	3.11	11.20	.04	.01	0	-3.26	1.00	272
260.34	3.00	257.00	0	9.26	7.30	8.00	0	3.02	11.20	.04	.01	0	-3.31	1.00	273
260.21	3.00	258.00	0	9.14	7.18	8.00	0	2.93	11.20	.04	.01	0	-3.35	1.00	274
261.98	3.00	259.00	0	9.02	7.05	8.00	0	2.84	11.20	.04	.01	0	-3.40	1.00	275
259.43	3.00	260.00	0	8.90	6.92	8.00	0	2.76	7.20	.04	.01	0	-3.45	1.00	276
259.79	3.00	261.00	0	8.79	6.79	8.00	0	2.67	7.20	.04	.01	0	-3.49	1.00	277
260.13	3.00	262.00	0	8.67	6.65	8.00	0	2.59	7.20	.04	.01	0	-3.54	1.00	278
260.94	3.00	263.00	0	8.54	6.52	8.00	0	2.50	7.20	.04	.01	0	-3.58	1.00	279
258.62	3.00	264.00	0	8.42	6.38	8.00	0	2.42	7.20	.03	.01	0	-3.63	1.00	280
258.85	3.00	265.00	0	8.30	6.25	8.00	0	2.34	7.20	.03	.01	0	-3.67	1.00	281
259.95	3.00	266.00	0	8.18	6.11	8.00	0	2.26	7.20	.03	.01	0	-3.71	1.00	282
257.37	4.00	275.00	0	7.05	5.97	4.00	0	.93	2.00	.01	.00	0	-4.61	1.00	283
254.81	4.00	276.00	0	6.92	5.83	4.00	0	.89	2.00	.01	.00	0	-4.62	1.00	284
255.16	4.00	277.00	0	6.79	5.69	4.00	0	.85	2.00	.01	.00	0	-4.63	1.00	285
255.48	4.00	278.00	0	6.65	5.54	4.00	0	.82	2.00	.01	.00	0	-4.65	1.00	286
256.28	4.00	279.00	0	6.52	5.40	4.00	0	.78	2.00	.01	.00	0	-4.66	1.00	287
253.95	4.00	280.00	0	6.38	5.25	4.00	0	.74	2.00	.01	.00	0	-4.67	1.00	288
254.17	4.00	281.00	0	6.25	5.10	4.00	0	.71	2.00	.01	.00	0	-4.68	1.00	289
255.25	4.00	282.00	0	6.11	4.94	4.00	0	.67	.80	.01	.00	0	-4.70	1.00	290
252.66	4.00	283.00	0	5.97	4.79	4.00	0	.64	.80	.01	.00	0	-4.71	1.00	291
250.09	4.00	284.00	0	5.83	4.63	4.00	0	.60	.80	.01	.00	0	-4.72	1.00	292
250.43	4.00	285.00	0	5.69	4.46	4.00	0	.57	.80	.01	.00	0	-4.73	1.00	293
250.74	4.00	286.00	0	5.54	4.30	4.00	0	.53	.80	.01	.00	0	-4.74	1.00	294
251.53	4.00	287.00		5.40	4.12	4.00	0	.50	.80	.01	.00	0	-4.75	1.00	295

solution in that it starts with a grade 4 12.5 foot sawlog, followed by a grade 2 16.5 foot sawlog at stage 138. The base of the 16.5 foot sawlogs corresponds to stage 105 and the solution from there down to the stump is the same as that outlined for stage 166. In comparing these two solutions, the stage 163 pattern replaces the grade 3 12.5 sawlog and grade 3 and 2 veneer logs with a grade 4 12.5 foot sawlog and a grade 2 16.5 foot sawlog.

Another similar type of analysis from array A can also be obtained. Rather than examine the effect of varying the merchantable height (stage number) limit, it is possible to examine the influence of varying the diameter limit utilized in the tree. In the original analysis, tree 60 was analyzed with no limiting top diameter limit. However, it is possible to find out what the best pattern is that would utilize the tree to, say, a 6 inch top diameter. This is done by examining the column in array A corresponding to log small end diameter inside bark and finding the value closest to 6 inches. In this case, this corresponds to stage 290 (height = 147 feet) where the diameter is 6.11 inches. Proceeding to the next stage would violate the 6 inch limit. At stage 290, the optimum value is $255.25. Forcing the bucker to utilize to this point would result in losing $14.09 ($269.34 - $255.25) since he could do better at stage 237. In the upper tree portion he would encounter small pulp and fuel logs with negative value.

The type of sensitivity analysis obtained from this table is dependent on how the tree is analyzed by the model. If the tree were presented to the model "upside down" so the analysis proceeded from the top toward the stump, then the solution at any stage would be the solution between that stage and the top. In this type of analysis, Table 26 would provide a different sensitivity analysis. It would show the effect of variations in stump height and could indicate the optimum solution if the butt end of the tree shattered during felling. The present version of the model cannot provide this type of analysis. To do so would require reprogramming certain accounting conventions and redefining the way in which the model perceives the tree which presently is from the stump toward the top.

Effect of Sweep, Crook, and Internal Defects

Although the data on log diagrams for the test trees did not reveal the presence of internal defects and provided no basis for reconstructing sweep or crook, an example was developed for tree 55 to include these internal defects along with the external defects. Table 35 portrays the data deck submitted. The tree was analyzed using the original economic data for the case when logs are produced for roundwood sale and when the firm could either sell roundwood or mill the logs. It was assumed that this tree has a butt rot enclosable in a cylinder or ellipsoid in the

Table 35

Data Deck for Tree 55 with Initial Economic Conditions and Data for Internal Defects, Crook, and Sweep

```
  1    4   .5   24   31    1
  1    1   8.   1.   18.  48.        91.        84.        72.        67.
  2    1  16.   .5   10.1000.        87.        40.        69.        64.
327  288  242  230  200  200  200  200  197  172  162  130   62 7.25  18.   1.
  2    1  14.   .5   10.1000.        74.        68.        59.        51.
278  245  206  196  170  170  170  170  167  146  138  110   53 7.25  18.   1.
  2    1  12.   .5   10.1000.        83.        76.        66.        61.
311  274  230  218  190  190  190  190  187  163  154  124   60 7.25  18.   1.
  2    1  10.   .5   10.1000.        78.        72.        62.        58.
294  259  218  207  180  180  180  180  177  155  146  117   56 7.25  18.   1.
  2    1   8.   .5   10.1000.        86.        79.        68.        63.
324  285  240  228  198  198  198  198  195  170  160  129   61 7.25  18.   1.
  3    1   8.    0    6.1000.        30.
  4    1   4.    0    4.1000.        20.
 35   35   30   30   15   10    8   18   18   18   18    1
150
 15
14.   4.  .70  .90
  0    1    0    1    1    1    1    1    1    1
  0 1.34 1.34 2.40 1.18 6.51 8.0016.7070.0027.00
      55        42        138        138        2        120  152    1    0    1
  1  10.
 10
       0        30        30
       6        24        24
       9        21        21
      12        18        18
      15        15        15
      18        12        12
      21         9         9
      24         6         6
      27         3         3
      30         0         0
      40        12         6
 14
       0         0
       5         4
      10         7
      13         8
      18         2
      22        -6
      25       -11
      28       -12
      37        -7
      45       -12
      54        -7
      72        -6
     100        -4
     138         0
```

first 30 feet. Although the data portray this defect as a cone, it could be portrayed as having virtually any shape. One crook with a 12 inch deviation occurs at 40 feet in the tree and the tree has sweep. The sweep data include a reverse curvature.

The solutions were obtained only for the cases where external defects were also considered during the analyses as shown in Table 36. The counterpart solutions from Table 22 are reproduced here for comparison. The inclusion of these scaling defects resulted in new patterns and a reduced usable volume and conversion surplus. Initially, the internal rot is too large to allow veneer logs to be chucked. Also the crook deviation exceeds manufacturers' specifications for veneer logs. Consequently veneer logs become infeasible in two regions where they formerly were viable alternatives.

On the roundwood log market these defects alter the solution such that the net usable cubic volume is reduced from 385.5 to 256.1 cubic feet. Total conversion surplus declined from 235.94 to 168.95. The butt rot caused the first two veneer logs to be infeasible and be replaced by 8.5 foot sawlogs that had high scaling losses. The remainder of the log pattern was the same but some of the logs suffered scaling reductions due to the defects.

When milling is considered as an alternative, all logs are produced for the sawmill but the bucking pattern

Table 36

Solutions for Tree 55 under the Initial Economic Conditions and Considering External Defects Plus Including and Excluding Hypothetical Data for Internal Defect, Sweep and Crook

	Roundwood sale		Roundwood, sale or milling	
	Solution without internal defect, sweep and crook	Solution with internal defect, sweep and crook	Solution without internal defect, sweep and crook	Solution with internal defect, sweep and crook
Cubic volume of logs	385.5	256.1 (net)	383.1	264.5 (net)
% Utilization of tree volume	95	63	94	65
Conversion surplus	235.94	168.95	417.05	299.12
Log pattern[1]	Veneer 9.0 1 R	SAW 8.5 1 R	SAW 8.5 1 M	SAW 8.5 1 M
	Veneer 9.0 3 R	SAW 8.5 3 R	SAW 16.5 3 M	SAW 8.5 3 M
	Veneer 9.0 1 R	Veneer 9.0 1 R	SAW 16.5 3 M	SAW 8.5 1 M
	Veneer 9.0 2 R	Veneer 9.0 2 R	SAW 16.5 3 M	SAW 8.5 2 M
	SAW 16.5 2 R	SAW 16.5 2 R	SAW 16.5 3 M	SAW 8.5 2 M
	Veneer 9.0 3 R	Veneer 9.0 3 R	SAW 16.5 4 M	SAW 16.5 3 M
	SAW 16.5 3 R	SAW 16.5 3 R	SAW 16.5 4 M	SAW 16.5 3 M
	SAW 16.5 4 R	SAW 16.5 4 R		SAW 16.5 4 M
	SAW 16.5 4 R	SAW 16.5 4 R		SAW 16.5 4 M

[1]Logs are listed from stump to top and for each is indicated the log type, total length, grade, and whether it is sold as roundwood (R) or used in the firm's mill (M).

is changed. With the inclusion of sweep and crook, the model produces more short length logs, an apparent move to buck short straight segments and avoid scaling deductions. The overall volume utilized declined from 383.1 to 264.5 cubic feet and the conversion surplus declined from $417.05 to $299.12.

The inclusion of these defects can greatly complicate the decision problem faced by log buckers. Some kinds of logs become infeasible over a portion of the stem because of these defects and care must be taken to buck feasible logs in a way that minimizes the impact of log scaling deductions on conversion surplus.

Computer Requirements of the Model

The bucking model developed in this study requires 52000 (octal) 60 bit words of central memory on the University of Washington CDC 6400/CYBER 73 computer system. Table 37 indicates the number of central processor seconds (decimal) used in this system for analyzing these test trees. These times are for the analyses with the initial economic conditions. For these trees, when external defects were considered during the solution and all options were considered, the time ranged from 17-77 central processor seconds. This excludes program compilation time which takes about 6 seconds. Time per analysis changed only slightly when the economic conditions were changed but

Table 37

Number of Central Processor Seconds Required for Solution of the Tree Bucking Problem

Compilation of Program 5.8 seconds

Solution Time

Tree	73	71	59	60	55
Number of relevant defects	140	269	123	231	152
Tree height	110	131	138	156	138
Time, defects ignored					
roundwood	5.8	9.9	13.5	15.8	14.0
roundwood and milling	7.9	14.6	20.8	24.4	21.4
Time, defects considered					
roundwood	14.8	72.3	40.5	68.5	59.7
roundwood and milling	17.3	71.1	47.8	77.1	67.7

did change for some trees when the utilization standards were changed. The greatest increase was about 15 seconds for tree 71 which has the most defects. Changing the saw-log and veneer log standards increased the feasible length in the tree for these products and resulted in more log grading in the model. Inclusion of defects in the solution process can add greatly to the solution time but the extent of this increase depends on the number of external defects relevant to the log grading rules, the degree that they are concentrated or scattered along the stem, and the step used in establishing alternative sets of log grading faces, presently ten degrees. Solution time is also affected by the number of log possibilities and log lengths which determine the stage interval, the tree and stump height which together with the stage interval determines the number of stages, the nature of log diameter and defect restrictions that can limit the feasibility of various kinds of logs.

The solution time for some trees could be improved if the highest possible grade that could be assigned to any log segment in the tree could be estimated and submitted as part of the tree data. If this were possible the grading procedure could be revised to ignore testing for grades that are not feasible. It is believed that computing time can also be reduced through efforts to increase the program efficiency. In this study the main thrust was to develop a program code that followed scaling and grading rules and practices closely. This was done to simplify the task of verification. It is quite likely that efficient short cuts could be developed that would reduce the solution time. It is also possible that use of a different system for log grading such as Rules of the Puget Sound Log Scaling and Grading Bureau (1978) would influence the solution time. A different set of rules may alter the number of relevant defects plus the grading logic and associated computer code would be changed. In the present model, it is obvious that grading strongly influences solution time. Approximately half of the code for the model is associated with the grading rules used in this study.

Chapter 6

DISCUSSION AND CONCLUSIONS

This study has found dynamic programming to be a powerful and flexible tool in analyzing the bucking problem. Unlike linear and integer programming, all important decision factors can be included in the dynamic programming model thus avoiding the tedious pre-calculation steps required of these techniques. Similarly the dynamic programming model can easily accept new conditions and log specifications without the substantial reformulation that often accompanies linear programming.

Earlier attempts at using dynamic programming to solve the bucking problem did not include important shape quality features of trees, log grading and scaling practices, end product yield or a suitable economic framework and made restrictive assumptions about log bucking procedures. The model in this study removes these restrictions and easily introduces these important factors.

Study of bucking these five test trees with the model indicates that the optimal solution is strongly influenced by the existence of external defects and the log grading rules which account for them and by the occurrence of sweep, crook, and internal defects which are considered by log scaling practices and which may render a log unsuitable for a particular end use. Furthermore, the model indicates that the solutions are often very sensitive to changes in economic and manufacturing conditions. Taken together, variations in these tree, economic and manufacturing factors often result in radical changes in the optimal bucking pattern for an individual tree. The variation in the pattern of logs comprising the solution not only involves changes in the mix of log sizes, it also involves changes in both the allocation of logs between the roundwood market and mill and in the identity of specific manufacturing end uses. Even when the total volume utilized or the economic value of the solution is changed in a minor way by variations in factors affecting bucking, the structure of the solution required to achieve nearly the same economic or physical yield is often markedly different.

The small size of this group of test trees precludes the possibility of reaching a judgment concerning general patterns in the solutions that could be used in developing heuristic approximations to the model. In timber with relatively uniform quality from tree to tree it may be possible to define heuristic rules than can be condensed into reasonable instructions for crews. Such rules could be defined for a given set of economic and manufacturing circumstances and periodically revised. This approach could link bucking of logs to forecast economic conditions and provide a basis for bucking to respond to changes. It is this writer's belief that this possibility is less likely to be achieved where quality variation from tree to tree is large. In this case solutions may change so drastically from tree to tree that no general pattern can be found. Only future research will be able to determine the feasibility of reaching useful general conclusions.

One deficiency in this study is the lack of comparison of the model with actual bucking practice. All of the sensitivity analyses and comparisons are based on comparing optimal solutions based on one set of conditions with optimal solutions where one or more conditions are changed. This study did establish the importance of incorporating information into bucking models that has not been included previously. Comparison of the model solutions with actual practice was beyond the scope and resources of this study. Due to a lack of information it was impossible to meaningfully compare the optimal solutions for the test trees with the original way they were bucked. In considering all of the factors that must be considered in arriving at a bucking solution it is highly unlikely that actual practice achieves optimal solutions except by chance. However, the key, and unanswered, question is "by how much do they miss?" This can only be answered by comparative field studies in which trees are observed bucked by cutting crews and the resulting value, pattern, and allocation compared with optimal solutions obtained from the model. In performing these studies, it will be difficult but very important to ensure that the model is reaching its solutions based on the same data base and criteria used by the cutting crew. It is also important that the comparison include economic return, the pattern, and the allocation as the bases of judgments and not the volume utilization. Many very different solutions will yield nearly the same volume utilization but the economic value and the pattern of logs and allocation may be very different.

Possible Applications of the Model

In viewing potential real world applications of the dynamic programming bucking model, direct application in the woods where woods labor would somehow be equipped with a device programmed with the model that could indicate optimum bucking is not contemplated. There would not be a convenient method to rapidly measure and enter the necessary tree data such as diameter, taper, length, and defects. However, there are other ways in which the model could be indirectly used as an aid in woods bucking. These are:

1. as an approach for training woods labor;
2. as a quality control tool for evaluating woods bucking performance;
3. as a benchmark for evaluating current or proposed empirical bucking rules.

In addition to these uses, the model could be easily adapted to the problem of re-bucking long or tree length logs into final sizes on a mechanical slasher or log deck. In addition to the indirect uses cited above, the model would have direct application in this setting. Today modern mechanized slashers and log decks are increasingly equipped with electronic scanners, video screens and mini-computers to perform tasks ranging from sensing and displaying dimensions, performing various calculations and accounting, to actually controlling the bucking operation. The model would be directly applicable to this situation.

Training Application

In this application, the model would be used in a fashion similar to the type of training simulator used for airline pilots or astronauts where the trainee can be placed in a variety of realistic situations and his skills and judgments tested against model solutions. It should be possible to depict an entire stem or long log on a video screen where the size, shape, surface defect locations and other pertinent data are displayed to scale. The trainee, given his knowledge of specifications by management for various kinds and sizes of logs, log grading rules, product recovery, costs and values, could examine the stem, rotate the view on the screen to observe the stem character and then designate his bucking cuts and indicate his reasons for his selection. Comparison with the optimal solution predicted by the model would highlight differences and reasons for poor performance by the trainee. Training sessions such as this, covering a range of situations likely to occur, could point out a lack of knowledge or understanding of the grading rules, products standards, expected product recoveries, or other factors which play a key role in bucking decisions. The training simulator would provide a useful means for rating individuals and upgrading their abilities.

The training simulator would require a data base of typical stems or long logs. These would be carefully measured and all defects would be diagramed. The data would be entered into a computer data base. The model would require an appropriate log grading routine so that it can grade any section being considered as a log. Management would specify log manufacturing parameters and economic data to be used. The trainee and model would each present a solution. Comparative study of the solutions, perhaps by another computer program, would produce a readout of what differences if any occurred and why.

Quality Control Application

To continue the training and evaluation of bucking personnel, the model could be used as a quality control device. Stems or long logs bucked by an individual could be sampled and the sample re-bucked by the model. This would provide a basis for monitoring performance and would indicate personnel with poor performance who need remedial action. Comparison of actual results with the model would provide hints as to where and why differences occur.

This application first requires development of a sampling plan to sample stems bucked by the individual. Both the frequency and number of sample units (stems or long logs) would need to be determined. Since this may be a costly activity, especially to acquire the field data for the model, the trade off between misbucking costs and sampling costs should be carefully balanced. Field work would include measuring the dimensions of the felled tree and bucked logs plus collecting defect diagrams and perhaps photographic records. The dimension and defect data would be entered into a computer data base which would be accessed by the model and used with current prices, costs, and log making parameters to develop the optimum bucking. A quality control chart, perhaps presenting the ratio of the buckers' performance to the optimum, could be used to evaluate the need for corrective action.

Benchmark for Other Bucking Approaches

Another indirect application of the model would be its use as a benchmark for evaluating or developing empirical bucking rules. This application would be similar to the quality control application except that the model would be used to judge the performance of other bucking procedures rather than the performance of personnel. This could be accomplished by comparing the model with field trial results from the alternative rules, comparing the model with a computer simulation of bucking based on the alternative rules, or a combination of both. These comparisons would require selecting a sample of trees, measuring their dimensions, collecting defect data, and creating a computer data base. In the case where actual field trials with the empirical rules were being made, the location of the actual bucking points would also be recorded.

Comparison with the model would provide insight into which empirical methods work best, the conditions when their relative effectiveness changes and why these variations occur. These investigations could improve bucking by providing managers with guidelines as to when certain rules should be preferred. These studies could also provide insights that would lead to new improved empirical rules.

In the three applications described, the field work requires log diagraming. The process of collecting these diagrams along with stem dimension data and transferring this information into a computer data base would be costly, perhaps prohibitively so. Research should be undertaken to devise techniques of data acquisition that reduce the work. The applications of the model would be considerably enhanced if, for instance, a mark sense form could be developed that, once filled out in the field, could be readily entered into a computer. An alternative would be to use a field device where the data are recorded in the field on a tape cassette. Imrpovements in this area would greatly enhance the use of the model in these indirect applications, and especially in the quality control situation. Undoubtedly, the trade off between economic losses associated with misbucking and the costs of implementing these corrective actions will, in the final analysis, determine just how much use the model will receive in these areas.

Direct Application on Log Decks and Log Slashers

As suggested earlier, log decks and slashers are increasingly being equipped with electronic scanners, video screens, and computers to aid re-bucking of long logs. In some cases, this has progressed to the point where bucking is fully automated and the bucking station operator actually performs bucking only when an unusual circumstance occurs. These automated systems use some type of computer model or a look up table based on a computer model to determine optimal cut locations and to activate the bucking station equipment. The dynamic programming bucking model could be readily adapted to this situation. This would mainly involve revising the input of the descriptors of the stem dimensions to be descriptors of long log dimensions as "observed" by an electronic scanner.

The scanner system can describe the log dimensions and shape to the computer model. Management would input the information on the desired log lengths, diameter ranges, end uses, product yields, and economic data. This management data would be periodically updated to reflect changing mill and market conditions.

The applicability of this use may be questioned since important defect data would not be made available by the scanner and that even if this were unimportant, the model may not be compatible with computers typically used in mills.

Currently available scanners cannot sense most log defects. However, a number of computer controlled bucking systems are in use in spite of this limitation. Bucking operators can punch in a visual estimate of the overall grade of the long log or a log grader in the log yard could mark the grade on the infeed end of the log. The operator could enter this grade data into the computer and this could act as a constraint in the model to preclude consideration of certain products. The operator also has the option to override the selected bucking points if some important factor such as rot, split, etc. not properly accounted for in the model is noticed. In present systems, when the operator overrides, he must estimate all of the cuts in the rest of the log since the computer system has no basis to recompute the solution. The log would be at the cut-off saw and there would be no time to recompute. The dynamic programming model has an important advantage over other approaches in this case. In the course of solving for the optimal bucking of the whole long log, it has also solved and stored the optimal bucking solution for subsections of it. Therefore, it has the optimal solution for the remainder of the log available for immediate retrieval. It would be a simple matter to note the length of the operator override and look up the model solution for the remainder. In the future, improved scanning technologies can be expected that will automatically indicate the locations of important defects to the computer and enable the bucking model to more accurately grade each section of the long log. As these new scanners emerge, a model like the dynamic programming model developed in this study will be even more effective.

Another important question is whether the model would be computationally feasible in the mill environment. In this study it was found that the solution time for large old growth trees could take nearly a minute and that a fairly large array size is needed to store stage by stage optima. Fortunately, the size of the program requirements and the computational time would be much smaller when the model is adapted to bucking long logs. Such logs are typically less than 40 feet in length and because of the many log constraints, some short log alternatives may frequently be infeasible. Consequently, the solution time for long logs may be much shorter, perhaps only a few seconds.

Extensions of the Model

There are several potential extensions of the model including other aspects of the bucking problem as well as other areas of forest products manufacture. One simple variation would involve the use of one or more additional sets of cost structures to reflect use of tree under multi-stage logging. Generally, fuel and pulp logs were found to be at an economic disadvantage in the study. These uses were almost always inferior to other uses in the lower bole and, towards the upper bole where other uses became infeasible, they were disadvantaged because they were assumed to be harvested and transported by the same technology as veneer logs and sawlogs. In this upper stem region, these uses suffered from the disadvantage of small log size. The model could be revised to examine the feasibility of multi-stage logging where logging systems posing different costs are brought into the forest in stages. In this approach, each logging system is designed to remove a different size category. This could be readily incorporated by revising subroutine COST to reflect the cost structures of the different logging stages. Then depending on the type of trial log, or perhaps position in the tree, a different set of costs could be utilized. The model could be used to indicate the overall optimal solution and identify which logs would be removed during a particular stage.

