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Although some of the most difficult problems in forest management occur as a result of timber harvest operations, present methodology in harvest planning emphasizes guidelines which rely heavily upon the experience of the individual forest manager for their correct application. This study was undertaken in an effort to develop a comprehensive methodology to assist forest managers in the design of timber harvest cutting units and the assignment of logging equipment to those units. The objective of the methodology is to maximize the total value of the timber harvested from a planning area, net of variable and fixed harvesting and transportation costs. The methodology thus developed consists of a two-part procedure. The first part considers the specific topographic and timber conditions on the planning area, plus any harvesting restrictions which may have been imposed on portions of the area because of expected environmental problems. This information is combined with the known mechanics of the logging systems under con-

sideration to determine the feasibility and cost of harvesting each parcel of timber from the area.

The second part of the methodology consists of a heuristic optimization algorithm which seeks to assign timber parcels to harvesting facilities so that total timber value, net of fixed and variable harvesting and transportation costs, is maximized. The output from this algorithm is a detailed harvest plan which specifies yarding system assignments and the physical layout of cutting units for each yarding system thus assigned.

The optimization problem confronted in this study is an application of facilities location theory, but with two unique characteristics which render the conventional mixed integer programming formulation unsuitable for this problem. First, the planning area is visualized as being dichotomized into timber parcels of equal size, each of which is to be assigned to some harvesting facility. Thus, the problem is a fully discrete one, and can be formulated as a 0-1 integer programming problem. Second, the problem exhibits a special "cascading fixed charge" structure. Stated simply, this implies that several levels of fixed charges must be incurred for any complete facility installation. Thus, if a specific logging cableway is to be emplaced at a certain landing, then the fixed charge associated with the construction of the landing must already have been incurred, and the fixed charge associated with the installation of some yarding system at the landing must also have been incurred. Unfortunately, the 0-1 integer programming formulation appropriate for this problem requires many thousands of variables and constraints, even for relatively small planning areas. To overcome the computational difficulties associated with the solution of such large integer programming problems, a heuristic algorithm was developed to find satisfactory, rather than optimal solutions. Applied to a realistic forest planning problem with 5507 variables and 6555 constraints, the algorithm found an initial feasible solution after 93.3 minutes on a CDC 3300 computer. The run was terminated after a total of 120 minutes, with the value of the final solution being only 0.09 percent better than that of the initial solution. Although the exact solution could not be verified, computational experience with smaller problems suggests that the initial feasible solution obtained with this algorithm is usually very close to the optimal solution.

Timber Harvest Layout
By Mathematical and Heuristic Programming

by

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TIMBER HARVEST LAYOUT
BY MATHEMATICAL AND HEURISTIC PROGRAMMING

I. INTRODUCTION

One of the most difficult tasks faced by forest resource managers is that of planning forest harvesting operations. Transportation systems must be devised, yarding[1] equipment selected, silvicultural treatments prescribed, and cutting units designed; simultaneously, consideration must be given to soil and water protection, slash disposal, site preparation and reforestation, recreation, wildlife, and aesthetics. Thus, forest managers are faced with the task of making decisions while considering multiple objectives that are often in conflict. Under such conditions, the rigorous examination of even a single proposal is often so difficult that any systematic evaluation of alternatives is essentially precluded. Yet a detailed analysis of alternatives is essential if the economic and environmental consequences of proposed forest operations are to be adequately considered.

According to Jemison and Lowden (1974), environmental restrictions on forest operations are likely to intensify, at least in the short run. The voices of conservation groups, the public at large, forestry-related professionals such as wildlife and recreation specialists, landscape architects, and even professional foresters have been raised more loudly and more often in recent years over the impact of forest opera-

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[1]A glossary has been included in the Appendix for the convenience of readers not familiar with timber harvesting terminology.

tions on non-timber resource values. These concerns have come at a time when the demand for wood products is at an all-time high and the supply base is shrinking due to withdrawal of commercial forest land for non-timber uses (Bolsinger, 1973; Darr and Fight, 1974). Recent projections suggest that the dual trends of a shrinking supply base (Forest Service, 1969; Beuter, Johnson, and Scheurman, 1976) and expanding demand (Marcin, 1974) will continue through at least the next two decades. Coupled with more restrictive environmental regulations on forest operations, the net result of these trends will be log extraction costs that increase both in absolute value and as a percentage of total timber production costs. Certainly, the challenge of moving timber from the stump to the mill at reasonable cost will require innovation, both in logging technology and in planning.

Objective

The purpose of this study is to develop and demonstrate a methodology to assist forest managers in planning timber harvesting operations. The intent of this methodology is to answer the following questions, given a specific forest planning area:

1. How should individual cutting units be designed?
2. What specific logging equipment should be assigned to each cutting unit?

In posing these questions, the forest manager's objective is assumed to be the maximization of total net revenue resulting from the harvest of timber on the planning area.

Scope

The primary focus of this research is on forest harvesting operations; related considerations, such as transportation systems and silviculture, are treated only in a limited way. The intent of the research has been to incorporate existing knowledge related to harvesting production rates, feasibility, costs, and environmental impacts into a comprehensive planning methodology. No effort has been made to derive new measures or standards, nor have proxy numbers been used to impute the "cost" or "value" of non-timber resources as is sometimes done in cost/benefit studies (Rickard, Hughes, and Newport, 1967; Grayson, 1972). As the research was constrained by a finite time horizon and limited budget, certain assumptions had to be made about the system under consideration in order to assure the feasibility of modeling that system. These assumptions include the following:

1. Actions taken on the planning area do not influence, and are not influenced by, the management of surrounding forest areas.
2. The location of roads and potential landing sites within the area to be harvested is fixed and exogenous.
3. The single silvicultural treatment to be employed on the planning area is that of clearcut regeneration harvesting.
4. Only cable yarding systems are to be used.
5. Environmental restrictions on the planning area are met or exceeded by the proper application of cable yarding systems.
6. The timber within each type island is homogeneous and uniformly distributed over the area of the type island.

7. The timber on the harvest area remains in a static condition for the duration of the planning horizon.
8. The order in which cutting units will be harvested is either exogenous, or is of no interest.

In the remainder of this section, these eight assumptions are discussed briefly to illustrate the motivation for specifying them. Where appropriate, the limitations imposed upon the study by the assumptions are also indicated.

Independence of the Planning Area

The planning area is assumed to be framed by a continuous boundary such that the area outside of the boundary has no influence upon, and is not influenced by, cutting unit design and logging system assignment within the planning area. If reasonable care is taken in defining the planning area, this assumption can often be met over much of the area. Usually it requires that the planning area be composed of one or more contiguous drainages so that the boundary is drawn along ridgetops.

Transportation System

The location of roads and potential landing sites within the area to be harvested is assumed to be fixed and exogenous (i.e. decisions related to the location, design, and construction of roads and landings are not treated explicitly in the model, although the methodology does treat the actual selection of landings to be occupied from among exogenously specified alternatives). In reality, the design of a transportation system for timber extraction interacts strongly with cutting unit design and logging equipment selection. In mountainous terrain, however, only a few feasible alternatives for access road location commonly exist. In addition, several well-developed models are available to forest managers for planning forest transportation systems. Carter, Gardner, and Brown (1973) have developed a nonlinear programming model that computes the optimum economic spacing of forest roads. Peters (1975) has developed analytical procedures for computing optimum road and landing spacing which are essentially extensions of earlier work by Matthews (1942) and Lussier (1961). Kirby (1973) and Mandt (1973) have also presented transportation planning models for low-volume forest roads, the former using integer programming and the latter using network analysis.

Silvicultural Method

Only clearcut silviculture is considered in this model. Explicit treatment of silvicultural alternatives would have made the development of an operating model, within the time limits of this study, impossible. The decision to employ a shelterwood system, for example, has implications for an entire array of entries over time as opposed to the single entry dictated by clearcutting. This would necessitate consideration of changes in price structure over time, mortality and growth, and discounting of future costs and revenues incurred through the time of the final overstory removal. In addition, partial cutting influences reforestation practices and costs, fire control and slash disposal, wildlife, soil and water, and aesthetic considerations. Admittedly, these considerations cannot be removed from the forest manager's sphere of responsibility. The present study has excluded them only in the interest of placing reasonable limits on the research to be done. And in a practical sense this is not an unreasonable limitation. On many private forest holdings clearcut silviculture is practiced exclusively, and even on the public forests of the Douglas-fir region[2] it remains the dominant silvicultural method, in terms of annual timber volume harvested[3].

Cable Yarding Systems

The yarding systems considered in this study are limited to four cable systems commonly used for harvesting old-growth timber indigenous to the Douglas-fir region. These are the following:

1. Highlead
2. Gravity-return (flyer) live skyline without haulback
3. Live skyline with haulback
4. Running skyline

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[3]The Douglas-fir region is commonly referred to as that portion of Washington and Oregon west of the Cascade divide plus a small portion of Northern California.

[4]Forest Service, USDA. Timber harvesting and the environment on the National Forests of the Pacific Northwest Region. Portland, USDA Forest Service Region 6 (informational brochure, no date). 7 p.

These yarding systems are illustrated schematically in Figures 1 - 4. They were selected for analysis because, in the aggregate, they presently account for a majority of the timber volume harvested in the Douglas-fir region (Studier and Binkley, 1974). Furthermore, their mechanical characteristics are sufficiently similar that valid economic comparisons among them can easily be drawn.

Three additional yarding systems which would conceptually fit into the scope of this study are tractor, balloon, and helicopter systems. All have had significant application in the Douglas-fir region. Tractor systems, however, are generally limited to relatively gentle slopes with stable soils. As the methodology presented here has been developed specifically for steep, environmentally sensitive areas, tractor systems have therefore been excluded.

In contrast with tractor systems, balloon and helicopter systems can be substituted for cable systems on virtually any kind of terrain (Peters, 1973; Burke, 1973). Balloon systems have been excluded from this study primarily on the basis that few such systems are currently in use. Peters (1973) reported recently that fewer than a half-dozen balloon logging systems were operating in North America, three of those in the Douglas-fir region. Thus, although balloon systems can conceivably be substituted for cable systems, the likelihood of actually having the system available is limited.

Helicopter logging systems are, in spite of their relatively recent introduction, fairly common in the Douglas-fir region. While helicopters are perhaps more versatile than any other logging system,

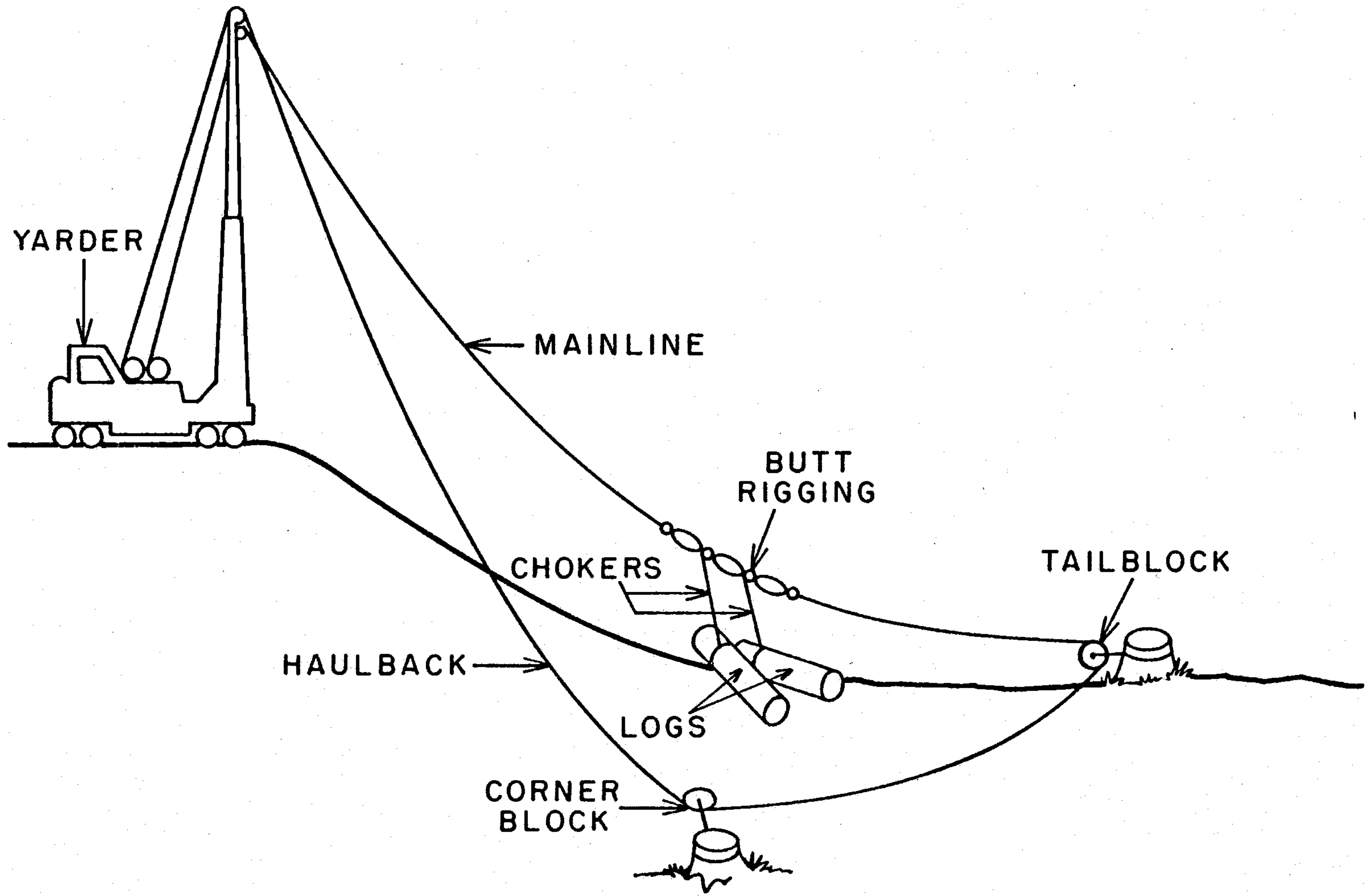

Figure 1. Highlead yarding system.

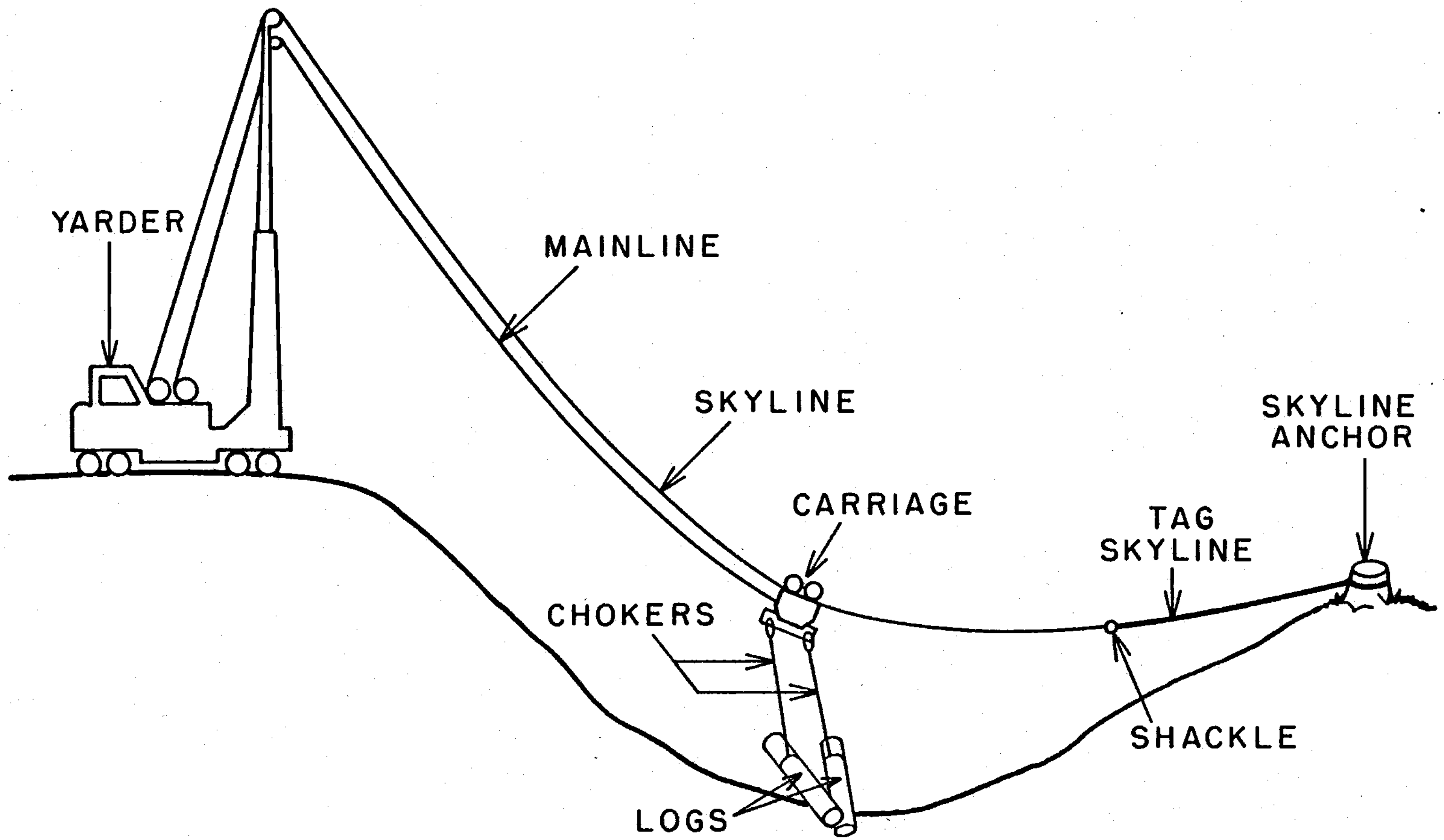

Figure 2. Gravity return (flyer) live skyline yarding system without haulback.

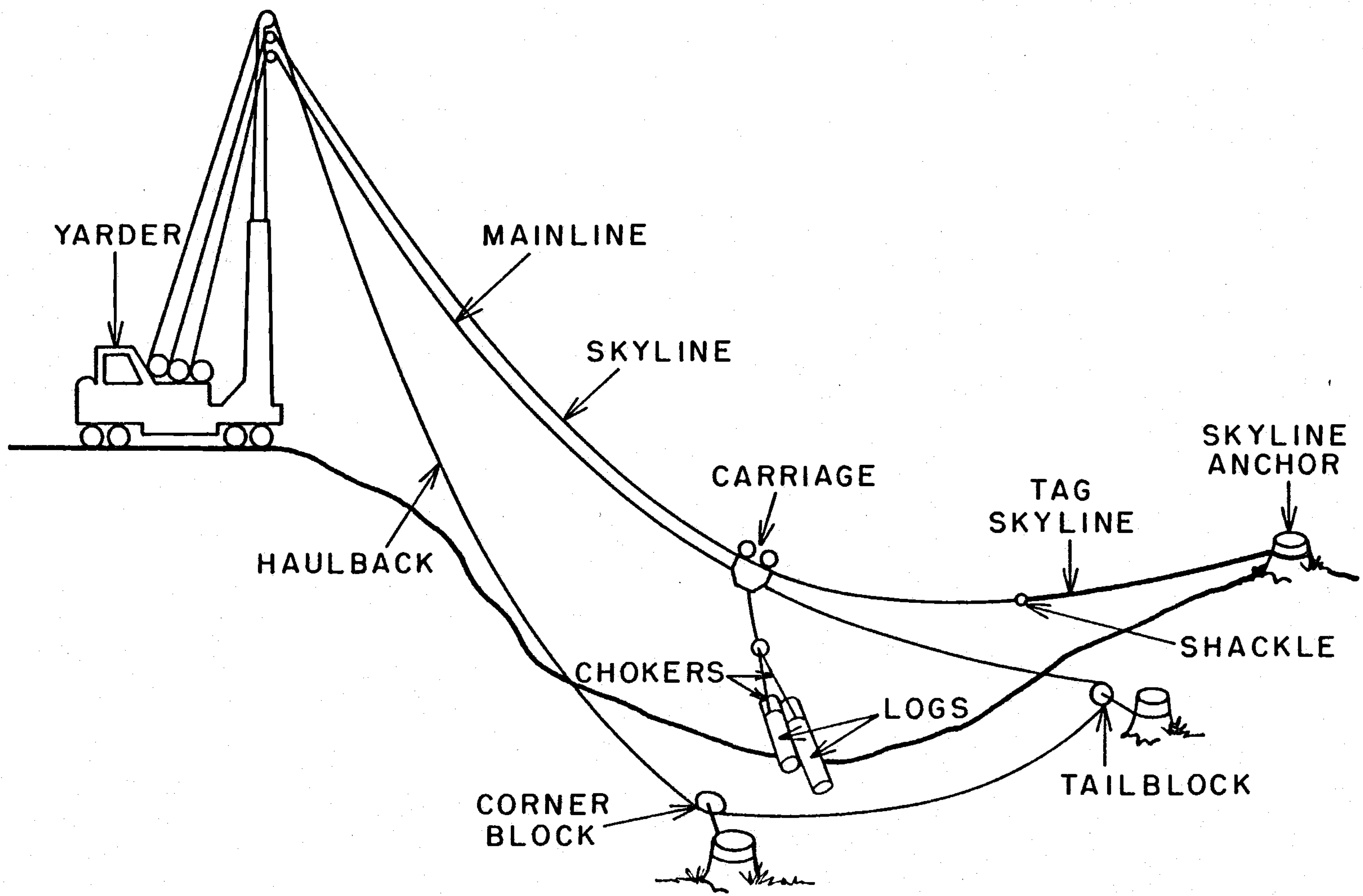

Figure 3. Live skyline yarding system with haulback.

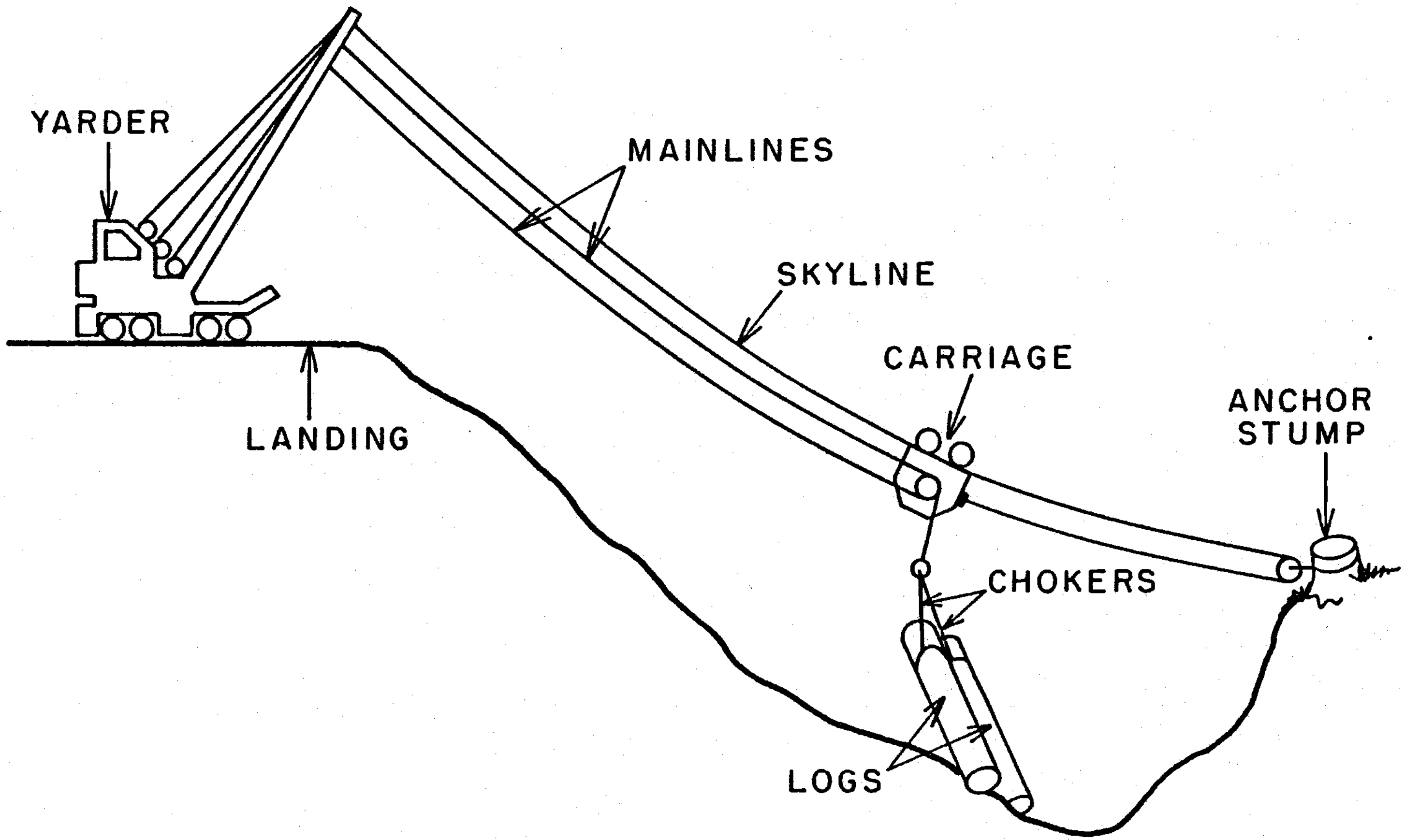

Figure 4. Running skyline yarding system.

their actual application remains highly subjective, requiring a significant and coordinated planning effort (McGonagill, 1973; Stevens and Clarke, 1974). Furthermore, although guidelines for the application of helicopters in logging have been devised (Gorsh, 1974), they have not been rigorously validated and cannot therefore be generally applied, particularly in a framework that seeks to compare alternative harvesting treatments for a single planning area. Finally, economic studies involving helicopter systems (Dykstra, 1975) have been limited to a very narrow range of conditions, and extrapolation beyond those limits would be difficult to justify.