The present version of the model has been used to examine the solutions based upon the final size specifications at mills. It could also be used to indicate the best pattern of long logs; logs that are produced in woods bucking that consist of combinations of the final log sizes. The long logs are bucked, harvested and transported to a site where they are re-bucked into final sizes. Although long log specifications could be submitted to the present model, solutions obtained would not be useful except to an operation that only produced long logs for sale in this form. For integrated firms that produce long logs and later re-buck them, the present model is inadequate because the long log bears only part of the economic burden while the short logs bear the remainder. In this situation, the long logs bear some of the costs, typically stumpage, woods bucking, skidding, loading, and hauling. These costs accrue to the long log but are sunk costs that should no longer be considered in deciding how to produce short logs from a particular long log. Short logs bear the costs of re-bucking and further handling and milling costs. Short logs also would be the basis for accruing revenues from processing. This situation, where long logs are produced and later processed into short logs, can be viewed as a pair of linked dynamic programming problems. The first phase consists of how to cut the trees into long logs but this is linked to the second phase of how to cut the long logs into final sizes. By linking these two problems together, the optimal solution for the location of long log cuts in the tree and short log cuts during re-bucking can be simultaneously produced. In addition, there may be economies of scale in logging larger long logs that will improve overall tree utilization and value. This approach may improve the prospects for fuel and pulp uses. Referring to Figure 38 and ignoring the notation that would be needed to identify specific end uses and log grades define:

D = dbh

H = total height

S = stump height

L_i = length specifications for L-th long log

L_{min} = min (L_i) smallest long log length

L_{max} = max (L_i) largest long log length

k = an interval of stem length that is the common denominator of the long log lengths, L_i, used as dynamic programming stage interval for long log part of the problem

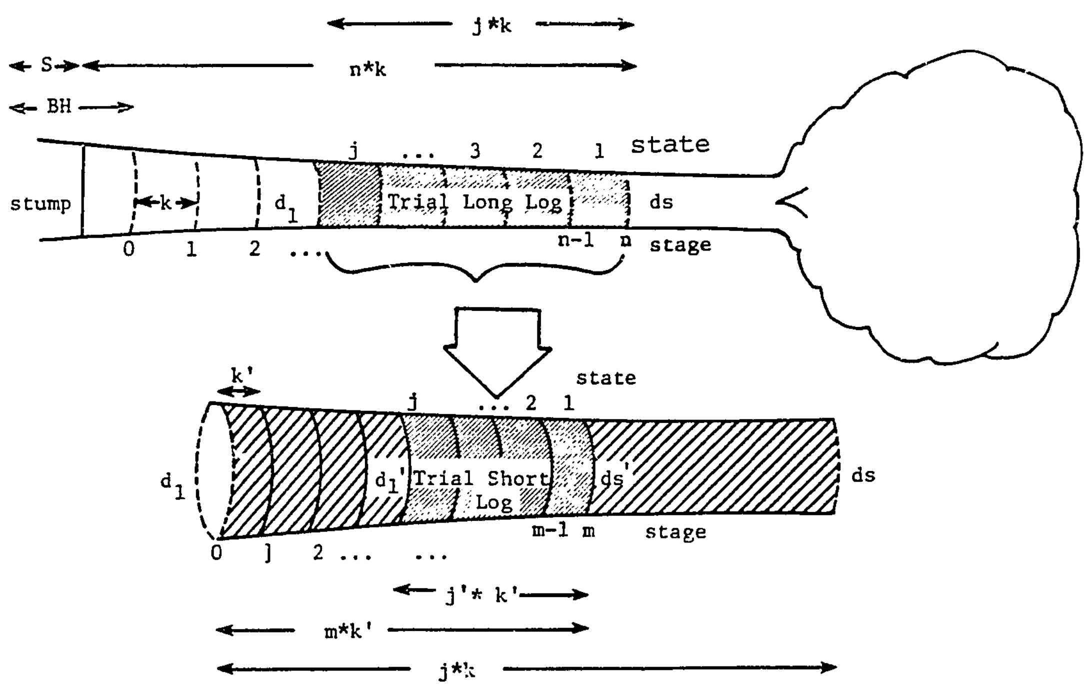
n = 1, 2, . . . INT [(H - S)/k]

= stage number such that $n*k + S$ is the height to a trial log bucking point in the tree

j = state = number of long log stage intervals to be combined into one long log where j is such that $j*k$, a trial long log length is in the range

$$L_{min} \leq j*k \leq \min(n*k, L_{max})$$

a) Problem of bucking long logs from a tree



b) Problem of bucking short logs from a long log

Figure 38. Notation for the long-log short-log dynamic programming bucking model.

and $j*k \ \varepsilon \ (L_i)$

d_ℓ, d_s = large and small end diameters of a trial long log of length j*k. There may be constraints on these diameters.

ℓ_z = length specifications for the z-th short log

ℓ_{min} = min (ℓ_z) smallest short log length

ℓ_{max} = max (ℓ_z) largest short log length

k' = an interval of long log length that is the common denominator of the short log lengths, ℓ_z, used as dynamic programming stage interval for solving the problem of short logs within a trial long log. Note: k and k' should either be the same or one should be an integer multiple of the other.

m = 1, 2, . . . INT (j*k/k')

= stage number such that m*k' is the distance from large end of a trial long log to the trial re-bucking point to make a short log

j' = state = number of short log stage intervals to be combined into one short log within a long log where j' is such that j'*k', a trial short log length, is in the range

$$\ell_{min} \leq j'*k' \leq \min\ (m*k',\ \ell_{max})$$

and $j'*k' \ \varepsilon \ (\ell_i)$

d', d_s' = large and small end diameters of a trial short log of length j'*k'. There may be constraints on these diameters.

Then, the recursion relationship for the problem is shown in Table 38. In this formulation, the same ideas developed in this study are used except that within the primary (long log) bucking phase, another dynamic programming application is used to evaluate the profitability of the current trial long log. This secondary phase evaluates the optimal way that the trial long log should eventually be re-bucked into finished log sizes.

The present model cannot deal with this extension although many of the subroutines could be used with little or no change. The principal changes would require that the main program, BUCK, and subroutine DYNPRO be rewritten to express the formulation, to orchestrate the proper sequences calling upon the other subroutines, and to handle additional accounting tasks. Research on this type of extension should be undertaken since it would greatly expand potential applicability of the dynamic programming operation as an operational, planning and training tool in bucking.

The approach using dynamic programming in this study has a number of potential applications in other areas of manufacture. Except for the differences in shape, a board can be considered analogous to a tree and the problems of edging and ripping a wide waney board into narrower finished sizes to improve grade and profit is in many ways

Table 38

Dynamic Programming Recursion Relationship for the Long-Log Short-Log Bucking Problem

$$\underbrace{F_n(H,D,S)}_{\substack{\text{Value of optimal solution of}\\ \text{bucking the tree through the n-th}\\ \text{stage (top of trial long log)}}} = \max_{j} \Big[\underbrace{f^*_m(j{*}k,\ d_\ell,\ d_s)}_{\substack{\text{Optimal rebucking value}\\ \text{for the trial long log}}} - \underbrace{c(j{*}k,\ d_\ell,\ d_s)}_{\substack{\text{Variable cost of logging and hauling}\\ \text{the trial long log to the rebucking site}}} + \underbrace{F_{n-j}(n{*}k - j{*}k,\ D,S)}_{\substack{\text{Value of optimal solution for bucking the portion}\\ \text{of the tree between the stump and the large end}\\ \text{of the trial long log}}} \Big]$$

$$\underbrace{f_m(j{*}k,\ d_\ell,\ d_s)}_{\substack{\text{Value of optimal solution for bucking the}\\ \text{trial long log through the n'-th stage}}} = \max_{j'} \Big[\underbrace{V(j'{*}k',\ d'_\ell,\ d'_s)}_{\substack{\text{Value of a trial short log of length j'*k'}\\ \text{large diameter } d'_\ell \text{ and small diameter } d'_s\\ \text{located within a trial long log with its small}\\ \text{end located at height n*k + S in the tree}}} - \underbrace{c(j'{*}k',\ d'_\ell,\ d'_s)}_{\substack{\text{Variable cost of rebucking and}\\ \text{processing the trial short log}}} + \underbrace{f_{m-j'}(m'{*}k' - j'{*}k',\ d'_\ell,\ d'_s)}_{\substack{\text{Value of optimal solution for bucking the portion of the trial}\\ \text{long log between its large end and the locus of the large end}\\ \text{of the trial short log}}} \Big]$$

similar to the bucking problem. Trimming of boards to square ends and to produce short lengths to improve grade and profit is another similar example. Even the problem of sawing a log into lumber may be viewed as an analogous area for potential application of dynamic programming. In the process of converting logs into veneer, green and dry clipping are areas that could be approached with this methodology. Indeed, in some processes such as lumber manufacture, the problems of primary breakdown, edging and trimming could be considered as a problem with phases of linked dynamic programming models. Such an approach would allow all phases of manufacture to be considered simultaneously and the optimum log breakdown strategy based on the interaction of the different operations could be devised. Research on the use of dynamic programming in these areas of manufacture is needed because this technique will provide a definite optimum against which current practices and other approaches can be benchmarked. It may also be discovered that this approach can be used operationally in view of the rapid advances being made in the fields of computing and scanning.

Chapter 7

SUMMARY AND RECOMMENDATIONS

Summary

Reviewing the objectives stated in Chapter 3 the following conclusions can be stated:

1. A flexible dynamic programming model for bucking trees into short logs has been developed for Douglas-fir that contains the capability of considering defects, grading rules, end product recovery and that can consider bucking logs at any point in the production process for roundwood sale and/or mill use.

2. It was verified that the model operates as intended for a small group of test trees.

3. Experimentation with the model indicates that inclusion of defect information and log grading and scaling practices alters optimum solutions. Inclusion of these factors does, however, involve an increase in solution time.

4. The model is versatile in examining questions such as how does changing the usable height or stump height affect the solution; how do changes in log specifications influence the solution; and what are the impacts of changes in relative prices and costs associated with producing and processing different kinds of logs.

Recommendations

From the experience accumulated during this study the following recommendations are made:

1. Further testing of the model with a larger sample of trees in an operational setting is needed for further validation and to determine the differential between current and optimal bucking practices.

2. The FORTRAN IV program code for the model should be reviewed carefully to seek possible improvements in computing efficiency.

3. The model should be expanded to include consideration of bucking long log combinations of these short logs corresponding to woods practice in many parts of the West.

4. Alternative log grading systems such as the official log scaling and grading rules of the scaling and grading bureaus (Puget Sound Log Scaling and Grading Bureau, 1978) and product recovery studies should be coded into a form that is coordinated with the model. This should be done to generalize the model to accommodate a wider range of production setups and other species.

5. Research in logging studies should be done to develop cost data that are more useful in assessing individual log economics according to log size and location in the tree.

6. Research should be undertaken to adapt the

model to the problem of bucking long logs on mill decks in conjunction with scanning technology capable of sensing defect information.

7. Research should be undertaken to use the technique of dynamic programming in areas such as optimal conversion of logs into lumber, including edging and ripping, trimming operations and optimal clipping of veneer.

8. Research should be undertaken to integrate the optimal single tree bucking problem into the broader problem of considering timber supplies and end products demands.

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Appendix A

INTRODUCTION TO DYNAMIC PROGRAMMING

The concepts of dynamic programming are best introduced by referring to a simple example. Adapting an introductory example from Dreyfus and Law (1977), suppose it is desired to find the way from point A to point B in the network portrayed in Figure 39 assuming that each link is one way and that the numbers along each link represent the effort, e, envolved in taking that link. Also assume that it is desired to find the path from A to B that requires the least effort. This simple problem could be solved by complete enumeration of all possibilities but this approach would quickly become unmanageable in all but the simplest problems. Alternatively, it is possible to reason that, although it cannot be decided whether to go diagonally up or down from point A, the best choice at A could be made if two additional values were known. These values are the total effort, S_{CB}, of the best path from point C to B and the total effort, S_{DB}, of the best path from D to B. The choice at a would be based on the simple calculation

$$S_{AB} = \min \begin{bmatrix} e_{AC} + S_{CB} \\ e_{AD} + S_{DB} \end{bmatrix} = \min \begin{bmatrix} 5 + S_{CB} \\ 4 + S_{DB} \end{bmatrix} \qquad (1)$$

This calculation depends on knowing S_{CB} and S_{DB} which can be readily obtained by reapplying this idea at points C and D, etc.

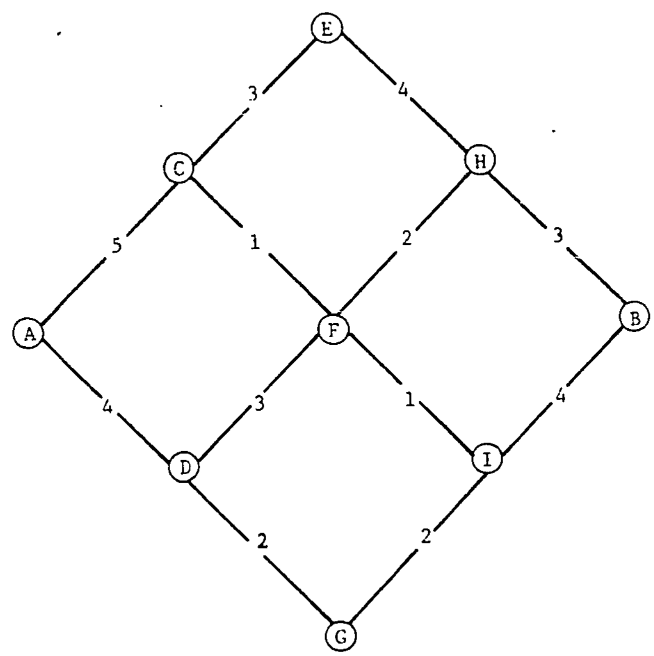

Figure 39. A simple network problem.

This simple problem illustrates the first key idea of dynamic programming. This idea is that only efforts along the best paths from C to B and from D to B are relevant in the calculations and the efforts the many inferior paths from C to B and D to B need never be computed. This observation is known as the principle of optimality:

> An optimal policy has the property that whatever the initial decision at A, the remaining path to B, starting from the next point after A, must be the best path from that point to B.

It is this principle that is cited as justification in writing formulas such as formula 1.

The second key idea of dynamic programming is the fact that although the numbers S_{CB} and S_{DB} are unknown initially, S_{CB} can be determined if S_{EB} and S_{FB} were known and S_{DB} can be determined if S_{FB} and S_{GB} were known. However, these depend on S_{HB} and S_{IB}. Calculations similar to formula 1 could be used to determine all of the S's if S_{HB} and S_{IB} are known which are trivial. Thus, working the computations <u>backward</u> from H and I to A allows calculation of all the desired values and identifies the optimal path. The identity of the optimal path is determined by noting which of the two possible first decisions, travel up or down from the current node, yielded that minimum in the previous calculations at each point on the network. If x represents any particular node in the network then let $P_{(x,x+1)}$ represent whether the solution represents traveling up or down from node x to node x+1. These P values can be defined as the S values are computed. Table 39 illustrates the calculations for this simple example.

The ideas illustrated by this example are the essence of dynamic programming. In the example, a complex problem was decomposed into a series of easily solved subproblems. In addition to obtaining the optimal path from A to B, the optimal path from any other point to B has also been found. The dynamic programming approach provides computational advantages over complete enumeration by requiring fewer additions and comparisons. There are many special tricks that have been devised to handle difficulties in solving certain dynamic programming problems but the basic concepts are unchanged.

There are several terms that are used in dynamic programming that can now be defined.

1. Optimal value function is the rule that assigns values to the various subproblems. The function S is the optimal value function in the network example.

2. Recurrence relation is a formula or set of formulas relating various values of S. The principle of optimality provides this relation.

3. The argument of the optimal value function is the subscript of S which refers to a particular subproblem.

Table 39

Solution of the Simple Network Example by Backward Dynamic Programming

zero nodes from B	$S_{BB} = 0$	P(0, 0) = --
one node from B	$S_{HB} = \min(e_{HB} + S_{BB}) = \min(3 + 0) = 3$	P(1, 0) = travel down to B from H
	$S_{IB} = \min(e_{IB} + S_{BB}) = \min(4 + 0) = 4$	P(1, 0) = travel up to B from I
two nodes from B	$S_{EB} = \min(e_{EH} + S_{HB}) = \min(4 + 3) = 7$	P(2, 1) = travel down to H from E
	$S_{FB} = \min\begin{pmatrix} e_{FH} + S_{HB} \\ e_{FI} + S_{IB} \end{pmatrix} = \min\begin{pmatrix} 2 + 3 \\ 1 + 4 \end{pmatrix} = 5$ tie	P(2, 1) = travel either up to H or down to I from F
	$S_{GB} = \min(e_{GI} + S_{IB}) = \min(2 + 4) = 6$	P(2, 1) = travel up to I from G
three nodes from B	$S_{CB} = \min\begin{pmatrix} e_{CE} + S_{EB} \\ e_{CF} + S_{FB} \end{pmatrix} = \min\begin{pmatrix} 3 + 7 \\ 1 + 5 \end{pmatrix} = 6$	P(3, 2) = travel down to F from C
	$S_{DB} = \min\begin{pmatrix} e_{DF} + S_{FB} \\ e_{DG} + S_{GB} \end{pmatrix} = \min\begin{pmatrix} 3 + 5 \\ 2 + 6 \end{pmatrix} = 8$ tie	P(3, 2) = travel either up to F or down to G from D
four nodes from B	$S_{AB} = \min\begin{pmatrix} e_{AC} + S_{CB} \\ e_{AD} + S_{DB} \end{pmatrix} = \min\begin{pmatrix} 5 + 6 \\ 4 + 8 \end{pmatrix} = 11$	P(4, 3) = travel up to C from A

The minimum effort path requires 11 effort units and, examining the policy function, P, this involves traveling from A to C, from C to F, from F to either H or I and then finally to B.

Thus S_{CB} means that the value of the best path from C to B is sought. The arguments of the optimal value function describe the current situation. The terms stage and state are often used in describing the argument of the optimal value function. Generally one component of the argument describes how many decisions have been made so far (or are left to be made) and it numerically is one more (or one less) on the right hand side of the recurrence relation than on the left, regardless of the particular decision. This monotonic component of the argument is called the stage variable. All of the remaining variables needed to describe the current situation, given the stage variable, are called state variables. In some applications of dynamic programming the description of the state variables may become complex and lengthy. This is termed the curse of dimensionality and may be sufficiently severe to overwhelm the memory storage capacity of the largest computer.

4. The optimal policy function is the rule that associates the best furst decision with each subproblem. This is the function P in the network example.

5. Boundary conditions are the value of the optimal value function for certain arguments. These are either assumed or given by the statement of the problem and from the definition of the optimal value function. In the example, the boundary condition is $S_{BB} = 0$.

Using these terms, problems are solved with dynamic programming by choosing the arguments of the optimal value function, and defining the optimal value function in such a way as to allow the use of the principle of optimality in writing the recurrence relation. Then, starting with the boundary conditions, the recurrence relation is used to concurrently determine the optimal value and policy functions. When the optimal value and decision is known for the value of the argument that represents the whole problem, the solution is completed and the best path can be identified using the optimal policy function alone.

It is important to note that dynamic programming is a viewpoint toward solving problems rather than a solution technique. Consequently there is no standard algorithm or computer program available to solve all problems formulated with the dynamic programming approach. Although computer programs have been devised for certain types of problems, the exact solution procedure developed for a specific problem area must generally be developed by the analyst.

This problem which was solved by calculations proceeding backward could also have been solved in a different way by proceeding forward. Note in Figure 39 that it would be possible to determine the best path from A to B if the best paths from A to H and A to I were known. These two values would be known if the efforts of the best paths from A to E, A to F and A to G were known, etc. In this case, the optimal value function reflects the value of the minimum effort path connecting the initial point A with a particular subsequent point. This definition contrasts with the optimal value function in the backward formulation which reflects the value of the minimum effort path connecting a particular point with the end point, B. In the forward problem, the boundary condition is $S_{AA} = 0$. Also, in addition to finding the optimal path from A to B, the optimal path from A to any subsequent point is also identified. The principle of optimality in this forward solution states that the best path from A to any particular vertex B, has the property that, whatever the vertex before B, call it C, the path must be the best path from A to C. Table 40 illustrates the solution using the forward method.

In summary, dynamic programming problems have the following characteristics (Hillier and Liebermann, 1967):

1. The problem can be divided into stages with a policy decision required at each stage.

2. Each stage has a number of states associated with it.

3. The effect of the decision at each stage is to transform the present state into a state associated with the next stage.

4. The principle of optimality must hold at each stage.

> An optimal policy has the property that whatever the initial state and initial decisions are, the

Table 40

Solution of the Simple Network Example by Forward Dynamic Programming

zero nodes from A	$S_{AA} = 0$	P(0, 0) = ---
one node from A	$S_{AC} = \min(e_{AC} + S_{AA}) = \min(5 + 0) = 5$	P(0, 1) = travel up to C from A
	$S_{AD} = \min(e_{AD} + S_{AA}) = \min(4 + 0) = 4$	P(0, 1) = travel down to D from A
two nodes from A	$S_{AE} = \min(e_{CE} + S_{AC}) = \min(3 + 5) = 8$	P(1, 2) = travel up to E from C
	$S_{AF} = \min\begin{Bmatrix} e_{CF} + S_{AC} \\ e_{DF} + S_{AD} \end{Bmatrix} = \min\begin{Bmatrix} 1 + 5 \\ 3 + 4 \end{Bmatrix} = 6$	P(1, 2) = travel down to F from C
	$S_{AG} = \min(e_{DG} + S_{AD}) = \min(2 + 4) = 6$	P(1, 2) = travel down to G from D
three nodes from A	$S_{AH} = \min\begin{Bmatrix} e_{EH} + S_{AE} \\ e_{FH} + S_{AF} \end{Bmatrix} = \min\begin{Bmatrix} 4 + 8 \\ 2 + 6 \end{Bmatrix} = 8$	P(2, 3) = travel up to H from F
	$S_{AI} = \min\begin{Bmatrix} e_{FI} + S_{AF} \\ e_{GI} + S_{AG} \end{Bmatrix} = \min\begin{Bmatrix} 1 + 6 \\ 2 + 6 \end{Bmatrix} = 7$	P(2, 3) = travel down to I from F
four nodes from A	$S_{AB} = \min\begin{Bmatrix} e_{HB} + S_{AH} \\ e_{IB} + S_{AI} \end{Bmatrix} = \min\begin{Bmatrix} 3 + 8 \\ 4 + 7 \end{Bmatrix} = 11^*$ tie	P(3, 4) = either travel down to B from H or up to B from I

The minimum effort path requires 11 effort units. Examining the policy function this path involves traveling from A to C, from C to F, from F to either H or I, and then to B.

> remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision (Bellman, 1957).

The principle has also been stated as:

> Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages (Hillier and Liebermann, 1967).

or:

> . . . if you don't do the best you can with what you happen to have got, you'll never do the best you might have done with what you should have had (Aris, 1964).

5. A recursive relationship can be developed that identifies the optimal policy for each state with n stages remaining, given the optimal policy for each state with (n-1) stages remaining. This recursive relationship is of the general form

$$f_n(s) = \text{optimum } x_n \{(V_s(x_n) + f_{n-1}(s - x_n)\}$$

where

$f_n(s)$ = the optimum value when starting in state s with n stages remaining and the optimization is over the possible values of the decision variable x_n

$V_s(x_n)$ = a value function

6. Using the recursive relationship, the solution procedure moves stage by stage. At each stage, an optimum solution from all previous stages, under any conditions, is found and carried into the next stage, until at the last stage, the optimum is found for the whole problem. It is important to note that, at each stage, it is only the optimum solution that is carried to the next stage thereby significantly reducing the number of combinations that must be examined.