Environmental Impacts

Environmental restrictions on the planning area are assumed to be met or exceeded by the proper application of cable yarding systems. This assumption has two implications for the present study: first, that "proper application" be defined explicitly, and second, that the methodology be sufficiently general in nature to permit the specification of this proper application for any given forest planning area. Further discussion of these two points is deferred until Chapter II.

Homogeneity of Timber

Timber within designated type islands on a vegetative type map of the planning area is assumed to be homogeneous with some known distribution of log volume, and felled logs are assumed to be equilaterally distributed over the type islands. Although this assumption may seem to be restrictive, it is actually a relaxation of the assumption which is commonly made in forest planning: that timber volume on a planning area is homogeneous and equilaterally distributed over the entire planning area. Furthermore, the methodology presented in this dissertation has been developed so that the size of an individual type island can be quite small. In essence, therefore, the assumption stated above only has to be observed at the limit. As a practical matter, however, timber inventory data are usually insufficient to permit type delineations less than several acres in size.

Static Model

The analysis of a given planning area by means of the methodology developed in this study assumes that the timber on the harvest area remains in a static condition for the duration of the planning horizon. Admittedly, forests are not static, and, except for small planning areas, a significant period of time will normally elapse before an entire planning area has been harvested. The assumption was made for this study in order to assure computational feasibility for the problem addressed. For old-growth forests, major changes in forest structure are not likely to occur even during long time periods; thus the assumption may not be entirely unreasonable. For young timber, however, it would not be wise to make this assumption without a thorough investigation of the sensitivity of the model to changes in price structure over time, mortality and growth, and discounting of future costs and revenues.

Order of Harvesting

In the context of this study, the order in which cutting units will be harvested is assumed to either be exogenous, or of no interest. For a static forest it is obvious that the order of cutting will not bear upon the decisions of interest (i.e. cutting unit design and logging equipment assignment). For young, vigorous forests the argument is not so straightforward, but recent work by Lembersky (1976) has shown that the timber which is appreciating in value at the slowest rate should always be harvested first. Thus, if a non-static forest condition is to be assumed this criterion can be applied to treat the interaction between cutting unit design and the order of harvesting.

Synthesis

The assumptions and limitations discussed in this section have important implications with respect to the specific problem which is being solved. It is assumed that the decision has already been made to clearcut an entire planning area, using one or more of the four types of cable systems considered in this analysis. The total elapsed time of harvesting must be short enough that the static model assumption is reasonable. To apply the methodology, certain detailed information must be available, as follows:

1. The topography of the planning area must be known accurately.
2. The location and estimated construction costs for all roads and landing sites must be known (some of these may not actually

have to be constructed, depending upon the final harvest plan for the area).

3. The location and extent of each timber type on the area must be known, and quantitative data describing the timber in each of those types must be available.
4. Areas which are subject to harvesting restrictions (because of expected environmental problems) must be delineated, and the type of restriction specified.
5. Detailed information must be available for each of the yarding systems which is to be considered. This includes fixed and operating costs, the effect of terrain and other factors on productivity, and data indicating the limitations and capabilities of the yarding system.
6. The location of all cableways to be considered in the analysis must be specified.

Much of this information is presently available to the forest manager, although the environmental restrictions (point 4) are usually given only indirect consideration. In addition, cableway locations (point 6) are almost always left to the discretion of the logging manager. This paper will demonstrate, however, that cableway location has immense significance in harvest planning and should therefore be given explicit consideration during the planning process.

The above discussion should answer the questions: What decisions have already been made? What kinds of data are required? An equally important question from the point of view of the forest manager is:

What do I get for my efforts? The methodology presented here provides a detailed harvest plan which includes the following:

1. An estimate of total timber value, net of fixed and variable harvesting and transportation costs, which would result if the "optimal" harvest plan were applied.
2. Accurate estimates of cable logging feasibility and costs, established by explicit consideration of environmental restrictions, timber type, and topography.
3. The "optimal" assignment of specific yarding equipment to landings.
4. The physical layout of cutting units for each of the yarding systems thus assigned, including the specification of individual cableways to be emplaced and the area to be yarded to each landing.
5. Detailed information about each cableway, including:
    a. estimated emplacement cost;
    b. estimated yarding costs along the cableway;
    c. estimated timber value, net of variable harvesting and transportation costs, for all timber which could be harvested over the cableway;
    d. an effective load profile for the cableway, which indicates the estimated maximum load capability of the yarding system at increments along the cableway;
    e. a ground surface profile along the cableway;
    f. the minimum height of the tailtree which would be required

in order to permit yarding over the cableway.

Study Procedure

To accomplish the objectives of this study within the scope outlined above, the following tasks were undertaken:

1. The specific problem to be solved was defined.
2. A systematic procedure was developed for evaluating the feasibility, and estimating the cost, of applying each of the four cable systems (highlead, flyer, live skyline, and running skyline) to a specific forest area.
3. A mathematical programming solution structure was formulated and tested.
4. A heuristic algorithm to find "satisfactory" solutions at a much lower computational cost than that required to find an optimal solution was developed and tested.
5. The resulting methodology, which consists of the procedure in (2) and the heuristic algorithm in (4), was applied to an actual forest planning area.

II. PROBLEM DEFINITION

Planning Forest Harvesting Operations

Present methodology in forest harvest planning emphasizes guidelines, which are essentially rules of thumb, for the design of cutting units (Binkley and Lysons, 1968; Forest Service, 1973 and 1974a), and for the assignment of logging equipment to those units (Studier and Binkley, 1974). These guidelines rely heavily upon the experience of the individual forest manager for their correct application. They are in no sense optimization tools. Furthermore, since topographic considerations are complex, and differences between available yarding systems are often difficult to assess, a comprehensive analysis of alternative cutting unit designs and logging equipment assignments is usually neglected.

Several important exceptions to this rule are worthy of note. As early as three decades ago, Matthews (1942) had developed numerous analytical procedures for timber harvest layout. These procedures used the calculus of one and two variables to determine optimum yarding distance and landing spacing for logging equipment operating in flat or uniformly sloping terrain. More recently, Lussier (1961) revised some of Matthews' work and showed how it could be applied more effectively by recognizing that forest operating areas differ markedly in those characteristics which influence logging production rates and costs. In addition, Lussier was probably responsible for the earliest applications of industrial engineering to timber harvest operations, with published applications ranging from linear programming and simulation to machinery replacement analysis and quality control (1960, 1961). His work in cutting unit layout, however, was oriented strongly toward the flat or uniformly sloping terrain characteristic of eastern Canada. Peters (1975) has recently completed a rigorous development, again by the use of calculus, which extends and generalizes the results of Matthews and Lussier. His work, however, like that of his predecessors, assumes at the outset that the basic shape of a cutting unit is to be a rectangle. This assumption is based upon the observation that ownership boundaries are normally rectangular, and that cutting boundaries often must conform to this pattern. In many areas this assumption is certainly valid. In the Douglas-fir region, however, many industrial and public forest ownerships are large enough that this consideration can be essentially ignored. Thus, procedures to determine optimum economic cutting unit shape, as opposed to boundary dimensions, are of interest. The study reported in this dissertation appears to be the first attempt to develop such procedures.

Operations Research Approaches to Optimal Harvest Planning

Because of the inherent complexity of forest operations, efforts have been made almost since the advent of mathematical programming to apply these techniques to forestry problems. Lussier (1960) reported that mathematical programming techniques had been used to improve timber harvesting operations in Canada as early as 1955. Many applications were published during the early 1960's, and by 1973 a bibliography of operations research applications in forestry (Martin and Sendak, 1973) required 90 pages. In spite of this wide array of applications, the following discussion will show that none of the timber harvesting models published to date has treated topographic influences in sufficient detail for the kind of investigation undertaken here, and none has considered the design of individual cutting units.

Newnham (1970) has developed several detailed models for studying the tree-by-tree extraction process in an effort to develop improved harvesting machinery. His models were designed specifically for the flat pulpwood stands typical of eastern Canada and thus do not consider topography. As Newnham's technique was developed to study individual tree processing by vehicles which are capable of moving from tree to tree through standing timber, an important requirement is a detailed inventory which includes the location and size of each tree in the stand. Much of Newnham's early work was involved with the generation of artificial populations of trees by computer for the purpose of simulating such inventories (cf. Newnham, 1968). His later work, however, incorporates actual stand data. This requires an inventory on a scale which is many times more detailed than that available for any known commercial forest. For Newnham's application, of course, this consideration is not important; but it would be of critical importance in the development of a model for planning harvest operations on actual forest sites.

Work by Woodland (1968), also in eastern Canada, contrasts with that of Newnham in that Woodland's model applies harvesting production rates over a specified volume of timber and thus does not simulate tree-by-tree processing. Rather than focusing on the conceptualization of improved machine design, Woodland attempts to improve equipment selection and scheduling for an industrial forestry operation. His model can be used to simulate the harvesting of a specific tract of timber by varying the harvesting production rate as appropriate to consider the effects of terrain and other variables. A disadvantage of his formulation, however, is that these production rates are essentially exogenous.

A computer simulation model which also treats production rates as exogenous is that of Hool et al. (1972). This model was designed to investigate the effect of system changes on production rates and component balance. This model, developed to simulate a harvesting operation for which empirical production rates were obtained by a time study, appears to have been useful for predicting the response of the harvesting system to changes in its components. By manipulating the components (and thus the production rate) exogenously, the authors were able to simulate an improved system with near-perfect component balance, whereas the original system was severely unbalanced. Although this result was not validated, it does illustrate the fact that simulations can be designed to converge toward an improved solution. This model has several shortcomings with respect to the present study, however: first, production rates are exogenous, which means that terrain and timber conditions are assumed to be constant over the harvesting area; second, it is not of sufficiently general design to permit the investigation of alternative logging systems which are not intrinsically ground-based; and finally, it includes no consideration of cutting unit design.

A more generalized timber harvesting simulator which appears to have been based largely upon the model developed by Hool et al. has been described by Webster (1973). Although more general than any of the models previously described, it is not capable of simulating systems which are inherently different than conventional ground skidding systems; cable systems, for example, are beyond its capabilities. Furthermore, it does not consider the design of individual cutting units.

Johnson, Gochenour, and Biller (1972) have reported the development of a model which is similar to the one described above in that it also simulates harvesting by means of ground skidding systems. Of some significance, however, is the fact that this model was validated by coordinating the simulation with time studies of actual operations. This represents an important advance beyond the studies described above. The model retains essentially the same fundamental characteristics, and the same drawbacks with respect to the present study, as those described previously, however.

A somewhat different approach to simulating an actual harvesting operation has been taken by Boyd and Lambert (1969). This model is a deterministic simulation of a grapple-rigged running skyline system and thus represents the first cable yarding application reviewed here. Its objective is to develop logging cost data for representative yarding distances so that the optimum yarding distance can be located by inspection. Although implemented as a simulation model, it could alternatively have been solved by means of a nonlinear programming algorithm which would yield the minimum logging cost directly. Whether or not this alternate formulation would be computationally more or less efficient than the simulation would of course have to be established empirically. Application of the model is limited with respect to the present study by the fact that it assumes that cutting unit boundaries are basically rectangular. Furthermore, the yarding production function used is a fourth-order linear polynomial based on yarding distance; applied strictly to the limits within which it was established this should pose no problem, but any extrapolation beyond those limits is likely to give unrealistic results. Finally, the model makes no consideration of topography, even though the yarding system under consideration was designed specifically for mountainous terrain.

A more flexible cable yarding simulation has been developed by Sinner (1973). This stochastic model was formulated specifically to incorporate timber and terrain conditions for the study of thinning operations in young growth Douglas-fir. It was validated extensively, and has been used in tests designed to measure the expected efficiencies of alternative work methods in skyline yarding. However, it simulates the actual yarding of a specific stand of timber for which yarding distances and other data are specified exogenously, and as such does not directly address the geometry of the area under consideration. Sinner's model is, however, probably the most complete simulation of a specific timber harvesting system which has appeared in the literature.

Gibson and Egging (1973) have described a mathematical model which is formulated to optimally select landings for rubber-tired skidder operations from among several alternative landing locations. Topography is considered explicitly, although in much the same sense as in Sinner's model rather than in the strict geometric sense (again, topographic influence is incorporated by means of the production function). The Gibson-Egging model, however, does permit the consideration of topographic constraints such as streams or other obstacles, and thus treats the geometry of yarding somewhat more generally than any of the other timber harvesting models reviewed. The heart of its optimization methodology is an algorithm which combines dynamic programming with a branch-and-bound technique in order to avoid complete enumeration of all possible solutions. Of the models reviewed here, the Gibson-Egging model comes perhaps closest to solving the type of problem addressed in this dissertation. It does, for example, treat the selection of actual landing sites to be occupied from among exogenously specified alternatives. Although it was not designed to select from among alternative yarding systems, the model appears flexible enough that it could be reformulated to do so. Its major disadvantages, however, are the following: first, it completely disregards the physical representation of the cutting units themselves (unit centroids are used); and second, the optimization methodology used is almost certainly restricted to very small problems. A detailed discussion of this latter point will be deferred until Chapter IV.

All of the models discussed above might be classified as "explicit timber harvesting models". That is, they are concerned directly with the harvesting operations themselves. Two other categories of operations research models which consider timber harvesting in a more vague frame of reference might be called "forest planning models" and "policy formulation models". Both categories are considered briefly in the interest of demonstrating why neither type of model is appropriate to the present study.

Forest Planning Models

These models are designed to provide information to forest managers regarding the expecting outcome of specific harvesting actions, but usually do not treat harvesting operations explicitly. Usually the unit of interest is a "stand" or "working circle". Models which fall into this category include those of Aulerich (1971, 1973), Clutter and Bamping (1965), Gibson, Orr, and Paine (1970), Leaf and Brink (1975), Lembersky and Johnson (1975), and Meyers (1973). Of these, only the Gibson-Orr-Paine model is deterministic. All six models are explicitly implemented over time, and all six consider growth, mortality, regeneration, and a range of silvicultural treatments. All but the Leaf-Brink model, which is concerned with water yields, peak flows, erosion, and sediment yields, are economic models. Except for Aulerich's model, all of them treat harvesting indirectly. Aulerich does permit the consideration of several different logging systems and treats the effect of topography on logging costs. His model is worthy of special mention in that it attempts to measure the desirability of logging a stand of timber at any point in time by considering two opposing points of view: that of the forester (who wants to maximize net growth over mortality) and that of the logger (who wants to maximize the net value of stumpage over logging costs). The netting of indices which measure these two points of view produces a final measure of overall utility from the point of view of the firm. Although the model as developed does not optimize this utility over time, it could be extended to do so. Clutter and Bamping also claim a model structure conducive to optimization, but whether or not this claim can be supported is not evident from their publication. The Gibson-Orr-Paine model does appear to be structured so that it could be optimized as a nonlinear programming problem, probably with some computational improvement over the present formulation. The study by Lembersky and Johnson is a probabilistic optimization in which management actions to be taken at any point in time can be determined from the observed condition of the stand at that time. The Leaf-Brink model and Myers' model, however, were intended for experimental investigations and hence provide no motivation for optimization.

It is evident in the discussion above that each of the models in the "forest planning" category attempts to answer the questions: Should I log at all? When should I log? What kind of silvicultural treatment should I use? None of the models is concerned with the design of cutting units or the assignment of logging equipment.

Policy Formulation Models

These models tend to resemble forest planning models but are developed for slightly different purposes and are thus implemented differently. Models which might properly fit into this category include those of Atkinson et al. (1974), Beuter, Johnson, and Scheurman (1976), Gould and O'Regan (1965), Navon (1971), and Sassaman, Holt, and Bergsvik (1972). Like forest planning models, these simulations are all designed to test management strategies over time. In general, however, they are more ambitious than forest planning models (the Beuter-Johnson-Scheurman model, for example, considers the entire State of Oregon), and are intended to provide information for policy makers at high levels (such as the Governor of a State or the Chief of the Forest Service). Only the model described by Atkinson et al. explicitly treats individual harvesting operations, and the treatment in that model does not retain the identity of individual cutting units throughout the simulation. In general, policy formulation models are concerned with the dynamic structure of a forest over time and the flow of resources from the forest as a result of policies imposed upon it.

Synthesis

This section has presented a discussion of operations research applications to the planning of forest harvesting operations. While none of those applications has addressed the specific problem which is considered in the present study, it should be evident that a considerable range of analytical tools is represented in the timber harvesting literature. Most studies which have been specifically concerned with detailed harvesting operations have employed computer simulations, apparently because of the flexibility and ease of representation which is inherent in that technique. Simulations can be either stochastic or deterministic, and changes in model structure are relatively easy to incorporate, so that hypothetical experiments can be conducted if desired. For detailed investigations of specific yarding systems, computer simulation therefore seems to be the most promising analytical tool presently available.

The study addressed in this dissertation, however, concerns the evaluation of existing systems, rather than the design of systems. It is therefore most closely related to the work of Matthews (1942), Lussier (1960, 1961), Peters (1975), and Gibson and Egging (1973). Of these, only the formulation by Gibson and Egging, which is a mathematical programming model, approaches the degree of flexibility required to investigate the design of cutting units and the assignment of logging equipment to those units. A detailed description of the model structure which is used in the present study to solve this problem is deferred until Chapter IV.

Environmental Considerations

As noted in the discussion of the scope of the study (Chapter I), one intent of this research is to develop some means by which environmental restrictions can be explicitly incorporated into the planning methodology. This section discusses briefly the nature of environmental impacts related to timber harvesting and indicates the methods by which restrictions on harvesting operations as a result of such impacts have been considered in this study.

Soil Values and Water Quality

Forest harvesting operations influence soil values in several ways, including surface disturbance, compaction, reduction of mechanical soil strength, and alteration of nutrient balance. The first three of these impacts tend to increase the probability of surface erosion and mass movement, both of which result in loss of the soil resource and degradation of water quality. Of the three, soil compaction has been shown to be relatively insignificant for most applications of cable systems, including highlead and skyline yarding (Dyrness, 1965 and 1967; Froehlich, 1974). Similarly, the reduction of mechanical soil strength results almost entirely from the removal of vegetation from a forest site (Swanston, 1974); the same is true of nutrient loss (Brown, 1973). The effects of compaction, reduction of mechanical soil strength, and nutrient loss are therefore disregarded in the present study as no significant difference in impact would be expected between clearcutting treatments with alternate cable logging systems.

The case with respect to surface disturbance is not so straightforward. Although research by Ruth (1967) and Dyrness (1965, 1967) suggests that the surface disturbance which results from yarding is not significantly different for highlead and skyline systems in any given application, it is not difficult to find situations for which special considerations must be taken into account. Different cable systems, for example, exhibit radically different capabilities for suspending heavy loads. In some instances, this capability may be of considerable importance in preventing degradation of the stream channel and can thus exert a major influence on water quality (Brown, 1973). For the purpose of this study, therefore, the planning methodology has been devised to avoid specific streamside "hazard zones" as outlined by the forest manager or soils specialist. Two categories of such zones are included: for minor streams or other less sensitive areas, the model requires that partial suspension of logs be observed as a minimum; for major streams or designated areas of especially fragile soils, full suspension of logs is required. On all undesignated portions of the planning area, cable systems are permitted which are not capable of suspending logs. An important consideration for implementing such capabilities in a planning methodology is the fact that the model has to be able to recognize not only the hazard zones themselves, but also the size of timber which has to be partially or fully suspended. Thus, a yarding system which is capable of fully suspending logs in one timber type may not be capable of even partial suspension in a different timber type.

Water Temperature and Stream Debris

Although water quality is inextricably bound to the soil, it may also be affected by treatments which influence water temperature (Brown and Krygier, 1970), and by variation in the quantity, type, and distribution of organic residues in streams (Froehlich, 1973; Ponce and Brown, 1974). Neither of these considerations is directly applicable to the present study, as they tend to be invariant for cable logging systems. Their relative costs, though, are highly dependent upon the economics and capabilities of the individual logging system. As an example, stream temperatures and debris can often be controlled by leaving a buffer strip of shade trees or other vegetation along streams[5] (Brazier and Brown, 1973; Froehlich, 1973). Cable logging costs are usually increased in the vicinity of such buffer strips because of the difficulty of threading yarding cables through standing timber and the extra care which is required to extract debris or logs from the buffer strip. Any planning model designed to incorporate the use of buffer strips (or other no-cut areas) should therefore be capable of incrementing yarding costs in the vicinity of such strips.

Non-Timber Resources

Emphasis in forest management, particularly on the public forests, has shifted in recent years from one of dominant use (oriented toward timber production) to one of multiple use. This means that non-timber resources, such as fisheries, wildlife, recreation, and aesthetic quality are all classified as resources to be managed. Thus, the forest manager must be concerned with the effect of harvest planning on these non-timber resources. A major difficulty with the consideration of non-timber resources is the fact that they are not usually bought and sold

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[5]In some cases, buffer strips are required by law (State of Oregon, 1973). Although the model developed in this study does not attempt their design, it does permit the forest manager to specify the design and location of buffer strips exogenously.

like timber, so that their value is difficult to quantify. Efforts to treat such resources quantitatively have had varying degrees of success. As an example, Sadler (1970) attempted to measure the value of a buffer strip of merchantable timber against the value of the commercial and sport fishing resource which he believed would be lost or impaired if the buffer strip were removed. To do so, he assumed that a commercial fish was worth its dockside price, and that a sport fish was worth the expected amount of money which would be spent annually by an average sport fisherman to catch one such fish. Interestingly, Sadler's analysis suggests that a Coho salmon is worth 16 times more if caught by a sport fisherman than if caught by a commercial fisherman.

Many attempts have been made to quantify landscape quality. Rickard, Hughes, and Newport (1967) proposed the use of "shadow prices" to impute the value of aesthetic quality from the cost of the additional management activities which must be undertaken or the revenues which must be foregone in order to obtain some desired level of aesthetic quality. Randall (1974) suggested that "bidding games" be devised to determine how much people "would be willing to pay" for an aesthetic experience. Shafer, Hamilton, and Schmidt (1969) used correlation and factor analysis to identify landscape qualities which forest visitors appeared to value highly. These qualities were then used as independent variables from which multiple regressions were derived for use in predicting the aesthetic quality of landscape views. Even after such relationships have been established, however, their application in forest management is limited because of the almost infinite combination of factors which influence the visual quality of a forest scene. Many of these factors are dynamic, varying with the time of day or season of the year. Almost all are dependent upon the position of the observer or his distance from the object being viewed. Because of this, recent efforts by the Forest Service to incorporate landscape management principles into routine timber management activities (Forest Service, 1973, 1974a, 1974b) have completely discarded all such quantitative models in favor of detailed guidelines intended for use by trained landscape architects. Similarly, in attempting to integrate fisheries, wildlife, recreation, and other non-timber resources more fully into resource management activities, the Forest Service and other public agencies have tended recently to encourage the use of trained specialists rather than quantitative models. This makes sense from the viewpoint of industrial engineering, which has long advocated an interdisciplinary approach to planning.

The purpose of this section has been to recognize the fact that forest management has come to mean not timber management but rather the integrated management of both timber and non-timber forest resources. With the exception of special considerations which are given to soil and water impacts related to timber harvesting (discussed in the previous section), non-timber resources are not explicitly considered in the planning methodology developed for this study. This does not imply that they are unimportant, or that the result of an application of the methodology described in the remainder of this dissertation would be complete without the additional consideration of those resource values.

The model formulated for this study, like all models, is an abstraction from reality. It may give optimum answers to the problem that has been formulated, but it should be evident from the discussion in this section that this formulation, by necessity, is an idealized one.

Planning Area Geometry

In order to develop a generalized planning methodology capable of treating a wide range of topographic and vegetative conditions, one must be concerned with the means by which such conditions can be described digitally for rapid computer analysis. Two primary methods of digital mapping are in common use (Amidon, 1974): mapping by fixed grid, and mapping by polygon. In the fixed grid method, data are stored in a matrix which is constructed so that each element of the matrix represents a fixed (usually square) parcel of land. The location of an individual parcel relative to other parcels is known by its position in the matrix. Thus, the fixed grid method is a direct analog of the coordinate grid systems commonly used in cartography. In the polygon method, each attribute of interest (such as a contour line, stream, or vegetative type boundary) is represented by a vector of x-y coordinates. Each pair of coordinates represents some specific point on the line being considered. The line segment joining any two sets of coordinates is thus a linear approximation to the location of the attribute itself between those two points. Maps reproduced from such vectors, therefore, are visually quite similar to conventional planimetric or contour maps. Figure 5 illustrates polygon and fixed grid map representations for a hypothetical planimetric map of several vegetative types. Although the polygon approximation in this illustration is clearly superior to the fixed grid, actual superiority in any given application is a function of the grid size which is used versus the frequency with which points are digitized on the polygon.

The fixed grid and polygon methods each have their advocates, often because of advantages or disadvantages inherent to some specific application. The primary disadvantage of the fixed grid method is that its storage requirements may be immense. To store two elements of data (say, vegetative type and elevation above mean sea level) for one-acre parcels on a 5,000-acre planning area, for example, 10,000 storage locations would be required. Furthermore, storage requirements with the fixed grid method vary with the square of the grid length (i.e. the length of one side of the parcel). As an example, the grid length for a one-acre parcel is approximately 208.71 feet. If this were reduced by one-half, to 104.35 feet, then each parcel would represent an area of approximately one-quarter of an acre. Thus, to store two elements of data for each quarter-acre parcel on the 5,000-acre planning area, storage requirements would be increased fourfold, to 40,000 locations.