Appendix B

LISTING OF PROGRAM BUCK AND DEFINITION OF VARIABLE NAMES

```
      PROGRAM BUCK (INPUT,OUTPUT,TAPE5=INPUT,TAPE2,TAPE6=OUTPUT)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      READ NUMBER OF TREES TO ANALYZE, LOG COMBINATIONS DESIRED BY
C      MANAGEMENT, DYNAMIC PROGRAMMING STAGE INTERVAL, WEIGHT
C      DENSITY  (OD LBS/CU. FT.) OF WOOD AND BARK, AND OUTPUT CODE.
C
      READ (5,115) NTREES,NOLOGS,STGL,WDENS,BDENS,IOUT
      WRITE (6,120) NTREES,NOLOGS,STGL,WDENS,BDENS,IOUT
C
C     READ IN SPECIFICATIONS FOR EACH LOG COMBINATION.  THESE INCLUDE
C        1. PRODUCT CODE (1=VENEER LOG,2=SAWLOG,3=PULPLOG,4=FUEL BOLT,
C        2. VALUATION BASIS OF ROUNDWOOD PRODUCT (1=CUBIC VOLUME,
C            2=BF VOLUME,3=LINEAL FOOTAGE,4=O.D. WEIGHT)
C           4=O.D. WEIGHT)
C        3. LOG TARGET LENGTH
C        4. LOG TRIM, IF ANY
C        5. MINIMUM SMALL END DIAMETER ACCEPTABLE
C        6. MAXIMUM SMALL END DIAMETER ACCEPTABLE
C        7. PRICE IF LOG IS GRADE 1
C        8. PRICE IF LOG IS GRADE 2
C        9. PRICE IF LOG IS GRADE 3
C       10. PRICE IF LOG IS GRADE 4
C
      ISAW = 0
      DO 10 J=1,NOLOGS
         READ (5,125) (DATAL(J,K),K=1,10)
         WRITE (6,130) (DATAL(J,K),K=1,10)
C      READ LUMBER ITEM AND RESIDUE PRICES FOR THE TARGET LENGTH
         IF (DATAL(J,1).NE.2.) GO TO 10
         ISAW = ISAW+1
```

```
      READ (5,155) (PRLUM(ISAW,L),L=1,16)
      WRITE (6,135) (PRLUM(ISAW,L),L=1,16)
 10   CONTINUE
C      READ VENEER ITEM AND RESIDUE PRICES
      READ (5,155) (VP(2,J),J=1,12)
      WRITE (6,140) (VP(2,J),J=1,12)
C      READ PULP PRICE PER OD TON OF PULP
      READ (5,155) PULPPR
C      READ FUEL CHIP PRICE PER OD TON
      READ (5,155) FUELPR
      WRITE (6,145) PULPPR,FUELPR
C
C     READ MANUFACTURING SPECIFICATIONS ON CULL ALLOWANCES
C
      READ (5,155) CLIM,SLIM,DLIMS,DLIMP
      WRITE (6,150) CLIM,SLIM,DLIMS,DLIMP
C      READ COST ITEMS
C      FIRST CARD IS BINARY SIGNAL OF WHICH COSTS ARE TO BE USED
      DO 15 I=1,2
         READ (5,155) (VCOST(I,J),J=1,10)
         WRITE (6,160) (VCOST(I,J),J=1,10)
 15   CONTINUE
      DO 110 J1=1,NTREES
         DO 20 I=1,10
            DO 20 J=1,3
               DO 20 K=1,5
                  DWEDGE(I,J,K) = 0.
 20      DELLPS(I,J,K) = 0.
         DO 25 I=1,5
            DO 25 J=1,3
 25      CROOK(I,J) = 0.
         DO 30 I=1,30
            DO 30 J=1,2
 30      SWEEP(I,J) = 0.
         DO 35 I=1,250
```

```
      DO 35 J=1,10
 35   DEFECT(I,J) = 0.
C
C     READ TREE NUMBER, DBHOB, TOTAL HEIGHT, MERCHANTABLE HEIGHT (USE
C     TOTAL HEIGHT IF NO FACTORS LIMIT POTENTIALLY USEFUL STEM), STUMP
C     HEIGHT, HEIGHT TO THE LAST MEASURED EXTERNAL DEFECT, NUMBER OF
C     RELEVANT EXTERNAL DEFECTS, NUMBER OF INTERNAL DEFECTS ENCLOSABLE
C     IN A CYLINDER OR ELLIPSOID, NUMBER OF INTERNAL DEFECTS ENCLOSABLE
C     IN A WEDGE SECTION, NUMBER OF CROOKS, PRESENCE(1) OR ABSENCE(0)
C     OF SWEEP, RINGS PER INCH.
C
      READ (5,165) TREENO,DBH,HEIGHT,HTMRCH,HTSTMP,HTDEF,NEXTNL,
     $ NINTNL,NWEDGE,NCROOK
      READ (5,170) ISWP,RINGS
      WRITE (6,175) TREENO,DBH,HEIGHT,HTMRCH,HTSTMP,HTDEF
      WRITE (6,180) NEXTNL,NINTNL,NWEDGE,NCROOK,ISWP,RINGS
C
C      READ EXTERNAL DEFECTS ON THE TREE
C
      IF (NEXTNL.EQ.0) GO TO 45
      DO 40 I=1,NEXTNL
         READ (2,185) (DEFECT(I,J),J=1,10)
 40   CONTINUE
      REWIND 2
C
C     IF THERE ARE INTERNAL DEFECTS, READ IN DATA POINTS FOR EACH.
C
 45   IF (NINTNL.EQ.0) GO TO 55
      READ (5,195) NPTSE
      WRITE (6,190) NPTSE
      DO 50 I=1,NINTNL
         READ (5,200) ((DELLPS(J,K,I),K=1,3),J=1,NPTSE)
         WRITE (6,205) ((DELLPS(J,K,I),K=1,3),J=1,NPTSE)
 50   CONTINUE
 55   IF (NWEDGE.EQ.0) GO TO 65
```

```
      READ (5,195) NPTSW
      WRITE (6,210) NPTSW
      DO 60 I=1,NWEDGE
         READ (5,200) ((DWEDGE(J,K,I),K=1,3),J=1,NPTSW)
         WRITE (6,205) ((DWEDGE(J,K,I),K=1,3),J=1,NPTSW)
 60   CONTINUE
C
C     IF THERE ARE CROOKS IN THE STEM READ DATA FOR EACH. DATA INCLUDES
C     HEIGHT OF CROOK, DEVIATION, AND TOTAL LENGTH AFFECTED.
C
 65   IF (NCROOK.EQ.0) GO TO 70
      READ (5,215) ((CROOK(I,J),J=1,3),I=1,NCROOK)
      WRITE (6,220) ((CROOK(I,J),J=1,3),I=1,NCROOK)
C
C     IF THERE IS SWEEP IN THE STEM, READ DATA POINTS WHICH INCLUDE
C     HEIGHT AND DEVIATION FROM A CHORD FROM THE TIP THROUGH THE
C     CENTER OF THE STEM BASE.
C
 70   IF (ISWP.EQ.0) GO TO 75
      READ (5,195) NPTSS
      WRITE (6,225) NPTSS
      READ (5,230) ((SWEEP(I,J),J=1,2),I=1,NPTSS)
      WRITE (6,235) ((SWEEP(I,J),J=1,2),I=1,NPTSS)
C
C     ESTIMATE CUBIC VOLUMES OF WOOD AND BARK OF WHOLE TREE AND OF STUMP
C
 75   WRITE (6,240)
      WRITE (6,245)
      DO 80 I=1,2
         CALL NEWTON (I,HEIGHT,0.,HEIGHT,10.,DBH,TVOL)
         CALL NEWTON (I,HEIGHT,0.,HTSTMP,10.,DBH,SVOL)
         IF (I.EQ.2) GO TO 80
         TVOL1 = TVOL
         SVOL1 = SVOL
 80   CONTINUE
```

```
      TBVOL = TVOL1-TVOL
      SBVOL = SVOL1-SVOL
      TWT = TVOL*WDENS/2000.
      SWT = SVOL*WDENS/2000.
      TBWT = TBVOL*BDENS/2000.
      SBWT = SBVOL*BDENS/2000.
      TWT1 = TWT+TBWT
      SWT1 = SWT+SBWT
      WRITE (6,250) TREENO,TVOL1,SVOL1,TWT1,SWT1
      WRITE (6,255) TVOL,SVOL,TWT,SWT
C
C     INITIALIZE SOLUTION STORAGE ARRAY
C
      DO 85 K=1,400
         DO 85 K1=1,12
 85      A(K,K1) = 0.
      CALL DYNPRO (HTSTMP,NOLOGS,DBH,HEIGHT,HTMRCH,STGL,NPTSE,NPTSW,
     $   NINTNL,NWEDGE,NSTGS)
C
C     IDENTIFY AND PRINT OPTIMUM SOLUTION
C
C
C     DETERMINE WHICH STAGE NUMBER CORRESPONDS TO OPTIMUM $ VALUE
C
      Q1 = 0.
      IQ2 = 0
      DO 100 I2=1,NSTGS
         IF (IOUT.EQ.0) GO TO 95
         IF (IOUT.EQ.2) GO TO 95
         IF (I2.GT.1) GO TO 90
         WRITE (6,260)
         WRITE (6,265)
         WRITE (6,270)
 90      WRITE (6,275) (A(I2,J),J=1,15),I2
 95      IF (A(I2,1).LE.Q1) GO TO 100
```

```
          IQ2 = I2
          Q1 = A(I2,1)
 100    CONTINUE
        WRITE (6,280) Q1,IQ2
C
C     PRINT OPTIMUM
C
        WRITE (6,285)
        WRITE (6,290)
        HTSTGE = FLOAT(IQ2)*STGL
        Q8 = 0.
        I9 = IQ2
 105    IF (A(I9,1).EQ.0.) GO TO 110
        J9 = IFIX(A(I9,2))
        IF (J9.EQ.0) GO TO 110
        WRITE (6,295) A(I9,2),(A(I9,J),J=4,15)
        Q8 = Q8+A(I9,7)+A(I9,8)
        IF (Q8.GE.HTSTGE) GO TO 110
        I9 = IFIX(A(I9,3))
        IF (I9.EQ.0) GO TO 110
        GO TO 105
C
 110  CONTINUE
C
 115  FORMAT (2I5,3F5.0,I5)
 120  FORMAT (1H1,2I5,3F5.0,I5)
 125  FORMAT (6F5.0,4F10.0)
 130  FORMAT (1H0,11HDATAL ARRAY,10F10.2)
 135  FORMAT (1H0,13HLUMBER PRICES,16F7.2)
 140  FORMAT (1H0,13HVENEER PRICES,12F7.2)
 145  FORMAT (1H0,10HPULP PRICE,F7.2,5X,10HFUEL PRICE,F7.2)
 150  FORMAT (1H ,15HMFG CULL LIMITS,4F10.2)
 155  FORMAT (16F5.0)
 160  FORMAT (1H0,4HCOST,10F7.2)
 165  FORMAT (6F10.0,4I5)
```

```
170  FORMAT (I5,F5.0)
175  FORMAT (1H0,9HTREE CARD,6F10.2)
180  FORMAT (1H0,5I5,F10.2)
185  FORMAT (10F10.2)
190  FORMAT (1H0,15HINTERNAL CIRCLE,I10)
195  FORMAT (I5)
200  FORMAT (3F10.0)
205  FORMAT (1H ,3F10.2)
210  FORMAT (1H0,14HINTERNAL WEDGE,I10)
215  FORMAT (3F10.0)
220  FORMAT (1H ,5HCROOK,3F10.2)
225  FORMAT (1H0,12HSWEEP POINTS,I10)
230  FORMAT (2F10.0)
235  FORMAT (1H ,2F10.2)
240  FORMAT (1H1,59H  TREE NO.  CUBIC VOL.  CUBIC VOL.    O.D. TONS   O
    $.D. TONS)
245  FORMAT (1H ,14X,4HTREE,8X,5HSTUMP,9X,4HTREE,8X,5HSTUMP)
250  FORMAT (1H ,F10.0,2F12.0,2F12.2,5X,14HINCLUDING BARK)
255  FORMAT (1H ,10X,2F12.0,2F12.2,5X,12HWITHOUT BARK)
260  FORMAT (1H1,30X,7HARRAY A)
265  FORMAT (1H0,127H   TOTAL     PROD     BASE    GRADE   DLGEIB   DSMLIB
    $  TARG    TRIM --GROSS--VOLUME --GROSS--WEIGHT     CULL      LOG    M
    $KT=1  STAGE)
270  FORMAT (1H ,120H   VALUE     CODE    STAGE
    $   LEN      LEN    CFWOB     BDFT     WOOD     BARK               VALUE   MI
    $LL=0)
275  FORMAT (1H ,15F8.2,I7)
280  FORMAT (1H1,22HOPTIMUM TREE VALUE OF ,F10.2,15HSTARTS AT STAGE,I6)
285  FORMAT (1H0,121HLOG TYPE    LOG       DIAMETER IB          LENGTH
    $  GROSS VOLUME    GROSS WEIGHT    PERCENT    TOTAL VALUE    LOG MAR
    $KET=1)
290  FORMAT (1H ,118H  CODE      GRADE     LARGE  SMALL     TARGET  TRIM
    $        CF       BF     WOOD     BARK     CULL           DOLLARS    OR MILL
    $=0)
295  FORMAT (1H ,F5.0,4X,F5.0,4X,4(F6.1,2X),2F8.1,2F8.2,F8.1,3X,F13.2,
```

```
$F8.0)                                                                    A1230
 END                                                                      A1235-
```

```
      SUBROUTINE DYNPRO(HTSTMP,NOLOGS,DBH,HT,HTM,STGL,NPTSE,NPTSW,NINTNL
     $,NWEDGE,NSTGS)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
      DIMENSION DINTNL(10,3,5)
      DIMENSION E(15)
      REAL ,NVOL,NBF,NWTIB
      TEMP = 1000.
C
C      COMPUTE NUMBER OF STAGES
C
      NSTGS = IFIX((HTM-HTSTMP)/STGL)
C
C      FIND FIRST STAGE THAT MUST BE ANALYZED
C
      DO 10 I=1,NOLOGS
         TLEN = DATAL(I,3)+DATAL(I,4)
         IF (TLEN.GE.TEMP) GO TO 10
         TEMP = TLEN
 10   CONTINUE
      MSTG = IFIX(TEMP/STGL)
C
C      BEGIN STAGE BY STAGE ANALYSIS
C
      IF (IOUT.LT.2) GO TO 15
      WRITE (6,140) MSTG,NSTGS
 15   DO 135 I=MSTG,NSTGS
C
C      SET ARRAY THAT WILL STORE TEMPORARY OPTIMUM OF LOGS EXAMINED
C      DURING ANALYSIS OF A STAGE
C
         DO 20 J=1,15
```

```
 20     E(J) = 0.
        E(1) = -1000000.
C
C      COMPUTE HEIGHT TO THE CURRENT STAGE WHICH IS ALSO THE HEIGHT TO
C      THE TOP OF A TRIAL LOG AND ESTIMATE THE SMALL END DIAMETER
C      INSIDE BARK
C
        HTSTGE = FLOAT(I)*STGL+HTSTMP
        CALL TAPER (2,DBH,HTSTGE,HT,DSMLIB)
C
C      BEGIN TESTING TRIAL LOGS WITH TOP ENDING AT THE STAGE HEIGHT
C
        IS = 0
        DO 125 J=1,NOLOGS
           VALMIL = -100000.
           VALMKT = -100000.
           IF (DATAL(J,1).EQ.2.) IS = IS+1
           LGRADE = 0
           PCULL = 0.
C
C      COMPUTE HEIGHT TO THE BASE OF THE TRIAL LOG AND TEST IF TRIAL
C      LOG IS FEASIBLE I.E. IS ITS BASE ABOVE THE STUMP AN   IS IT
C      WITHIN SMALL END DIAMETER SPECIFICATIONS
C
           HTDLGE = HTSTGE-DATAL(J,3)-DATAL(J,4)
           I9 = IFIX(HTDLGE*10000.+.5)
           I8 = IFIX(HTSTMP*10000.)
           IF (I9.LT.I8) GO TO 125
           IF (DSMLIB.LT.DATAL(J,5)) GO TO 125
           IF (DSMLIB.GT.DATAL(J,6)) GO TO 125
C
C      COMPUTE LARGE END DIAMETER INSIDE BARK, LOG CUBIC VOLUME INSIDE
C      AND OUTSIDE BARK, BARK AND WOOD WEIGHT IN OD TONS, AND SCRIBNER
C      BF VOLUME
C
```

```
      CALL TAPER (2,DBH,HTDLGE,HT,DLGEIB)
      DO 25 K=1,2
         CALL NEWTON (K,HT,HTDLGE,HTSTGE,4.,DBH,GVOL)
         IF (K.EQ.2) GO TO 25
         GVOLOB = GVOL
   25 CONTINUE
      BWT = (GVOLOB-GVOL)*BDENS/2000.
      GWTIB = GVOL*WDENS/2000.
      GBF = (AINT(DSMLIB)**2-3.*(AINT(DSMLIB)))/10.*DATAL(J,3)/2.
C
C     COMPUTE LOSS IN SCALE DUE TO INTERNAL DEFECT , SWEEP AND CROOK
C
      IC = 1
      IF (NINTNL.EQ.0) GO TO 30
      CALL DEDUCT (IC,NINTNL,NPTSE,DELLPS,HTDLGE,HTSTGE,DSMLIB,
     $      DROT,P)
C
C     IF TRIAL LOG IS FOR VENEER CHECK IF CHUCKABLE
C
      IF (DATAL(J,1).EQ.1..AND.DROT.GE.CLIM) GO TO 125
      PCULL = PCULL+P
   30 IC = 2
      IF (NWEDGE.EQ.0) GO TO 35
      CALL DEDUCT (IC,NWEDGE,NPTSW,DWEDGE,HTDLGE,HTSTGE,DSMLIB,
     $      DROT,P)
      PCULL = PCULL+P
   35 IF (DATAL(J,1).GT.2.) GO TO 45
      IF (ISWP.EQ.0) GO TO 40
      CALL SWEEPR (HTDLGE,HTSTGE,DSMLIB,J,SW,P)
C
C     IF TRIAL LOG IS FOR VENEER CHECK IF EXCEEDS SWEEP SPECIFICATIONS
C
      IF (DATAL(J,1).EQ.1..AND.SW.GE.SLIM) GO TO 125
      PCULL = PCULL+P
   40 IF (NCROOK.EQ.0) GO TO 45
```

```
      CALL CROOKR (HTDLGE,HTSTGE,DSMLIB,J,CR,P)
C
C     IF TRIAL LOG IS FOR VENEER CHECK IF EXCEEDS CROOK SPECIFICATIONS
C
      IF (DATAL(J,1).EQ.1..AND.CR.GE.SLIM) GO TO 125
      PCULL = PCULL+P
 45   IF (PCULL.GT.1.) PCULL = 1.
C
C     IF TRIAL LOG IS FOR LUMBER OR PULP CHECK IF EXCEEDS CULL
C     FRACTION SPECIFICATIONS.
C
      IF (DATAL(J,1).EQ.2..AND.PCULL.GE.DLIMS) GO TO 125
      IF (DATAL(J,1).EQ.3..AND.PCULL.GE.DLIMP) GO TO 125
C
C     COMPUTE NET SCALE
C
      NVOL = GVOL*(1.-PCULL)
      NBF = GBF*(1.-PCULL)
      NWTIB = GWTIB*(1.-PCULL)
      GREV = 0.
      GREV1 = 0.
      TVCOST = 0.
      TVCOST1 = 0.
      IF (IOUT.LT.2) GO TO 50
      WRITE (6,145) I,J,HTSTGE,DSMLIB,HTDLGE,DLGEIB,GVOLOB,BWT,
     $      GWTIB,GBF,PCULL
C
C     IF THE TRIAL LOG IS TO BE USED FOR VENEER OR LUMBER, OBTAIN
C     PNW LOG GRADE.
C
 50   IQ2 = I-IFIX((DATAL(J,3)+DATAL(J,4))/STGL)
      IF (IQ2.LT.0) IQ2 = 0
      JTYPE = IFIX(DATAL(J,1))
      GO TO (55,55,70,70,70,70,70), JTYPE
C
```

```
C       DETERMINE IF LOG THAT WOULD ADJOIN THE BUTT OF THE TRIAL LOG
C       IS A CULL
C
 55          IF (IQ2.EQ.0) GO TO 60
             RLG = A(IQ2,2)
             IF (A(IQ2,13).GE..67) RLG = -1.
 60          IF (NEXTNL.EQ.0) LGRADE = 1
             IF (NEXTNL.EQ.0) GO TO 65
C
C      ASSUME LOG GRADE=4 IF TRIAL LOG ENTERS TOP REGION WITH NO
C      EXTERNAL DEFECT DATA
C
             IF (HTSTGE.GT.HTDEF) LGRADE = 4
             IF (HTSTGE.GT.HTDEF) GO TO 65
             CALL GRADE (RLG,HTSTGE,HTDLGE,LGRADE)
C
C       VALUATION OF LOG IF SOLD ON ROUNDWOOD MARKET
C
 65          IFL = 1
             IF (DATAL(J,LGRADE+6).EQ.0.) GO TO 80
             IF (DATAL(J,2).EQ.1.) GREV1 = NVOL*DATAL(J,LGRADE+6)/100.
             IF (DATAL(J,2).EQ.2.) GREV1 = NBF*DATAL(J,LGRADE+6)/1000.
             IF (DATAL(J,2).EQ.3.) GREV1 = DATAL(J,3)*DATAL(J,LGRADE+6)
             IF (DATAL(J,2).EQ.4.) GREV1 = NWTIB*DATAL(J,LGRADE+6)
             GO TO 75
C
 70          IFL = 1
             IF (DATAL(J,7).EQ.0.) GO TO 80
             IF (DATAL(J,2).EQ.1.) GREV1 = NVOL*DATAL(J,7)/100.
             IF (DATAL(J,2).EQ.2.) GREV1 = NBF*DATAL(J,7)/1000.
             IF (DATAL(J,2).EQ.3.) GREV1 = DATAL(J,3)*DATAL(J,7)
             IF (DATAL(J,2).EQ.4.) GREV1 = NWTIB*DATAL(J,7)
 75          CALL COST (IFL,JTYPE,NVOL,PYLD,TVCOST1)
             VALMKT = GREV1-TVCOST1
C
```

```
C       VALUATION OF LOG IF MILLED.  FIRST ESTIMATE LOG SCALING
C       DIAMETER FOR RECOVERY PREDICTION.
C
 80           IFL = 0
              T = DLGEIB-DSMLIB
              A1 = 2.
              B = 2.*T
              C = T**2-(NVOL*24.**2*2.)/(3.14159*(HTSTGE-HTDLGE))
              F = B**2-4.*A1*C
              IF (F.LT.0.) STOP
              ROOT1 = -B+SQRT(F)/(2.*A1)
              ROOT2 = -B-SQRT(F)/(2.*A1)
              SDIA = ROOT2
              IF (ROOT1.GT.0.AND.ROOT1.LT.DSMLIB) SDIA = ROOT1
              SDIA = AINT(SDIA)
              GO TO (85,90,95,100,105,105,105), JTYPE
 85           IF (VP(2,1).EQ.0.) GO TO 110
              CALL VENYLD (LGRADE,SDIA,BWT,NVOL,GREV)
              GO TO 105
C
 90           IF (PRLUM(IS,1).EQ.0.) GO TO 110
              CALL LUMYLD (LGRADE,IS,SDIA,BWT,NVOL,GREV)
              GO TO 105
C
 95           IF (PULPPR.EQ.0.) GO TO 110
              CALL PULP (NWTIB,PYLD,GREV)
              GO TO 105
C
 100          IF (FUELPR.EQ.0.) GO TO 110
              GREV = (NWTIB+BWT)*FUELPR
 105          CALL COST (IFL,JTYPE,NVOL,PYLD,TVCOST)
              VALMIL = GREV-TVCOST
C
C       COMPARE ROUNDWOOD SALE VERSUS MILLING ALTERNATIVE FOR THE
C       TRIAL LOG AND ADD BEST TO CONVERSION SURPLUS OF LOGS
```

```
C      ADJOINING  BUTT OF CURRENT TRIAL LOG, TEST IF THIS TOTAL
C      EXCEEDS THE BEST OF OTHER TRIAL LOGS EXAMINED SO FAR AT THE
C      CURRENT STAGE, AND IF SO STORE THE NEW TEMPORARY OPTIMUM FOR
C      THE CURRENT STAGE.
C
 110        IF (IOUT.LT.2) GO TO 115
            WRITE (6,150) IQ2,LGRADE,GREV1,TVCOST1,GREV,TVCOST,VALMKT,
     $      VALMIL
 115        IFLOPT = 1
            VALUE = VALMKT
            IF (VALMIL.GE.VALMKT) VALUE = VALMIL
            IF (VALMIL.GE.VALMKT) IFLOPT = 0
            IF (IQ2.EQ.0) TVALUE = VALUE
            IF (IQ2.EQ.0) GO TO 120
            TVALUE = VALUE+A(IQ2,1)
 120        IF (TVALUE.LT.E(1)) GO TO 125
            E(1) = TVALUE
            E(2) = DATAL(J,1)
            E(3) = IQ2
            E(4) = LGRADE
            E(5) = DLGEIB
            E(6) = DSMLIB
            E(7) = DATAL(J,3)
            E(8) = DATAL(J,4)
            E(9) = GVOL
            E(10) = GBF
            E(11) = GWTIB
            E(12) = BWT
            E(13) = PCULL
            E(14) = VALUE
            E(15) = IFLOPT
 125     CONTINUE
C
C      PERMANENTLY STORE FINAL STAGE OPTIMUM
C
```

```
      DO 130 J=1,15
130     A(I,J) = E(J)
135   CONTINUE
      RETURN
C
140   FORMAT (1HO,6HDYNPRO,5X,10HMSTG NSTGS,2I10)
145   FORMAT (1HO,5HSTAGE,I5,9HTRIAL LOG,I5,9F10.4)
150   FORMAT (1H ,2I10,6F10.2)
      END
```

```
      SUBROUTINE NEWTON(ICODE,HEIGHT,BASE,TOP,DIV,DBH,VOL)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
      REAL K,J2
      SECTL = (TOP-BASE)/DIV
      T1 = 0
      K = 0.
   10 IF (K.GT.DIV) GO TO 30
      POS = (BASE+K*SECTL)
      CALL TAPER (ICODE,DBH,POS,HEIGHT,DSECT)
      DSECT = DSECT/12.
      IF (K.EQ.0.) GO TO 20
      IF (K.EQ.DIV) GO TO 20
      J2 = K/2.-AINT(K/2.)
      IF (J2.GT.0.) GO TO 15
      T1 = T1+DSECT*DSECT
      GO TO 25
C
   15 T1 = T1+2.*DSECT*DSECT
      GO TO 25
C
   20 T1 = T1+.5*DSECT*DSECT
   25 K = K+1.
      GO TO 10
C
   30 VOL = .5236*SECTL*T1
      RETURN
      END
```

```
      SUBROUTINE TAPER(ICODE,DBH,HI,HT,DI)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      COMPUTE DIB
C
      DI = .80747-1.39037*(HI/HT)+.58290*(HI/HT)**2
      IF (DI.LT.0.) DI = 0.
      DI = DBH*SQRT(DI)
      IF (ICODE.EQ.1) GO TO 10
      GO TO 15
C
C      COMPUTE DOB
C
 10   DBT = .1*DI
      DI = DI+DBT
 15   RETURN
      END
```

```
      SUBROUTINE DEDUCT(IC,N,NPTS,DINTNL,HTDLGE,HTSTGE,DSMLIB,D,PCTCUL)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PPLUM(5,16)
C
C       ESTIMATION OF INTERNAL DEFECT LOSSES FOR THOSE DEFECTS
C      ENCLOSABLE IN A CYLINDER OR ELLIPSOID OR A WEDGE SECTION
C      ASSUMES THAT A VECTOR OF MEASUREMENTS OF THE DEFECT IS
C      GIVEN, INCLUDING THE START AND END POINT.  FOR A CYLINDER
C      OR ELLIPSOID, MEASUREMENTS ARE THE MAJOR AND MINOR
C      DIAMETERS AT VARIOUS HEIGHT POINTS IN THE TREE.  FOR A
C      WEDGE SECTION MEASUREMENTS ARE DEGREES OF CIRCUMFERENCE
C      FROM A BASELINE TO EACH EDGE OF THE DEFECT AT VARIOUS
C      HEIGHT POINTS.   PRESENTLY IT IS ASSUMED THAT ALL DEFECTS
C      IN EACH CATEGORY HAVE THE SAME NUMBER OF MEASUREMENT
C      POINTS.
C
      DIMENSION DINTNL(10,3,5)
      D = 0.
      PCTCUL = 0.
      DO 95 I=1,N
         PCT = 0.
C
C     FIND OUT IF DEFECT IS WITHIN THE TRIAL LOG
C
         IF (DINTNL(1,1,I).GE.HTSTGE.AND.DINTNL(NPTS,1,I).GE.HTSTGE) GO
     $   TO 95
         IF (DINTNL(1,1,I).LE.HTDLGE.AND.DINTNL(NPTS,1,I).LE.HTDLGE) GO
     $   TO 95
C
C       DEFECT IS WITHIN THE TRIAL LOG
C
         DO 85 J=1,NPTS
C
```

```
C     TEST IF DEFECT POINT IS WITHIN TRIAL LOG
C
            IF (DINTNL(J,1,I).GE.HTDLGE.AND.DINTNL(J,1,I).LT.HTSTGE) GO
     $      TO 15
C
C      TEST CASE WHEN TRIAL LOG IS BETWEEN DEFECT MEASUREMENT POINTS
C
            IF (DINTNL(J,1,I).LT.HTDLGE.AND.DINTNL(J+1,1,I).GE.HTSTGE)
     $       GO TO 10
C
C      DEFECT POINT IS IRRELEVANT
C
            GO TO 85
C
C      TRICK FOR SPECIAL CASE WHEN TRIAL LOG IS BETWEEN DEFECT POINTS.
C
 10         J = J+1
            GO TO 20
C
C      HAVE LOCATED LOWEST MEASURED DEFECT POINT IN TRIAL LOG. NOW
C      DETERMINE WHICH ENDS, IF ANY, OF THE LOG SHOW THE DEFECT.
C
 15         IF (J.NE.1.AND.DINTNL(NPTS,1,I).LE.HTSTGE) GO TO 35
            IF (J.EQ.1.AND.DINTNL(NPTS,1,I).GT.HTSTGE) GO TO 45
            IF (J.EQ.1.AND.DINTNL(NPTS,1,I).LE.HTSTGE) GO TO 60
C
C     DEFECT IS OBSERVABLE AT  BOTH ENDS OF TRIAL LOG
C
 20         DLEN = HTSTGE-HTDLGE
            DIA1 = DINTNL(J-1,2,I)-(DINTNL(J-1,2,I)-DINTNL(J,2,I))/
     $      (DINTNL(J,1,I)-DINTNL(J-1,1,I))*(HTDLGE-DINTNL(J-1,1,I))
            DIA2 = DINTNL(J-1,3,I)-(DINTNL(J-1,3,I)-DINTNL(J,3,I))/
     $      (DINTNL(J,1,I)-DINTNL(J-1,1,I))*(HTDLGE-DINTNL(J-1,1,I))
            DO 25 K=J,NPTS
               IF (DINTNL(K,1,I).GT.HTSTGE) GO TO 30
               IF (DINTNL(K,2,I).GT.DIA1) DIA1 = DINTNL(K,2,I)
```

```
         IF (DINTNL(K,3,I).GT.DIA2) DIA2 = DINTNL(K,3,I)
 25    CONTINUE
 30    D1 = DINTNL(K-1,2,I)-(DINTNL(K-1,2,I)-DINTNL(K,2,I))/(DINTNL
     $ (K,1,I)-DINTNL(K-1,2,I))*(HTSTGE-DINTNL(K-1,1,I))
       D2 = DINTNL(K-1,3,I)-(DINTNL(K-1,3,I)-DINTNL(K,3,I))/(DINTNL
     $ (K,1,I)-DINTNL(K-1,2,I))*(HTSTGE-DINTNL(K-1,1,I))
       IF (D1.GT.DIA1) DIA1 = D1
       IF (D2.GT.DIA2) DIA2 = D2
       GO TO 70
C
C   DEFECT OBSERVABLE ONLY AT LARGE END OF LOG
C
 35    DLEN = DINTNL(NPTS,1,I)-HTDLGE
       DIA1 = DINTNL(J-1,2,I)-(DINTNL(J-1,2,I)-DINTNL(J,2,I))/
     $ (DINTNL(J,1,I)-DINTNL(J-1,1,I))*(HTDLGE-DINTNL(J-1,1,I))
       DIA2 = DINTNL(J-1,3,I)-(DINTNL(J-1,3,I)-DINTNL(J,3,I))/
     $ (DINTNL(J,1,I)-DINTNL(J-1,1,I))*(HTDLGE-DINTNL(J-1,1,I))
       DO 40 K=J,NPTS
         IF (DINTNL(K,2,I).GT.DIA1) DIA1 = DINTNL(K,2,I)
 40    IF (DINTNL(K,3,I).GT.DIA2) DIA2 = DINTNL(K,3,I)
       GO TO 70
C
C   DEFECT OBSERVABLE ONLY AT SMALL END OF LOG
C
 45    DLEN = HTSTGE-DINTNL(1,1,I)
       DIA1 = 0.
       DIA2 = 0.
       DO 50 K=1,NPTS
         IF (DINTNL(K,1,I).GT.HTSTGE) GO TO 55
         IF (DINTNL(K,2,I).GT.DIA1) DIA1 = DINTNL(K,2,I)
 50    IF (DINTNL(K,3,I).GT.DIA2) DIA2 = DINTNL(K,3,I)
 55    D1 = DINTNL(K-1,2,I)-(DINTNL(K-1,2,I)-DINTNL(K,2,I))/(DINTNL
     $ (K,1,I)-DINTNL(K-1,2,I))*(HTSTGE-DINTNL(K-1,1,I))
       D2 = DINTNL(K-1,3,I)-(DINTNL(K-1,3,I)-DINTNL(K,3,I))/(DINTNL
     $ (K,1,I)-DINTNL(K-1,2,I))*(HTSTGE-DINTNL(K-1,1,I))
       IF (D1.GT.DIA1) DIA1 = D1
```

```
      IF (D2.GT.DIA2) DIA2 = D2
      GO TO 70
C
C     DEFECT NOT OBSERVABLE  AT EITHER END
C
 60   DLEN = DINTNL(NPTS,1,I)-DINTNL(1,1,I)
      DIA1 = 0.
      DIA2 = 0.
      DO 65 K=1,NPTS
         IF (DINTNL(K,2,I).GT.DIA1) DIA1 = DINTNL(K,2,I)
 65   IF (DINTNL(K,3,I).GT.DIA2) DIA2 = DINTNL(K,3,I)
C
C     HAVE DEFECT LENGTH AND MAXIMUM DIAMETERS.  NOW COMPUTE CULL
C     LOSS FROM GRUSENBAUGH†S (1952) FORMULA.
C
 70   GO TO (75,80), IC
 75   PCT = ((DIA1*DIA2)/(DSMLIB-1.)**2)*(DLEN/(HTSTGE-HTDLGE))
      D = DIA1
      IF (DIA2.GT.DIA1) D = DIA2
      GO TO 90
C
 80   PCT = DLEN/(HTSTGE-HTDLGE)*(DIA2-DIA1)/350.
      GO TO 90
C
 85   CONTINUE
 90   PCTCUL = PCTCUL+PCT
      IF (IOUT.LT.2) GO TO 95
      WRITE (6,100) PCT,PCTCUL,DLEN,DIA1,DIA2,J
 95   CONTINUE
      IF (PCTCUL.GT.1.) PCTCUL = 1.
      RETURN
C
 100  FORMAT (1H ,6HDEDUCT,5F10.2,I5)
      END
```

```
      SUBROUTINE SWEEPR(HTDLGE,HTSTGE,DSMLIB,INDEX,SWPMX,PCTSWP)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      ESTIMATION OF LOSS DUE TO SWEEP ASSUMING A VECTOR OF DATA
C      CONSISTING OF DEVIATIONS FROM A CHORD FROM THE TIP THROUGH
C      THE CENTER OF THE TREE BASE.  COMPUTE ONLY FOR PEELERS,
C      SAWLOGS, AND POLES.
C
      PCTSWP = 0.
      IF (DATAL(INDEX,2).EQ.3.) GO TO 70
      IF (DATAL(INDEX,2).EQ.4.) GO TO 70
      IF (DATAL(INDEX,2).EQ.5.) GO TO 70
      IF (ISWP.EQ.0) GO TO 70
C
C     DETERMINE DEVIATION AT BASE OF LOG
C
      IT1 = 0
      IT = 0
      DO 25 I=1,NPTSS
         IF (IT.GT.0.AND.IT1.GT.0) GO TO 30
         IF (IT.GT.0) GO TO 15
         IF (SWEEP(I,1).LT.HTDLGE) GO TO 25
         IF (SWEEP(I,1).EQ.HTDLGE) DEVBAS = SWEEP(I,2)
         IF (SWEEP(I,1).EQ.HTDLGE) GO TO 10
         DEVBAS = SWEEP(I-1,2)+((HTDLGE-SWEEP(I-1,1))/(SWEEP(I,1)-SWEEP
     $   (I-1,1)))*(SWEEP(I,2)-SWEEP(I-1,2))
   10    IT = I
         GO TO 25
C
C     DETERMINE DEVIATION AT TOP OF LOG
C
```

```
15      IF (SWEEP(I,1).LT.HTSTGE) GO TO 25
        IF (SWEEP(I,1).EQ.HTSTGE) DEVTOP = SWEEP(I,2)
        IF (SWEEP(I,1).EQ.HTSTGE) GO TO 20
        DEVTOP = SWEEP(I-1,2)+((HTSTGE-SWEEP(I-1,1))/(SWEEP(I,1)-SWEEP
     $  (I-1,1)))*(SWEEP(I,2)-SWEEP(I-1,2))
20      IT1 = I
25    CONTINUE
C
C     NOW HAVE LOG TOP AND BOTTOM DEVIATIONS FROM TREE CHORD.  NOW USE
C     INTERMEDIATE MEASURES ALONG LOG TO FIND MAXIMUM DEPARTURE.
C      REVERSE SWEEP IS CONSIDERED BY ADDING THE MAXIMUM POSITIVE
C      AND NEGATIVE SWEEP OF THE LOG.
C
30    SWPMX = 0.
      SWPNEG = 0.
      SWPPOS = 0.
      IF (IOUT.LT.2) GO TO 35
      WRITE (6,75) IT,IT1,DEVBAS,DEVTOP
35    IF (IT.GE.IT1) GO TO 60
      IF (IT.EQ.IT1-1) GO TO 60
      DO 55 I=IT,IT1-1
        IF (SWEEP(I,1).EQ.HTDLGE.OR.SWEEP(I,1).EQ.HTSTGE) GO TO 40
        AC = SQRT((HTSTGE-HTDLGE)**2-((DEVBAS-DEVTOP)/12.)**2)
        ED = (DEVTOP-DEVBAS)*(SWEEP(I,1)-HTDLGE)/(HTSTGE-HTDLGE)
        DX = (DEVBAS+ED)-SWEEP(I,2)
        SWP = AC*DX/(HTSTGE-HTDLGE)
        GO TO 45
C
40      SWP = 0.
45      IF (IOUT.LT.2) GO TO 50
        WRITE (6,80) SWP
50      IF (SWP.LE.0..AND.ABS(SWP).GT.SWPNEG) SWPNEG = ABS(SWP)
        IF (SWP.GT.0..AND.SWP.GT.SWPPOS) SWPPOS = SWP
55    CONTINUE
60    SWPMX = SWPNEG+SWPPOS
```

```
C
C     COMPUTE SWEEP LOSS FROM GROSENBAUGH↑S (1952) FORMULA
      PCTSWP = (SWPMX-2.)/DSMLIB
      IF (IOUT.LT.2) GO TO 65
      WRITE (6,85) PCTSWP
   65 IF (PCTSWP.LT.0.) PCTSWP = 0.
      IF (PCTSWP.GT.1.) PCTSWP = 1.
   70 RETURN
C
   75 FORMAT (1H ,6HSWEEPR,2I5,2F10.4)
   80 FORMAT (1H ,F10.4)
   85 FORMAT (1H ,6HSWEEPR,F10.2)
      END
```

```
      SUBROUTINE CROOKR(HTDLGE,HTSTGE,DSMLIB,INDEX,TDEV,PCTCRK)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      ESTIMATION OF LOSS DUE TO CROOK.  COMPUTERD ONLY FOR PEELERS,
C      SAWLOGS, AND POLES.
C
      PCTCRK = 0.
      IF (DATAL(INDEX,2).EQ.3.) GO TO 35
      IF (DATAL(INDEX,3).EQ.4.) GO TO 35
      IF (DATAL(INDEX,2).EQ.5.) GO TO 35
      IF (NCROOK.EQ.0) GO TO 35
      TDEV = 0.
      TLEN = 0.
      DO 25 I=1,NCROOK
         DIST = CROOK(I,3)/2.
         TOP = CROOK(I,1)+DIST
         BASE = CROOK(I,1)-DIST
C
C      TEST IF CROOK IS ENTIRELY OUTSIDE TRIAL LOG
C
         IF (BASE.GT.HTSTGE) GO TO 25
         IF (TOP.LE.HTDLGE) GO TO 25
C
C     TEST IF MAXIMUM DEVIATION IS WITHIN TRIAL LOG
C
         IF (CROOK(I,1).GE.HTDLGE.AND.CROOK(I,1).LE.HTSTGE) GO TO 15
C
C      HAVE CASE WHERE MAXIMUM DEVIATION IS NOT INSIDE THE TRIAL LOG.
C      TEST WHICH END IS AFFECTED.
C
         IF (TOP-HTDLGE.LT.DIST) GO TO 10
```

```
C
C     CROOK AFFECTS SMALL END OF LOG
C
         DEV = CROOK(I,2)*(HTSTGE-BASE)/DIST
         AFFECT = HTSTGE-BASE
         GO TO 20
C
C      CROOK AFFECTS LARGE END OF LOG
C
 10      DEV = CROOK(I,2)*(TOP-HTDLGE)/DIST
         AFFECT = TOP-HTDLGE
         GO TO 20
C
 15      DEV = CROOK(I,2)
         AFFECT = TOP-BASE
         IF (TOP.GT.HTSTGE) AFFECT = HTSTGE-BASE
         IF (BASE.LT.HTDLGE) AFFECT = TOP-HTDLGE
C
C     ACCUMULATE DEVIATIONS AND LENGTH AFFECTED
C
 20      TDEV = TDEV+DEV
         TLEN = TLEN+AFFECT
 25   CONTINUE
C
C      COMPUTE CROOK DEDUCTION USING GROSENBAUGH'S (1952) FORMULA
C
      PCTCRK = TLEN/(HTSTGE-HTDLGE)*TDEV/DSMLIB
      IF (IOUT.LT.2) GO TO 30
      WRITE (6,40) PCTCRK
 30   IF (PCTCRK.GT.1.) PCTCRK = 1.
      IF (PCTCRK.LT.0.) PCTCRK = 0.
 35   RETURN
C
 40   FORMAT (1H ,6HCROOKR,F10.2)
      END
```

```
      SUBROUTINE GRADE(RLG,HTTOP,HTBASE,IGRADE)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
      DIMENSION TRLDF(100,10), TALLY(20,4), IP(4)
      DIMENSION BL(20,2)
      DO 10 I=1,100
         DO 10 J=1,10
 10   TRLDF(I,J) = 0.
      DO 15 I=1,20
         DO 15 J=1,2
 15   BL(I,J) = 0.
      IGRADE = 5
      ICNT = 0
      KBL = 0
      RLGLEN = HTTOP-HTBASE
C
C      SCREEN DEFECT FILE AND STORE IN TRLDF THOSE DEFECTS THAT ARE
C      WITHIN THE TRIAL LOG.
C
      DO 40 I=1,NEXTNL
         IF (DEFECT(I,5).GE.HTTOP) GO TO 40
         IF (DEFECT(I,8).LE.HTBASE) GO TO 40
         ICNT = ICNT+1
         DO 20 J=1,10
 20      TRLDF(ICNT,J) = DEFECT(I,J)
C
C      DETERMINE IF DEFECT IS ONLY PARTIALLY WITHIN THE TRIAL LOG
C      IF SO MODIFY DATA TO REFLECT EXIT POINTS
C
         IF (DEFECT(I,5).LT.HTBASE) GO TO 25
         IF (DEFECT(I,8).GT.HTTOP) GO TO 30
         GO TO 35
```

```
C
C      INTERPOLATE POINTS WHERE DEFECT EXITS BOTTOM OF TRIAL LOG
C
 25      TRLDF(ICNT,6) = TRLDF(ICNT,6)-(HTBASE-TRLDF(ICNT,5))/(TRLDF
     $   (ICNT,8)-TRLDF(ICNT,5))*(TRLDF(ICNT,6)-TRLDF(ICNT,9))
         TRLDF(ICNT,7) = TRLDF(ICNT,7)-(HTBASE-TRLDF(ICNT,5))/(TRLDF
     $   (ICNT,8)-TRLDF(ICNT,5))*(TRLDF(ICNT,7)-TRLDF(ICNT,10))
         TRLDF(ICNT,5) = HTBASE
         GO TO 40
C
C      INTERPOLATE POINTS WHERE DEFECT EXITS TOP OF TRIAL LOG
C
 30      TRLDF(ICNT,9) = TRLDF(ICNT,9)-(HTTOP-TRLDF(ICNT,8))/(TRLDF(ICNT
     $   ,5)-TRLDF(ICNT,8))*(TRLDF(ICNT,9)-TRLDF(ICNT,6))
         TRLDF(ICNT,10) = TRLDF(ICNT,10)-(HTTOP-TRLDF(ICNT,8))/(TRLDF
     $   (ICNT,5)-TRLDF(ICNT,8))*(TRLDF(ICNT,10)-TRLDF(ICNT,7))
         TRLDF(ICNT,8) = HTTOP
C
C      SOUND BURLS
C
 35      IF (TRLDF(ICNT,1).NE.6.) GO TO 40
         KBL = KBL+1
         BL(KBL,2) = TRLDF(ICNT,6)
         IF (TRLDF(ICNT,6).GT.TRLDF(ICNT,9)) BL(KBL,2) = TRLDF(ICNT,9)
         BL(KBL,1) = TRLDF(ICNT,7)
         IF (TRLDF(ICNT,7).LT.TRLDF(ICNT,10)) BL(KBL,1) = TRLDF(ICNT,10)
         ICNT = ICNT-1
 40    CONTINUE
C
C      GRADE THE SOUND BURLS IF ANY AND ASSIGN PRELIMINARY LOG GRADE
C
       WDTH = 0.
       IF (KBL.EQ.0) GO TO 105
       IF (KBL.GT.1) GO TO 45
C      HAVE ONLY ONE BURL, DETERMINE ITS SPAN.
```

```
      IF(BL(1,2).GT.BL(1,1)) WDTH=BL(1,1)-(BL(1,2)-360.0)
      IF (BL(1,2).LE.BL(1,1)) WDTH = BL(1,1)-BL(1,2)
      GO TO 105
C
C      MORE THAN ONE BURL, FIND MINIMUM CIRCUMFERENCE IN DEGREES THAT
C      ENCLOSES ALL OF THEM.
C
C      FIRST SORT BURLS INTO ASCENDING ORDER ACCORDING TO LEFT EDGE DATA
 45   DO 55 K1=1,KBL-1
         DO 50 J1=K1+1,KBL
            IF (BL(J1,1).GE.BL(K1,1)) GO TO 50
            T = BL(K1,1)
            T1 = BL(K1,2)
            BL(K1,1) = BL(J1,1)
            BL(K1,2) = BL(J1,2)
            BL(J1,1) = T
            BL(J1,2) = T1
 50      CONTINUE
 55   CONTINUE
C      DETERMINE IF ANY BURLS OVERLAP COMPLETELY AND IF SO, ELIMINATE
C      SMALLER BURL(S) BY ZEROING.
      DO 70 K1=1,KBL
         DO 65 J1=1,KBL
             IF(J1.EQ.K1) GO TO 60
            IF (BL(K1,2).LE.BL(J1,2).AND.BL(K1,1).GT.BL(J1,1)) GO TO 60
            GO TO 65
C
 60         BL(J1,1) = 0.
            BL(J1,2) = 0.
 65      CONTINUE
 70   CONTINUE
C
C      NOW COMPARE EACH BURL WITH THE NEAREST NEIGHBOR TO ITS LEFT
C
      DO 80 K1=1,KBL-1
```

```
      IF (BL(K1,1).EQ.0..AND.BL(K1,2).EQ.0.) GO TO 80
      J1 = K1+1
 75   IF (BL(J1,1).EQ.0..AND.BL(J1,2).EQ.0.) J1 = J1+1
      IF (BL(J1,1).EQ.0..AND.BL(J1,2).EQ.0.) GO TO 75
      D = BL(J1,2)-BL(K1,1)
      IF (D.GT.WDTH) WDTH = D
 80   CONTINUE
C      COMPARE FIRST AND LAST BURLS
      DO 85 K1=1,KBL
      IF (BL(K1,1).EQ.0..AND.BL(K1,2).EQ.0.) GO TO 85
      GO TO 90
C
 85   CONTINUE
   90 KB = -KBL
      DO 95 J1=KB,-1,1
      KB  = -J1
      IF (BL(KB,1).EQ.0..AND.BL(KB,2).EQ.0.) GO TO 95
      GO TO 100
C
 95   CONTINUE
 100  D = BL(K1,2)-(360.-BL(KB,1))
      IF (D.GT.WDTH) WDTH = D
      WDTH = 360.-WDTH
C      ASSIGN PRELIMINARY GRADE TO THE LOG
 105  IGO = 1
      IF (WDTH.GT.90..AND.WDTH.LE.270.) IGO = 2
      IF (WDTH.GT.270.) IGRADE = 4
      IF (IGRADE.EQ.4) GO TO 675
C
C      BURLS HAVE NOT DEGRADED TO GRADE 4 SO SET UP AND ANALYZE
C      GRADING FACES.  ARRAY TRLDF CONTAINS DATA ON DEFECTS IN THE
C      TRIAL LOG.  NOW DETERMINE POSSIBLE SETS OF GRADING FACES AND
C      GRADE THE LOG FOR EACH SET, FINDING THE HIGHEST POSSIBLE
C      GRADE FOR THE LOG.
      IF (ICNT.EQ.0) IGRADE = 1
```

```
      IF (ICNT.EQ.0) GO TO 675
C
C      DEFINE THE GRADING FACES IN DEGREES
C
      DO 670 I=0,80,10
         DO 110 I1=1,20
            DO 110 J=1,4
 110     TALLY(I1,J) = 0.
         RI = FLOAT(I)
C
C      NOW TAKE A DEFECT ON THE TRIAL LOG, FIND THE MAXIMUM
C      CIRCUMFERENCE IT OCCURIES AND THE FACE(S) IT OCCUPIES.
C
         DO 380 J=1,ICNT
            BOTR = TRLDF(J,6)-RI
            IF (BOTR.LT.0.) BOTR = 360.+BOTR
            BOTL = TRLDF(J,7)-RI
            IF (BOTL.LT.0.) BOTL = 360.+BOTL
            TOPR = TRLDF(J,9)-RI
            IF (TOPR.LE.0.) TOPR = 360.+TOPR
            TOPL = TRLDF(J,10)-RI
            IF (TOPL.LT.0.) TOPL = 360.+TOPL
            DO 115 K=1,4
 115        IP(K) = 0
            IFLAG = -1
            IF (TOPR.GT.TOPL.AND.BOTR.LE.BOTL.AND.BOTR.LE.TOPR)
     $       GO TO 125
            IF (TOPR.LE.TOPL.AND.BOTR.GT.BOTL.AND.BOTR.LE.TOPR)
     $       GO TO 125
            IF (TOPR.GE.TOPL.AND.BOTR.GT.BOTL.AND.BOTR.GE.TOPR)
     $       GO TO 130
            IF (TOPR.GT.TOPL.AND.BOTR.LE.BOTL.AND.BOTR.GE.TOPR)
     $       GO TO 130
            IF (BOTR.GT.BOTL.AND.TOPR.GT.TOPL) GO TO 120
C
```

```
C       CASE 1   THE DEFECT DOES NOT SPAN THE ZERO LINE OR
C
             IFLAG = 1
C
C       CASE 2 TWO CORNERS OF THE DEFECT ARE ON ONE SIDE OF THE ZERO
C       LINE.  IN THIS CASE IFLAG  REMAINS NEGATIVE.
C
 120         RGTMST = BOTR
             IF (RGTMST.GT.TOPR) RGTMST = TOPR
             RLEFT = BOTL
             IF (RLEFT.LT.TOPL) RLEFT = TOPL
             GO TO 135
C
C      CASE 3 OR 4  ONE CORNER OF THE DEFECT  IS CUT BY THE ZERO LINE
C
 125         RGTMST = TOPR
             RLEFT = BOTL
             GO TO 135
C
C       CASE 5 OR 6    SAME AS CASES 3 AND 4 BUT ↑LEAN↑ OF THE DEFECT IS
C       OPPOSITE
C
 130         RGTMST = BOTR
             RLEFT = TOPL
 135         IPOS1 = IFIX(RGTMST/90.+1.)
             IPOS2 = IFIX(RLEFT/90.+1.)
             IF (IFLAG.EQ.-1) GO TO 145
             DO 140 K=IPOS1,IPOS2
 140         IP(K) = 1
             GO TO 160
C
 145         DO 150 K=IPOS1,4
 150         IP(K) = 1
             DO 155 K=1,IPOS2
 155         IP(K) = 1
```

```
C
C     NOW USE GRADE REQUIREMENTS TO PUT DEFECT IN APPROPRIATE PART
C     OF THE TALLY ARRAY.
C
 160      N = IFIX(TRLDF(J,1))
          GO TO (380,305,305,295,295,380,285,380,285,285,380,380,380,
     $    165,165,235,255,265,380,305,380,380,325,380,380,380,315,275)
     $    , N
C
C     SOUND KNOTS
C
 165      IF (TRLDF(J,2).LE.1.) GO TO 225
C     KNOT IS LARGER THAN ONE INCH. DETERMINE IF IT IS WITHIN 6 INCHES
C     OF THE LOG END.
          IF (TRLDF(J,5).GT.HTBASE+.5.OR.TRLDF(J,8).LT.HTTOP-.5)
     $     GO TO 175
          DO 170 J1=1,4
 170      IF (IP(J1).EQ.1) TALLY(2,J1) = TALLY(2,J1)+1.
 175      IF (TRLDF(J,2).LE.3.0) GO TO 185
C     KNOT IS LARGER THAN 3 INCHES
          DO 180 J1=1,4
 180      IF (IP(J1).EQ.1) TALLY(6,J1) = TALLY(6,J1)+1.
 185      IF (TRLDF(J,2).LE.2.0) GO TO 215
C     KNOT IS LARGER THAN 2 INCHES
          IF (TRLDF(J,8).GT.HTBASE+RLGLEN/2.) GO TO 195
C     KNOT IS ENTIRELY IN LOWER HALF OF FACE
          DO 190 J1=1,4
 190      IF (IP(J1).EQ.1) TALLY(4,J1) = TALLY(4,J1)+1.
          GO TO 380
C
 195      IF (TRLDF(J,5).LT.HTBASE+RLGLEN/2.) GO TO 205
C     KNOT IS ENTIRELY IN UPPER HALF OF FACE
          DO 200 J1=1,4
 200      IF (IP(J1).EQ.1) TALLY(5,J1) = TALLY(5,J1)+1.
          GO TO 380
```

```
C       KNOT IS IN LOWER AND UPPER HALF OF FACES
 205          DO 210 J1=1,4
                 IF (IP(J1).EQ.1) TALLY(4,J1) = TALLY(4,J1)+1.
 210          IF (IP(J1).EQ.1) TALLY(5,J1) = TALLY(5,J1)+1.
              GO TO 380
C       KNOT IS LESS THAN OR EQUAL TO  2 INCHES
 215          DO 220 J1=1,4
 220          IF (IP(J1).EQ.1) TALLY(3,J1) = TALLY(3,J1)+1.
              IF (TRLDF(J,2).GT.1.0) GO TO 380
C       KNOT IS LESS THAN OR EQUAL TO ONE INCH
 225          DO 230 J1=1,4
 230          IF (IP(J1).EQ.1) TALLY(1,J1) = TALLY(1,J1)+1.
              GO TO 380
C
C       ROTTEN KNOTS
C
 235          IF (TRLDF(J,2).GT.3.0) GO TO 245
              DO 240 J1=1,4
 240          IF (IP(J1).EQ.1) TALLY(7,J1) = TALLY(7,J1)+1.
              GO TO 380
C
 245          DO 250 J1=1,4
 250          IF (IP(J1).EQ.1) TALLY(8,J1) = TALLY(8,J1)+1.
              GO TO 380
C
C      KNOT INDICATORS LARGER THAN ONE INCH
C
 255          DO 260 J1=1,4
 260          IF (IP(J1).EQ.1) TALLY(9,J1) = TALLY(9,J1)+1.
              GO TO 380
C
C       KNOT CLUSTERS
C
 265          DO 270 J1=1,4
 270          IF (IP(J1).EQ.1) TALLY(10,J1) = TALLY(10,J1)+1.
```

```
      GO TO 380
C
C     KNOT CLUSTER INDICATORS
C
 275  DO 280 J1=1,4
 280  IF (IP(J1).EQ.1) TALLY(11,J1) = TALLY(11,J1)+1.
      GO TO 380
C
C     CONKS, CANKERS, UNSOUND BURLS
C
 285  DO 290 J1=1,4
 290  IF (IP(J1).EQ.1) TALLY(12,J1) = TALLY(12,J1)+1.
      GO TO 380
C
C     BUMPS AND BULGES LARGER THAN 6 INCHES DIAMETER AND WITHIN 8
C     FEET OF THE GROUND.
C
 295  DO 300 J1=1,4
 300  IF (IP(J1).EQ.1) TALLY(13,J1) = TALLY(13,J1)+1.
      GO TO 380
C
C     EPICORMIC BRANCHES, BIRD PECK, HOLES
C
 305  DO 310 J1=1,4
 310  IF (IP(J1).EQ.1) TALLY(14,J1) = TALLY(14,J1)+1.
      GO TO 380
C
C     ROTTEN SCARS
C
 315  DO 320 J1=1,4
 320  IF (IP(J1).EQ.1) TALLY(15,J1) = TALLY(15,J1)+1.
      GO TO 380
C
C     SOUND SCARS
C
```

```
 325       IF (TRLDF(J,5).GE.8.0) GO TO 335
C      SOUND SCAR  BASE IS WITHIN 8 FEET OF THE GROUND
           DO 330 J1=1,4
 330       IF (IP(J1).EQ.1) TALLY(16,J1) = TALLY(16,J1)+1.
           IF (TRLDF(J,8).GE.8.0) GO TO 340
           GO TO 380
C
 335       IF (TRLDF(J,5).GE.HTBASE+.25*RLGLEN) GO TO 350
C      SCAR IS IN THE FIRST QUARTER OF THE LOG
 340       DO 345 J1=1,4
 345       IF (IP(J1).EQ.1) TALLY(17,J1) = TALLY(17,J1)+1.
           IF (TRLDF(J,8).GT.HTBASE+.25*RLGLEN) GO TO 350
           GO TO 380
C      TEST SECOND QUARTER
 350       IF (TRLDF(5,J).GE.HTBASE+.5*RLGLEN) GO TO 360
C      SCAR IS IN SECOND QUARTER
           DO 355 J1=1,4
 355       IF (IP(J1).EQ.1) TALLY(18,J1) = TALLY(18,J1)+1.
           IF (TRLDF(8,J).GT.HTBASE+.5*RLGLEN) GO TO 360
           GO TO 380
C      TEST THIRD QUARTER
 360       IF (TRLDF(5,J).GE.HTBASE+.5*RLGLEN) GO TO 370
C      SCAR IS IN THIRD QUARTER
           DO 365 J1=1,4
 365       IF (IP(J1).EQ.1) TALLY(19,J1) = TALLY(19,J1)+1.
           IF (TRLDF(8,J).GT.HTBASE+.75*RLGLEN) GO TO 370
           GO TO 380
C      SCAR IS IN FOURTH QUARTER
 370       DO 375 J1=1,4
 375       IF (IP(J1).EQ.1) TALLY(20,J1) = TALLY(20,J1)+1.
 380     CONTINUE
C
C      NOW HAVE TALLY TABLE DONE.  INSPECT AND DETERMINE LOG GRADE
C      BASED ON CURRENT GRADING FACES AND STORE THE BEST LOG GRADE
C      OBTAINED SO FAR.  NOTE THAT AS SOON AS THE GRADE = 1,
```

```
C       THE SEARCH CAN BE STOPPED.
C
C
C       TEST SOUND KNOT CONDITIONS
          IG = IGO
          GO TO (385,395,410), IG
C
C       GRADE 1
 385      CNT = 0.
          CNT = TALLY(1,1)+TALLY(1,2)+TALLY(1,3)+TALLY(1,4)
          CNT1 = TALLY(2,1)+TALLY(2,2)+TALLY(2,3)+TALLY(2,4)
          IF (CNT+CNT1.GT.1.) GO TO 395
          CNT = 0.
          DO 390 J=1,4
 390      CNT = CNT+TALLY(3,J)+TALLY(4,J)+TALLY(5,J)
          IF (CNT-CNT1.GT.0.) GO TO 395
          GO TO 425
C       GRADE 2
 395      IG = 2
          CNT = 0.
          DO 400 J=1,4
 400      IF (TALLY(1,J)+TALLY(3,J)+TALLY(4,J)+TALLY(5,J).GT.0.) CNT =
     $     CNT+1.
          IF (CNT.GT.2.) GO TO 410
          CNT = 0.
          DO 405 J=1,4
 405      IF (TALLY(4,J).GT.0..OR.TALLY(5,J).GT.0.) CNT = CNT+1.
          IF (CNT.GT.1.) GO TO 410
          GO TO 425
C       GRADE 3
 410      IG = 3
          CNT = 0.
          DO 415 J=1,4
 415      IF (TALLY(6,J)+TALLY(8,J).GT.0.) CNT = CNT+1.
          IF (CNT.GT.1.) GO TO 420
```

```
      GO TO 425
C    GRADE 4
 420   IG = 4
       GO TO 665
C
C    TEST KNOT INDICATOR CONDITIONS
C
 425   GO TO (430,445,445), IG
C    GRADE 1
 430   CNT = 0.
       DO 435 J=1,4
 435   IF (TALLY(9,J).GT.0.) CNT = CNT+1.
       IF (CNT.GT.2.) GO TO 440
       GO TO 445
C    GRADE 2
 440   IG = 2
C
C    TEST KNOT CLUSTER CONDITIONS
C
 445   GO TO (450,460,470), IG
C    GRADE 1
 450   DO 455 J=1,4
 455   IF (TALLY(10,J).GT.0.) GO TO 460
       GO TO 485
C    GRADE 2
 460   IG = 2
       CNT = 0.
       DO 465 J=1,4
 465   CNT = CNT+TALLY(10,J)
       IF (CNT.GT.1.) GO TO 470
       GO TO 485
C    GRADE 3
 470   IG = 3
       CNT = 0.
       DO 475 J=1,4
```

```
 475      IF (TALLY(10,J).GT.0.) CNT = CNT+1.                                  H2095
          IF (CNT.GT.2.) GO TO 480                                             H2100
          GO TO 485                                                            H2105
C       GRADE 4                                                                H2110
 480      IG = 4                                                               H2115
          GO TO 665                                                            H2120
C                                                                              H2125
C       TEST KNOT INDICATOR CLUSTER CONDITIONS                                 H2130
C                                                                              H2135
 485      GO TO (490,505,505), IG                                              H2140
C       GRADE 1                                                                H2145
 490      CNT = 0.                                                             H2150
          DO 495 J=1,4                                                         H2155
 495      CNT = CNT+TALLY(11,J)                                                H2160
          IF (CNT.GT.1.) GO TO 500                                             H2165
          GO TO 505                                                            H2170
C       GRADE 2                                                                H2175
 500      IG = 2                                                               H2180
C                                                                              H2185
C       TEST BUMP AND BULGE CONDITIONS                                         H2190
C                                                                              H2195
 505      GO TO (510,530,530), IG                                              H2200
C       GRADE 1                                                                H2205
 510      IF (HTBASE.GT.8.) GO TO 530                                          H2210
          CNT = 0.                                                             H2215
          DO 520 J=1,ICNT                                                      H2220
             IF (TRLDF(J,1).EQ.4..OR.TRLDF(J,1).EQ.5.) GO TO 515               H2225
             GO TO 520                                                         H2230
C                                                                              H2235
 515         IF (TRLDF(J,5).GT.8..OR.TRLDF(J,8).LT.HTBASE) GO TO 520           H2240
             GO TO 525                                                         H2245
C                                                                              H2250
 520      CONTINUE                                                             H2255
          GO TO 530                                                            H2260
C       GRADE 2                                                                H2265
```

```
 525      IG = 2
C
C       TEST EPICORMIC BRANCHES, BIRD PECK, AND HOLES CONDITIONS
C
 530      GO TO (535,550,550), IG
C       GRADE 1
 535      CNT = 0.
          DO 540 J=1,4
 540      IF (TALLY(14,J).GT.0.) CNT = CNT+1.
          IF (CNT.GT.1.) GO TO 545
          GO TO 550
C       GRADE 2
 545      IG = 2
C
C       TEST ROTTEN SCAR CONDITIONS
C
 550      GO TO (555,555,565), IG
 555      CNT = 0.
          DO 560 J=1,4
 560      IF (TALLY(15,J).GT.0.) CNT = CNT+1.
          IF (CNT.GT.0..AND.IG.EQ.1) IG = 2
          IF (CNT.GT.1..AND.IG.EQ.2) IG = 3
C
C       TEST SOUND SCAR CONDITIONS
C
 565      GO TO (570,625,625), IG
C       GRADE 1
 570      IF (HTBASE.GT.8.) GO TO 585
C       TRIAL LOG IS WITHIN FIRST 8 FEET OF TREE, TEST SOUND SCARS
          DO 580 J=1,ICNT
             IF (TRLDF(J,1).EQ.23.) GO TO 575
             GO TO 580
C
 575         IF (TRLDF(J,5).GT.8..OR.TRLDF(J,8).LT.HTBASE) GO TO 580
             GO TO 620
```

```
C
 580     CONTINUE
C      EITHER TRIAL LOG IS ABOVE 8 FEET IN THE TREE OR IF NOT NO
C      DEGRADING  SOUND SCARS IN THE PORTION OF THE TRIAL LOG
C      WITHIN THE FIRST 8 FEET OF THE TREE.  TEST SOUND SCARS
C      LARGER THAN 6 INCHES BY 6 INCHES.
 585     CNT = 0.
         DO 590 J=1,4
            CNT1 = TALLY(17,J)+TALLY(18,J)+TALLY(19,J)+TALLY(20,J)
 590     IF (CNT1.GT.0.) CNT = CNT+1.
         IF (CNT.GT.1.) GO TO 595
         GO TO 625
C
 595     IF (CNT.GT.2.) GO TO 620
C      HAVE ONLY TWO FACES WITH SCARS, CHECK FOR FURTHER GRADE 1
C      CONDITIONS.
         IC = 0
         DO 605 J=1,4
            CNT1 = 0.
            IF (TALLY(17,J).GT.0.) CNT1 = CNT1+1.
            IF (TALLY(18,J).GT.0.) CNT1 = CNT1+1.
            IF (TALLY(19,J).GT.0.) CNT1 = CNT1+1.
            IF (TALLY(20,J).GT.0.) CNT1 = CNT1+1.
            IF (CNT1.EQ.0.) GO TO 605
            IF (IC.EQ.0) GO TO 600
            INDX2 = J
            CT2 = CNT1
            GO TO 605
C
 600        INDX1 = J
            CT1 = CNT1
            IC = 1
 605     CONTINUE
         IF (INDX1.EQ.1.AND.INDX2.EQ.4) GO TO 610
         IF (INDX2-INDX1.GT.1) GO TO 620
```

```
C       FACES ARE CONTIGUOUS.  CHECK IF ONLY ONE QUARTER IN EACH IS
C       AFFECTED AND IF THE ARE ALSO CONTIGUOUS.
 610      IF (CT2.GT.1..OR.CT1.GT.1.) GO TO 620
          DO 615 J=17,20
             IFL1 = 0
             IFL2 = 0
             IF (TALLY(J,INDX1).GT.0.) IFL1 = 1
             IF (TALLY(J,INDX2).GT.0.) IFL2 = 1
             IF (IFL1.NE.IFL2) GO TO 620
 615      CONTINUE
          GO TO 625
C       GRADE 2
 620      IG = 2
C
C       TEST CONK, CANKER, UNSOUND BURL, AND ROTTEN  KNOT CONDITIONS
C
 625      GO TO (630,645,660), IG
C       GRADE 1
 630      CNT = 0.
          DO 635 J=1,4
 635      CNT = CNT+TALLY(12,J)+TALLY(7,J)+TALLY(8,J)
          IF (CNT.GT.0.) GO TO 640
          GO TO 660
C
 640      IG = 2
          GO TO 660
C       GRADE 2
 645      CNT = 0.
          DO 650 J=1,4
 650      CNT = CNT+TALLY(12,J)+TALLY(7,J)+TALLY(8,J)
          IF (CNT.GT.0.) GO TO 655
          GO TO 660
C
 655      IG = 3
C
```

```
C       TEST IF LOG IS ADJACENT TO A CULL, IF SO LOSE 1 GRADE
C
 660      IF (IG.EQ.4) GO TO 665
          IF (RLG.EQ.-1.) IG = IG+1
C       STORE BEST GRADE FOUND AMONG THE GRADING FACE SETS EXAMINED
C       SO FAR.
 665      IF (IG.LT.IGRADE) IGRADE = IG
          IF (IGRADE.EQ.1) GO TO 675
 670    CONTINUE
 675    RETURN
        END
```

```
      SUBROUTINE LUMYLD(LG,L,SDIA,BWT,VOL,VALUE)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
      DIMENSION PL(2,16)
C
C      RECOVERY OF LUMBER GRADES AND RESIDUES BASED ON
C      PLANK AND HENLEY, 1976.
C
      IF (SDIA.LT.6.) SDIA = 6.
      IF (SDIA.GT.60.) SDIA = 60.
      VALUE = 0.
      PL(1,16) = BWT
      GO TO (10,15,20,25), LG
C
C     RECOVERY FROM PNW LOG GRADE NO. 1
C
 10   CFLUM = (51.81+.714*SDIA-.010*SDIA**2)*VOL/100.
      BFLUM = (6.41+.0657*SDIA-.00101*SDIA**2)*VOL
      PL(1,1) = 5.60+.00369*SDIA
      PL(1,2) = -7.14+.927*SDIA-.00798*SDIA**2
      PL(1,3) = -1.54+.352*SDIA-.00444*SDIA**2
      PL(1,4) = -3.42+.406*SDIA-.00525*SDIA**2
      PL(1,5) = -3.68+.317*SDIA-.00324*SDIA**2
      PL(1,6) = -3.91+.330*SDIA-.00370*SDIA**2
      PL(1,7) = -4.12+.369*SDIA-.00447*SDIA**2
      PL(1,8) = .52
      PL(1,9) = 66.83-1.786*SDIA+.0119*SDIA**2
      PL(1,10) = 55.47-1.804*SDIA+.0159*SDIA**2
      PL(1,11) = 7.41-.00131*SDIA**2
      PL(1,12) = 5.74
      PL(1,13) = 1.34+.000738*SDIA**2
      PL(1,14) = 9.58+1.177*SDIA-.0160*SDIA**2
```

```
      PL(1,15) = 85.05-.900*SDIA+.0128*SDIA**2
      GO TO 30
C
C      RECOVERY FROM PNW LOG GRADE NO. 2
C
 15   CFLUM = (49.66+.928*SDIA-.0147*SDIA**2)*VOL/100.
      BFLUM = (6.22+.0866*SDIA-.00157*SDIA**2)*VOL
      PL(1,1) = -1.43+.00897*SDIA**2
      PL(1,2) = -6.15+.614*SDIA-.00295*SDIA**2
      PL(1,3) = -4.15+.526*SDIA-.00697*SDIA**2
      PL(1,4) = -5.48+.570*SDIA-.00773*SDIA**2
      PL(1,5) = -4.27+.00248*SDIA**2
      PL(1,6) = -3.42+.293*SDIA-.00262*SDIA**2
      PL(1,7) = -4.25+.412*SDIA-.00452*SDIA**2
      PL(1,8) = -.760+.090*SDIA-.00104*SDIA**2
      PL(1,9) = 41.53-.707*SDIA
      PL(1,10) = 53.54-1.286*SDIA+.00829*SDIA**2
      PL(1,11) = 22.06-.580*SDIA+.00519*SDIA**2
      PL(1,12) = 7.20+.00133*SDIA**2
      PL(1,13) = 2.71+.000567*SDIA**2
      PL(1,14) = 14.09+.999*SDIA-.0152*SDIA**2
      PL(1,15) = 86.04-.993*SDIA+.0147*SDIA**2
      GO TO 30
C
C      RECOVERY FROM PNW LOG GRADE NO. 3
C
 20   CFLUM = (33.73+2.465*SDIA-.0421*SDIA**2)*VOL/100.
      BFLUM = (4.18+.288*SDIA-.00512*SDIA**2)*VOL
      PL(1,1) = -2.13+.210*SDIA-.00148*SDIA**2
      PL(1,2) = -3.86+.330*SDIA
      PL(1,3) = -1.58+.170*SDIA
      PL(1,4) = -.774+.107*SDIA
      PL(1,5) = -.268+.032*SDIA
      PL(1,6) = -4.39+.437*SDIA-.00597*SDIA**2
      PL(1,7) = -5.55+.600*SDIA-.00832*SDIA**2
```

```
      PL(1,8) = -.877+.108*SDIA-.00148*SDIA**2
      PL(1,9) = 11.86+.231*SDIA-.00842*SDIA**2
      PL(1,10) = 64.34-1.420*SDIA+.00694*SDIA**2
      PL(1,11) = 22.93-.00502*SDIA**2
      PL(1,12) = 13.82-.383*SDIA+.0127*SDIA**2
      PL(1,13) = 7.34-.497*SDIA+.0123*SDIA**2
      PL(1,14) = 6.62+1.899*SDIA-.0293*SDIA**2
      PL(1,15) = 93.40-1.900*SDIA+.0243*SDIA**2
      GO TO 30
C
C      RECOVERY FROM PNW LOG GRADE NO. 4
C
 25   CFLUM = (33.78+2.086*SDIA-.0349*SDIA**2)*VOL/100.
      BFLUM = (4.23+.241*SDIA-.00423*SDIA**2)*VOL
      PL(1,1) = -.632+.0547*SDIA
      PL(1,2) = -2.61+.273*SDIA-.00313*SDIA**2
      PL(1,3) = .126+.000124*SDIA
      PL(1,4) = .304-.338*SDIA+.00884*SDIA**2
      PL(1,5) = -1.50+.142*SDIA-.00184*SDIA**2
      PL(1,6) = -.219+.00278*SDIA**2
      PL(1,7) = -2.95+.297*SDIA
      PL(1,8) = -.738+.0788*SDIA
      PL(1,9) = .851+.236*SDIA-.00500*SDIA**2
      PL(1,10) = 40.54-.705*SDIA
      PL(1,11) = 2.76+.00272*SDIA
      PL(1,12) = 19.21+.279*SDIA
      PL(1,13) = 1.62+.0000001*SDIA**2
      PL(1,14) = 12.24+1.078*SDIA-.0156*SDIA**2
      PL(1,15) = 88.26-1.160*SDIA+.0172*SDIA**2
C
C      CALIBRATE PERCENTAGES AND COMPUTE VALUE
C
 30   SUM = 0.
      IF (IOUT.LT.2) GO TO 35
      WRITE (6,60) CFLUM,BFLUM
```

```
      WRITE (6,60) (PL(1,J),J=1,16)
 35   DO 40 I=1,13
         IF (PL(1,I).LT.0.) PL(1,I) = 0.
         SUM = SUM+PL(1,I)
 40   CONTINUE
      DO 45 I=1,13
         PL(1,I) = PL(1,I)*(1.-(SUM-100.)/100.)
         PL(2,I) = PL(1,I)/100.*BFLUM/1000.*PRLUM(L,I)
         VALUE = VALUE+PL(2,I)
 45   CONTINUE
      SUM = 0.
      DO 50 I=14,15
         SUM = SUM+PL(1,I)
 50   CONTINUE
      DO 55 I=14,15
         PL(1,I) = PL(1,I)*(1.-(SUM-100.)/100.)
         PL(2,I) = PL(1,I)/100.*(VOL-CFLUM)*PRLUM(L,I)*WDENS/2000.
         VALUE = VALUE+PL(2,I)
 55   CONTINUE
      VALUE = VALUE+PL(1,16)*PRLUM(L,16)
      RETURN
C
 60   FORMAT (1H ,16F8.2)
      END
```

```
      SUBROUTINE VENYLD(LG,SDIA,BWT,VOL,VREV)
C
C      RECOVERY OF VENEER AND RESIDUE FROM EQUATIONS BASED ON WOODFIN
C
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
      IF (SDIA.LT.10.) SDIA = 10.
      IF (SDIA.GT.60.) SDIA = 60.
      GO TO (10,15,20,25), LG
C      GRADE 1 VENEER LOGS
 10   CFVEN = (.2493+.0229*SDIA-.0004*SDIA**2)*VOL
      SFVEN = (8.0083+.7672*SDIA-.0121*SDIA**2)*VOL
      VP(1,1) = (-4.3970+.3076*SDIA)
      VP(1,2) = (3.9789+.3596*SDIA)
      VP(1,3) = (-1.4637+.2706*SDIA)
      VP(1,4) = (11.4281+.0981*SDIA)
      VP(1,5) = (69.4019-.9505*SDIA)
      VP(1,6) = (21.0518-.0853*SDIA)
      GO TO 30
C      GRADE 2 VENEER LOGS
 15   CFVEN = (.2246+.0212*SDIA-.0003*SDIA**2)*VOL
      SFVEN = (7.4973+.6965*SDIA-.0099*SDIA**2)*VOL
      VP(1,1) = (-3.4911+.2264*SDIA)
      VP(1,2) = (-5.6803+.5702*SDIA)
      VP(1,3) = (-1.5951+.2036*SDIA)
      VP(1,4) = (1.6300+.4154*SDIA)
      VP(1,5) = (74.5566-1.2536*SDIA)
      VP(1,6) = (34.5799-.1619*SDIA)
      GO TO 30
C      GRADE 3 VENEER LOGS
 20   CFVEN = (.1198+.0293*SDIA-.0005*SDIA**2)*VOL
      SFVEN = (4.5025+.9124*SDIA-.0149*SDIA**2)*VOL
```

```
      VP(1,1) = (1.4894-.1643*SDIA+.0053*SDIA**2)
      VP(1,2) = (4.6036-.5223*SDIA+.0178*SDIA**2)
      VP(1,3) = (2.1044-.1819*SDIA+.0057*SDIA**2)
      VP(1,4) = (-7.1942+.6403*SDIA-.0026*SDIA**2)
      VP(1,5) = (82.5624-3.8282*SDIA+.0548*SDIA**2)
      VP(1,6) = (16.4343+4.0564*SDIA-.0810*SDIA**2)
      GO TO 30
C      GRADE 4 VENEER LOGS
 25   CFVEN = .36*VOL
      SFVEN = 11.6*VOL
      VP(1,1) = (4.6437-.3976*SDIA+.0097*SDIA**2)
      VP(1,2) = (.7599-.1870*SDIA+.0095*SDIA**2)
      VP(1,3) = (-2.7078+.2050*SDIA-.0008*SDIA**2)
      VP(1,4) = (-4.8265+.3912*SDIA-.0008*SDIA**2)
      VP(1,5) = (13.4055-.0111*SDIA-.0008*SDIA**2)
      VP(1,6) = (88.7251-.0005*SDIA+.0014*SDIA**2)
C
C      COMPUTE RESIDUE ITEM AND SHRINKAGE PERCENTS OF THE NET LOG
C      VOLUME NOT BECOMING DRY UNTRIMMED VENEER.
C
 30   VSHRNK = -1.59+.488*SDIA+.00678*SDIA**2
      VP(1,7) = 82.50-3.06*SDIA+.0322*SDIA**2
      VP(1,8) = -7.18+1.19*SDIA-.0163*SDIA**2
      VP(1,9) = .718+.176*SDIA-.00187*SDIA**2
      VP(1,10) = 12.43
      VP(1,11) = 13.96+1.37*SDIA-.0116*SDIA**2
      VP(1,12) = BWT
C
C      CALIBRATE AND COMPUTE VALUE
C
      IF (IOUT.LT.2) GO TO 35
      WRITE (6,60) (VP(1,J),J=1,12),VSHRNK,CFVEN,SFVEN
 35   VREV = 0.
      SUM = 0.
      DO 40 I=1,6
```

```
         IF (VP(1,I).LT.0.) VP(1,I) = 0.
         SUM = SUM+VP(1,I)
 40   CONTINUE
      DO 45 I=1,6
         VP(1,I) = VP(1,I)*(1.-(SUM-100.)/100.)
         VP(1,I) = VP(1,I)/100.*SFVEN*3./1000.*VP(2,I)
         VREV = VREV+VP(1,I)
 45   CONTINUE
      SUM = VSHRNK
      DO 50 I=7,11
         IF (VP(1,I).LT.0.) VP(1,I) = 0.
         SUM = SUM+VP(1,I)
 50   CONTINUE
      DO 55 I=7,11
         VP(1,I) = VP(1,I)*(1.-(SUM-100.)/100.)
         VP(1,I) = VP(1,I)/100.*(VOL-CFVEN)*VP(2,I)*WDENS/2000.
         VREV = VREV+VP(1,I)
 55   CONTINUE
      VREV = VREV+VP(1,12)*VP(2,12)
      RETURN
C
 60   FORMAT (1H ,15F8.2)
      END
```

```
      SUBROUTINE PULP(WT,PYLD,REV)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      YIELD AND REVENUE FROM UNBLEACHED KRAFT PULP
C
      PYLD = .51*WT
      REV = PYLD*PULPPR
      RETURN
      END
```

```
      SUBROUTINE COST(INDX1,LCODE,CFLOGN,PWT,GCOST)
      COMMON A(400,15),DATAL(20,10),NEXTNL,NCROOK,ISWP,RINGS,CROOK(5,3)
      COMMON SWEEP(30,2),VP(2,12),WDENS,BDENS,VCOST(2,10),NPTSS
      COMMON PULPPR,FUELPR,IOUT,HTDEF,CLIM,SLIM,DLIMS,DLIMP
      COMMON DWEDGE(10,3,5),DELLPS(10,3,5)
      COMMON DEFECT(250,10),PRLUM(5,16)
C
C      VARIABLE COSTS SUMMED DEPENDING ON USER DESIGNATION OF WHICH
C      ITEMS ARE VARIABLE.
C
      REAL MILL,LMBNG,LOAD
      STMPGE = VCOST(1,1)*VCOST(2,1)*CFLOGN/100.
      BCKING = VCOST(1,2)*VCOST(2,2)
      LMBNG = VCOST(1,3)*VCOST(2,3)
      SKID = VCOST(1,4)*VCOST(2,4)
      LOAD = VCOST(1,5)*VCOST(2,5)
      HAULUN = VCOST(1,6)*VCOST(2,6)*CFLOGN/100.
      MILL = 0.
      IF (INDX1.EQ.1) GO TO 30
      GO TO (15,10,20,25), LCODE
C      SAWMILL
 10   MILL = VCOST(1,8)*VCOST(2,8)*CFLOGN/100.
      GO TO 30
C      VENEER MILL
 15   MILL = VCOST(1,9)*VCOST(2,9)*CFLOGN/100.
      GO TO 30
C      PULP MILL
 20   MILL = VCOST(1,7)*VCOST(2,7)*CFLOGN/100.
      MILL = MILL+VCOST(1,10)*VCOST(2,10)*PWT
      GO TO 30
C      FUEL CHIPPING
 25   MILL = VCOST(1,7)*VCOST(2,7)*CFLOGN/100.
 30   GCOST = STMPGE+BCKING+LMBNG+SKID+LOAD+HAULUN+MILL
      RETURN
      END
```

```
****************** DEFINITION OF VARIABLES IN BUCK *****************************

  BUCK    A          ARRAY STORING STAGE BY STAGE OPTIMA
  BUCK    BDENS      WEIGHT DENSITY OF BARK, OD LB/CU FT
  BUCK    CLIM       MAXIMUM INTERNAL DEFECT DIAMETER ALLOWED IN VENEER LOGS, INCH
  BUCK    CROOK      ARRAY STORING INPUT DATA DESCRIBING CROOKS
  BUCK    DATAL      ARRAY STORING INPUT DATA ON LOG SPECIFICATIONS
  BUCK    DBH        TREE DIAMETER BREAST HEIGHT, INCHES
  BUCK    DEFECT     ARRAY STORING INPUT DATA DESCRIBING EXTERNAL DEFECTS
  BUCK    DELLPS     ARRAY STORING INPUT DATA DESCRIBING INTERNAL DEFECTS
                     ENCLOSABLE IN AN ELLIPSOID OR CYLINDER
  BUCK    DLIMP      MAXIMUM CULL LOSS FRACTION ALLOWED IN PULP LOGS
  BUCK    DLIMS      MAXIMUM CULL LOSS FRACTION ALLOWED IN SAW LOGS
  BUCK    DWEDGE     ARRAY STORING INPUT DATA DESCRIBING INTERNAL DEFECTS
                     ENCLOSABLE IN A WEDGE SECTION
  BUCK    FUELPR     PRICE FOR FUEL CHIPS PRODUCED FROM ROUNDWOOD LOGS
  BUCK    HEIGHT     TREE TOTAL HEIGHT, FEET
  BUCK    HTDEF      TREE HEIGHT TO HIGHEST DESCRIBED EXTERNAL DEFECT, FEET
  BUCK    HTMRCH     TREE MERCHANTABLE HEIGHT LIMIT, FEET
  BUCK    HTSTGE     HEIGHT TO THE CURRENT STAGE, FEET
  BUCK    HTSTMP     TREE STUMP HEIGHT, FEET
  BUCK    IOUT       OUTPUT CODE: 0=FINAL SOLUTION ONLY, 1=INCLUDE ARRAY A, 2=
                     EXCLUDE ARRAY A BUT INCLUDE DETAILED CALCULATIONS, 3=ALL
                     OUTPUT
  BUCK    IQ2        STAGE NUMBER CORRESPONDING TO THE LOCATION OF THE LARGE END
                     OF A LOG
  BUCK    ISAW       FLAG USED TO COORDINATE LOCATION OF LUMBER PRICE DATA IN
                     ARRAY PPLUM WITH CORRESPONDING SAWLOG LENGTH IN DATAL
  BUCK    ISWP       INPUT VARIABLE INDICATING IF TREE SWEEP EXISTS
  BUCK    NCROOK     INPUT VARIABLE INDICATING NUMBER OF CROOKS IN A TREE
  BUCK    NEXTNL     INPUT VARIABLE INDICATING NUMBER OF EXTERNAL DEFECTS IN THE T
                     THAT ARE RELEVANT TO THE LOG GRADING RULES
  BUCK    NINTNL     INPUT VARIABLE INDICATING NUMBER OF INTERNAL DEFECTS
                     ENCLOSABLE IN AN ELLIPSOID OR A CYLINDER
  BUCK    NULOGS     INPUT VARIABLE INDICATING NUMBER OF LOG POSSIBILITIES
  BUCK    NPTSE      INPUT VARIABLE INDICATING NUMBER OF DATA POINTS DESCRIBING
```

```
                     EACH INTERNAL DEFECT ENCLOSABLE IN AN ELLIPSOID OR A CYLINDER
  BUCK    NPTSS      INPUT VARIABLE INDICATING NUMBER OF DATA POINTS DESCRIBING
                     SWEEP
  BUCK    NPTSW      INPUT VARIABLE DESCRIBING NUMBER OF DATA POINTS DESCRIBING
                     EACH INTERNAL DEFECT ENCLOSABLE IN A WEDGE SECTION
  BUCK    NSTGS      NUMBER OF STAGES
  BUCK    NTREES     NUMBER OF TREES TO BE ANALYZED
  BUCK    NWEDGE     INPUT VARIABLE INDICATING NUMBER OF INTERNAL DEFECTS
                     ENCLOSABLE IN A WEDGE SECTION
  BUCK    PRLUM      ARRAY STORING INPUT PRICES FOR LUMBER AND ASSOCIATED RESIDUES
  BUCK    PULPR      PRICE FOR KRAFT PULP
  BUCK    Q1         CONVERSION SURPLUS OF OPTIMUM SOLUTION
  BUCK    Q8         CUMULATIVE LENGTH OF LOGS IN OPTIMUM SOLUTION
  BUCK    RINGS      NUMBER OF RINGS PER INCH IN THE TREE
  BUCK    SBVOL      STUMP BARK VOLUME, CU FT
  BUCK    SBWT       STUMP BARK WEIGHT, OD TONS
  BUCK    SLIM       MAXIMUM ALLOWABLE SWEEP OR CROOK DEVIATION IN VENEER LOGS, IN
  BUCK    STGL       STAGE INTERVAL, FEET
  BUCK    SVOL       STUMP VOLUME INSIDE BARK, CU FT
  BUCK    SVOL1      STUMP VOLUME OUTSIDE BARK, CU FT
  BUCK    SWEEP      ARRAY STORING INPUT DATA DESCRIBING TREE SWEEP
  BUCK    SWT        STUMP WEIGHT INSIDE BARK, OD TONS
  BUCK    SWT1       STUMP WEIGHT OUTSIDE BARK, OD TONS
  BUCK    TBVOL      TREE BARK VOLUME, CU FT
  BUCK    TBWT       TREE BARK WEIGHT, OD TONS
  BUCK    TREENO     TREE NUMBER
  BUCK    TVOL       TREE VOLUME INSIDE BARK, CU FT
  BUCK    TVOL1      TREE VOLUME OUTSIDE BARK, CU FT
  BUCK    TWT        TREE WEIGHT INSIDE BARK, OD TONS
  BUCK    TWT1       TREE WEIGHT OUTSIDE BARK, OD TONS
  BUCK    VCOST      ARRAY STORING BINARY FLAGS AND UNIT RATES OF COST ITEMS
  BUCK    VP         ARRAY STORING PRICES OF VENEER AND RESIDUES
  BUCK    WDENS      WEIGHT DENSITY OF WOOD, OD LB/CU FT
****************** DEFINITION OF VARIABLES IN DYNPRO ***************************
****************** ONLY NEW VARIABLES ARE DEFINED ******************************
  DYNPRO BWT         LOG BARK WEIGHT, OD TONS
```