For a comparable area, storage requirements with the polygon method are usually much less than with the fixed grid method (Mees, 1974), particularly when the feature to be represented is large, as is often the case in type mapping. This is because an individual type island can be described completely by its perimeter; the interior is carried implicitly. Unlike the fixed grid method, therefore, the polygon method

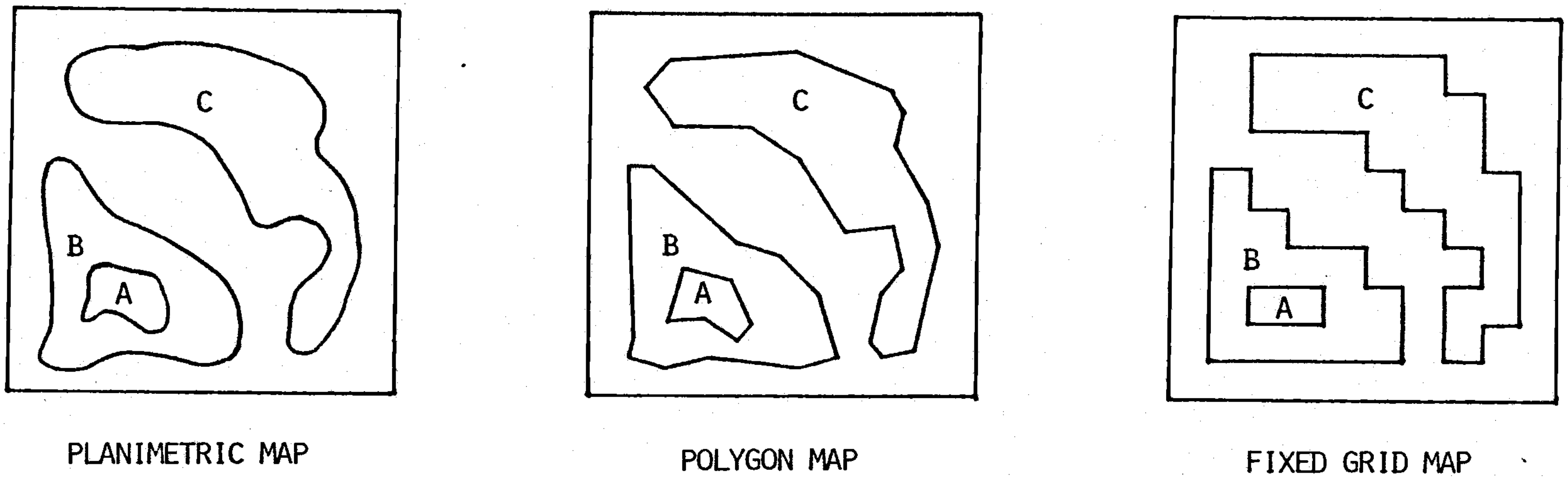

Figure 5. Comparison of polygon and fixed grid representations of a hypothetical vegetative type map.

can accommodate requirements for different amounts of information over different portions of a map. Whether or not this facility is useful depends upon the specific application of the mapping system.

For the present study, three attributes are considered: elevation, vegetative type, and physical features such as roads, streams, buffer strips, and areas of especially fragile soils. The application of the digital map is to determine these three attributes for any specified point within the planning area. Other research has shown (Travis, *et al.*, 1975), that in such applications, the fixed grid method is generally superior to the polygon method. This is because all that is required with the fixed grid method is the ability to "look up" the values in the matrix (plus, perhaps, interpolation between the centroids of several adjacent parcels to improve the estimate of elevation). With the polygon method, on the other hand, considerable software may be necessare to determine the attributes of interest which describe the point. Determination of ground elevation is especially cumbersome, since it requires first that the appropriate contour lines be isolated, and then that interpolation between those lines, often in several directions, be undertaken. This can require a significant amount of computation time. In the forest harvesting problem, for which large areas are likely to be of interest, this consideration could be of critical importance. Therefore, the fixed grid method was selected for this study, rather than the polygon method. To minimize storage problems, random access data files have been used. Such files allow an individual matrix location to be addressed directly, so that the computation time associated with looking up attribute values is minimized. A preferable alternative would be to store the entire matrix within the computer memory; even small problems, however, would exceed the capacity of most computers unless an unrealistically large grid length were used.

Summary

This chapter has discussed factors which were considered during the problem definition phase of the study. Hopefully, the wide range of topics has demonstrated the breadth of coverage that was necessary in order to develop an appropriate approach to solving the harvest planning problem as outlined in Chapter I. Summarizing the development in both Chapters I and II, the problem may be re-stated as follows:

Develop a comprehensive methodology to assist the forest manager in planning timber harvesting operations for any forest planning area. Specifically, this methodology should assist with the design of cutting units and the assignment of cable logging equipment to those units so that the total value of the timber harvested from the area, net of variable and fixed harvesting and transportation costs, is maximized. This will require the development of methods for estimating the feasibility and cost of harvesting the area, and the selection of an appropriate model for solving the optimization, once these cost and feasibility estimates have been made for alternative logging systems. The feasibility analysis should consider topography, cable system mechanics, timber type, and special physical features such as streams, buffer strips, and areas of especially fragile soils. While non-timber resources other than soil and water are not explicitly considered, the planning methodology should be flexible enough that adjustments can be made to the solution in order to test the effect of such considerations on costs and harvesting feasibility.

III. LOGGING FEASIBILITY AND COST ANALYSIS

This chapter discusses the theory and application of computer routines which were developed as part of this study to evaluate the feasibility and cost of harvesting forest planning areas by means of four cable logging systems: highlead, flyer, live skyline, and running skyline. The first section of the chapter briefly reviews the extensive literature on cable logging system mechanics which has been developed in the United States during the past half-century[6]. Later sections discuss the means by which this theory has been applied in the present study.

Literature Review

More than 50 years ago, Anderson (1921) recognized the fact that a logging cable loaded by its own weight hangs in the shape of a catenary. More importantly, he was able to show that when a cable is loaded at one point, the conformation of the cable is that of two arcs of a common catenary, with the point of intersection at the load. Using this fact, he derived expressions for computing the tensions in the cable at each support, and for calculating the load carrying capacity of the cable at the loaded point. Later, Mills (1932) simplified and extended Anderson's work, and Davies (1942) converted the analy-

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[6]A considerable body of work has also been published in Europe, the Soviet Bloc countries, and Japan, but is not reviewed here.

tical work of both Anderson and Mills into a series of tables and graphs which could be more readily applied in the field. Little additional development took place until the mid-1960's, when Lysons and Mann (1967) published a handbook which utilized a combined graphical, physical analog, and tabular approach for the solution of skyline catenary problems. Shortly afterward, Perkins (1967) published the first computer-oriented system for skyline logging system design. Since that time, an extensive body of literature related to skyline catenary problems has developed, the bulk of it having been contributed by the Forest Engineering Project of the Pacific Northwest Forest and Range Experiment Station, USDA Forest Service. Mann (1969) derived the first catenary equations for the solution of running skyline problems, and applied the methodology of Lysons and Mann (1967) to the solution of those problems. Shortly thereafter, Carson and Mann (1970) provided an efficient new technique for solving skyline catenary equations; they also (1971) analyzed the error which results from the use of rigid-link analysis to approximate catenary solutions. Recent emphasis has been on the practical solution of skyline logging system design problems by computer (Carson and Studier, 1973), programmable desktop calculator (Carson, 1975a; Sessions, 1976), and hand-held programmable calculator (Carson, 1975b).

It is important to note that all of the procedures reviewed above have been developed for the analysis of skyline feasibility along a specific cableway emplacement. That is, the locations of the tower and skyline anchor, and data describing the ground profile along the cableway, are all specified exogenously; the load capability or other parameters of interest are then calculated at various intermediate points for the purpose of testing the feasibility of the emplacement. Although the method used in the present study borrows heavily from this procedure, it differs in one important respect: the compilation of a ground profile and evaluation of feasibility is completely endogenous. Furthermore, the method used here considers the effect of individual timber types at any point on the planning area, and accounts for actions which must be taken due to the existence of special physical features such as buffer strips or areas of sensitive soils. This permits the rapid evaluation of a great many alternatives, so that the analysis of large planning areas is made possible.

Yarding System Geometry

Before proceeding with a discussion of the feasibility analysis as implemented in this study, it will be useful to define several terms and to describe the geometry of cable yarding systems.

Vertical Plane

Figure 6 is a schematic drawing which illustrates cable system geometry in the vertical plane. The notation in Figure 6 is defined as follows:

L = the horizontal span of the cableway;

D = the horizontal distance from the spar to the load;

Y = the vertical distance from the spar to the load;

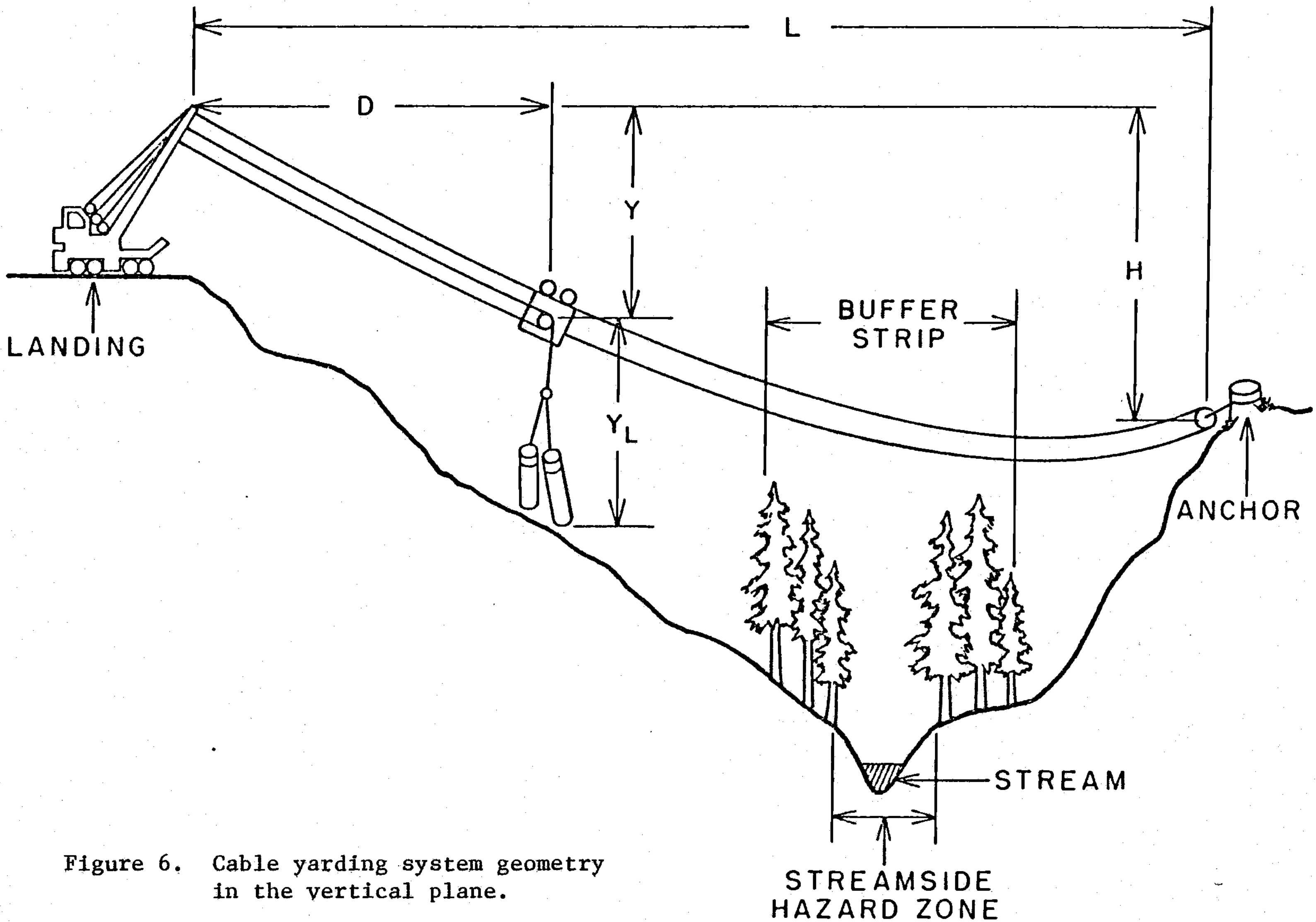

Figure 6. Cable yarding system geometry in the vertical plane.

Y_L = the vertical clearance which is necessary if the turn of logs is to be partially or fully suspended (full suspension is illustrated);

H = the vertical difference between the headspar and the anchor.

An additional parameter which is not shown in the figure, but will be of interest later, is the chord, which is a line segment connecting the spar and the anchor. In addition to the above, several physical features are also shown in Figure 6 which would be considered in a feasibility analysis of that cableway; these are the buffer strip, stream, and streamside hazard zone. Additional features, as discussed in Chapter II, could also have been included.

While the configuration of the cables will vary from that of the running skyline system shown in Figure 6, the basic geometry will remain the same. When full or partial log suspension is unnecessary, however, Y_L is set equal to a constant, say five feet, which represents an adequate distance for the carriage to clear the ground. For the highlead system, the butt rigging is normally very close to the ground and Y_L is assumed to be equal to zero.

Horizontal Plane

Figure 7 illustrates cable system geometry in the horizontal plane. Note that the cableway is defined implicitly by the location of the spar and the anchor; the distance between these points corresponds to the span, L, in Figure 6. External yarding distance is defined by the intersection of the cableway and a boundary. Often this "boundary"

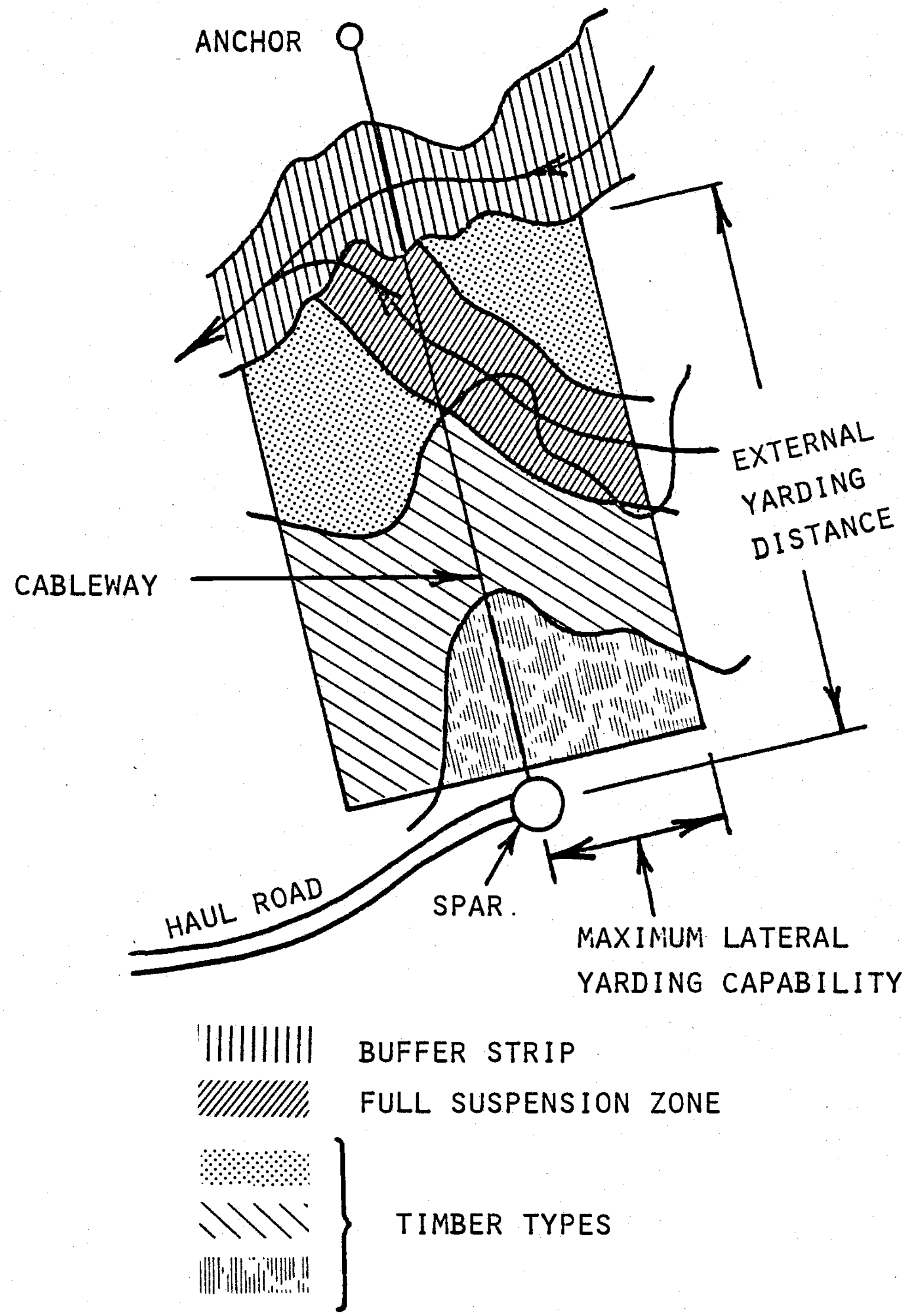

Figure 7. Cable yarding system geometry in the horizontal plane.

would be the anchor point itself, or the boundary of the planning area. In Figure 7, it is the margin of a buffer strip[7]. A yarding "road", or corridor, consists of the area between the spar and the point of external yarding, bounded by the lateral yarding width of the cableway emplacement. Usually, as shown, yarding roads are approximately rectangular in the horizontal plane. Also shown in Figure 7 are several timber types, and a streamside hazard zone which has been designated for full log suspension.

Highlead Feasibility Analysis

In spite of the fact that the highlead has been the most widely used cable yarding system in the United States (Studier and Binkley, 1974), no analytical work has been published relative to the mechanics of highlead yarding. This is apparently due to the comparative simplicity of the system (Figure 1), and the fact that its limitations usually provide little motivation for a rigorous study of load carrying capacity. These limitations include the fact that the highlead has little or no capability for suspending logs above the ground; in fact, the system generally has only a slight capability for partial suspension. In addition, the lateral reach of the system is limited by the distribution of logs on the ground and the length of the chokers which

[7]Sometimes yarding is permitted in corridors which have been cut through a buffer strip. This permits the area on one side of the buffer strip to be yarded to a landing on the opposite side. The current version of the methodology developed for the present study, however, prohibits yarding through buffer strips.

are being used. Normally, it is difficult to overload a highlead system designed to operate in old-growth timber unless very large logs or exceptional topographic conditions are encountered. The highlead feasibility analysis presented here is concerned primarily with the evaluation of such conditions.

Blind Lead Areas

Consider the hypothetical yarding system shown schematically in Figure 8. Note that the chord passes through a section of the ground profile along the cableway. This creates a condition on the anchor side of the intersection which is called a "blind lead". Because the mainline is deflected by the surface of the ground in the vicinity of the chord intersection, the tower is unable to provide lift to any turn which is yarded from the blind lead area. This means that yarding efficiency is greatly reduced in that area; furthermore, deep soil gouging frequently results from attempts to yard from such areas (Studier and Binkley, 1974). Present harvest planning guidelines usually discourage or prohibit the use of highlead systems where blind lead areas cannot be avoided. Therefore, the procedure adopted in this methodology is to fix the external yarding distance at the point of intersection of the chord and the ground surface, if any such intersection occurs along a proposed cableway. The feasibility analysis then continues as described below.

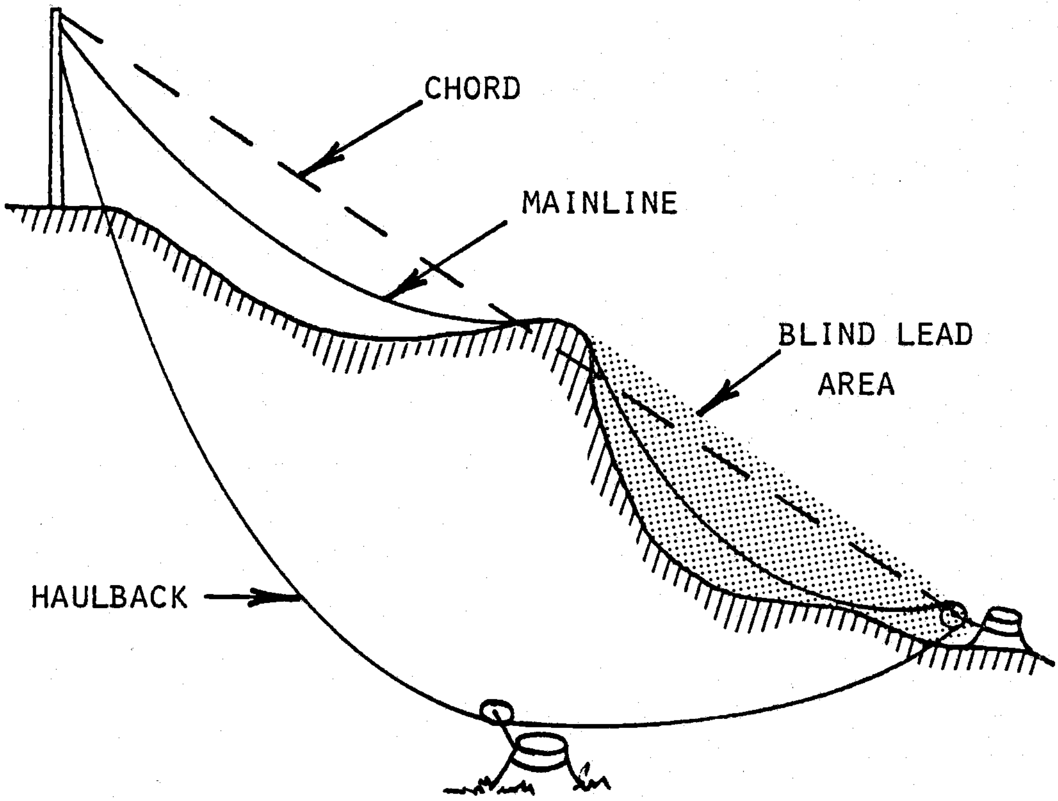

Figure 8. Blind lead area for a hypothetical highlead cableway.

Physical Features

As noted earlier, the highlead system has essentially no capability for partial or full suspension of logs[8]. Therefore, when features are encountered which require this capability (such as streams or areas of fragile soils), the external yarding distance is fixed on the spar side of the first such obstacle encountered.

Other physical features which are considered in this analysis are buffer strips, roads, landings, and the planning area boundary. If any of these is encountered along a cableway, then the external yarding distance for that cableway is fixed as described above.

Rigging Capability

The maximum distance between the spar and the tailhold for a highlead system is limited by the storage capacity of the mainline and haulback drums onto which the working lines are reeved at the yarder. Of the two cables, the mainline, which is larger, is usually the more limiting. For a feasible emplacement, therefore, the total mainline length must be at least equal to

$$G + 2H_S \qquad [3.1]$$

[8] This statement is not entirely true; given the right topographic and load conditions, some highlead systems are capable of fully suspending logs for short distances, and almost all are capable of partial suspension for short distances. To fully or partially suspend logs over extended distances, however, the use of a skyline system is required.

where G = the total slope distance from the spar to the tailhold, measured along the ground surface;

H_S = the height of the spar.

In this case, if feasibility is not indicated, then the entire cableway must be abandoned. Otherwise, the evaluation proceeds to the load capability analysis.

Load Capability Analysis

The load capability of a cable yarding system is important in two respects: first, it suggests whether or not the proposed cableway is feasible; and second, it is used to estimate the cost of yarding timber which is accessible to that cableway. Only the first point is considered here; the second point is discussed in the section of this chapter which deals with yarding costs.

In order to develop a procedure for estimating the load capability of a highlead system at any point along the ground surface between the spar and the anchor, a static, rigid-link analysis of the system was made. This analysis ignores the fact that the mainline actually hangs in the shape of a catenary. Carson and Mann (1971) have shown, however, that for loaded logging cables, the rigid-link assumption seldom results in errors greater than about 0.2 percent. The advantage of rigid-link analysis is that it permits the derivation of algebraic expressions which can be solved directly for the parameters of interest. In the catenary formulation, the analogous expressions are transcendental (see, for example, Carson and Mann, 1970). This means that an iterative solution procedure is required. For large problems involving many thousands of evaluations, such as the problem addressed in this study, the additional computation time required by the catenary formulation would be difficult to justify.

The objective of the load capability analysis is to determine, for some minimum acceptable load, the tension in the mainline which would result if that load were applied at the point in question. This tension is then checked against the maximum safe tension for the specific mainline cable which is being evaluated. If the estimated mainline tension is greater than the maximum safe tension, then the cableway emplacement is infeasible.

Figures 9 and 10 illustrate the specific assumptions which were made for this analysis. Note, from Figure 9, that:

1. The slope of the mainline is assumed to be parallel to the surface of the ground in the vicinity of the load;
2. The log, or turn of logs, is assumed to drag along the ground;
3. The haulback line is also assumed to drag along the surface of the ground;
4. Any influence imparted by the haulback line, other than that between the load and the anchor, is ignored.

Figure 10 shows the forces which are considered in the evaluation. The notation in the figure refers to the following:

W_{ML} = the weight of the mainline;

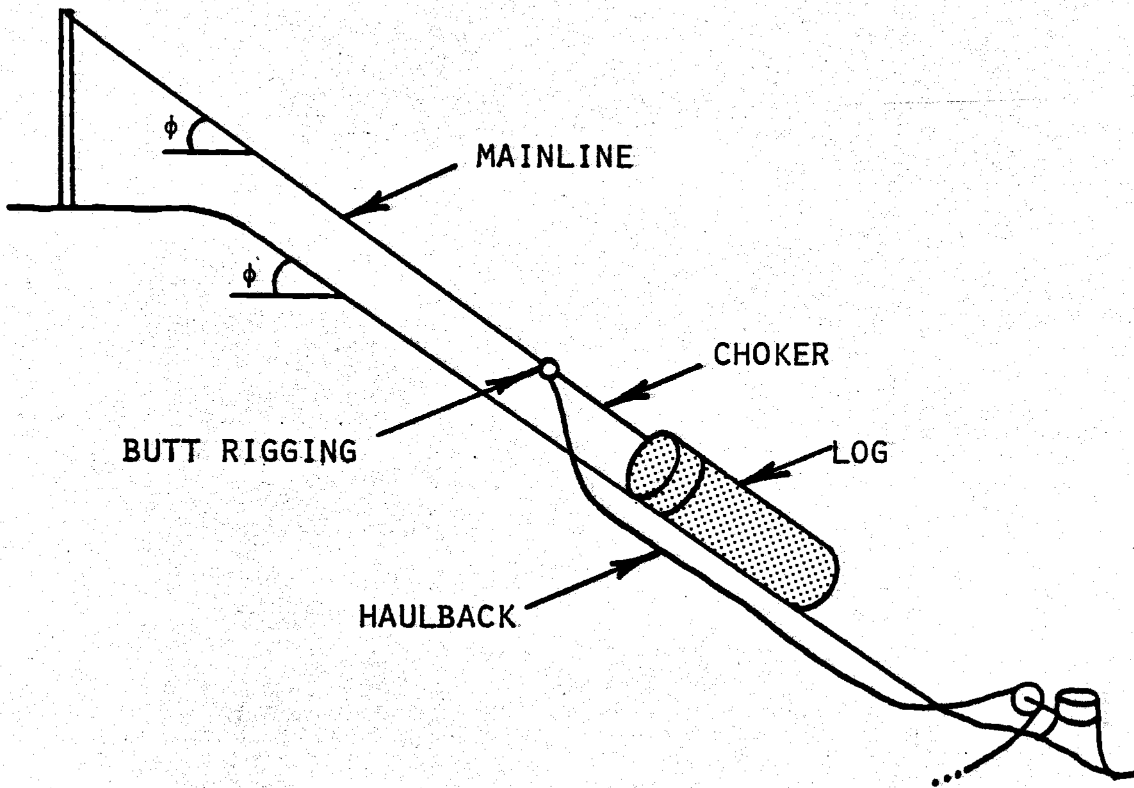

Figure 9. Highlead system configuration assumed for the load capability analysis.

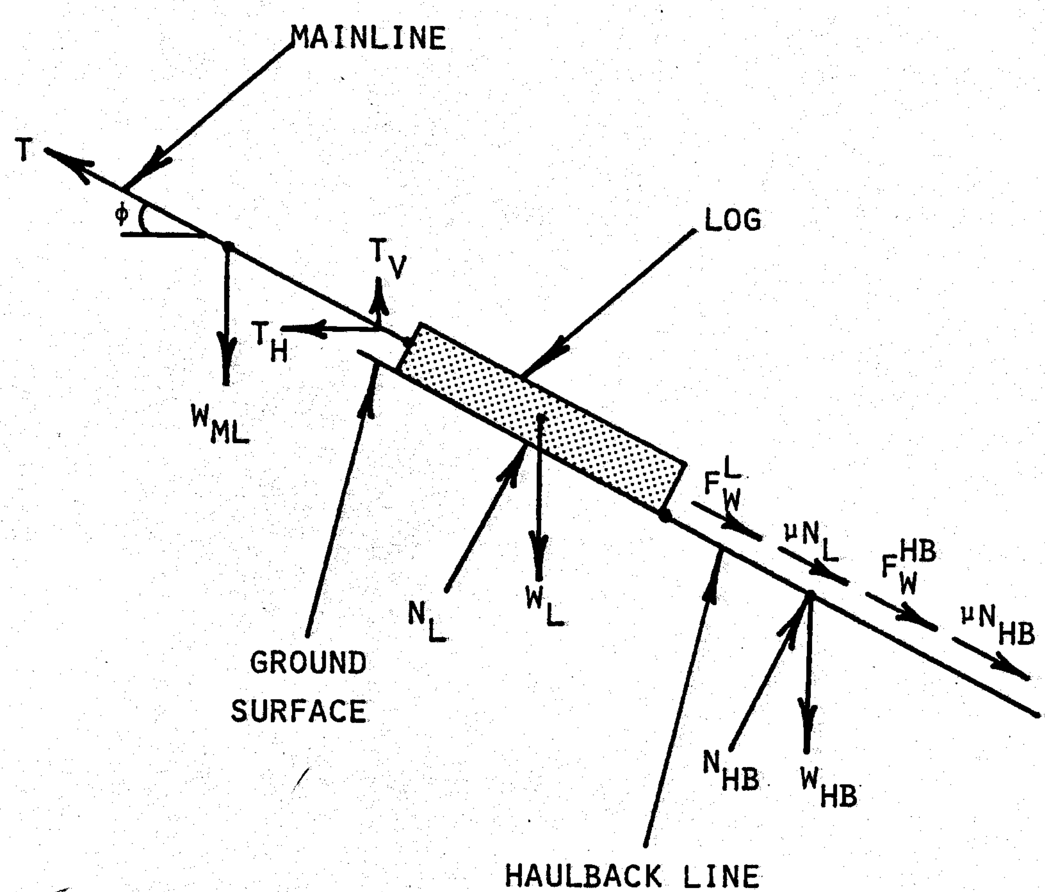

Figure 10. Relationship of system components and forces considered in the highlead load capability analysis.

W_L = the weight of the log;

N_L = the normal reaction force exerted against the log by the ground;

W_{HB} = the weight of the haulback line;

N_{HB} = the normal reaction force exerted against the haulback line by the ground;

T = the tension in the mainline;

T_V = the vertical component of mainline tension;

T_H = the horizontal component of mainline tension;

F_W^L = the force exerted along the ground by the weight of the log;

μN_L = the drag imposed on the log by friction;

F_W^{HB} = the force exerted along the ground by the weight of the haul-back line;

μN_{HB} = the drag imposed on the haulback line by friction.

Assuming that the mainline is a rigid member pinned at the spar and at the log,

$$W_{ML} = \omega_{ML}(D^2 + Y^2)^{1/2} \qquad [3.2]$$

where ω_{ML} = the unit weight of the mainline cable;

D and Y are the horizontal and vertical distances to the point of loading, as shown in Figure 6.

Then,

$$F_W^L = W_L \sin \phi \qquad [3.3]$$

$$\mu N_L = \mu W_L \cos \phi \qquad [3.4]$$

where μ is the coefficient of friction, assumed to be 0.6 in this study, as suggested by Biggs (1973).

During highlead yarding, two loads are essentially in tow; the turn of logs, and the haulback line. Thus, the forces imposed by the haulback line must also be considered:

$$W_{HB} = \omega_{HB} \left((L-D)^2 + (Y-H)^2\right)^{1/2} \qquad [3.5]$$

$$F_W^{HB} = W_{HB} \sin \phi \qquad [3.6]$$

$$\mu N_{HB} = \mu W_{HB} \cos \phi \qquad [3.7]$$

where ω_{HB} = the unit weight of the haulback line;

L, D, Y, and H are distances as shown in Figure 6.

The intention of this analysis is to compute T, the tension in the mainline. Taking moments about the mainline at the spar,

$$\sum M_{spar} = T_V D + T_H Y - W_{ML}\left(\frac{D}{2}\right) - D\left(F_W^L + \mu N_L\right)\sin\phi$$

$$- Y\left(F_W^L + \mu N_L\right)\cos\phi - \left(D + \frac{L-D}{2}\right)\left(F_W^{HB} + \mu N_{HB}\right)\sin\phi \quad [3.8]$$

$$- \left(Y - \frac{H-Y}{2}\right)\left(F_W^{HB} + \mu N_{HB}\right)\cos\phi$$

$$= 0$$

Using the identities $T_H = T_V/\tan\phi$ and $Y = D\tan\phi$, and solving for T_V,

$$T_V = \frac{W_{ML}}{4} + \left(F_W^L + \mu N_L\right)\sin\phi + \left(\frac{1}{2} + \frac{L-D}{4D}\right)\left(F_W^{HB} + \mu N_{HB}\right)\sin\phi$$

$$+ \left(\frac{\tan\phi}{2} + \frac{H-Y}{4D}\right)\left(F_W^{HB} + \mu N_{HB}\right)\cos\phi \quad [3.9]$$

To this point, the analysis has neglected the weight of the butt rigging, which is often several hundred pounds. Assuming that the butt rigging is fully suspended (Figure 9),

$$T'_V = T_V + W_{BR} \quad [3.10]$$

where W_{BR} = the weight of the butt rigging.

Finally,

$$T = T'_V / \sin \phi \qquad [3.11]$$

Then, if T is greater than the maximum safe tension for the mainline cable (T_{max}), the proposed load is too large. In the procedure implemented for this study, W_L is equal to some minimum acceptable load, which may vary by timber type. Therefore, T is computed at intervals along the cableway. At each point, the timber type (and thus W_L) can be determined. Then, if $T > T_{max}$ at any such point, the cableway emplacement is infeasible.

Skyline Feasibility Analysis

The evaluation of feasibility for the three skyline systems in this study proceeds in essentially the same manner as that for the highlead system. The problems encountered in skyline yarding, however, are slightly different because the nature of the system and its application are different. Many skyline systems are capable of lateral yarding, so that logs which are as far as 100 or even 200 feet from the cableway may be within reach, depending upon the limits of the individual yarding system. This capability has the effect of increasing the potential width of yarding roads (Figure 7), which can reduce the total number of cableways required to harvest a given area. The ability to yard laterally also improves possibilities for loading the system to near (or above) its load carrying capacity, since the number of logs which can be hooked is less dependent upon the distribution of logs on the ground. All of the skyline systems considered here are capable of full log suspension over extended distances. The ability of a given system to suspend logs in a particular application, however, is dependent upon the weight of the load to be carried and the topography over which it is to be flown.

Blind Lead Areas

Although blind lead conditions are at least as restricting with skyline systems as with the highlead, they are not explicitly considered in the analysis. This is because the load capability evaluation, which is discussed below, will always discover such conditions. By contrast, the procedure used in the load capability analysis for the highlead system was not capable of doing so.

Physical Features

The primary importance of physical features in the skyline feasibility analysis is to define the external yarding distance along any cableway, and to act as signals for the type of yarding which is to be done along segments of the cableway. Major streams and areas of especially fragile soils, for example, require full log suspension. Other features, such as minor stream crossings, may require partial suspension, and undesignated areas require only that the carriage be clear of the ground. The load carrying capacity of a skyline system, and therefore its cost, is related to the yarding prescription; this capacity is minimized for full suspension, and maximized for ground skidding. Thus, in an economic analysis it is important to limit log suspension to those areas where it is specifically required.

In addition to features which require full or partial suspension, a proposed cableway may also encounter buffer strips, roads, landings, or the planning area boundary. The appropriate response in this case is the same as for the highlead; the external yarding distance for that cableway is fixed on the spar side of the first such obstacle encountered.

Rigging Capability

This analysis is essentially the same as for the highlead system, with one difference. In order to provide sufficient clearance for full or partial suspension along any portion of a cableway, it may be necessary to elevate the tailhold by hanging it in a tree, called a tailtree. For a feasible emplacement, therefore, the total skyline length must be at least equal to

$$G + 2H_S + 2H_T \qquad [3.12]$$

where G and H_S are as defined for the highlead system;

H_T = the height of the tailtree.

For the flyer and live skyline systems (Figures 2 and 3), it is sometimes possible to add an extension, called a "tag skyline", so that the skyline span can be increased without having to increase the size of the skyline drum. Whenever a tag skyline is added, however, a fixed charge will be incurred.

Load Capability Analysis

As indicated in the literature review earlier in this chapter, a significant body of analytical work has been published relative to the mechanics of skyline yarding. Rather than develop a new procedure for the load capability analysis as was done for the highlead system, therefore, the procedure of Carson and Mann (1971) was used. This procedure has also been used by Carson (1975b) and by Sessions (1976).

Assumptions appropriate to the Carson-Mann procedure are illustrated in Figure 11. Again, a rigid-link analysis is used to approximate the catenary relationships. The mainline is envisioned as being pinned at the spar and at the carriage. The skyline, however, is pinned at the spar but is deflected past the carriage by an arrangement of sheaves. Thus, the tension in segment 2 of the skyline is known to be equal to the tension in segment 1. Similarly, for the running skyline system the tension in skyline segment 3 is equal to that in segment 2 because the skyline is deflected around a block at the tailhold. Skyline segments 2 and 3 are parallel and of equal length; skyline segment 1 and the mainline are also parallel and of equal length. For the flyer and live skyline systems, skyline segment 3 is missing because the skyline is anchored at the tailhold. The influence of the haulback line on the load capability of the live

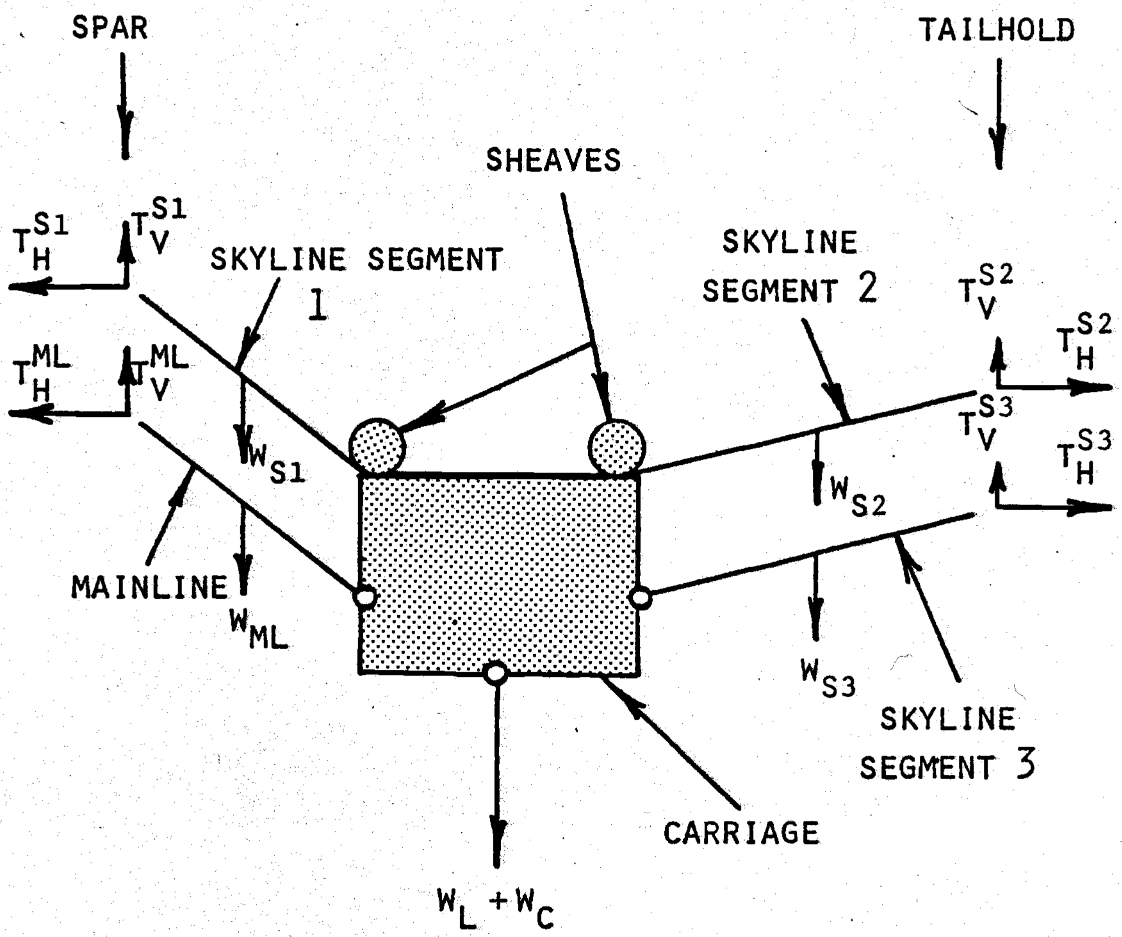

Figure 11. Relationship of system components and forces in the skyline feasibility analysis (illustrated for the running skyline).

skyline is small and is thus neglected. Therefore, the analyses for the flyer and the live skyline systems are identical.

A complete development of the algebraic expressions for the load capability of the live and running skyline systems is given in Carson (1975b). Briefly, his development shows that the load capability for both systems can be described as a function of the horizontal component of tension in skyline segment 2, the weight of the carriage, and the weights of the mainline and the individual skyline segments. The expression which results is as follows:

$$W_L = \tau T_H^{S2} \left(\frac{Y}{D} + \frac{Y-H}{L-D}\right) - \frac{1}{2}\left(W_{S1} + \tau W_{S2} + W_{ML}\right) - W_C \qquad [3.13]$$

where $\tau = \begin{cases} 1 \text{ for the flyer and live skyline systems;} \\ 2 \text{ for the running skyline system;} \end{cases}$

T_H^{S2} = the horizontal component of tension in skyline segment 2;

W_C = the weight of the carriage;

L, D, Y, and H are known from the geometry of the situation (see Figure 6);

W_{S1}, W_{S2}, and W_{ML} are computed in the same manner as the analogous quantities were computed in [3.2] and [3.5]. Note, however, that if two mainlines are used with the running skyline system to provide for lateral yarding (Figure 4), then W_{ML} is equal to the sum of the weights of both lines.

The horizontal component of tension in skyline segment 2 is given by

$$T_H^{S2} = \frac{\omega_{SL}(L-D)}{2\left(1+\left(\frac{Y-H}{L-D}\right)^2\right)^{1/2}} \left\{\frac{Y-H}{L-D} + \left(4\left(\frac{T_{max}}{\omega_{SL}(L-D)} - \frac{Y}{L-D}\right)^2 - 1\right)^{1/2}\right\} \qquad [3.14]$$

where ω_{SL} = the unit weight of the skyline cable;

T_{max} = the maximum safe tension in the skyline cable.

To check the feasibility of a particular cableway, W_L is computed at intervals along the cableway. If its value is less than the minimum acceptable load at any point (which may vary by timber type), then the cableway emplacement is infeasible.

An important feature of the skyline load capability analysis is the fact that requirements for partial or full suspension can be entered directly into equations [3.13] and [3.14]. Observe, in Figure 6, that Y is dependent upon the ground elevation at the load point, and upon Y_L. Let

Y_L^F = the vertical clearance necessary for full suspension;

Y_L^P = the vertical clearance necessary for partial suspension;

Y_L^G = a vertical distance which is sufficient to provide clearance of the carriage (in this study, Y_L^G = 5 feet).

Y' = the vertical distance from the spar to the ground surface at the load point.

Then, if full suspension is required at the point,

$$Y = Y' - Y_L^F \qquad [3.15]$$

If partial suspension is required,

$$Y = Y' - Y_L^P \qquad [3.16]$$

Otherwise, ground skidding is permitted, and

$$Y = Y' - Y_L^G \qquad [3.17]$$

If either partial suspension or ground skidding is permitted, then the result of equation [3.13] must be increased to account for the fact that the load is partially supported by the ground. This situation has recently been analyzed by Carson (1975c), who showed that even for the rigid-link analysis, an iterative procedure is required to solve for the exact value of W_L. To avoid this requirement, Sessions (1976) has concluded, after solving many problems both with equation [3.13] and with the method of Carson (1975c), that

$$W_L' \cong 1.5\, W_L \qquad [3.18]$$

where W_L' = the load capability of the skyline system when the turn of logs is being skidded or partially suspended;

W_L = the result of equation [3.13].

This approximation has been used in the present study.

The final provision which has been incorporated into the skyline load capability analysis permits the use of elevated tailholds to increase the load capability of the skyline. The purpose of elevating a tailhold is to compensate for topographic conditions which prevent the minimum acceptable load from being successfully flown or skidded past a particular point on the cableway (Figure 12). Elevated tailholds are normally avoided if possible because their preparation requires a significant effort, thereby increasing the cableway emplacement cost. Furthermore, tailtrees must have certain size and quality characteristics (Studier and Binkley, 1974), and suitable candidates may not always be available near the anchor point.

The methodology developed for this study permits the forest manager to specify ΔH (Figure 12). Tailhold height (H_T) is initially set equal to zero for each cableway. If the computed W_L (or W_L', as appropriate) is less than the minimum acceptable load at any point along the cableway, then H_T is increased by 25 feet. If $H_T > \Delta H$, then the cableway is infeasible. Otherwise, W_L (or W_L') is recalculated and a new evaluation is made. Thus, the analysis proceeds in 25-foot increments up to the maximum tailhold height of ΔH, if necessary. If W_L (or W_L') $\geq$ the minimum acceptable load for $H_T \leq \Delta H$, then the cableway is feasible.

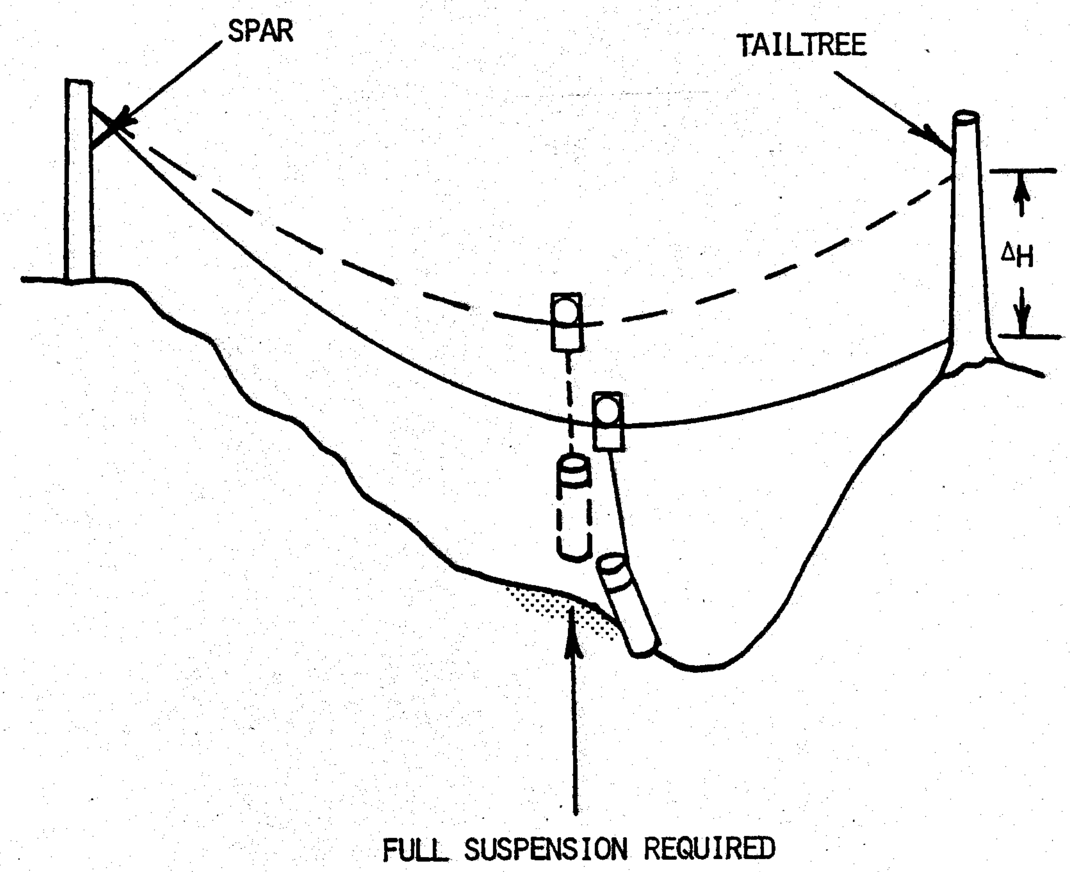

Figure 12. Effect of tailhold height on skyline suspension capability.

Estimation of Logging Costs

As mentioned earlier, the objective of the forest manager is presumed to be an economic one: to design cutting units and assign logging equipment to those units in such a manner that the total value of the timber harvested, net of fixed and variable logging costs, is maximized. While the feasibility analysis discussed in this chapter is designed to find out whether the cable yarding of a particular area by a specific yarding system is feasible, it is also useful for the estimation of yarding costs. Additional costs which are considered in the optimization and heuristic procedures presented in Chapters IV and V are the fixed costs of landing and spur road construction, yarding system installation, and cableway emplacement. The cost of hauling logs to a mill or appraisal point is also considered, as it is expected to vary for each landing in the planning area. Loading costs, however, are expected to be essentially constant for alternative logging systems, and thus are not considered.

Yarding and Hauling Costs

As the planning area is represented digitally by a fixed grid of timber parcels, the procedure presented here is designed to compute an estimate of the cost of yarding each parcel which is accessible to any proposed (feasible) cableway. This cost is then added to the expected cost of transporting the timber in a particular parcel from the landing to the mill or appraisal point. The total of these two costs is subtracted from the delivered value of the timber; this gives the expected value of the parcel if it is to be harvested over a specific cableway, by means of a particular yarding system, to a certain landing. Thus, at least one and possibly many expected values will be associated with an individual parcel, depending upon how many feasible alternatives exist by which it can be harvested. The task of the procedures discussed in Chapters IV and V is to select the best assignment of parcels to facilities, so that the total value of those assignments, net of fixed costs, is maximized.

For the purpose of this study, yarding cost is assumed to be a linear function of certain variables which can be estimated for any timber parcel and any cableway alternative. A linear regression model is used to compute an estimate of the time required to yard a single turn of logs from the centroid of a specific parcel to the appropriate landing. The general form of this model is as follows:

$$Y_k = \delta \cdot \left(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \varepsilon\right) \qquad [3.19]$$

where Y_k = the expected total time required to yard one turn, in minutes, by means of yarding system k;

δ = a constant, ≥ 1, which is known as the "delay coefficient" and is used to adjust the yarding time estimate for expected delays; the value for δ is specified exogenously for each yarding system alternative, k;

β_0 = the regression constant;

β_1 through β_6 = regression coefficients; estimates of β_0 through β_6 are specified exogenously for each yarding system alternative, k;

ε = the amount by which an individual Y_k may fall off the regression surface (assumed to be a normally distributed random variable with mean = 0 and a constant, unknown variance);

X_1 = expected volume per turn, in board feet;

X_2 = expected volume per log, in board feet;

X_3 = average slope yarding distance, measured along the surface of the ground, from a particular timber parcel to the appropriate landing, in feet;

X_4 = average slope lateral yarding distance, measured from the centroid of the parcel along a line perpendicular to the cableway, in feet;

X_5 = expected number of logs per turn;

X_6 = the slope of the chord from the spar to the anchor, in percent (negative if the anchor is below the spar).

All of the X_i are estimated endogenously with the exception of X_2, which is a function of timber type.

The linear regression model [3.19] was selected for use in this study because work by numerous authors (for example, Van Winkle, 1976a) suggests that it is an appropriate model for the estimation of cable yarding production rates. Reasons for including each of the above X_i in the model are discussed in detail by Van Winkle. Other production studies, such as those reported by Aulerich, Johnson, and Froehlich (1974), Sinner (1973), and Chamberlain (1965) have also used either the same X_i or a subset of them. This means that published regression coefficients are available for a wide range of cable yarding machinery. Furthermore, the fact that nearly all of the X_i can be estimated endogenously is an attractive feature in a planning methodology.