DYNPRO	CR	MAXIMUM AMOUNT OF CROOK DEVIATION IN LOG, INCHES
DYNPRO	DLGEIB	LOG LARGE END DIAMETER INSIDE BARK, INCHES
DYNPRO	DROT	DIAMETER OF INTERNAL DEFECT IN LOG, INCHES
DYNPRO	DSMLIB	LOG SMALL END DIAMETER INSIDE BARK, INCHES
DYNPRO	E	ARRAY STORING OPTIMUM OF SOLUTIONS EXAMINED SO FAR DURING ANAYLSIS OF THE CURRENT STAGE
DYNPRO	GBF	GROSS SCRIBNER LOG VOLUME, BOARD FEET
DYNPRO	GREV	GROSS REVENUE OF MILLED PRODUCTS AND RESIDUES FROM A LOG OR GROSS REVENUE FROM LOG IN ROUNDWOOD SALE
DYNPRO	GVOL	GROSS LOG VOLUME INSIDE BARK, CU FT
DYNPRO	GVOLOB	GROSS LOG VOLUME OUTSIDE BARK, CU FT
DYNPRO	GWTIB	GROSS LOG WEIGHT INSIDE BARK, OD TONS
DYNPRO	HT	TREE HEIGHT, FEET
DYNPRO	HTDLGE	TREE HEIGHT TO LOCATION OF THE LARGE END OF A LOG, FEET
DYNPRO	HTM	TREE MERCHANTABLE HEIGHT LIMIT, FEET
DYNPRO	I	STAGE LOOP INDEX
DYNPRO	IC	FLAG INDICATING IF AN INTERNAL DEFECT IS ENCLOSABLE IN AN ELLIPSOID OF CYLINDER(1) OR A WEDGE SECTION(2)
DYNPRO	IFL	FLAG INDICATING WHEN A LOG IS ANALYZED FOR ROUNDWOOD SALE(1) OR MILLING(0)
DYNPRO	IFLUPT	STORES VALUE OF IFL CORRESPONDING TO MODEL CHOICE OF MILLING OR SELLING A LOG
DYNPRO	IS	FLAG COORDINATING SAWLOG LOCATION IN ARRAY DATAL WITH CORRESPONDING LUMBER PRICE INFORMATION IN ARRAY PRLUM
DYNPRO	I8	INDEX VALUE OF STUMP HEIGHT
DYNPRO	I9	INDEX VALUE OF HEIGHT TO LOG LARGE END
DYNPRO	J	STATE (TRIAL LOG) LOOP INDEX
DYNPRO	JTYPE	LOG PRODUCT CODE
DYNPRO	LGRADE	LOG GRADE
DYNPRO	MSTG	INDEX OF FIRST STAGE ABOVE STUMP THAT MUST BE ANALYZED
DYNPRO	NBF	LOG NET SCRIBNER VOLUME, BOARD FEET
DYNPRO	NVOL	LOG NET VOLUME INSIDE BARK, CU FT
DYNPRO	NWTIB	LOG NET WEIGHT INSIDE BARK, OD TONS
DYNPRO	P	FRACTION OF LOG SCALE LOST DUE TO A SCALING DEFECT
DYNPRO	PCULL	TOTAL FRACTION OF LOG SCALE LOST DUE TO ALL SCALING DEFFCTS
DYNPRO	PYLD	PULP YIELD FROM A LOG, OD TONS

```
DYNPRO RLG        FLAG WHICH IF NEGATIVE INDICATES THAT THE CURRENT LOG
                  ADJOINS A CULL LOG
DYNPRO ROOT1,ROOT2 ROOTS OF QUADRATIC EQUATION SOLUTION FOR LOG SCALING
                  DIAMETER
DYNPRO SDIA       LOG SCALING DIAMETER, INCHES
DYNPRO SW         MAXIMUM SWEEP DEVIATION IN A LOG, INCHES
DYNPRO TEMP       MINIMUM LOG LENGTH, FEET
DYNPRO TLEN       TOTAL LOG LENGTH, INCLUDING TRIM, FEET
DYNPRO TVALUE     CUMULATIVE CONVERSION SURPLUS THROUGH THE CURRENT STAGE
DYNPRO TVCOST     TOTAL VARIABLE COST OF CONVERTING CURRENT LOG THROUGH A MILL
DYNPRO TVCOST1    TOTAL VARIABLE COST OF CONVERTING CURRENT LOG FOR ROUNDWOOD
                  SALE
DYNPRO VALMIL     CONVERSION SURPLUS OF CURRENT LOG IF MILLED
DYNPRO VALMKT     CONVERSION SURPLUS OF CURRENT LOG IF SOLD AS ROUNDWOOD
DYNPRO VALUE      MAXIMUM OF VALMIL, VALMKT
***************** DEFINITION OF VARIABLES IN NEWTON *****************
***************** ONLY NEW VARIABLES ARE DEFINED *********************
NEWTON BASE       HEIGHT TO THE BASE OF THE TREE SECTION FOR WHICH A
                  VOLUME ESTIMATE IS DESIRED, FEET
NEWTON DIV        NUMBER OF SUBDIVISIONS TO USE IN CALCULATING TREE
                  SECTION VOLUME
NEWTON DSECT      DIAMETER OF A SUBDIVISION, FEET
NEWTON ICODE      FLAG INDICATING IF INSIDE (<> 1) OR OUTSIDE (1) BARK
                  VOLUME IS DESIRED
NEWTON J2         FLAG INDICATING ODD OR EVEN NUMBERED SUBDIVISION
NEWTON K          SUBDIVISION COUNTER
NEWTON POS        HEIGHT TO SUBDIVISION, FEET
NEWTON SECTL      SUBDIVISION LENGTH, FEET
NEWTON TOP        HEIGHT TO THE TOP OF THE TREE SECTION FOR WHICH A
                  VOLUME ESTIMATE IS DESIRED
NEWTON VOL        GROSS VOLUME OF TREE SECTION, CU FT
****************** DEFINITION OF VARIABLES IN TAPER ******************
****************** ONLY NEW VARIABLES ARE DEFINED *********************
TAPER  DBT        DOUBLE BARK THICKNESS, INCHES
TAPER  DI         DIAMETER INSIDE BARK, INCHES
TAPER  HI         HEIGHT IN TREE TO POINT WHERE DIAMETER IS TO BE ESTIMATED
```

```
****************** DEFINITION OF VARIABLES IN DEDUCT ******************
****************** ONLY NEW VARIABLES ARE DEFINED *********************
  DEDUCT D         MAXIMUM OF DIA1, DIA2
  DEDUCT DIA1      DEFECT MAJOR AXIS WHERE IT EXITS LARGE END OF LOG,
                   INCHES OR DEGREES
  DEDUCT DIA2      DEFECT MINOR AXIS WHERE IT EXITS LARGE END OF LOG,
                   INCHES OR DEGREES
  DEDUCT DINTNL    ARRAY STORING INTERNAL DEFECT MEASUREMENT DATA
  DEDUCT DLEN      DEFECT LENGTH WITHIN LOG. FEET
  DEDUCT D1        DEFECT MAJOR AXIS WHERE IT EXITS SMALL END OF LOG,
                   INCHES OR DEGREES
  DEDUCT D2        DEFECT MINOR AXIS WHERE IT EXITS SMALL END OF LOG,
                   INCHES OR DEGREES
  DEDUCT N         NUMBER OF INTERNAL DEFECTS
  DEDUCT NPTS      NUMBER OF MEASUREMENT POINTS ALONG EACH DEFECT
  DEDUCT PCT       FRACTION LOSS DUE TO A DEFECT
  DEDUCT PCTCULL   FRACTION LOSS DUE TO ALL INTERNAL DEFECTS IN LOG
****************** DEFENITION OF VARIABLES IN SWEEPR ******************
****************** ONLY NEW VARIABLES ARE DEFINED *********************
  SWEEPR DEVBAS    SWEEP DEVIATION FROM TREE CHORD AT LOG BASE, INCHES
  SWEEPR DEVTOP    SWEEP DEVIATION FROM TREE CHORD AT LOG TOP, INCHES
  SWEEPR INDEX     STATE NUMBER CORRESPONDING TO THE LOG
  SWEEPR IT, IT1   FLAGS THE TREE SWEEP MEASUREMENTS CLOSEST TO LOG ENDS
  SWEEPR PCTSWP    FRACTION LOSS IN LOG SCALE DUE TO SWEEP
  SWEEPR SWP       MAXIMUM SWEEP DEVIATION IN THE LOG, INCHES
  SWEEPR SWPMX     SUM OF SWPNEG AND SWPPOS
  SWEEPR SWPNEG    MAXIMUM ≠NEGATIVE≠ SWEEP DEVIATION IN THE LOG, INCHES
  SWEEPR SWPPOS    MAXIMUM ≠POSITIVE≠ SWEEP DEVIATION IN THE LOG, INCHES
****************** DEFINTION OF VARIABLES IN CROOKR ******************
****************** ONLY NEW VARIABLES ARE DEFINED *********************
  CROOKR AFFECT    LOG LENGTH AFFECTED BY A CROOK, FEET
  CROOKR BASE      TREE HEIGHT TO THE BASE OF A CROOK, FEET
  CROOKR DEV       MAXIMUM CROOK DEVIATION IN A LOG, INCHES
  CROOKR DIST      LENGTH IN TREE ABOVE AND BELOW THE POINT OF MAXIMUM
                   CROOK DEVIATION, FEET
  CROOKR PCTCRK    FRACTION LOSS IN LOG SCALE DUE TO CROOKS
```