For any given timber parcel and cableway, the independent variables are estimated as follows:

1. Expected volume per turn. An estimate of W_L for the parcel is obtained, as appropriate, by successive applications of equations [3.9] through [3.11] (for the highlead system), or from equation [3.13] (for the skyline systems); if necessary, the skyline result is adjusted via equation [3.18]. W_L (or W_L') is then converted to a board foot volume by means of an exogenous density conversion factor, which may vary by timber type. The result is checked against an exogenously specified "maximum expected volume per turn", which is a function of both timber type and yarding system. The smaller volume is selected; then, using the expected volume per log, this result is truncated to the nearest half-log (a "log" is assumed to be 32 feet in length).

2. Expected volume per log. This quantity is specified exogenously, and may vary by timber type.

3. Average slope yarding distance. As shown in Figure 13, the point of intersection of the cableway and a line drawn perpendicular to

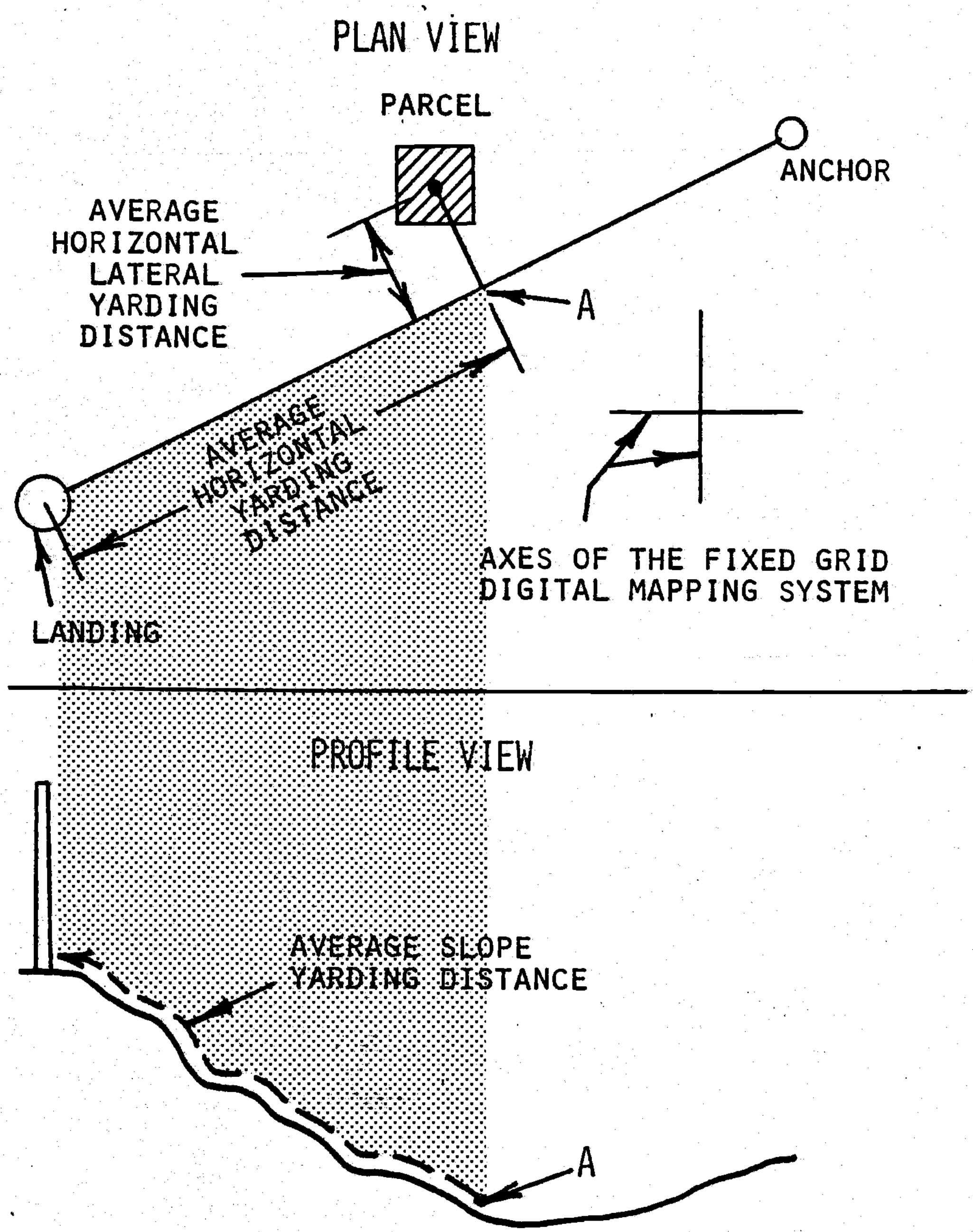

Figure 13. Determination of average yarding distances for a particular timber parcel.

it from the centroid of the parcel is determined (point A). The distance from this point to the landing, along the surface of the ground, is taken to be the average slope yarding distance for the parcel if it is harvested over this cableway.

4. Average slope lateral yarding distance. The horizontal distance from the centroid of the parcel to point A (Figure 13) is computed. Then, from the known elevations of point A and the parcel centroid, the length of the chord connecting the two points is determined; this length is taken to be the average slope lateral yarding distance for the parcel if it is harvested over this cableway.

5. Expected number of logs per turn. This estimate is computed directly from the known volume per log for the parcel and the previously estimated volume per turn:

$$X_5 = X_1/X_2 \tag{3.20}$$

6. Chordslope. Referring to Figure 6, this value may be determined as follows:

$$\text{Chordslope} = \left(-\frac{H}{L}\right)100 \tag{3.21}$$

To compute an estimate of the total cost of yarding parcel i over cableway j, the total volume of timber on the parcel must be known. This volume is given by

$$V_i = \frac{\gamma^2 \nu}{43560} \qquad [3.22]$$

where γ = the grid length, in feet, of the fixed-grid digital mapping system being used;

ν = the volume per acre (Mfbm/ac) for the timber type corresponding to parcel i;

43560 = the number of square feet in one acre.

Then, the total time, in hours, which is required to yard the timber in parcel i over cableway j by means of yarding system k to landing ℓ is estimated as follows:

$$Y^T_{ijk\ell} = \left(\frac{V_i}{X_1}\right)\left(\frac{Y_k}{60}\right)1000 \qquad [3.23]$$

Next, total estimated yarding cost is determined:

$$C^Y_{ijk\ell} = Y^T_{ijk\ell} C^S_k \qquad [3.24]$$

where C^S_k = the total fixed and operating costs of yarding system k, in \$/hr, including both equipment and labor costs.

Finally, the expected value of parcel i, if it is harvested over cableway j by means of yarding system k to landing ℓ, is computed:

$$v_{ijk\ell} = V_i P - C^Y_{ijk\ell} - V_i C^H_\ell \qquad [3.25]$$

where P = the delivered price, in \$/Mfbm, of the timber in the type associated with parcel i;

C_ℓ^H = estimated hauling costs, in \$/Mfbm, from landing ℓ to the mill or appraisal point.

Fixed Costs

The costs of landing construction and yarding system installation are estimated exogenously, and thus are not considered here. Cableway emplacement cost, however, is assumed to vary with the distance from the landing to the anchor, as suggested in a recent analysis by Van Winkle (1976b), and with tailtree height, as discussed by McGonagill (1975). It is also presumed to be dependent upon whether the cables have to be threaded through standing timber, as mentioned in Chapter II. The specific relationships between these variables and cableway emplacement time vary with the yarding system, but are assumed to be of the form

$$E_{jk\ell} = \alpha_0 + \alpha_1 \left(L^2+H^2\right)^{1/2} + \alpha_2 H_t + \alpha_3 B + \varepsilon \qquad [3.26]$$

where $E_{jk\ell}$ = the time required to emplace cableway j for yarding system k at landing ℓ, in minutes;

α_0 = the regression constant;

α_1 through α_3 are regression coefficients (α_0 through α_3 are specified exogenously for each yarding system k);

ε = the random error term (as in [3.19]);

L and H are given as in Figure 6;

H_t = tailtree height, in feet;

$$B = \begin{cases} 1 & \text{if the lines must be threaded through a buffer strip or other standing timber;} \\ 0 & \text{otherwise.} \end{cases}$$

The fixed cost of emplacing cableway j for use with yarding system k at landing ℓ is then given by

$$f_{jk\ell} = E_{jk\ell}\, C_k^S \qquad [3.27]$$

where C_k^S = the hourly cost associated with yarding system k, as used in equation [3.24].

Implementation of the Feasibility and Cost Analysis Procedures

The procedures discussed in this chapter have been programmed in FORTRAN IV, and complete program listings are presented in the Appendix. The programs were subjected to extensive tests, and appear to perform correctly within the limits established in the scope of the study (see Chapter I). Many of the routines which had to be written have not been discussed explicitly in this dissertation, particularly those which deal with the geometry of the fixed grid method of digital mapping. The programs are well documented, however, and anyone who is interested in the details of the implementation and is familiar with FORTRAN should have no difficulty following them.

To demonstrate the application of the feasibility and cost analysis procedures, a small but realistic example has been prepared. The situation is illustrated in Figure 14. A planning area, which consists of six timber parcels, can be yarded to either (or both) of two landings. Two cableway locations have been proposed for each landing; lines drawn from parcel centroids to the cableways suggest possible assignments of parcels to facilities. Two yarding systems are available to do the yarding, each of which can be installed at either landing. Each parcel represents an area of approximately 1/4 acre (the grid length is equal to 100 feet). Other data relevant to the problem are presented in Table 1, and an appropriate fixed grid map is illustrated in Figure 15.

Portions of the output from the cable yarding feasibility and cost analysis programs are shown in Tables 2 and 3. Table 2 is used to check the input data for the problem; Table 3 shows the detailed results of the analysis for cableway number 2, computed for both the highlead and running skyline systems. Note that the report for each system is in two parts: a parcel summary and a cableway profile summary. The parcel summary lists relevant data for each parcel which can feasibly be harvested over cableway 2 by the yarding system in question. Note that the expected value of parcels (4,3) and (4,4), which correspond to parcels 5 and 6 in Figure 14, is higher for the running skyline system than for the highlead. This reflects greater operating efficiency for the running skyline as estimated by the yarding regression

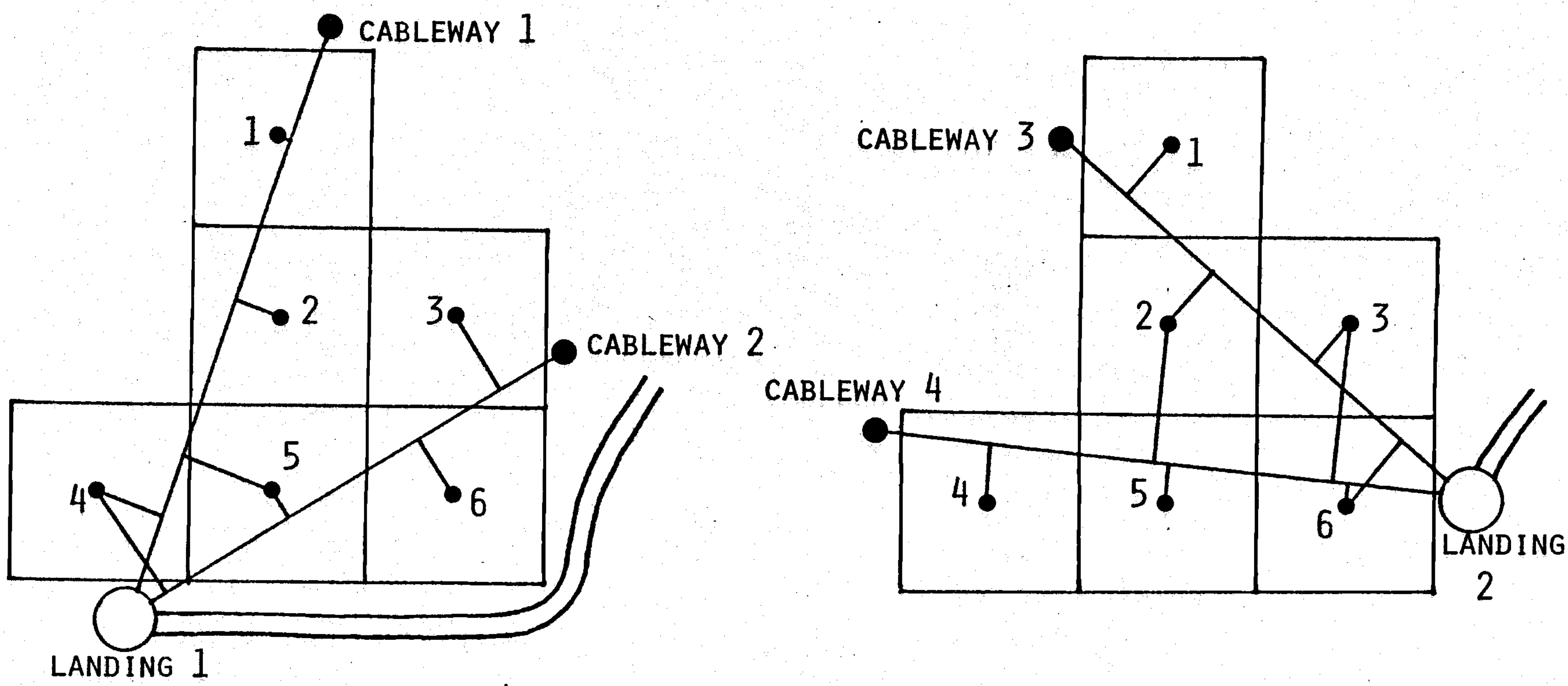

Figure 14. Landing and cableway alternatives for the example problem area.

Table 1. DATA FOR THE EXAMPLE PROBLEM.

A. TIMBER PARCEL DATA

	Parcel					
	1	2	3	4	5	6
Elevation	800	830	840	920	880	860
Timber Type[1]	1	1	1	2	2	2
Physical Feature[2]	1	2	99	99	99	99

[1]Timber type data are summarized in part B.
[2]Feature codes: 1 = full suspension required;
2 = partial suspension required;
99 = no suspension requirement.

B. TIMBER TYPE DATA

	Type	
	1	2
Volume per acre (Mfbm/ac)	30.2	63.8
Volume per log (fbm/log)	140	230
Wood density (lbs/fbm)	8.5	8.0
Maximum expected logs per turn:		
Yarding system 1	3	2
Yarding system 2	5	4
Delivered log price ($/Mfbm)	125.00	175.00

C. LANDING DATA

	Landing	
	1	2
Landing and spur road construction cost ($)	18000	16000
Hauling cost to mill ($/Mfbm)	11.00	10.00
Location of spar on fixed grid	(5,2)	(4,5)

D. CABLEWAY DATA

	Anchor Location
Cableway 1	(1,3)
Cableway 2	(3,5)
Cableway 3	(2,2)
Cableway 4	(4,1)

Table 1 (Continued)

E. YARDING SYSTEM DATA

	Yarding System	
	1	2
System type	Highlead	Running Skyline
Maximum reach (ft)	950	2000
Maximum lateral reach (feet)	75	200
Mainline unit weight (lbs/ft)	1.42	2.14
Haulback unit weight (lbs/ft)	1.04	-
Skyline unit weight (lbs/ft)	-	1.42
Maximum safe tension (lbs)	26500	26500
Weight of the butt rig. or carr. (lbs)	300	1000
Height of the spar (ft)	50	50
Maximum tailtree height (ft)	0	50
Carr. clearance, full susp. (ft)	0	50
Carr. clearance, partial susp. (ft)	0	20
Min. acceptable volume/turn (fbm)	200	300
Total yarding system cost ($/hr)	75.00	95.00
Yarding system installation cost ($)	650	1000
Cableway emplacement parameters:		
α_0 (min)	20	30
α_1 (min/ft)	0.01	0.05
α_2 (min/ft)	0	0.20
α_3 (min)	40	20
Yarding regression coefficients:		
β_0 (min)	3.695	3.191
β_1 (min/fbm)	2.880×10^{-3}	1.003×10^{-3}
β_2 (min/fbm)	-4.034×10^{-3}	-1.063×10^{-3}
β_3 (min/ft)	1.700×10^{-3}	2.337×10^{-3}
β_4 (min/ft)	0	1.186×10^{-2}
β_5 (min/log)	0	0
β_6 (min/pct)	0	0
Delay coefficient	1.15	1.20

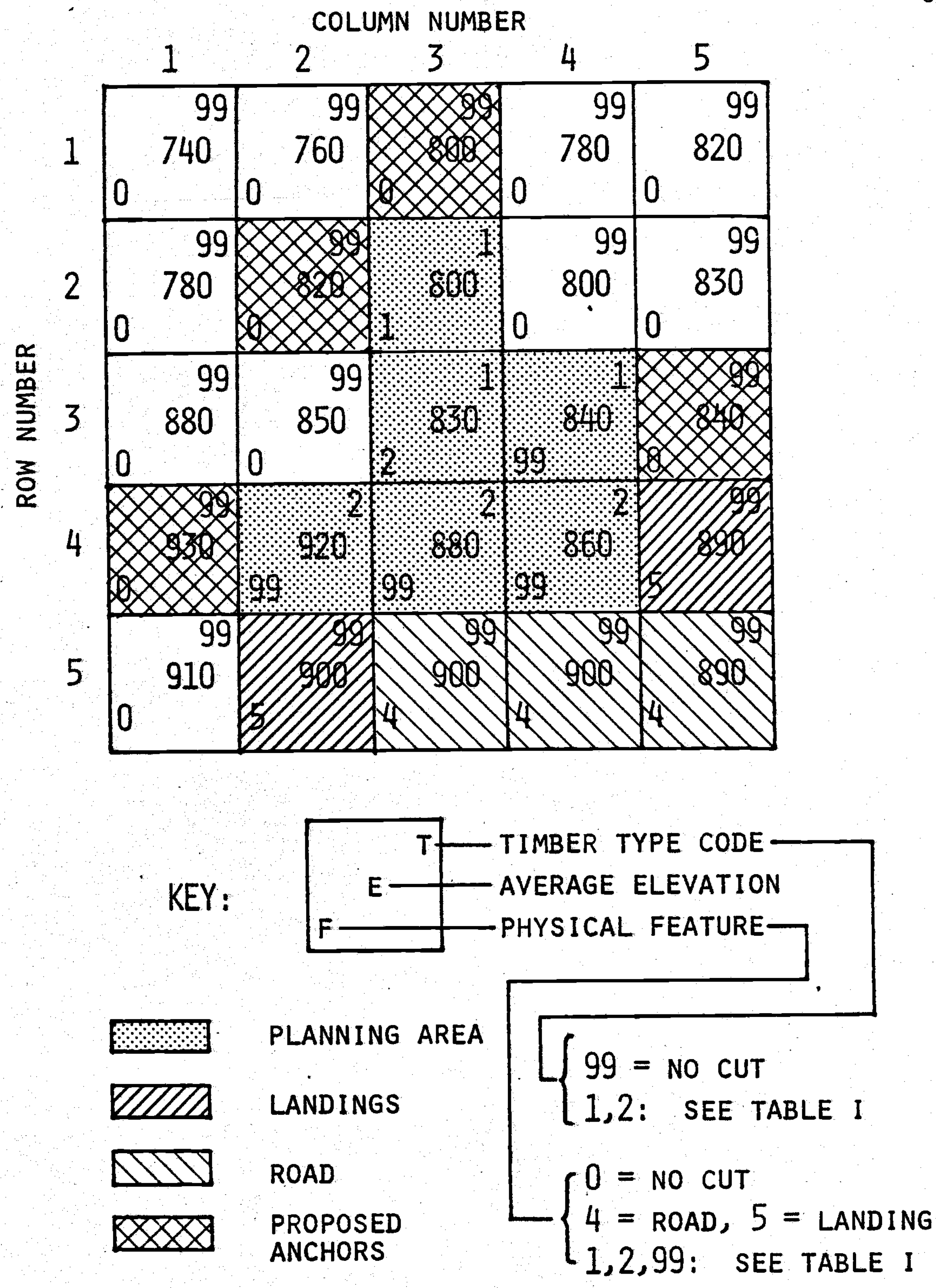

Figure 15. Fixed grid digital map for the example problem.

Table 2. INPUT DATA SUMMARY FOR THE LOGGING FEASIBILITY AND COST ANALYSIS PROGRAM.

CABLE LOGGING SYSTEM FEASIBILITY AND COST ANALYSIS

EXAMPLE PROBLEM -- HIGHLEAD AND RUNNING SKYLINE

GRID SIZE= 100.00 FEET

DATA MATRIX HAS 5 ROWS AND 5 COLUMNS.

SUMMARY OF YARDING SYSTEM DATA

SYS NO.	SYS TYPE	MAX REACH	MAX LATERAL	SEG1 WT	SEG2 WT	MAX TENSION	CARR WEIGHT	SPAR HT	MAX TAIL HT	SUSPENSN CARR FULL	SUSPENSN CLR PART	MIN FBM/ TURN	COST $/HR	MOVE COST	TAILTREE RIG TIME (MIN/FT)	ROAD ..A0.	CHANGE ...A1.	BUFFER ADD TIME
1	1	950	75	1.42	1.04	26500	300	50	0	0	0	200	75.00	650	0	20.0	.010	40
2	3	2000	200	1.42	2.14	26500	1000	50	50	50	20	300	95.00	1000	.2000	30.0	.050	20

SUMMARY OF YARDING REGRESSION COEFFICIENTS

SYSTEM	CONSTANT (MIN)	VOL/TURN (MIN/FBM)	VOL/LOG (MIN/FBM)	YARD DIST (MIN/FOOT)	LAT DIST (MIN/FOOT)	LOGS/TURN (MIN/LOG)	CHORDSLOPE (MIN/PCT)	DELAY FACTOR
1	3.6950E 00	2.8800E-03	-4.0340E-03	1.7000E-03	0E 00	0E 00	0E 00	1.15
2	3.1910E 00	1.0030E-03	-1.0630E-03	2.3370E-03	1.1860E-02	0E 00	0E 00	1.20

Table 2 (Continued)

SUMMARY OF LANDING DATA

LANDING NO.	SPAR LOCATION ROW	COL	LANDING AND SPUR CONSTR.	HAUL COST $/M
1	5	2	18000	11.00
2	4	5	16000	10.00

SUMMARY OF FOREST TYPE DATA

TYPE	AVG VOL/AC	AVG VOL/LOG	DENSITY LBS/FBM	.MAX SYSTM.	TURN. LOGS	MILL PRICE
1	30200	140	8.5	1	3.0	125.00
				2	5.0	
2	63800	230	8.0	1	2.0	175.00
				2	4.0	

Table 3. FEASIBILITY AND COST ANALYSIS RESULTS FOR CABLEWAY 2 IN THE EXAMPLE PROBLEM.

CANDIDATE ANCHOR POINT SUMMARY

LANDING 1 SYSTEM 1 ANCHOR (3, 5): CABLEWAY EMPLACEMENT=$ 29.71

AVE HOR YARD DIST	AVE SLOPE YARD DIST	AVE LAT YARD DIST	AVE LOGS PER TURN	AVE VOL PER TURN	YARD COST PER M FBM	PARCEL	EXP VALUE
139	141	67	2.0	460	13.53	(4, 3)	2203.79
222	227	67	2.0	460	13.99	(4, 4)	2197.10

ESTIMATED GROUND DISTANCE, SPAR TO ANCHOR: 367 FEET

CABLEWAY PROFILE:

POINT	DIST FROM SPAR	GROUND ELEV
SPAR	0	900
1	100	892
2	200	863
3	300	852
TAIL	361	840

LANDING 1 SYSTEM 2 ANCHOR (3, 5): CABLEWAY EMPLACEMENT=$ 85.26

AVE HOR YARD DIST	AVE SLOPE YARD DIST	AVE LAT YARD DIST	AVE LOGS PER TURN	AVE VOL PER TURN	YARD COST PER M FBM	PARCEL	EXP VALUE	
194	198	111	5.0	700	14.99	(3, 3)	686.41	**PARTIAL SUSPENSION**
277	282	55	5.0	700	13.74	(3, 4)	695.10	
139	141	67	4.0	920	10.30	(4, 3)	2251.13	
222	227	67	4.0	920	10.72	(4, 4)	2245.05	

ESTIMATED GROUND DISTANCE, SPAR TO ANCHOR: 367 FEET

CABLEWAY PROFILE:

POINT	DIST FROM SPAR	GROUND ELEV	LOAD CAPAC
SPAR	0	900	
1	100	892	21407
2	200	863	16032
3	300	852	16032
TAIL	361	840	

TAIL TREE HEIGHT= 25 FEET

KEY: System 1 = highlead;
2 = running skyline.

equations for the specific conditions encountered along cableway 2. The average number of logs per turn, which for large timber would depend primarily upon the load capability of the yarding system at any point, is in this case limited by the distribution of logs on the ground. Since the running skyline has greater lateral capability (Table 2), more logs per turn can be hooked to that system, and less total time is required to yard a given parcel. The result is lower total yarding costs, and therefore higher net parcel values.

Table 3 also indicates that the running skyline is capable of yarding four timber parcels over cableway 2, as opposed to only two parcels for the highlead. Thus, cableway emplacement costs can be amortized over a larger volume of timber if the running skyline system is selected. Whether this is actually the best selection to make depends, of course, upon the total difference in cableway emplacement costs (which are higher for the running skyline) and yarding system emplacement costs (which are also higher for the running skyline), and upon the results of similar analyses for the other cableways to be considered. Techniques to decide the actual assignment of parcels to facilities are considered in Chapters IV and V.