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  CROOKR TDEV      SUM OF INDIVIDUAL CROOK MAXIMUM DEVIATIONS IN A LOG
  CROOKR TLEN      TOTAL LENGTH IN LOG AFFECTED BY ALL CROOKS, FEET
  CROOKR TOP       TREE HEIGHT TO THE TOP OF A CROOK, FEET
****************** DEFINITION OF VARIABLES IN GRADE *******************
****************** ONLY NEW VARIABLES ARE DEFINED *********************
  GRADE  BL        ARRAY STORING SOUND BURLS WITHIN A TRIAL LOG
  GRADE  BOTL, BOTR CIRCUMFERENCE DEGREES TO THE BOTTOM CORNERS OF
                   TRAPEZOID ENCLOSING A DEFECT
  GRADE  CNT, CNT1 DEFECT COUNTERS
  GRADE  CT1, CT2  COUNTERS FOR SOUND SCARS
  GRADE  D         CIRCUMFERENCE DISTANCE BETWEEN SOUND BURLS, DEGREES
  GRADE  HTBASE    HEIGHT TO LOG BASE, FEET
  GRADE  HTTOP     HEIGHT TO LOG TOP, FEET
  GRADE  IC        FLAG USED TO TEST WHICH QUARTERS OF GRADING FACES
                   CONTAIN SOUND SCARS
  GRADE  ICNT      NUMBER OF DEFECTS IN A LOG
  GRADE  IFLAG     A FLAG WHICH IS -1 IF A DEFECT SPANS THE ZERO BASELINE
                   AND +1 OTHERWISE
  GRADE  IFL1, IFL2 FLAGS USED TO DETERMINE IF SOUND SCARS ARE IN CONTIGUOUS
                   QUARTERS OF GRADING FACES
  GRADE  IG        GRADE ASSIGNED TO LOG USING CURRENT GRADING FACES
  GRADE  IGRADE    FINAL LOG GRADE
  GRADE  IGO       PRELIMINARY LOG GRADE AFTER INSPECTING SOUND BURLS
  GRADE  INDX1, INDX2 FLAGS INDICATING WHICH GRADING FACES ARE SPANNED BY
                   A SOUND SCAR
  GRADE  IP        ARRAY STORING FLAGS INDICATING WHICH GRADING FACES
                   CONTAIN A DEFECT
  GRADE  IPOS1, IPOS2 FLAGS INDICATING WHICH GRADING FACES ARE SPANNED BY
                   A DEFECT
  GRADE  KB        NEGATIVE VALUE OF THE NUMBER OF SOUND BURLS IN A LOG
  GRADE  KBL       NUMBER OF SOUND BURLS IN A LOG
  GRADE  N         DEFECT CODE
  GRADE  RGTMST    MAXIMUM OF BOTR, TOPR
  GRADE  RLEFT     MINIMUM OF BOTL, TOPL
  GRADE  RLGLEN    LOG LENGTH
  GRADE  TALLY     ARRAY STORING DEFECT COUNTS BY GRADING FACE AND DEFECT
```