The cableway profile summary in Table 3 is useful for constructing a ground profile, if one is desired. Note that points are summarized in equal 100-foot increments from the spar; the size of these increments for any problem is equal to the specified grid length for the problem. For skyline systems, the computed load capacity at each profile point is printed. This information could be useful to the logging manager, as it suggests guidelines for the maximum size of turn which could be hooked at intervals along the cableway. Note that the computed load capacity of the running skyline system at profile point 3 is equal to that for point 2. A load capability analysis for this ground profile (Figure 16) shows that a load of about 32,500 lbs could actually be supported at point 3. However, any load which is hooked at point 3 must also be skidded or flown, as prescribed, past point 2. Thus, the effective load capacity at any point along the cableway is limited to the minimum of the load capacities for all points closer to the spar. Gibson (1975) has called the function representing this phenomenon an "effective load curve". Peters, however, had previously (1972) defined a logging system "load curve" in an entirely different context. In order to avoid confusion, the step function illustrated in Figure 16 is therefore referred to in this study as an "effective load profile".

In addition to the preparation of reports such as those illustrated in Tables 2 and 3, the logging feasibility and cost analysis programs prepare several output files which are subsequently used by the heuristic optimization processor discussed in Chapter V. Examples of these files are presented in the Appendix. A complete user's guide to the programs described in this chapter is also included in the Appendix, as well as an example of the data file which is used to drive those programs.

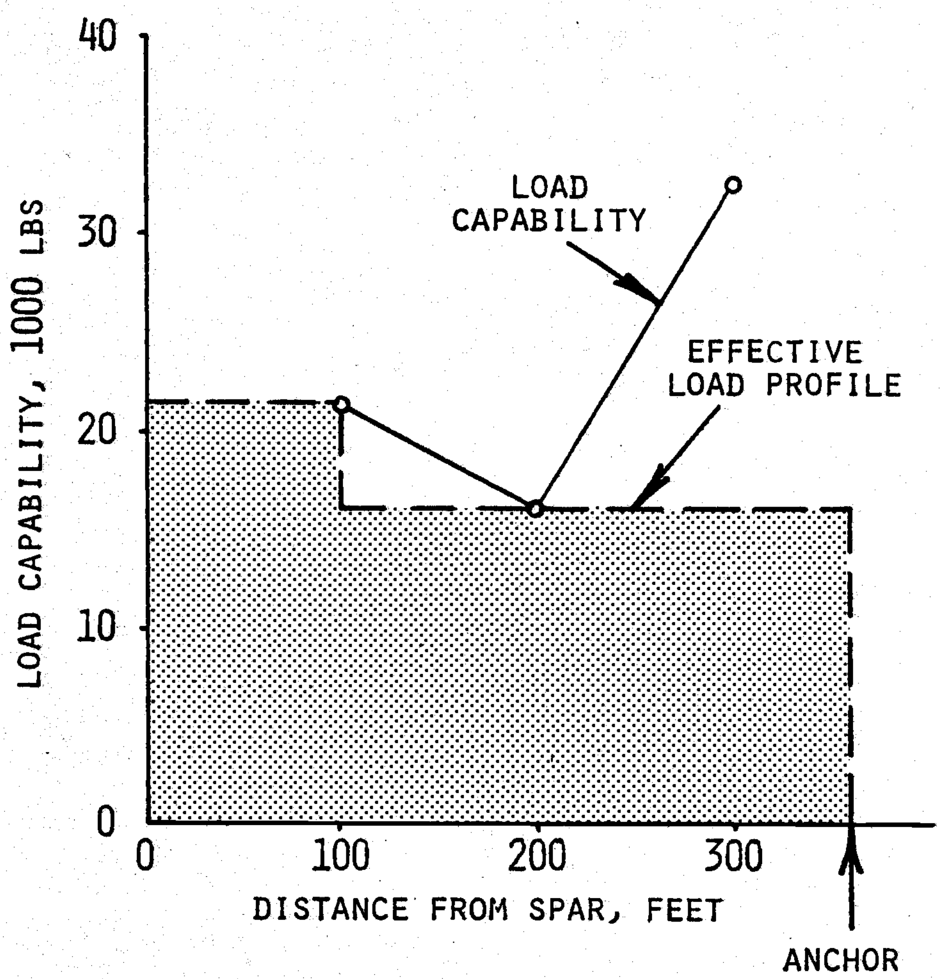

Figure 16. Load capability profiles for the example problem.

Summary

This chapter has presented the methodology by which logging feasibility and costs are evaluated for the cable systems in this study. The procedures used to evaluate load capability are based upon static analyses of the specific cable configurations under consideration. For the highlead system, this kind of analysis had not been published previously. The method developed here is rudimentary, but represents a starting point from which more elegant derivations can proceed. The procedures used for the skyline systems, on the other hand, were adapted from published methods that have been widely used in the forest industry.

In addition to load capability, the feasibility analysis also considers blind lead areas, rigging capability, and physical features such as roads, landings, and buffer strips. The methodology also permits the specification of partial or full log suspension over any point on the planning area. The blending of these capabilities represents an important advance in timber harvest planning methodology, because it provides the forest manager with a flexible tool for assessing cable logging feasibility over a wide range of conditions. It is the first harvest planning methodology to permit the specification of varying harvest restrictions on a single planning area, and the first to utilize an automated procedure designed to free the analyst from many of the chores associated with harvest planning. In addition, it provides much more information than would normally be available in conventional harvest planning.

Yarding costs are estimated by means of a linear regression model which has been widely used in the analysis of logging time study data. A particularly attractive feature of this model is that estimates for nearly all of the independent variables are obtained during the course of the feasibility analysis. The heart of the cost analysis is the fact that it considers logging feasibility under the conditions described above, and also considers the characteristics of individual timber types. This means that accurate estimates of the value of the timber in each parcel, net of variable yarding and transportation costs, can be determined. This net value is a function not only of the timber itself but also depends upon the yarding system used and the specific cableway over which it is to be yarded. Thus, several values will normally be associated with each parcel; one value for each yarding alternative by which the parcel can be harvested. This is an important concept, because it is the basis upon which the optimization and heuristic procedures discussed in the following two chapters depend.

IV. FORMULATION OF A SOLUTION STRUCTURE

In some cases, the information developed by the feasibility and cost analysis presented in Chapter III may be sufficient to permit the forest manager to make satisfactory decisions regarding the design of cutting units and the assignment of logging equipment to those units (e.g. the optimal solution to the small example problem could be found by inspection, or by enumeration). For large planning areas, however, the quantity of data generated by that analysis may simply add to the confusion. It is therefore of interest to identify methods by which these data can be searched in order to find an optimal assignment of timber parcels to cableway facilities. This chapter presents one procedure for doing so. An approximation method, which cannot be guaranteed to give optimal solutions but is computationally feasible for much larger problems, is described in the following chapter.

Facilities Location-Allocation Problems

The problem which has been posed in this dissertation belongs to a class of problems which was originally described by Cooper (1963) as "location-allocation" problems[9]. The objective of such problems is to

[9]Actually, the problem addressed by Cooper was that of locating facilities on a continuous plane. Here, the "discrete facilities location-allocation problem" is considered; in this problem, facility sites are to be selected from a finite set that includes all acceptable locations (Ellwein and Gray, 1971).

determine the number, location, and sometimes the size, of facilities needed to service a set of demand centers (customers), and simultaneously to assign specific demand centers to facilities so that total distribution cost is minimized. This distribution cost is composed of transportation costs plus the fixed costs associated with installing and operating the facilities. Thus, the problem of minimizing total distribution cost may be visualized as that of balancing transportation costs against facility costs (Figure 17). Transportation costs will fall as the number of facilities increases, but at the same time, total facility costs will rise. Francis and White (1974) point out that if there were no fixed costs, the optimum solution to this problem would be to install a facility at every site; this solution corresponds to the rightmost point on the transportation cost curve in Figure 17. Conversely, if there were no transportation costs, the best strategy would be to install a single facility at the site of lowest fixed cost; this solution corresponds to the leftmost point on the facility cost curve in Figure 17.

The classical location-allocation problem, which is also known simply as the "warehouse location problem" or, because of its special structure, as the "fixed charge problem", is usually formulated as a mixed-integer programming problem:

$$\text{minimize} \quad \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} x_{ij} + \sum_{j=1}^{n} f_j y_j \qquad [4.1]$$

$$\text{subject to} \quad \sum_{i=1}^{m} x_{ij} \leq m\, y_j, \; j=1,\ldots,n \qquad [4.2]$$

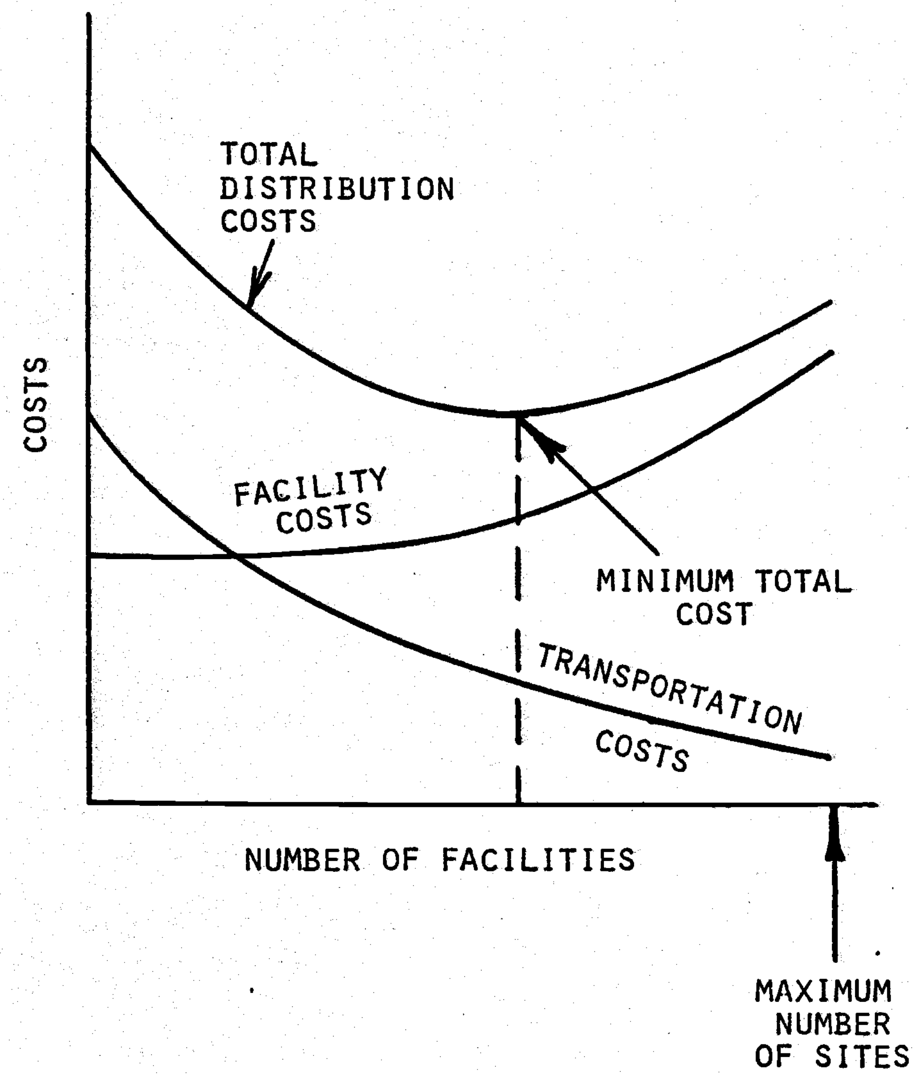

Figure 17. Costs considered in the facilities location-allocation problem.

$$\sum_{j=1}^{n} x_{ij} = 1, \; i=1,\ldots,m \qquad [4.3]$$

$$x_{ij} \geq 0, \text{ for all } i, j \qquad [4.4]$$

$$y_j = 0 \text{ or } 1, \text{ for all } j \qquad [4.5]$$

where m = the number of customers;

n = the number of possible facility locations;

x_{ij} = the fraction of the demand of customer i which is satisfied by a facility located at site j;

$y_j = \begin{cases} 1 \text{ if a facility is located at site } j; \\ 0 \text{ otherwise;} \end{cases}$

c_{ij} = the cost of supplying the entire demand of customer i from a facility located at site j;

f_j = the fixed cost incurred if a facility is located at site j.

The objective function, [4.1], gives the cost when $\sum_{j=1}^{n} y_j$ facilities are established at locations for which $y_j=1$. According to [4.2], the total fraction of customer demand supplied by facility j must be equal to zero if facility j is not established; otherwise, it cannot exceed the number of customers (i.e. the total demand). Constraints [4.3] insure that the demand of every customer is met exactly. [4.4] and [4.5] specify that all of the x_{ij} must be nonnegative and all of the y_j must be either 0 or 1 (integer) for a feasible solution.

An enormous body of literature related to this problem has developed during the past 10 or 15 years, apparently because of its general appeal in a wide range of applications. Elson (1972), for example, has described it as "among the most important problems in industry". Numerous techniques have been applied to the fixed charge problem, although none has been successful in solving extremely large problems. Major approaches which have been used include branch-and-bound mixed integer programming, dynamic programming, and heuristic programming.

Branch-and-Bound Methods

Branch-and-bound, or implicit enumeration, is a method of separating an integer programming problem into restricted subproblems by placing contradictory constraints on some or all of the integer variables. For the fixed charge problem, the integer variables are restricted to values of either 0 or 1; therefore, the branching technique is designed, at each branch, to set some of the y_j equal to 0, and the remaining y_j equal to 1. The resulting subproblem can then be solved by linear programming. By a judicious choice of the specific y_j which are set equal to 0 (or 1), it is possible to avoid solving all possible subproblems and yet be able to guarantee (at some point) that an optimal solution to the problem [4.1] - [4.5] has been found; thus the term "implicit enumeration". The first application of this procedure to the fixed charge problem was published by Efroymson and Ray (1966), who reported satisfactory test results for problems with up to 50 facilities and 200 customers. The major difficulty encountered with this method, however, is that computation time tends to be exponentially related to the number of possible facility sites in the problem (Khumawala, 1971). Recent attention has therefore been directed primarily at attempts to reduce the number of branches which have to be searched, either by ranking the extreme points (Murty, 1967), by improving the origin of the search (Spielberg, 1969), or by means of more efficient branching rules (Sá, 1969; Khumawala, 1972). Improvements in the basic branch-and-bound algorithm itself have also been significant, particularly those based upon the work of Glover (1968), Geoffrion (1969), and Davis, Kendrick, and Weitzman (1971). In spite of these efforts, however, no computationally attractive results have been presented for large facilities location problems; usually, solution times are satisfactory only if the number of integer variables in the problem is less than about 100. With respect to the present study, a moderate forest harvest planning area would encompass perhaps 200 acres. If five landing sites were considered, each of which could accommodate one of four possible yarding systems, and if 50 cableways could be emplaced for each yarding system at each landing, then the total number of facilities to be considered is equal to (5)(4)(50)=1000. Thus, the forest harvesting problem appears to be too large for solution by a branch-and-bound technique.

Dynamic Programming

The first demonstration that a facilities location-allocation problem could be formulated as a dynamic programming problem appears to have been that of Bellman (1965), who suggested a formulation to solve the problem of Cooper (1963). More recently, Ballou (1968) has presented a dynamic programming formulation designed to consider optimal location of facilities over time; this model thus treats the relocation of facilities as demand and distribution costs change. His application, however, is for a very small problem (five facilities), and no computational experience is given. Wesolowsky and Truscott (1975) have revised and extended Ballou's work, but again consider only very small problems. Finally, Curry and Skeith (1969) have presented a dynamic programming formulation to a facilities location problem for which they claim that solution time is only linearly related to the number of possible facility sites. To obtain this relationship, however, they have ignored the fixed charges, and have thus solved a different problem than the one with which the present study is concerned.

Heuristic Programming

Probably the greatest number of published applications of facilities location problems have incorporated heuristic techniques. Heuristic programming has been described as a "formal, orderly presentation of aids to discovery" (Michael, 1972). That is, the scheduled procedure, or program, attempts to use experience, inductive reasoning, or similar devices to reduce the amount of searching that has to be done in order to find a solution. The emphasis in heuristic programming is on obtaining "practical" and "satisfactory", rather than optimal, solutions. For many problems, the use of an exact mathematical programming technique cannot be justified, either because of a lack of information or because the problem itself is loosely structured. In other cases, the methods available for obtaining exact solutions are either intractable or too expensive when problems of practical size are attempted.

As recently as 15 years ago, heuristic programming was considered by some practitioners in operations research to be an approach of questionable value, or perhaps even dangerous to the science of management (Michael, 1972). Recently, however, its stature has grown; as an example, the 1975 Lanchester Prize, which is awarded annually by the Operations Research Society of America to the "best English-language published contribution to operations research", was presented to the authors of a paper describing a heuristic methodology for the dynamic relocation of fire companies in New York City (Kolesar and Walker, 1974).

One of the best-known heuristic approaches for solving facilities location problems was developed by Kuehn and Hamburger (1963). Their approach uses a two-part procedure. First, facilities are added one at a time until no further additions can be made without increasing total costs. Then, a "bump and shift" routine evaluates the cost implications of dropping individual facilities or shifting them from one location to another. It eliminates any facility which is no longer economical because some of the demand centers originally assigned to it are now served by facilities located subsequently. Then it considers shifting each facility from its currently assigned location to the other potential sites within its territory.

Although Kuehn and Hamburger claim that their procedure is capable of solving problems with several hundred potential facility sites and several thousand demand centers, it does not appear to be a useful approach for the forest harvesting problem because its basic method is that of adding facilities one at a time. For the problems posed by Kuehn and Hamburger, the procedure seems to work well. In the forest harvesting problem, however, a given timber parcel can usually be harvested only by means of a few cableways. Thus, if this procedure were used, much of the early computation would be involved with infeasible solutions. Furthermore, if a run had to be terminated early, the solution at termination might not be a feasible one. This suggests that a more appropriate procedure would be to start with all or most of the facilities assigned, and then evaluate the advantage of dropping some of them.

Feldman, Lehrer, and Ray (1966) have developed a procedure which uses a "drop" heuristic in this manner. In fact, they developed it specifically to handle the possibility of infeasible routes. The approach is to evaluate, for each demand center, the total incremental cost associated with shipments from each of the potential facilities. Demand centers are assigned to facilities by a procedure that attempts to minimize the total cost associated with this initial assignment. Then, facilities are dropped one at a time until no facility can be dropped without increasing total cost or causing infeasibility.

A number of other heuristic approaches have been developed. Some of these (e.g. Cooper, 1964) consider the location of facilities anywhere on a continuous plane when transportation costs are linearly related to the Euclidian distance between demand centers and facilities[10]. Most, however, are concerned with the discrete facilities location problem, where facility locations are selected from a finite set of possible sites. A procedure formulated by Cooper and Drebes (1967) appears promising for this kind of problem, but has been tested only for small problems. Another procedure, which has been extensively tested for this class of problems, is the "steepest ascent one-point move algorithm" (Manne, 1964). Again, only small problems were analyzed and it is not clear whether the method would be useful for solving large problems.

Recent approximation procedures which have been developed for larger problems include those of Sá (1969), Shannon and Ignizio (1970), and Khumawala (1971). The method of Sá borrows heavily from both the Kuehn-Hamburger and the Feldman-Lehrer-Ray techniques, and has been shown to give nearly optimal results for small to medium-sized problems. None of the test problems reported, however, are large enough to permit conclusions regarding the validity of the approach for very large problems.

The method developed by Shannon and Ignizio appears to be very

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[10]Other common formulations are for costs proportional to rectilinear distance and to squared-Euclidian distance. An excellent discussion of these problems and methods for their solution is contained in Francis and White (1974).

efficient for large problems, including one involving 600 demand centers and 600 facility sites. The problem solved by this technique, however, is not the fixed charge problem but rather the simplified problem formulated by Curry and Skeith (1969); the primary application of this procedure therefore seems to be in the area of set covering problems, where a set of demand centers is to be "covered" (i.e. all of them must be served), but fixed costs are not important (Francis and White, 1974).

The approximation method developed by Khumawala (1971) departs radically from those reviewed above. It borrows heavily from branch-and-bound methodology, but rather than implicitly enumerating the entire set of 2^n combinations of n potential facility locations, uses heuristic branching rules to reduce the search. Khumawala has reported test results for many problems, several of which are fairly large (up to 100 facility sites and 200 demand centers). For many of these problems, his procedure found the optimal solution, and in all cases the solution discovered was very good. Computing times for all of the problems were quite fast, about 10 seconds (on an IBM 360/75) being the time required for the largest problems. Furthermore, Khumawala states that computing time is less than linearly related to the number of potential facility locations considered. It is not clear, however, whether this methodology would be useful for solving the much larger and somewhat more complex problem posed in this dissertation.

Synthesis

The literature reviewed in this section does not present an encouraging picture with respect to the solution of large facilities location problems such as the forest harvesting problem. Certainly, computational experience with exact procedures appears to rule all of them out from the standpoint of practicality. A formulation of the forest harvesting problem which can be solved by an exact procedure (for small problems) is presented in the next section, primarily for the purpose of more fully describing the structure of the problem and laying the groundwork for suggestions as to the direction that future research might take for obtaining exact solutions to such problems economically. Chapter V then discusses a heuristic algorithm based loosely upon the work of Kuehn and Hamburger (1963), Feldman, Lehrer, and Ray (1966), Sá (1969), and Khumawala (1971), and Chapter VI shows how the algorithm can be used with the methodology presented in Chapter III to solve a realistic forest harvest planning problem.

A Facilities Location-Allocation Problem With Cascading Fixed Charges

The specific problem addressed in this dissertation is that of assigning timber parcels to cableway facilities so that the resulting expected value of the parcels, net of all fixed charges, is maximized. Thus, if timber parcel i is to be assigned to cableway j for yarding system k at landing ℓ, then

1. the fixed cost associated with the emplacement of cableway j

must have been incurred;

2. the fixed cost associated with the installation of yarding system k at landing ℓ must have been incurred;

3. the fixed cost associated with the construction of landing ℓ must have been incurred.

This special structure has not been discussed previously in the facilities location literature, and is referred to here as a "cascading fixed charge" structure. A somewhat related problem which has been described by Jones and Soland (1969) is the "multi-level fixed-charge problem". Their formulation is for a fixed charge problem which has a nondecreasing, separable objective function with a finite number of jump discontinuities. Such problems might arise, for example, if the cost of producing some item jumps by the cost of additional production facilities for quantities greater than the capacity of existing facilities. An analogy in forest harvest planning would be the decision of whether:

1. to construct a single landing large enough to store all timber yarded to it during some period of time (minus whatever volume of timber could be transported to the mill during that time);
2. to construct several smaller landings with the same total capacity as the larger landing (but different construction and yarding costs); or
3. to restrict the landing size and accept a reduced rate of production.

In the present analysis, all landings are assumed to be large enough to handle whatever intermediate storage may be required between the time logs arrive at the landing and are loaded onto trucks.

In addition to the forest harvesting problem, numerous problems exist which appear to exhibit the cascading fixed charge structure. A partial list of such problems would include the following:

1. In real estate development, the allocation of residential lots to main and branch utilities (i.e. sewer and water, electricity, telephone, and cable television lines) so that the total cost of establishing and maintaining the main and branch lines is minimized;
2. In warehouse location problems, the allocation of customers among main and branch warehouses so that total distribution costs are minimized;
3. On commercial farms or large-scale nurseries, the assignment of garden plots to main and branch irrigation lines so that the total cost of emplacing and maintaining the lines is minimized;
4. In forest transportation planning, the allocation of timber stands among spur roads, which feed into main arterials, so that the total costs of construction, maintenance, and transportation are minimized.

No claim is made that these problems could be solved directly by the methods presented in this dissertation. They do, however, appear to exhibit the same kind of structure as the forest harvesting problem, and have been listed here on that basis.

Mathematical Formulation

The problem of optimally assigning timber parcels to harvesting facilities so that the total value of that assignment, net of cascaded fixed charges, is maximized, may be stated as follows:

$$\text{maximize} \quad \sum_{\ell}\sum_{k}\sum_{j}\sum_{i} v_{ijk\ell}x_{ijk\ell} - \sum_{\ell}\sum_{k}\sum_{j} f_{jk\ell}x_{jk\ell} - \sum_{\ell}\sum_{k} f_{k\ell}x_{k\ell} - \sum_{\ell} f_{\ell}x_{\ell} \qquad [4.6]$$

$$\text{subject to} \quad \sum_{\ell}\sum_{k}\sum_{j} x_{ijk\ell} = 1, \text{ for all } i \qquad [4.7]$$

$$x_{ijk\ell} - x_{jk\ell} \leq 0, \text{ for all } i, j, k, \ell \qquad [4.8]$$

$$x_{jk\ell} - x_{k\ell} \leq 0, \text{ for all } j, k, \ell \qquad [4.9]$$

$$x_{k\ell} - x_{\ell} \leq 0, \text{ for all } k, \ell \qquad [4.10]$$

$$\sum_{k} x_{k\ell} \leq 1, \text{ for all } \ell \qquad [4.11]$$

$$x_{ijk\ell} = 0 \text{ or } 1, \text{ for all } i, j, k, \ell \qquad [4.12]$$

$$x_{jk\ell} = 0 \text{ or } 1, \text{ for all } j, k, \ell \qquad [4.13]$$

$$x_{k\ell} = 0 \text{ or } 1, \text{ for all } k, \ell \qquad [4.14]$$

$$x_{\ell} = 0 \text{ or } 1, \text{ for all } \ell \qquad [4.15]$$

where $v_{ijk\ell}$ = the value of parcel i as computed in equation [3.25];

$$x_{ijk\ell} = \begin{cases} 1 \text{ if parcel } i \text{ is harvested over cableway } j \text{ by system } k \text{ at landing } \ell; \\ 0 \text{ otherwise;} \end{cases}$$

$$x_{jk\ell} = \begin{cases} 1 \text{ if cableway } j \text{ is emplaced for yarding system } k \text{ at landing } \ell; \\ 0 \text{ otherwise;} \end{cases}$$

$$x_{k\ell} = \begin{cases} 1 \text{ if yarding system } k \text{ is installed at landing } \ell; \\ 0 \text{ otherwise;} \end{cases}$$

$$x_{\ell} = \begin{cases} 1 \text{ if landing } \ell \text{ is constructed;} \\ 0 \text{ otherwise;} \end{cases}$$

$f_{jk\ell}$ = the fixed cost of emplacing cableway j for yarding system k at landing ℓ, as computed in equation [3.27];

$f_{k\ell}$ = the fixed cost of installing yarding system k at landing ℓ (entered exogenously);

f_{ℓ} = the fixed cost of constructing landing ℓ (entered exogenously).