```
                         TYPE
GRADE  TOPL, TOPR CIRCUMFERENCE DEGREES TO TOP CORNERS OF TRAPEZIOD
                  ENCLOSING A DEFECT
GRADE  TRLOF      ARRAY STORING ALL EXTERNAL DEFECTS, EXCEPT SOUND BURLS,
                  WITHIN THE POSITION IN THE TREE OCCUPIED BY A TRIAL LOG
GRADE  WDTH       SPAN OF LOG CIRCUMFERENCE IN DEGREES OCCUPIED BY A SOUND
                  BURL ^ LATER REDEFINED TO REPRESENT MAXIMUM CLEAR CIR-
                  CUMFERENCE BETWEEN SOUND BURLS
***************** DEFINITION OF VARIABLES IN LUMYLD ******************
***************** ONLY NEW VARIABLES ARE DEFINED *********************
 LUMYLD BFLUM     BOARD FEET LUMBER TALLY IN LOG
 LUMYLD CFLUM     CUBIC FEET OF LUMBER IN LOG
 LUMYLD L         SAME AS ↑IS↑ IN DYNPRO
 LUMYLD LG        LOG GRADE
 LUMYLD PL        ARRAY STORING LUMBER GRADE AND RESIDUE YIELDS AND
                  ASSOCIATED REVENUES FROM THE LOG
 LUMYLD SUM       CUMULATIVE LUMBER GRADE YIELD PERCENT
 LUMYLD VALUE     TOTAL REVENUE OF LOG WHEN PROCESSED FOR LUMBER
 LUMYLD VOL       NET LOG SCALE, CU FT
***************** DEFINITION OF VARIABLES IN VENYLD ******************
***************** ONLY NEW VARIABLES ARE DEFINED *********************
 VENYLD CFVEN     CUBIC FEET OF VENEER IN LOG
 VENYLD SFVEN     SQUARE FEET OF VENEER, 1/8≠ BASIS
 VENYLD SUM       CUMULATIVE VENEER GRADE YIELD PERCENT
 VENYLD VP        ARRAY STORING VENEER PRICES AND VENEER GRADE AND
                  RESIDUE YIELDS FROM THE LOG
 VENYLD VREV      TOTAL REVENUE OF LOG WHEN PROCESSED INTO VENEER
 VENYLD VSHRNK    VENEER SHRINKAGE
***************** DEFINITION OF VARIABLES IN PULP ********************
***************** ONLY NEW VARIABLES ARE DEFINED *********************
 PULP   REV       REVENUE FROM PULP IN THE LOG
 PULP   WT        LOG WEIGHT, OD TONS
***************** DEFINITION OF VARIABLES IN COST ********************
***************** ONLY NEW VARIABLES ARE DEFINED *********************
 COST   BCKING    BUCKING COST OF LOG
 COST   CFLOGN    NET LOG VOLUME, CU FT
```

COST	GCOST	TOTAL VARIABLE COST ASSOCIATED WITH PRODUCING AND PROCESSING THE LOG
COST	HAULUN	HAUL AND UNLOAD COST OF LOG
COST	INDX1	FLAG INDICATING IF LOG IS TO BE SOLD AS ROUNDWOOD SO MILLING COSTS ARE INGNORED
COST	LCODE	FLAG INDICATING WHICH MILLING PROCESS LOG ENTERED
COST	LMBNG	LIMBING COST OF LOG
COST	LOAD	LOADING COST OF LOG
COST	MILL	MILLING COST OF LOG
COST	PWT	PULP YIELD OF LOG, OD TONS
COST	SKID	SKIDDING COST OF LOG
COST	STMPGE	STUMPAGE COST OF LOG

Appendix C

DESCRIPTION OF PROGRAM DIG

This program converts data entered onto magnetic tape from the ALTEK digitizer into information that is easier to use in subsequent processing and converts the digitized coordinates into coordinates reflecting the position of defects in the tree. Figure 40 presents a flow diagram of this program.

After dimensioning and initializing certain arrays, subroutine DGINIT is called. This is a subroutine supplied by the University of Washington Academic Computer Center and must be called before any data can be read from the digitized tape. The subroutine arguments specify the name of the digitized file and indicate the control character, here a comma, used to separate fields in the text information that accompanies the coordinates.

Next, another supplied subroutine, DGREC, is called. This subroutine actually reads the coordinates and text from the digitized file. It scans the variable format file and returns the information to the program in an easier to use fixed format. The text information is stored in variables X and Y, and the lengths of the fields in ALPHA are stored in array NCOL. In addition to these tasks, DGREC also scans one record ahead to determine if the digitizer

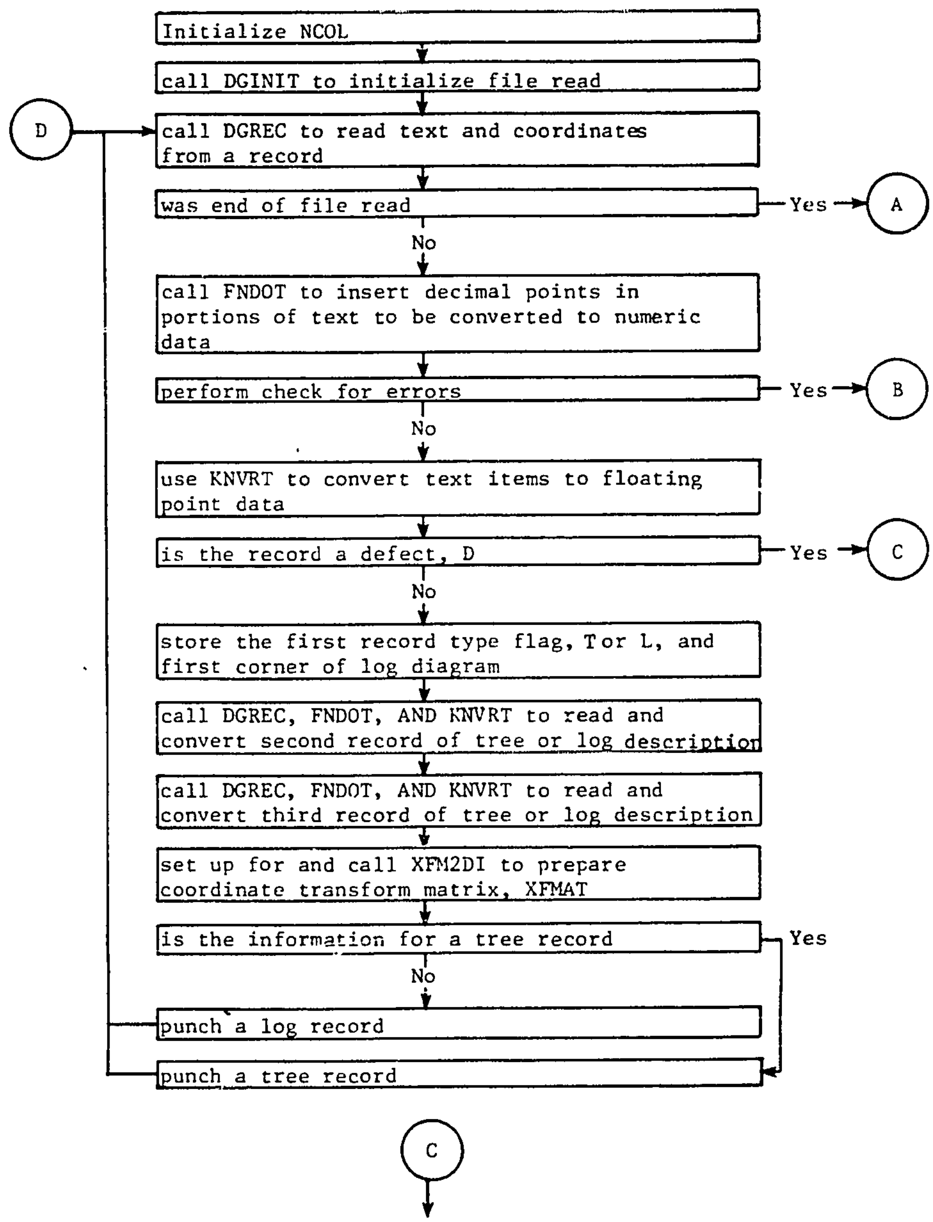
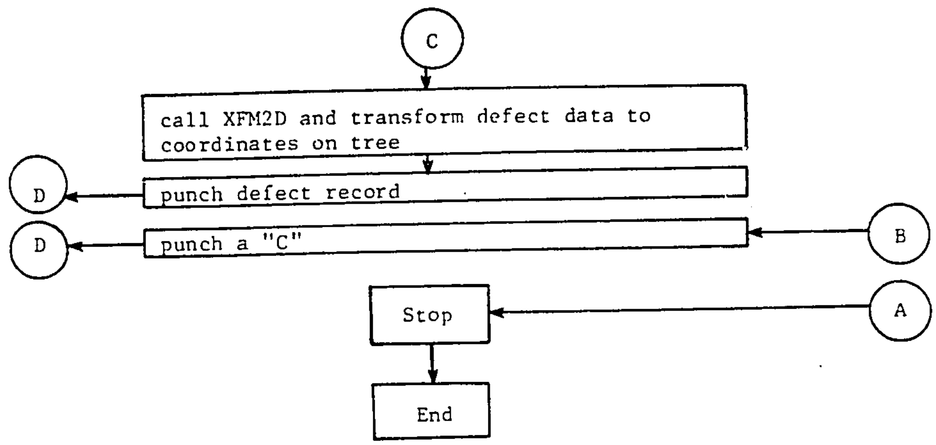


Figure 40. Flow diagram of program DIG.

Figure 40. Continued



operator typed ERR as the text thereby indicating that an error had just been made in digitizing. If this flag is found, DGREC discards the current record and the ERR text. Thus the user's program need never be concerned with erroneous data that is flagged by this means. The arguments of DGREC are

X, Y	the floating point coordinates of the digitized point
ALPHA	the array in which the text information is returned in fixed format
NFIELD	= 10, the maximum number of fields into which the text can be broken by control characters
NCOL	the array containing the lengths (number of characters) of the fields in ALPHA
IR	a flag returned as zero if a record was read and as -1 if the end of file was encountered.

Assuming that the first record for a tree was read, the information would consist of the first of the three lines describing the tree and butt log. Except for the first item, all entries in the text accompanying the coordinates are to be used as numeric data but are returned to DGREC as string data. Consequently, a conversion step is needed for these items. A system function, KNVRT, performs this task but it expects a decimal point to be present in each of the string values to be converted. Since the digitizer operator frequently did not type decimals after whole numbers, the subroutine FNDOT was developed to place decimal points where needed. FNDOT scans each of the string text items to be converted in a character by character fashion and determines if a decimal is present. If so, the text information is stored in array ALOUT; otherwise, FNDOT scans until the first blank in the text is encountered and replaces the blank with a decimal. The system function ISCAN was used to facilitate this action. After this operation, certain error flag conditions are checked and then the text information in array ALOUT is converted to floating point data by KNVRT and the result stored in array STR1. The function KNVRT also yields the count, NUM, of the items converted.

Assuming these tasks were performed for the first tree record, it is known that two more records follow that contain additional text information and the coordinates of two more corners of the log diagram. The tree record identifier, the first item in the text information, is stored in variable ASV and the X and Y coordinates of the log diagram corners are stored in XFROM(1) and YFROM91). Next, the first of the two remaining tree and butt log records is read by DGREC and submitted to FNDOT and KNVRT. The numeric text information from this record is stored in STR2 and the number of these items is stored in NUM1. The second log diagram corner coordinates are stored in XFROM(2) and YFROM(2). A similar series of steps stores the text information from the last tree and butt log record in array STR3, the number of items in NUM2, and the third log diagram corner X and Y coordinate values in SFROM(3) and YFROM(3).

The next operation involves calling a supplied subroutine XFM2DI which takes the three digitized log diagram corner coordinates and returns a matrix, XFMAT, representing the transformation to the final coordinate system. This matrix provides the basis for converting digitizer coordinates of the defects to coordinates reflecting defect positions along the circumference (0-360) and length (0'-total height) of the tree. Arguments for this subroutine are

XFROM, YFROM arrays containing the X and Y digitizer coordinates of the three log diagram corners

XTO an array containing height coordinates in the tree corresponding to the values in XFROM

XTO(1) = XTO(2) = height to the base of the log

XTO(3) = height to the top of the log

YTO an array containing circumference coordinates in the tree corresponding to the values in YFROM

YTO(1) = 0

YTO(2) = YTO(3) = 360

XFMAT matrix representing the transform

IERR normally returned as zero unless the points derived from XFROM and YFROM are collinear so no transform can be computed. In this case IERR is positive.

At this point the tree information is punched and control returns to the first call of DGREC to read the next record. FNDOT and KNVRT convert the text descriptors and a test is made to determine if the first text item is the letter D signifying that the record reflects a defect entry. If so, control transfers to another supplied subroutine, XFM2D, which uses the transform matrix XFMAT to convert the digitized defect coordinates to coordinates in the scale of the tree. After this operation the defect information is punched. This procedure is repeated until a record is encountered with an L as the first text item signalling that the first of the three records of the next log diagram is encountered. The same procedure used with the initial tree and butt log records is followed to update the transformation martix XFMAT thereby properly locating the log and its defects within the tree. This procedure continues for all trees, logs, and defects in the file until an end of file condition is encountered.

```
      PROGRAM DIG(OUTPUT,PUNCH,TAPE7=PUNCH,DGTAPE=0)
      INTEGER ALPHA(10),ASV,ALOUT(9)
      DIMENSION NCOL(10),STR1(10),STR2(10),STR3(10)
      DIMENSION XFROM(3),YFROM(3),XTO(3),YTO(3),XFMAT(3,3)
      DO 10 I=1,10
   10 NCOL(I)=10
      CALL DGINIT(≠DGTAPE≠,≠,≠)
   11 CALL DGREC(X,Y,ALPHA,10,NCOL,IR)
      IF(IR.EQ.-1) GO TO 100
      CALL FNDOT(ALPHA,ALOUT)
      IF(ALPHA(1).EQ.≠DT≠) ALPHA(1)=≠T≠
      IF(ALPHA(1).EQ.≠CANCEL≠) GO TO 300
      IF(ALPHA(1).EQ.≠ERR≠) GO TO 300
      NUM=KNVRT(ALOUT,1,90,STR1,10)
      IF(ALPHA(1).EQ.≠D≠) GO TO 200
C  NEW LOG OR TREE
      ASV=ALPHA(1)
      XFROM(1)=X
      YFROM(1)=Y
      CALL DGREC(XFROM(2),YFROM(2),ALPHA,10,NCOL,IR)
      CALL FNDOT(ALPHA,ALOUT)
      NUM1=KNVRT(ALOUT,1,90,STR2,10)
      CALL DGREC(XFROM(3),YFROM(3),ALPHA,10,NCOL,IR)
      CALL FNDOT(ALPHA,ALOUT)
      NUM2=KNVRT(ALOUT,1,90,STR3,10)
      XTO(1)=XTO(2)=STR2(2)
      YTO(1)=0.
      YTO(2)=YTO(3)=360.
      XTO(3)=XTO(1)+STR2(3)
      CALL XFM2D1(XFROM,YFROM,XTO,YTO,XFMAT,IR)
      IF(ASV.EQ.≠T≠) GO TO 400
      PRINT 90,ASV,(STR2(I),I=1,NUM1),(STR3(I),I=1,NUM2)
      WRITE(7,95) ASV,(STR2(I),I=1,NUM1),(STR3(I),I=1,NUM2)
   95 FORMAT(A10,8F8.2)
      GO TO 11
  400 PRINT 90,ASV,(STR1(I),I=1,NUM),(STR2(I),I=1,NUM1)
      PRINT 90,ASV,(STR3(I),I=1,NUM2)
      WRITE(7,95) ASV,(STR1(I),I=1,NUM),(STR2(I),I=1,NUM1)
```

```
      WRITE(7,95) ASV,(STR3(I),I=1,NUM2)
      GO TO 11
  200 CALL XFM2D(X,Y,XT,YT,XFMAT)
      PRINT 90,ALPHA(1),XT,YT,(STR1(I),I=1,NUM)
   90 FORMAT(1H ,A10,3F8.2)
      WRITE(7,95) ALPHA(1),XT,YT,(STR1(I),I=1,NUM)
      GO TO 11
  300 PRINT 91
   91 FORMAT(1H ,≠C≠)
      WRITE(7,96)
   96 FORMAT(≠C≠)
      GO TO 11
  100 STOP
      END
```

```
      SUBROUTINE FNDOUT(ALPHA,ALOUT)
      INTEGER ALPHA(10),ALOUT(9)
      INTEGER BLNK,OUT
      BLNK=≠ ≠
      OUT=≠.≠
      DO 20 I=1,9
   20 ALOUT(I)=10H
      DO 50 II=2,10
      IF(ALPHA(II).EQ.10H           ) RETURN
      I=ISCAN(ALPHA(II),1,10,OUT,1,1,I1)
      IF(I1.NE.0) GO TO 51
C  ALPHA FIELD HAS NO OUT; SO PUT ONE IN
      I=ISCAN(ALPHA(II),1,10,BLNK,1,1,I1)
C  I1 HOLDS POSITION OF FIRST BLANK-- MAKE THIS A OUT
      ALOUT(II-1)=ALPHA(II)
      CALL PUTC(ALOUT(II-1),I1,OUT)
      GO TO 50
   51 ALOUT(II-1)=ALPHA(II)
   50 CONTINUE
      RETURN
      END
```

Appendix D

DESCRIPTION OF PROGRAM DFLE

Program DFLE takes the data punched onto cards by program DIG and creates a disk file containing a simplified, condensed description of only those defects that are relevant to the log grading rules used in this study. This disk file is the basis for the log grading performed by subroutine GRADE in the model. Table 41 indicates the defects that are not relevant to the log grading rules used in this study and Figures 41 and 42 presenta flow diagram of DFLE. Following Figure 42 is a listing of this program. The final description of each relevant defect is outlined in Table 7 of Chapter 4.

Table 41

Defects that are not Relevant to the Log Grading Rules

Bark distortion	Mechanical damage
Butt swell	Sap rot
Crook	Sweep
Flange	Undercut
Flute	Weather checks

Sound scars and seams smaller than 6" x 6" that occur above 8 feet in the tree

Sound burls that are smaller than 6" in diameter

Bumps and bulges smaller than 6" x 6" that occur within 8 feet of the ground and all that occur above 8 feet in the tree

Knot indicators (overgrowths) less than or equal to one inch diameter

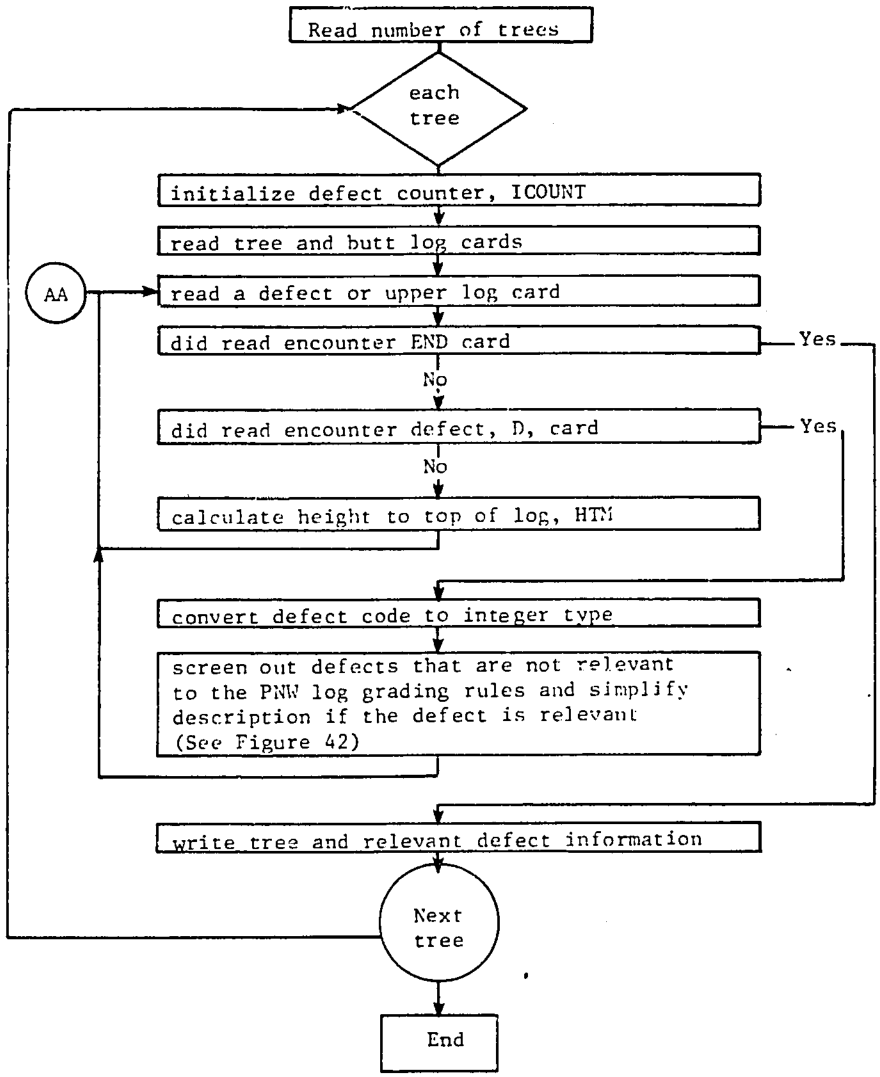


Figure 41. Flow diagram of program DFLE.

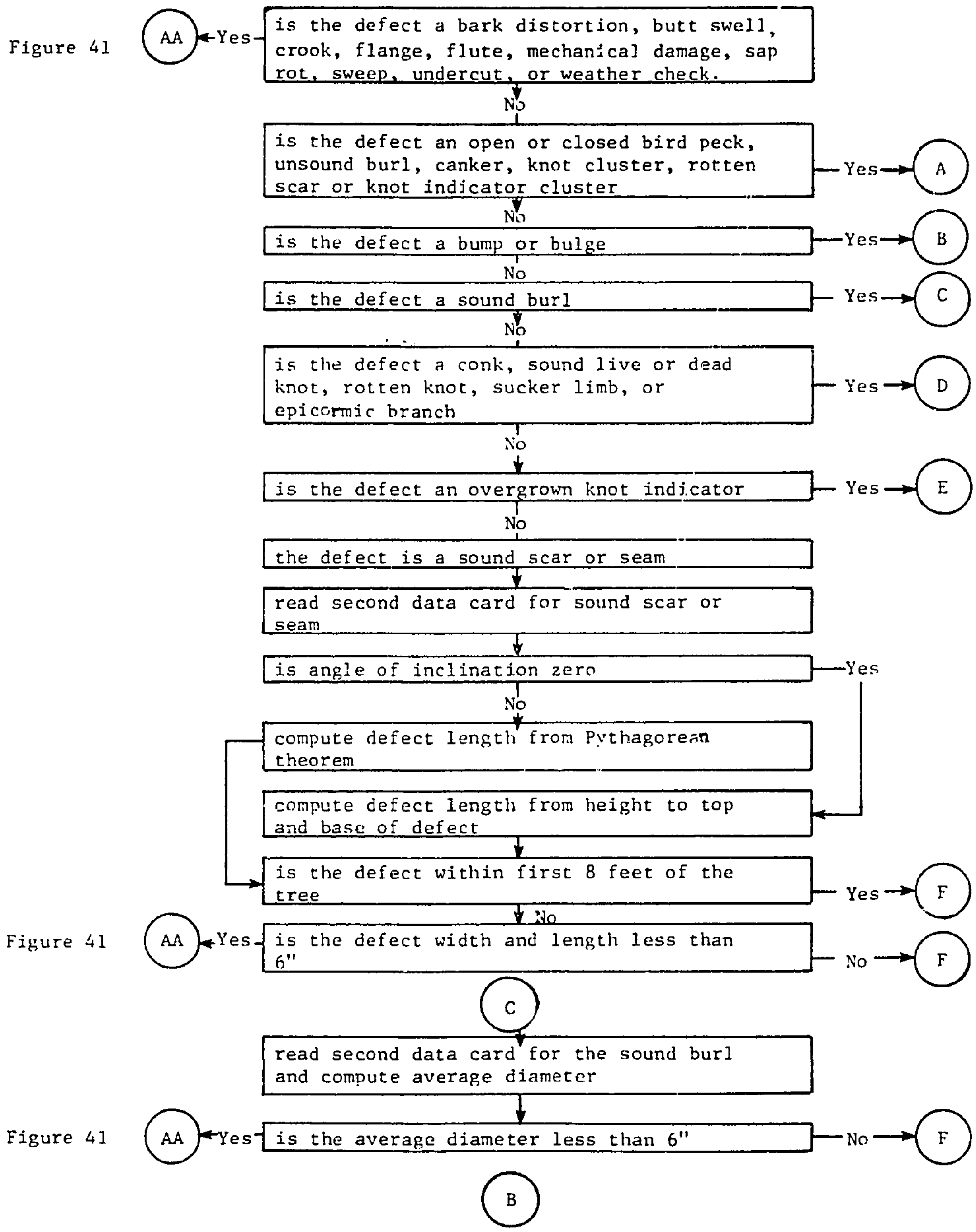
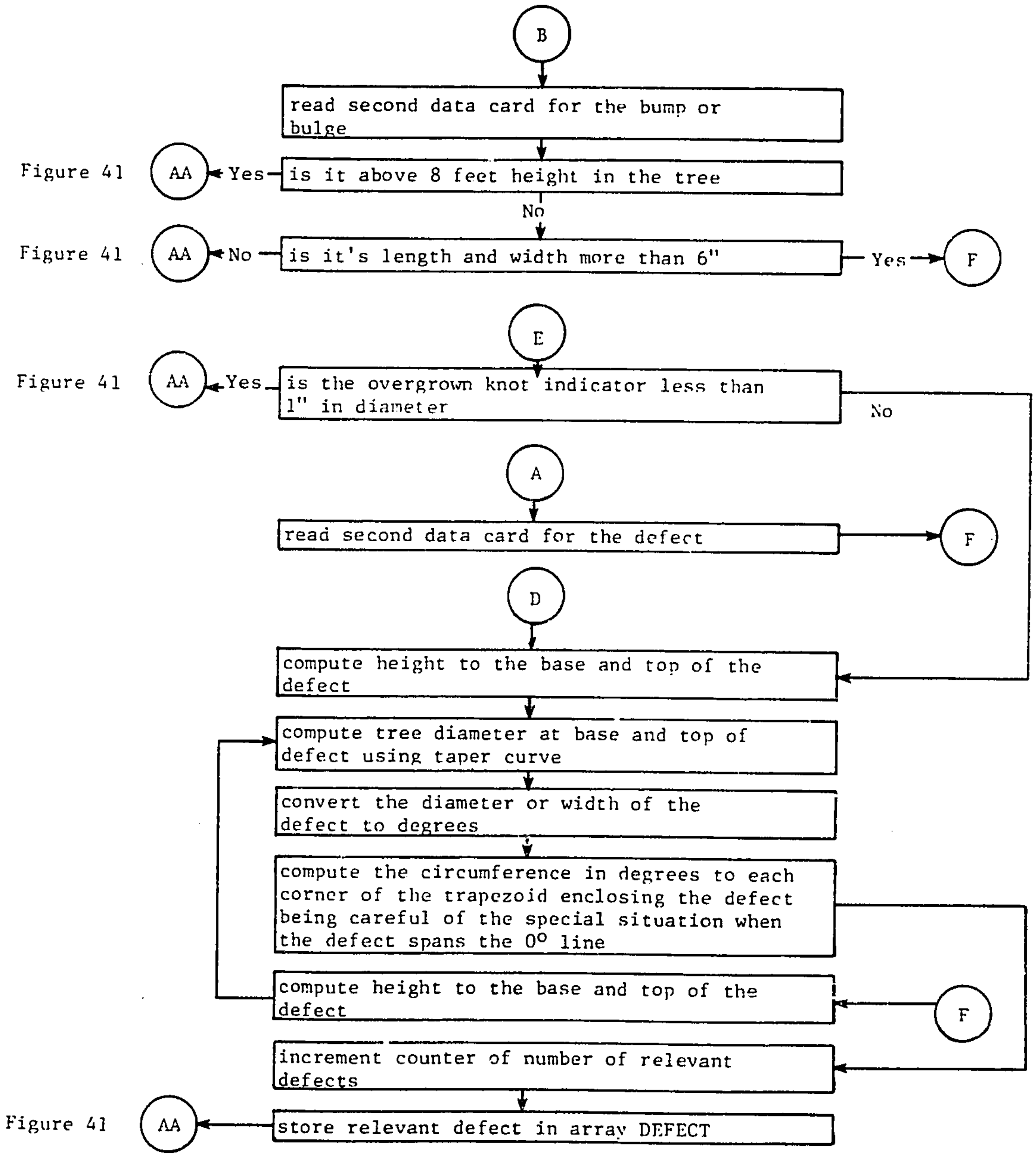


Figure 42. Flow diagram of DFLE portion for screening out irrelevant external tree defects and simplifying the description of relevant defects.

Figure 42 Continued



```
      PROGRAM DFLE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE1)
      DIMENSION DEFECT(300,10),DATA(8),CATA(8)
      READ(5,90),NTREES
   90 FORMAT(I10)
      DO 1000 I=1,NTREES
      DO 1003 J=1,200
      DO 1003 K=1,10
 1003 DEFECT(J,K)=0.
      ICOUNT=0
C     READ TREE CARDS WHICH ALSO CONTAIN INFO FOR THE FIRST LOG
      READ(5,91),ACODE,TREENO,DBH,HEIGHT,HTSTMP,RLOGNO,HTBASE,RLENGT
      READ(5,91),ACODE,CROOK1,CROOK2,CROOK3,SWEEP1,SWEEP2
   91 FORMAT(A10,7F8.2)
C     READ A DEFECT OR LOG CARD
   11 READ(5,92),BCODE,(DATA(J),J=1,8)
   92 FORMAT(A10,8F8.2)
      IF(BCODE.EQ.≠END≠) GO TO 12
      IF(BCODE.EQ.≠D≠) GO TO 10
C     HAVE A LOG CARD SO CALCULATE THE HEIGHT TO THE TOP OF THE LOG.
C     AFTER THE LAST LOG HTM WILL BE THE HEIGHT TO THE TOP OF THE
C     DEFECT DATA
      HTM=DATA(2)+DATA(3)
      GO TO 11
C     SCREEN OUT IRRELEVANT DEFECTS  USING THE PNW CRUISING GRADES
C     SEE PNW RESEARCH PAPER 203
   10 N=IFIX(DATA(3))
      GO TO(11,29,29,23,23,21,29,11,29,30,11,11,11,30,30,30,22,29,30,30,
     111,11,20,11,11,11,29,29),N
C     ALL SCARS AND SEAMS ARE RELEVANT WITHIN 8 FEET OF THE GROUND
C     ONLY SCARS AND SEAMS LARGER THAN 5 IN BY 5 IN ARE RELEVANT ABOVE 8
C     FEET
   20 READ (5,92),BCODE,(CATA(J),J=1,8)
      IF(DATA(5).EQ.0.) GO TO 201
      DIST=ABS((CATA(1)-DATA(1)))/SIN(DATA(5))*12.
      GO TO 202
  201 DIST=ABS((CATA(1)-DATA(1)))*12.
  202 IF(DATA(1).LE.8.) GO TO 31
      IF(DATA(4).LT.5..AND.DIST.LT.5.) GO TO 11
```

```
      GO TO 31
C     ALL SOUND BURLS ARE RELEVANT IF LARGER THAN 3 INCHES IN DIAMETER
C     1 AVERAGE THE DIAMETER MEASUREMENTS
   21 READ(5,92),BCODE,(DATA(J),J=1,6)
      DAVG=((ABS(DATA(1)-DATA(3)))*12.+DATA(4))/2.
      IF(DAVG.LE.6.)  GO TO 11
      GO TO 31
C     BUMPS AND BULGES ARE RELEVANT WHEN BOTH WITHIN 8 FEET OF THE
C     GROUND ANDLARGER THAN 6 IN BY 6 IN.
   23 READ(5,92),BCODE,(DATA(J),J=1,6)
      DIST=ABS(DATA(1)-DATA(3))*12.
      IF(DATA(1).GT.8.) GO TO 11
      IF(DATA(4).LE.6..AND.DIST.LE.6.) GO TO 11
      GO TO 31
C     ALL KNOT INDICATORS ARE RELEVANT IF LARGER THAN ONE INCH DIAMETER
   22 IF(DATA(4).LE.1.) GO TO 11
      GO TO 30
C     COMPUTE CORNERS OF TRAPEZOID SURROUNDING THE RELEVANT DEFECT
C     WHICH HAS A DIAMETER MEASUREMENT AND THE LOCUS OF THE DEFECT
C     CENTER.  IF BIRD PECK, UNSOUND BURL, CANKER, OR KNOT CLUSTER, READ
C     CARD FOR THE TOP OF THE DEFECT
   29 READ(5,92),BCODE,(DATA(J),J=1,6)
      GO TO 31
   30 HT1=DATA(1)-DATA(4)/24.
      HT2=DATA(1)+DATA(4)/24.
   33 CALL TAPER(DBH,HT1,HEIGHT,D1)
      CALL TAPER(DBH,HT2,HEIGHT,D2)
      DEG1=(DATA(4)/(3.14159*D1))*360.
      DEG2=(DATA(4)/(3.14159*D2))*360.
      X1A=DATA(2)-DEG1/2.
      X1B=DATA(2)+DEG1/2.
      X2A=DATA(2)-DEG2/2.
      X2B=DATA(2)+DEG2/2.
      IF(X1A.LT.0.) X1A=X1A+360.
      IF(X1B.LT.0.) X1B=X1B+360.
      IF(X2A.LT.0.) X2A=X2A+360.
      IF(X2B.LT.0.) X2B=X2B+360.
      IF(X1A.GT.360.) X1A=X1A-360.
```

```
      IF(X1B.GT.360.) X1B=X1B-360.
      IF(X2A.GT.360.) X2A=X2A-360.
      IF(X2B.GT.360.) X2B=X2B-360.
      GO TO 32
C      COMPUTE CORNERS OF TRAPEZOID SURROUNDING THE RELEVANT DEFECT
C     WHICH HAS THE WIDTH, POSSIBLE ANGLE OF INCLINATION, AND LOCUS
C     OF DEFECT TOP AND BOTTOM MEASURED
   31 HT1=DATA(1)
      HT2=DATA(1)
      GO TO 33
   32 ICOUNT=ICOUNT+1
C     STORE RELEVANT DEFECT IN ARRAY DEFECT
      DEFECT(ICOUNT,1)=DATA(3)
      DEFECT(ICOUNT,2)=DATA(4)
      DEFECT(ICOUNT,3)=DATA(5)
      DEFECT(ICOUNT,4)=DATA(5)
      DEFECT(ICOUNT,5)=HT1
      DEFECT(ICOUNT,6)=X1A
      DEFECT(ICOUNT,7)=X1B
      DEFECT(ICOUNT,8)=HT2
      DEFECT(ICOUNT,9)=X2A
      DEFECT(ICOUNT,10)=X2B
      GO TO 11
C     DONE WITH TREE SO WRITE DEFECT ARRAY TO FILE
   12 WRITE(5,80),TREENO,DBH,HTSTMP,HEIGHT,HTA,ICOUNT
   80 FORMAT(1H1,5F10.2,I10)
      DO 1002 J=1,ICOUNT
      WRITE(5,81)(DEFECT(J,K),K=1,10)
   81 FORMAT(1H ,10F10.2)
      WRITE(1,82)(DEFECT(J,K),K=1,10)
   82 FORMAT(10F10.2)
 1002 CONTINUE
 1000 CONTINUE
      END
```

```
SUBROUTINE TAPER(DBH,HI,HT,DI)
DI=.80747-1.39037*(HI/HT)+.55290*(HI/HT)**2
IF(DI.LT.0.) DI=0.
DI=DBH*SQRT(DI)
RETURN
END
```

```
******************* DEFINITION OF VARIABLES IN DFLE **************************

ACODE            ALPHA CODE, T, READ FROM A TREE CARD
BCODE            ALPHA CODE, D OR L, READ FROM A LOG OR DEFECT CARD
CATA(8)=DATA(8)  STORES DATA FOR TOP AND BASE OR CENTER OF A DEFECT
                   1 = HEIGHT TO DEFECT POINT
                   2 = CIRCUMFERENCE IN DEGREES TO DEFECT POINT
                   3 = DEFECT CODE
                   4 = DEFECT DIAMETER OR WIDTH
                   5 = DEFECT HEIGHT OR DEPTH FROM STEM SURFACE
                   6 = DEFECT ANGLE OF INCLINATION
CROOK1, CROOK2, CROOK3  CROOK MEASUREMENTS FROM LOG
DEFECT(200,10)   STORES DATA FOR DEFECTS IN THE TREE THAT ARE
                 RELEVANT TO THE PNW LOG GRADING RULES
                   1 = DEFECT CODE
                   2 = DEFECT DIAMETER OR WIDTH
                   3 = DEFECT HEIGHT OR DEPTH FROM STEM SURFACE
                   4 = ANGLE OF INCLINATION OF DEFECT
                   5 = HEIGHT TO BASE OF DEFECT
                   6 = DEGREES OF CIRCUMFERENCE TO DEFECT BASE
                       CORNER CLOSEST TO ZERO DEGREE BASELINE
                   7 = DEGREES OF CIRCUMFERENCE TO DEFECT BASE
                       CORNER FURTHEST FROM ZERO DEGREE BASELINE
                   8 = HEIGHT TO TOP OF DEFECT
                   9 = DEGREES OF CIRCUMFERENCE TO DEFECT TOP
                       CORNER CLOSEST TO ZERO DEGREE BASELINE
                  10 = DEGREES OF CIRCUMFERENCE TO DEFECT TOP
                       CORNER FURTHEST FROM ZERO DEGREE BASELINE
DBH              DIAMETER BREAST HEIGHT
DIST             LENGTH OF A DEFECT
DAVG             AVERAGE DIAMETER OF A DEFECT
D1               TREE DIAMETER AT DEFECT BASE
D2               TREE DIAMETER AT DEFECT TOP
DEG1             CIRCUMFERENCE OF TREE IN DEGREES OCCUPIED BY DEFECT BASE
DEG2             CIRCUMFERENCE OF TREE IN DEGREES OCCUPIED BY DEFECT TOP
HEIGHT           TREE HEIGHT
```

```
HTSTMP          STUMP HEIGHT
HTBASE          HEIGHT TO BASE OF LOG
HTM             HEIGHT TO TOP OF LOG
HT1             HEIGHT TO DEFECT BASE
HT2             HEIGHT TO DEFECT TOP
ICOUNT          DEFECT COUNTER
NTREES          NUMBER OF TREES
N               INTEGER VERSION OF DEFECT CODE
RLOGNO          LOG NUMBER
RLENGT          LOG LENGTH
SWEEP1, SWEEP2  SWEEP MEASUREMENTS OF THE LOG
TREENO          TREE NUMBER
X1A             DEGREES OF CIRCUMFERENCE TO DEFECT BOTTOM CORNER
                CLOSEST TO ZERO DEGREE BASELINE
X1B             DEGREES OF CIRCUMFERENCE TO DEFECT BOTTOM CORNER
                FURTHEST FROM ZERO DEGREE BASELINE
X2A             DEGREES OF CIRCUMFERENCE TO DEFECT TOP CORNER
                CLOSEST TO ZERO DEGREE BASELINE
X2B             DEGREES OF CIRCUMFERENCE TO DEFECT TOP CORNER
                FURTHEST FROM ZERO DEGREE BASELINE
```

CURRICULUM VITAE

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1970-1971	Programmer I, College of Forest Resources, University of Washington, Seattle
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