The objective function, [4.6], measures the total value of the assignment of parcels to facilities, net of cascaded fixed charges. Constraints [4.7] insure that every parcel is assigned to exactly one cableway (i.e. all timber is scheduled for harvest). By constraints [4.8] - [4.10], the cascading of facilities as discussed earlier is assured for a feasible solution. Constraints [4.11] require that at most one yarding system is emplaced at each landing. Constraints [4.12] - [4.15] indicate that partial assignments are not acceptable; an assignment must either be made fully, or not at all.

Numerical Example

To illustrate the application of the model in [4.6] - [4.15], consider the example problem represented by the data in Table 4. This problem may be visualized much the same as the example presented in Chapter III; parcel values and fixed charges, however, have been simplified. Numbers in the main body of the table are parcel values; as an example, $v_{3312} = 1400$. Fixed charges have been entered immediately beneath the corresponding decision variables; f_{221}, for example, is equal to 500. This tableau format does a good job of representing the cascading structure of fixed charges in the problem. It is immediately evident, for example, that to emplace the cableway corresponding to x_{211}, not only does the fixed charge f_{211} have to be incurred, but fixed charges f_{11} and f_1 must also be incurred. Parcels which are infeasible for some cableway have no value in the column representing that cableway. Thus, parcel 6 cannot be harvested by means of the cableways corresponding to x_{111} and x_{121}.

The total number of decision variables in the problem may be

Table 4. FIXED CHARGES AND PARCEL VALUES FOR THE EXAMPLE PROBLEM.

Cascading Fixed Charges		x_1				x_2			
		18000				16000			
		x_{11}		x_{21}		x_{12}		x_{22}	
		2000		2200		1800		2000	
		x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}
		1000	800	600	500	1100	700	800	700
Timber Parcels	1	3000	--	800	--	1000	--	--	--
	2	3200	--	1100	--	900	600	800	--
	3	--	1000	--	--	1400	--	1200	--
	4	3500	--	2000	--	--	900	--	1200
	5	600	700	--	--	--	1000	700	900
	6	--	800	--	1200	700	700	700	700

found by counting the number of numerical entries in Table 4, as each entry is the cost coefficient for a corresponding variable in the objective function. In this (small) example, there are 40 variables, which is not such a small integer programming problem. Table 5 is a representation of the problem written in matrix form, and Figure 18 is the corresponding RPM network (after Riggs and Inoue, 1975). For convenience, constraints [4.7] - [4.11] are referred to in Table 5 and Figure 18 as constraint types [1] - [5]. The cascading structure of the facilities is clearly evident in both the matrix and the RPM network. Note also the high degree of triangularity[11] exhibited by the problem, and the fact that all of the non-zero elements in the matrix are equal either to 1 or to -1. Coupled with the fact that all of the elements in the right-hand side vector are equal to either 0 or 1, this suggests a strong natural tendency toward integer solutions (Wagner, 1970). Sometimes problems with such tendencies can be solved with existing linear programming codes, and will always give integer results. An example of a problem with this convenient nature is the Hitchcock-Koopmans transportation problem (Hadley, 1963). In fact, however, tests have shown that for problem [4.6] - [4.15], the solution found by linear programming is far from the optimal integer solution, and that "rounding" the LP solution is usually not possible if feasibility is to maintained. As an example, the linear programming solution

[11]The matrix is not triangular in the mathematical sense; this statement is only meant to imply that it "looks" triangular.

Table 5. Matrix representation of the example 0-1 integer programming problem.

	ACTIVITY REPRESENTED	HARVEST TIMBER PARCELS (ijkℓ)																										EMPLACE CABLEWAYS (jkℓ)								INSTALL YARDING SYSTEMS (kℓ)				CONSTRUCT LANDINGS (ℓ)			
	DECISION VARIABLES	x_{1111}	x_{1121}	x_{1312}	x_{2111}	x_{2121}	x_{2312}	x_{2412}	x_{2322}	x_{3211}	x_{3321}	x_{3322}	x_{4111}	x_{4121}	x_{4412}	x_{4422}	x_{5111}	x_{5211}	x_{5412}	x_{5322}	x_{5422}	x_{6211}	x_{6221}	x_{6312}	x_{6412}	x_{6322}	x_{6422}	x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}	x_{11}	x_{21}	x_{12}	x_{22}	x_1	x_2		
	VALUE OR COST	3000	800	1000	3200	1100	900	600	800	1000	1400	1200	3500	2000	900	1200	600	700	1000	700	900	800	1200	700	700	700	700	-1000	-800	-600	-500	-1100	-700	-800	-700	-2000	-2200	-1800	-2000	-18000	-16000		
CONSTRAINTS	TYPE [1]	1	1	1																																							=	1
						1	1	1	1	1																																		=	1
												1	1	1																															=	1
															1	1	1	1																											=	1
																			1	1	1	1	1																						=	1
																								1	1	1	1	1	1																=	1
	TYPE [2]	1																										-1													≤	0
			1																												-1											≤	0
				1																														-1									≤	0
					1																						-1													≤	0
						1																								-1											≤	0
							1																										-1									≤	0
								1																											-1								≤	0
									1																													-1							≤	0
										1																		-1												≤	0
											1																					-1									≤	0
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																									1								-1								≤	0
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																											1								-1						≤	0
	TYPE [3]																											1								-1						≤	0
																													1							-1						≤	0
																														1								-1					≤	0
																															1							-1					≤	0
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																																	1							-1				≤	0
																																		1								-1			≤	0
																																			1							-1			≤	0
	TYPE [4]																																			1				-1		≤	0
																																					1			-1		≤	0
																																						1				-1	≤	0
																																							1		-1	≤	0
	TYPE [5]																																			1	1					≤	1
																																						1	1			≤	1

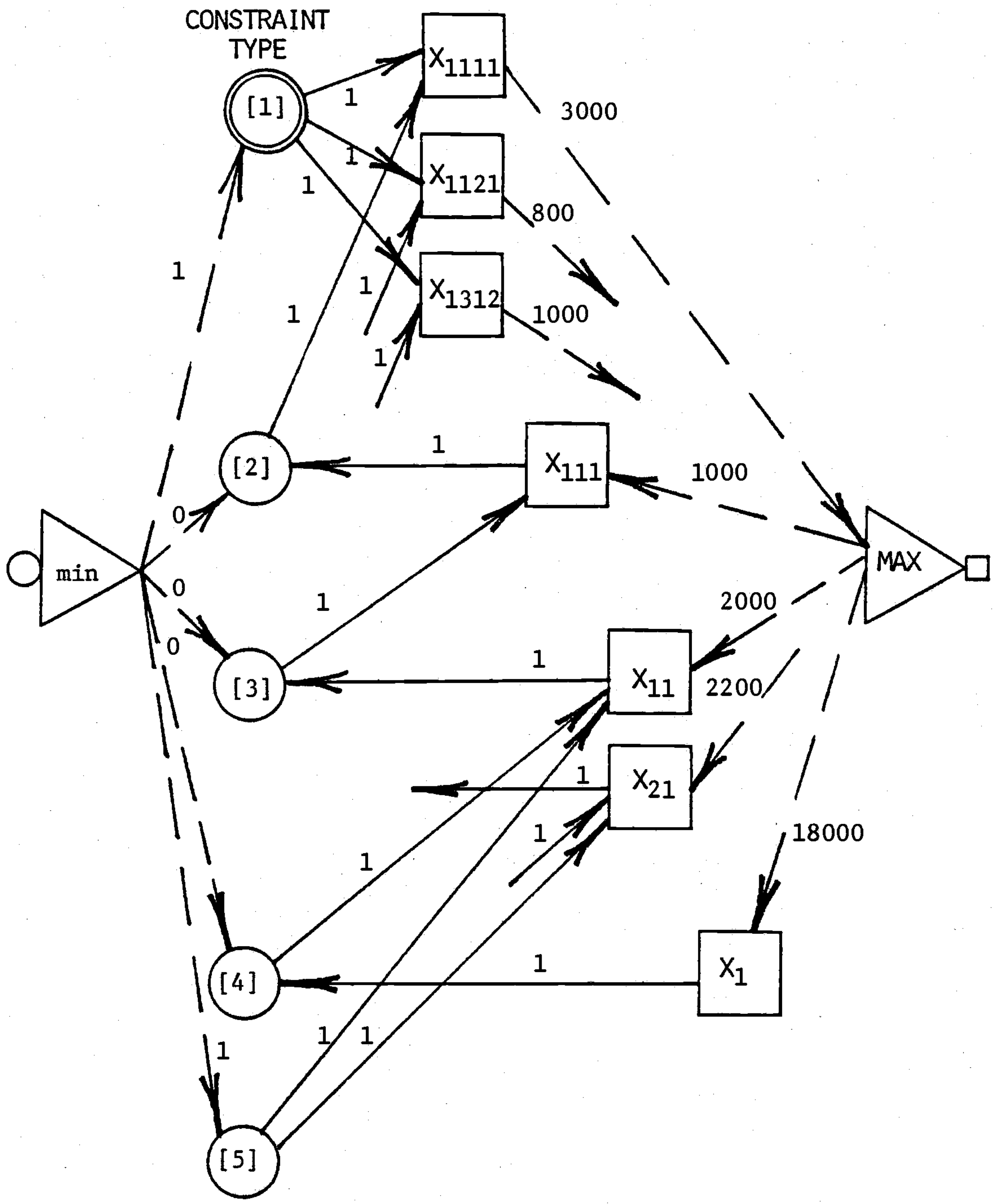

Figure 18. RPM network for the example problem (illustrated for the first constraint of each type).

for the example problem is given in Table 6. Only a casual inspection of this table is needed to see that any attempt to generate an integer solution by rounding will prove futile.

An exact integer solution for the problem in Table 4 has been obtained by means of a cutting plane method developed by Bowman (1969). The procedure followed in this method is, first, to solve the integer programming problem as though it were a linear programming problem. Then, if the result is not an all-integer solution, generate an additional linear constraint (called a cutting hyperplane) and solve the (new) linear programming problem. This procedure is repeated until an all-integer solution (which is optimal) is found, or until an infeasibility indicator is received. The foundations of this approach were constructed by Gomory (1958), and since that time, numerous techniques have been proposed for generating "deeper" cuts in order to speed convergence. Perhaps the most notable success in this endeavor (for certain types of all-integer problems) has been that of Martin (Geoffrion and Marsten, 1972), whose technique has been able to successfully solve 0-1 problems with as many as 7000 variables. Bowman's method is essentially an efficient way of generating Martin's deep cuts. As presently programmed for use on the Oregon State University CDC 3300 computer, however, the method is limited to a total of 100 variables and constraints. Thus, the problem in Table 5, with 40 variables and 46 constraints, is near the upper limit of its present capability. The all-integer optimal solution to this problem is exhibited in Table 7. Computing time on the CDC 3300 to obtain this solution was 38.4 seconds, which is actually much faster than times reported

Table 6. OPTIMAL LINEAR PROGRAMMING SOLUTION FOR THE EXAMPLE PROBLEM.

MAXIMUM OBJECTIVE = -7400.000000

COLUMN	INDICATOR	AMOUNT	OBJECTIVE
X1111	BASIS	.333333	3000.000000
X1121	BASIS	.333333	800.000000
X1312	BASIS	.333333	1000.000000
X2111	BASIS	.333333	3200.000000
X2121	BASIS	.333333	1100.000000
X2312	BASIS	.333333	900.000000
X2412	LOWER LIMIT	0	600.000000
X2322	LOWER LIMIT	0	800.000000
X3211	BASIS	.333333	1000.000000
X3312	BASIS	.333333	1400.000000
X3322	BASIS	.333333	1200.000000
X4111	BASIS	.333333	3500.000000
X4121	BASIS	.333333	2000.000000
X4412	BASIS	0	900.000000
X4422	BASIS	.333333	1200.000000
X5111	BASIS	0	600.000000
X5211	BASIS	.333333	700.000000
X5412	BASIS	0	1000.000000
X5322	BASIS	.333333	700.000000
X5422	BASIS	.333333	900.000000
X6211	BASIS	.333333	800.000000
X6221	BASIS	0	1200.000000
X6312	BASIS	.333333	700.000000
X6412	BASIS	0	700.000000
X6322	BASIS	.333333	700.000000
X6422	BASIS	0	700.000000
X111	BASIS	.333333	-1000.000000
X211	BASIS	.333333	-800.000000
X121	BASIS	.333333	-600.000000
X221	LOWER LIMIT	0	-500.000000
X312	BASIS	.333333	-1100.000000
X412	BASIS	0	-700.000000
X322	BASIS	.333333	-800.000000
X422	BASIS	.333333	-700.000000
X11	BASIS	.333333	-2000.000000
X21	BASIS	.333333	-2200.000000
X12	BASIS	.333333	-1800.000000
X22	BASIS	.333333	-2000.000000
X1	BASIS	.333333	-18000.000000
X2	BASIS	.333333	-16000.000000

Table 7. OPTIMAL INTEGER PROGRAMMING SOLUTION FOR THE EXAMPLE PROBLEM.

MAXIMUM INTEGER OBJECTIVE = -9600.000000

COLUMN	AMOUNT	OBJECTIVE
X1111	1.000000	3000.000000
X1121	0	800.000000
X1312	0	1000.000000
X2111	1.000000	3200.000000
X2121	0	1100.000000
X2312	0	900.000000
X2412	0	600.000000
X2322	0	800.000000
X3211	1.000000	1000.000000
X3312	0	1400.000000
X3322	0	1200.000000
X4111	1.000000	3500.000000
X4121	0	2000.000000
X4412	0	900.000000
X4422	0	1200.000000
X5111	0	600.000000
X5211	1.000000	700.000000
X5412	0	1000.000000
X5322	0	700.000000
X5422	0	900.000000
X6211	1.000000	800.000000
X6221	0	1200.000000
X6312	0	700.000000
X6412	0	700.000000
X6322	0	700.000000
X6422	0	700.000000
X111	1.000000	-1000.000000
X211	1.000000	-800.000000
X121	0	-600.000000
X221	0	-500.000000
X312	0	-1100.000000
X412	0	-700.000000
X322	0	-800.000000
X422	0	-700.000000
X11	1.000000	-2000.000000
X21	0	-2200.000000
X12	0	-1800.000000
X22	0	-2000.000000
X1	1.000000	-18000.000000
X2	0	-16000.000000

for many problems of similar size by Geoffrion and Marsten (1972). The Geoffrion-Marsten study is a state-of-the-art analysis of integer programming algorithms, and includes computational experience with a great many commercial codes. With reference to the example problem in Table 5, it is interesting to note that the optimal linear programming solution was obtained in 21.1 seconds after 50 iterations, and only a single cutting hyperplane was required to force the integer solution.

While the 0-1 integer programming model in [4.6] - [4.15] can be solved for small problems, present integer programming codes are not usually suited to problems with more than a few hundred binary variables (Geoffrion and Marsten, 1972). The single notable exception is the work of Martin, but his largest applications (of up to 7000 variables) have usually included only a few (perhaps 150) constraints. Computational effort in the linear programming step of the algorithm is strongly influenced by the number of constraints. In general, the number of constraints (m) and variables (n) in the model [4.6] - [4.15] is given by

$$n = \sum_\ell \sum_k \sum_j \sum_i \; I_{ijk\ell} + \sum_\ell \sum_k \sum_j \; J_{jk\ell} + \sum_\ell \sum_k \; K_{k\ell} + L \qquad [4.16]$$

where $I_{ijk\ell} = \begin{cases} 1 & \text{if parcel } i \text{ can feasibly be assigned to cableway } j \text{ which has been emplaced for yarding system } k \text{ at landing } \ell; \\ 0 & \text{otherwise;} \end{cases}$

$J_{jk\ell} = \begin{cases} 1 & \text{if cableway } j \text{ can be emplaced for yarding system } k \text{ at landing } \ell; \\ 0 & \text{otherwise;} \end{cases}$

$$K_{k\ell} = \begin{cases} 1 \text{ if yarding system k can be installed at landing } \ell; \\ 0 \text{ otherwise;} \end{cases}$$

L = the number of acceptable landing sites in the planning area.

$$m = n + P \qquad [4.17]$$

where P = the total number of parcels in the planning area which are to be scheduled for harvest.

Suppose that a planning area of 200 acres, which has been dissected into 1/4-acre parcels, is being considered, and that five landing sites are available on the area. Assuming that:

1. four alternative yarding systems are available, each of which could be installed at any landing;
2. 15 feasible cableways could be emplaced for each yarding system at each landing;
3. 20 parcels could be harvested by means of each cableway;

then n = 6325, and m = 7125, which is a very large integer programming problem. As the planning area considered above is by no means a "large" forest planning area, it does not appear reasonable to expect that present integer programming codes are capable of solving the type of problem addressed in this study for any planning area of practical size. It would be possible, of course, to reduce the size of the problem by increasing the area represented by each timber parcel. In doing so, however, there would be a substantial risk of oversimplifying the problem to the point that the feasibility and cost analysis discussed earlier would lose its meaning. Rather than accept such an oversimplification, the approach adopted in this study was to develop a heuristic algorithm specifically to solve the forest harvesting problem. This algorithm is presented next.

V. A HEURISTIC ALGORITHM FOR SOLVING LOCATION-ALLOCATION PROBLEMS WITH CASCADING FIXED CHARGES

This chapter describes an approximation method which was developed in an effort to find satisfactory feasible solutions to location-allocation problems of the type investigated in this dissertation. The first section of the chapter presents a detailed mathematical description of the algorithm, and a simplified explanation with a brief numerical example is given later in the chapter. A summary of the operations performed during execution of the algorithm is given in Table 8.

Mathematical Description

Throughout the discussion of the algorithm, frequent reference is made to "facilities" ℓ, $(k\ell)$, and $(jk\ell)$. In the context of the forest harvesting problem, these refer to the following:

ℓ = the index of a specific landing;

$(k\ell)$ = the index of a specific yarding system installed at landing ℓ;

$(jk\ell)$ = the index of a specific cableway emplaced for yarding system $(k\ell)$ at landing ℓ.

With regard to the specific problem being solved, the algorithm makes the following assumptions:

1. The objective is to maximize the total expected value of the timber parcels in the planning area, net of cascaded fixed costs.
2. No more than one yarding system may be installed at any

Table 8. SUMMARY OF THE HEURISTIC ALGORITHM FOR SOLVING LOCATION-ALLOCATION PROBLEMS WITH CASCADING FIXED CHARGES.

Step	Description
1	Initialization.
1.1	Sometimes certain timber parcels can only be harvested by a specific facility. Install any such facilities and assign the appropriate parcels to them, but permit no more than one yarding system ($k\ell$) at any landing ℓ.
1.2	Assign as many parcels as possible to the facilities established in Step 1.1, without regard to the total value of those assignments.
1.3	Improvement check: reassign parcels among facilities in such a manner that the total value of those assignments is maximized.
1.4	Establish facilities to serve the remaining parcels so that, for each parcel, the sum of its value minus incremental, fixed costs is maximized. Permit only one yarding system ($k\ell$) at any landing ℓ. At the conclusion of this step, either an <u>initial feasible solution</u> will have been found, or the problem is infeasible.
2	Drop uneconomical facilities.
2.1	Drop any facility, say m, unless it was the most recently added facility during the previous pass though Step 3 or the present pass through Step 2, for which the additional cost of using other facilities to harvest the parcels currently assigned to m is more than offset by the reductions in fixed cost which will result from the closure. Do not, however, drop m unless the action can be taken without installing more than one yarding system ($k\ell$) at any landing ℓ.
2.2	Allocate, among the remaining facilities (plus any which were added to retain feasibility), the parcels which were previously assigned to m. Execute these reassignments so that the total value of the resulting solution is maximized.
2.3	If Step 3 has not been executed at least once, go directly to it. Otherwise, if at least one facility was dropped in this pass through Step 2, or if at least one facility was added in the previous pass through Step 3, then go to Step 3. Otherwise, the solution obtained at the end of Step 2 cannot be improved further by this algorithm; therefore, exit.

TABLE 8. (Continued)

3	Add facilities which will improve the solution.
3.1	Add any facility, say n, for which the incremental, cascaded fixed costs will be more than offset by improvements in value of parcels which could be assigned to n. Do not, however, add n if the action will result in the installation of more than one yarding system ($k\ell$) at any landing ℓ.
3.2	If a facility was added in Step 3.1, then redistribute the timber parcels among all current facilities so that total value is maximized.
3.3	If at least one facility was added in this pass through Step 3, or if at least one facility was dropped in the previous pass through Step 2, then return to Step 2. Otherwise, the solution obtained at the end of Step 3 cannot be improved further by this algorithm; therefore, exit.

landing.

3. Timber parcels are indivisible (i.e. the assignment of timber parcel i to facility ($jk\ell$) connotes that the entire parcel is to be harvested by means of that facility).

All of these assumptions are consistent with the 0-1 integer programming formulation presented in Chapter IV.

Before describing the algorithm in detail, it will be useful to define the following:

$\underline{A}$ = {indices ($jk\ell$) of facilities which have been assigned};

$\underline{U}$ = {indices ($jk\ell$) of facilities which have not been assigned};

$\underline{a}$ = {indices i of timber parcels to which facilities have been assigned (this set contains all i after initialization, unless the problem is infeasible)};

$\underline{u}$ = {indices i of parcels to which facilities have not been assigned (this set is empty after initialization, unless the problem is infeasible)};

Λ = {indices ℓ of landings to which yarding systems have been assigned};

Π_ℓ = {indices ($k\ell$) of yarding systems which have been assigned to landing ℓ};

$\Phi_{jk\ell}$ = {parcels i presently assigned to facility ($jk\ell$)};

$\Phi'_{jk\ell}$ = {parcels i which could be assigned to facility ($jk\ell$) if it were established};

$\Gamma_{jk\ell}$ = the index of the last facilty ($jk\ell$) dropped during the execution of the algorithm; similarly, $\Gamma_{k\ell}$ and Γ_ℓ are defined for facilities ($k\ell$) and ℓ};

$\Gamma'_{jk\ell}$ = the index of the last facility $(jk\ell)$ added during the execution of the algorithm (not including initialization); $\Gamma'_{k\ell}$ and Γ'_{ℓ} are similarly defined for facilities $(k\ell)$ and ℓ.

STEP 1. Initialization.

First, initialize all lists. U initially contains all $(jk\ell)$; u contains all i. The set of lists $\Phi'_{jk\ell}$ should be compiled by a rigorous feasibility analysis such as that discussed in Chapter III. All other lists are initially empty.

Step 1.1 Establish all facilities $(jk\ell)$ for any $i\varepsilon\Phi'_{jk\ell}$ for which $i\notin\Phi'_{j'k'\ell'}$ for every $(j'k'\ell')\neq(jk\ell)$. This says that parcel i can be harvested by one and only one facility, $(jk\ell)$. Therefore, $(jk\ell)$ must be established if a feasible solution is to be obtained. Having established such facilities, revise lists A, U, a, u, and $\Phi_{jk\ell}$. Next, construct lists Λ and Π_ℓ from A. For any $\ell\varepsilon\Lambda$, if Π_ℓ contains more than one $(k\ell)$, then the problem is infeasible; exit.

Note that the establishment of any facility $(jk\ell)$ necessitates the establishment of facilities $(k\ell)$ and ℓ, unless they are already in place. The heuristic rule applied in this step is that facilities $(k\ell)$ and ℓ need not be considered explicitly, except to judge feasibility.

Step 1.2 Assign as many parcels i as possible to each of the facilities $(jk\ell)$ added in Step 1.1. This is accomplished simply by assigning, for all $(jk\ell)\varepsilon$A, every $i\varepsilon$u $\cap\,\Phi'_{jk\ell}$. That is, the list of currently assigned facilities is scanned, and every parcel which could be assigned to those facilities is added, so long as it has not already been assigned to some other facility. No effort is made to maximize the value of these assignments; they are simply made in the order in which facilities are listed in A. Heuristically, the algorithm seeks feasibility as quickly as possible, and leaves value maximization for the next step. After the above assignments, revise lists a, u, and $\Phi_{jk\ell}$.

Step 1.3 Improvement check. The purpose of this step is to improve upon the assignments made in Step 1.2 (those made in Step 1.1 are fixed in order to provide feasibility and hence cannot be improved). For each $i \varepsilon \underline{a}$, compute

$$v_i^* = \max_{(jk\ell)\varepsilon \underline{A}} \{v_{ijk\ell}\} \qquad [5.1]$$

where $v_{ijk\ell}$ = the expected value of parcel i if it is harvested by means of facility $(jk\ell)$.

Then, assign parcel i to the facility $(jk\ell)$ corresponding to v_i^*. Fixed costs are not considered in this evaluation because they have already been incurred for all $(jk\ell)\varepsilon \underline{A}$. Following any re-assignments in this step, revise list $\Phi_{jk\ell}$.

Step 1.4 Complete the initialization by adding facilities as necessary to obtain an initial feasible solution (i.e. to insure that all timber parcels can be harvested). To choose a facility to be added, compute

$$V^*_{jk\ell} = \max_{(jk\ell)\epsilon \underline{U}:\{[\ell\notin\Lambda]\,\cup\,[\ell\epsilon\Lambda\,\cap\,(k\ell)\epsilon\Pi_\ell]\}} \left(-\overline{F}_{jk\ell} + \sum_{i\epsilon \underline{u}\,\cap\,\Phi'_{jk\ell}} \{v_{ijk\ell}\}\right) \qquad [5.2]$$

where $\overline{F}_{jk\ell}$ = the <u>incremental</u> fixed cost which would be incurred if facility ($jk\ell$) were established.

This criterion states that the facility to be added should maximize the sum of parcel values which can be harvested via that facility, net of incremental fixed costs required to establish the facility, and that only facilities should be considered which are either (a) at a landing to which no yarding system is currently assigned, or (b) can be affixed to the yarding system at an established landing.

Only incremental fixed costs are considered in computing $V^*_{jk\ell}$ because some portion of the total cascaded fixed cost associated with ($jk\ell$) may already have been incurred as a result of some previous facility assignment. Specifically, if some other cableway $(j'k'\ell')\epsilon\underline{A}$ has already been established, and if $\ell'=\ell$, then landing ℓ has already been established and its fixed costs incurred. Furthermore, since no more than one yarding system can be installed at any landing, it follows that the $\overline{F}_{jk\ell}$ are defined as follows:

(a) if $\ell\notin\Lambda$, then $\overline{F}_{jk\ell} = f_{jk\ell} + f_{k\ell} + f_\ell$;

(b) if $\ell\epsilon\Lambda$ and $(k\ell)\epsilon\Pi_\ell$, then $\overline{F}_{jk\ell} = f_{jk\ell}$;

(c) otherwise, $\overline{F}_{jk\ell} = \infty$ (<u>i.e</u>. the facility cannot be established),

where $f_{jk\ell}$ = the cost of emplacing cableway ($jk\ell$);

$f_{k\ell}$ = the cost of installing yarding system $(k\ell)$;

f_{ℓ} = the cost of constructing landing ℓ.

If a $V^*_{jk\ell}$ is found which satisfies either (a) or (b), establish $(jk\ell)$ and assign to it all $i\varepsilon \underline{u} \cap \Phi'_{jk\ell}$. Then revise lists $\underline{a}$, $\underline{u}$, $\underline{A}$, $\underline{U}$, $\Phi_{jk\ell}$, Λ, and Π_{ℓ}. Then execute the improvement check (Step 1.3), and repeat Step 1.4 for the remaining $i\varepsilon\underline{u}$.

If for any $i\varepsilon\underline{u}$ a $V^*_{jk\ell}$ cannot be found which satisfies either (a) or (b), then the problem is infeasible; exit. Otherwise, at the conclusion of Step 1.4 an initial feasible solution will have been found. Then go on to STEP 2.

Before continuing the discussion of the algorithm, it is worthwhile to note that criterion [5.2] is somewhat analogous to the concepts of local demand, used by Kuehn and Hamburger (1963), and local volume, used by Feldman, Lehrer, and Ray (1966). As with both of those concepts, there is no theoretical justification for using [5.2] in the manner outlined in Step 1.4. That is, it does not necessarily generate the "best" starting solution. Computationally, though, it seems to perform well; for small problems it almost always finds the optimal solution immediately. Heuristically, it is a reasonable criterion because one would expect many of the timber parcels "closest" to a specific facility $(jk\ell)$ to be assigned to that one facility in the optimal solution. This is essentially the idea of the Kuehn-Hamburger and Feldman-Lehrer-Ray techniques, but [5.2] also takes into account some measure of the fixed costs associated with each facility. No consideration is given to fixed costs during initial assignments in either the Kuehn-Hamburger or the Feldman-Lehrer-Ray technique. In the forest harvesting problem it is not appropriate to ignore fixed costs during the initial assignments because of their cascading structure and the fact that they typically exhibit a high degree of variance. Experience with an earlier version of this algorithm which considered only parcel values and cableway emplacement costs showed, in fact, that the initial feasible solutions obtained with that method were often very poor and could lead to situations where the algorithm stalled in later steps at a solution that was far from optimal.

STEP 2. In this step uneconomical facilities are dropped, and the parcels previously assigned to them are redistributed among the remaining facilities (plus any which have to be added in order to retain feasibility).

Step 2.1 To make it worthwhile to drop any facility, say (jkℓ), the additional costs of using other facilities to harvest the parcels presently assigned to facility (jkℓ) must be more than offset by the reductions in fixed cost which will result from the closure, plus any improvements in parcel value which might result. The criterion used for this purpose by Feldman, Lehrer, and Ray (and the related criteria developed by Sá (1969) and Khumawala (1971) for similar problems) considers the advantage of transferring, to some other single facility, all customers (parcels) presently assigned to the facility which is being evaluated for closure. This is not an appropriate criterion for the forest harvesting problem, because it is rarely possible (due to the large number of infeasible routes in the problem) to make a wholesale swap of facilities in that manner. A criterion which considers the reallocation of the presently served parcels among multiple facilities is used here. This "drop criterion", $\delta_{jk\ell}$, is computed for every $\{(jk\ell)\varepsilon\underline{A}:(jk\ell)\notin\Gamma'_{jk\ell}\}$, as follows:

$$\delta_{jk\ell} = \overline{F}_{jk\ell} + I_{jk\ell} + \sum_{i\varepsilon\Phi_{jk\ell}}\left\{\max_{\substack{(j'k'\ell')\varepsilon\underline{U}\cup\underline{A}\\(j'k'\ell')\neq(jk\ell)}}\left(v_{ij'k'\ell'}-v_{ijk\ell}-\overline{F}_{j'k'\ell'}\right)\right\} \quad [5.3]$$

where $\overline{F}_{jk\ell}$ = the incremental fixed cost saved by closing facility $(jk\ell)$;

$I_{jk\ell}$ = the improvement in total value due to shifts which could be made via the improvement check (Step 1.3) if facility $(jk\ell)$ were dropped;

$\overline{F}_{j'k'\ell'}$ = the incremental fixed cost incurred if facility $(j'k'\ell')$ has to be established.

To insure feasibility, any $(j'k'\ell')\varepsilon\underline{U}$ must also meet the requirement that either $\ell'\notin\Lambda$ or $\ell'\varepsilon\Lambda\cap(k'\ell')\varepsilon\Pi_{\ell'}$. If for any $i\varepsilon\Phi_{jk\ell}$ this requirement cannot be met and there are no $(j'k'\ell')\varepsilon\underline{A}$ then facility $(jk\ell)$ cannot be dropped.

Note that in computing criterion [5.3], any possibility of closing the facility which was most recently added (usually during a previous execution of STEP 3) is specifically excluded. The purpose of excluding this facility, $(jk\ell)\varepsilon\Gamma'_{jk\ell}$, is to reduce the possibility of cycling. If a facility were to be dropped which had just been added, it is possible that in STEP 3 it would be added back again, and so on. Thus, it is simply not considered as a candidate to be dropped, although it may again become a candidate in some later pass. This method of reducing the possibility of cycling resembles one used by Shannon and Ignizio (1970) in a similar context.

During any pass through STEP 2, $\delta_{jk\ell}$ is computed for all $\{(jk\ell)\varepsilon\underline{A}:(jk\ell)\notin\Gamma'_{jk\ell}\}$. If, for any such $(jk\ell)$, $\delta_{jk\ell}>0$, then it is worthwhile dropping facility $(jk\ell)$. If on the other hand $\delta_{jk\ell}\leq 0$, no apparent improvement can be made by dropping $(jk\ell)$ at present. In this case, continue computing $\delta_{jk\ell}$ for the remaining facilities to be evaluated, or, if the list has been completed, go on to Step 2.2.

Note that if $\delta_{jk\ell}=0$ for any $(jk\ell)$, the solution obtained by dropping facility $(jk\ell)$ would be an alternate to the present solution with the same value of the objective function. The algorithm does not investigate any such alternate solutions.

<u>REMARK 1</u>. Experimentation with this algorithm has shown that the order in which facilities are evaluated by equation [5.3] can significantly influence the final result. To capitalize on this fact, decide which facility to consider first by computing, for each $\{(jk\ell)\varepsilon\underline{A}:(jk\ell)\notin\Gamma'_{jk\ell}\}$,

$$O_{jk\ell} = -f_{jk\ell} + \sum_{i\varepsilon\Phi_{jk\ell}} \{v_{ijk\ell}\} \qquad [5.4]$$

Then consider first the facility for which $O_{jk\ell}$ is <u>minimized</u>. Note, however, that although criterion [5.4] specifies the order in which facilities are to be considered during STEP 2, it does not guarantee the order in which they will actually be dropped. Infeasibilities may cause a high-priority facility to be retained, but permit a low-priority facility to be dropped.

Step 2.2 Once the decision to drop facility $(jk\ell)$ has been made, the related decision of how to reallocate the parcels presently served by $(jk\ell)$ must also be made. In keeping with criterion [5.3], compute, for each $i \varepsilon \Phi_{jk\ell}$,

$$\delta_{jk\ell}^{(i)} = \max \{v_{ij'k'\ell'} - v_{ijk\ell} - \overline{F}_{j'k'\ell'}\} \qquad [5.5]$$

where $(jk\ell)$ and $(j'k'\ell')$ are restricted as in [5.3].

Then remove parcel i from $(jk\ell)$ and assign it to the $(j'k'\ell')$ corresponding to $\delta_{jk\ell}^{(i)}$. Having done this, revise lists $\underline{A}$, $\underline{U}$, Λ, Π_ℓ, and $\Phi_{jk\ell}$, and place the index of $(jk\ell)$ in $\Gamma_{jk\ell}$. Also, if dropping facility $(jk\ell)$ required that facility $(j'k'\ell')$ be added, place the index of $(j'k'\ell')$ in $\Gamma'_{jk\ell}$. Then execute the improvement check (Step 1.3), and repeat Steps 2.1 and 2.2 for the remaining $\{(jk\ell)\varepsilon\underline{A}:(jk\ell)\notin\Gamma'_{jk\ell}\}$. When the list of $(jk\ell)\varepsilon\underline{A}$ has been exhausted, go on to Step 2.3.

REMARK 2. The description of STEP 2 has to this point been concerned only with dropping cableway facilities $(jk\ell)$. In fact, however, the algorithm also considers the possibility of dropping yarding systems $(k\ell)$ and landings ℓ. In either case, at least one but possibly many facilities $(jk\ell)$ would be dropped as a consequence. The procedure for evaluating these options is essentially the same as outlined above, except that this "imbedding" of attached facilities must also be considered.

The criterion corresponding to [5.3] which is used to evaluate whether to drop facility $(k\ell)$ is the following:

$$\delta_{k\ell} = \overline{F}_{k\ell} + I_{k\ell} + \sum_j \left(\sum_{i\varepsilon\Phi_{jk\ell}} \left\{ \max_{\substack{(j'k'\ell')\varepsilon \underline{U} \cup \underline{A} \\ (j'k'\ell') \neq (jk\ell)}} \left(v_{ij'k'\ell'} - v_{ijk\ell} - \overline{F}_{j'k'\ell'} \right) \right\} - \overline{F}_{k'\ell'} \right) \quad [5.6]$$

where $\overline{F}_{k\ell}$, $I_{k\ell}$, and $\overline{F}_{k'\ell'}$ are analogous to $\overline{F}_{jk\ell}$, $I_{jk\ell}$, and $\overline{F}_{j'k'\ell'}$ in equation [5.3].

This criterion is computed for every $\{(k\ell)\notin\Gamma'_{k\ell}:[(k\ell)\varepsilon\Pi_\ell \cap \ell\varepsilon\Lambda]\}$. If $\delta_{k\ell}>0$, then it is worthwhile dropping facility $(k\ell)$; otherwise, it is not.

Similarly, to evaluate the utility of dropping facility ℓ, compute

$$\delta_\ell = \overline{F}_\ell + I_\ell + \sum_k \left(\sum_j \left(\sum_{i\varepsilon\Phi_{jk\ell}} \left\{ \max_{\substack{(j'k'\ell')\varepsilon \underline{U} \cup \underline{A} \\ (j'k'\ell') \neq (jk\ell)}} \left(v_{ij'k'\ell'} - v_{ijk\ell} - \overline{F}_{j'k'\ell'} \right) \right\} - \overline{F}_{k'\ell'} \right) - \overline{F}_{\ell'} \right) \quad [5.7]$$

where similar analogies hold as between [5.6] and [5.3].

This criterion is computed for every $\{\ell\varepsilon\Lambda:\ell\notin\Gamma'_\ell\}$. As above, if $\delta_\ell>0$, then landing ℓ is dropped; otherwise, it is not.

Regardless of whether a cableway ($jk\ell$), yarding system ($k\ell$), or landing ℓ is dropped, the parcels which are "freed" by that action are allocated among the remaining facilities (and any which must be added to retain feasibility) via equation [5.5].

Again, experimentation has shown that the order in which yarding systems or landings are considered for dropping is important, just as it is with cableways. Thus, order criteria are computed for these facilities which are analogous to equation [5.4] for cableways. These criteria are the following:

(a) for yarding systems,

$$O_{k\ell} = -f_{k\ell} + \sum_j \left(-f_{jk\ell} + \sum_{i\varepsilon\Phi_{jk\ell}} \{v_{ijk\ell}\}\right) \qquad [5.8]$$

(b) and for landings,

$$O_\ell = -f_\ell + \sum_k \left(-f_{k\ell} + \sum_j \left(-f_{jk\ell} + \sum_{i\varepsilon\Phi_{jk\ell}} \{v_{ijk\ell}\}\right)\right) \qquad [5.9]$$

These criteria are applied in the same way that equation [5.4] is applied for cableway evaluation.

Although the presentation here has considered cableways first, the current implementation of the algorithm acutally considers dropping landings first, followed by yarding systems and then individual cableways (Figure 19). The purpose of evaluating the facilities in this order is to give "first chance" to dropping those facilities which typically cost the most.

Step 2.3 This step is a decision point from which the algorithm either continues in an attempt to improve the current solution, or exits. If STEP 3 has not been executed at least once, proceed directly to it. Otherwise, if $\Gamma_{jk\ell} = \Gamma_{k\ell} = \Gamma_{\ell} = \{\cdot\}$ (i.e. no facilities were dropped during this pass through STEP 2) and $\Gamma'_{jk\ell} = \Gamma'_{k\ell} = \Gamma'_{\ell} = \{\cdot\}$ (no facilities were added during this pass through STEP 2 or during the previous pass through STEP 3), then exit; otherwise, go on to STEP 3.

STEP 3. In this step facilities which will more than recover their fixed costs are added, and the timber parcels are redistributed among both the new and old facilities in an effort to maximize the total value of those assignments.

The procedure in STEP 2 may add facilities as a consequence of dropping those for which the drop criterion is strictly positive. Where possible, however, it will simply consolidate the allocation of parcels among the facilities established in STEP 1 without adding new ones. Since, as a result of the operations in STEP 2 the structure of initial allocation (which was somewhat arbitrary anyway) may have been changed, it is possible that some facilities have now become attractive candidates for addition. STEP 3 is designed to add any cableway which will improve upon the present solution as measured by the value of the objective function.

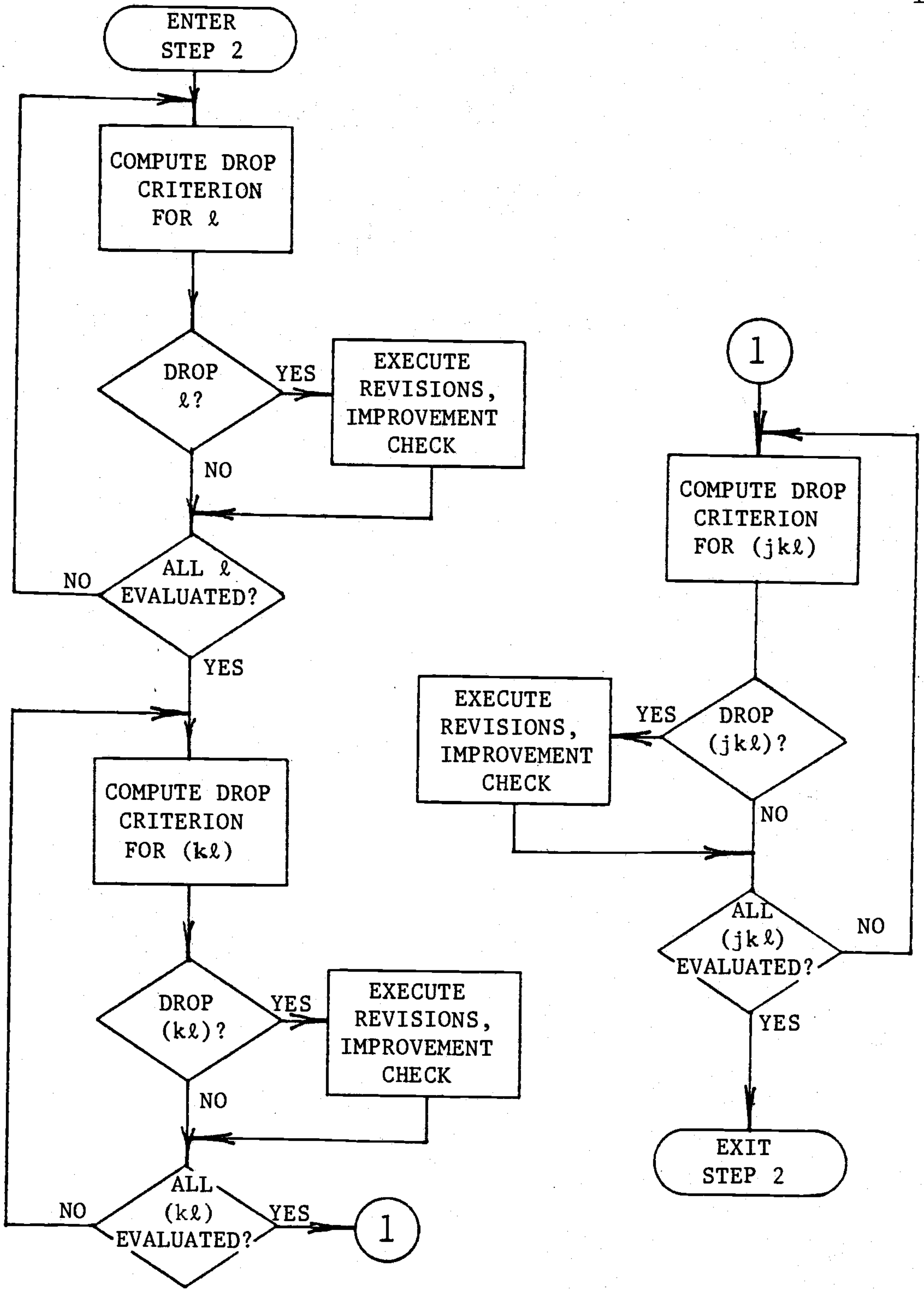

Figure 19. General order of evaluation of facilities during Step 2.

Step 3.1 The procedure at this step is to compute, for all $\{(jk\ell)\varepsilon\underline{U}:(jk\ell)\notin\Gamma_{jk\ell}\}$, an "add criterion", $\alpha_{jk\ell}$, as follows:

$$\alpha_{jk\ell} = -\overline{F}_{jk\ell}+I_{jk\ell}+\sum_{i\varepsilon\Phi'_{jk\ell}}\left\{\max_{(j'k'\ell')\varepsilon\underline{A}}\left[(v_{ijk\ell}-v_{ij'k'\ell'}+\overline{F}_{j'k'\ell'}),0\right]\right\} \quad [5.10]$$

where $\overline{F}_{jk\ell}$ = the incremental fixed cost incurred if facility $(jk\ell)$ is added;

$I_{jk\ell}$ = the improvement in total value due to shifts which could be made via the improvement check (Step 1.3) if facility $(jk\ell)$ were added;

$\overline{F}_{j'k'\ell'}$ = the incremental fixed cost saved by closing some part of facility $(j'k'\ell')$.

If $\alpha_{jk\ell}\leq 0$ for any $\{(jk\ell)\varepsilon\underline{U}:(jk\ell)\notin\Gamma_{jk\ell}\}$, then no apparent improvement can be made in the objective function by adding facility $(jk\ell)$ at present. Therefore, continue computing criterion [5.10] for the remaining facilities to be considered for addition, or, if the list has been exhausted, go on to Step 3.3. If on the other hand $\alpha_{jk\ell}>0$, then it is worthwhile adding facility $(jk\ell)$; therefore, proceed to Step 3.2.

REMARK 3. Note that in [5.10] the maximum is taken over a function similar to that in equation [5.3], except that here those cases are not considered for which the result of $(v_{ijk\ell}-v_{ij'k'\ell'}+\overline{F}_{j'k'\ell'})$ is less than zero. Such cases had to be considered in [5.3], because if the facility in question were to be abandoned, the full consequence of that action would have to be absorbed. The present step, however, is evaluating the possibility of adding a new facility, $(jk\ell)$. If that facility is added, there is no requirement that <u>all</u> of the parcels $i\varepsilon\Phi'_{jk\ell}$ be harvested by means of it. Rather, it only makes good economic sense to assign parcels to the new facility if they will result in an improved solution. In some cases, of course, this may be all of them.

<u>Step 3.2</u> To add any facility $(jk\ell)$ for which $\alpha_{jk\ell}>0$, revise lists $\underline{A}$, $\underline{U}$, Λ, and Π_ℓ. At the same time, remove from these lists the indices of any facilities which can be dropped as a result of adding facility $(jk\ell)$. Then, to redistribute the timber parcels among all current facilities so that total value is maximized, execute the improvement check (Step 1.3), and revise the lists $\Phi_{jk\ell}$. Place the index of the facility added into $\Gamma'_{jk\ell}$ (and update $\Gamma'_{k\ell}$ and Γ'_ℓ, if appropriate); also, place the index of any facility dropped into $\Gamma_{jk\ell}$ $(\Gamma_{k\ell}, \Gamma_\ell)$. Then repeat Steps 3.1 and 3.2 for the remaining $\{(jk\ell)\varepsilon\underline{U}:(jk\ell)\notin\Gamma_{jk\ell}\}$. When the list of $(jk\ell)\varepsilon\underline{U}$ has been exhausted, go on to Step 3.3.

<u>REMARK 4</u>. In contrast to the procedure for considering facilities to be dropped (STEP 2), the algorithm does not explicitly consider the addition of yarding systems $(k\ell)$ or landings (ℓ). Typically, because of the high fixed costs involved, one would not be interested in adding a new landing or yarding system (given a "good" initial feasible solution) unless some other landing or yarding system were simultaneously being dropped. Although the procedure in STEP 3 could manage this kind of switching, STEP 2 was specifically designed to do so (and al-

ready should have, before STEP 3 is reached). In any case, computational experience with the algorithm suggests that facilities are seldom added during STEP 3. Because of the large number of infeasible routes in the forest harvesting problem, the strength of the algorithm seems to rest largely on the quality of actions taken in STEPS 1 and 2, although some minor improvement may occasionally result during the execution of STEP 3.

Step 3.3 In this step the decision is made whether to return to STEP 2 for another pass or to exit with the current solution. As in STEP 2, both sets of indices ($\Gamma'_{jk\ell}$, $\Gamma'_{k\ell}$, Γ'_{ℓ} and $\Gamma_{jk\ell}$, $\Gamma_{k\ell}$, Γ_{ℓ}) must be empty in order to guarantee that the algorithm has found the best solution of which it is capable. Therefore, if both sets of indices are empty, then exit. Otherwise, return to STEP 2.

Implementation

The algorithm presented in this chapter has been coded in FORTRAN IV, and complete computer program listings are included in the Appendix. As with the feasibility and cost analysis programs, these have been tested extensively, and appear to execute correctly. Variable names used in the programs correspond as closely as possible to those used in the preceding section, but some conventions have been changed in order to permit the development of a more efficient code. The programs are well documented, however, and usually any such discrepancies are noted in the listings.

Numerical Example

Consider the example problem of Chapter IV (Table 4). Although a problem of this size can easily be solved with existing integer programming codes, it may be helpful to demonstrate the basic procedure of the algorithm by means of such a problem. Furthermore, the optimal solution to the problem is already known (Table 7), and will serve as a good check on the result obtained with the algorithm. For the purposes of this example, the tableau introduced in Chapter IV will be used to avoid the more laborious procedure of maintaining the lists discussed during the explanation of the algorithm. As will become clear in the example, this tableau actually contains all of the lists implicitly.

Step 1.1

Checking Table 4, note that all parcels can be harvested over at least two cableways. Therefore, as there is no facility which must be established for a feasible solution, go directly to Step 1.4.

Step 1.4

Compute $V^*_{jk\ell}$. Using the format in Table 9, this can be accomplished by summing the parcel values in each column, and then subtracting the total fixed costs which would have to be incurred in order to establish the cableway represented by that column. The result of this operation is a $V_{jk\ell}$ corresponding to each column $x_{jk\ell}$; the appropriate values for the example problem are listed in the bottom row of Table 9.

Table 9. STEP 1.4: FIND $V^*_{jk\ell}$.

Cascading Fixed Charges		x_1				x_2			
		18000				16000			
		x_{11}		x_{21}		x_{12}		x_{22}	
		2000		2200		1800		2000	
		x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}
		1000	800	600	500	1100	700	800	700
Timber Parcels	1	3000	--	800	--	1000	--	--	--
	2	3200	--	1100	--	900	600	800	--
	3	--	1000	--	--	1400	--	1200	--
	4	3500	--	2000	--	--	900	--	1200
	5	600	700	--	--	--	1000	700	900
	6	--	800	--	1200	700	700	700	700
$V_{jk\ell}$		-10700	-18300	-16900	-19500	-14900	-15300	-15400	-15900

↑ $V^*_{jk\ell}$ (arrow points to -10700)

It is important to recognize that since no facilities have yet been established, and since the current step is evaluating the possibility of adding a single cableway, all fixed charges are included in the total for each column. Thus, columns are considered independently. This is equivalent to the operation in equation [5.2], excluding the maximization.

Having obtained all of the column totals, select the column with the largest total. This total is $V^*_{jk\ell}$, and the cableway $(jk\ell)$ should be added. In Table 9, $V^*_{jk\ell} = -10700$, which corresponds to cableway $(_{111})$.

Next, assign to cableway $(_{111})$ all of the parcels which can be harvested by means of that cableway and have not already been assigned to some other facility. In the present step, since no facilities were previously established, each parcel for which a value is listed in column (x_{111}) should be assigned to cableway $(_{111})$. The circled values in Table 10 represent these assignments.

Normally, after executing Step 1.4, the improvement check (Step 1.3) would be executed. In this case, however, only one facility has been assigned. Therefore, no improvements can be made by shifting assigned parcels among assigned facilities, and the algorithm continues by executing Step 1.4 for the remaining unassigned facilities.

Step 1.4, Second Pass

At this point it is helpful to cross out the rows corresponding to parcels which have previously been assigned (Table 11). This is be-

Table 10. STEP 1.4 (Continued): PARCEL ASSIGNMENTS.

Cascading Fixed Charges		x_1				x_2			
		18000				16000			
		x_{11}		x_{21}		x_{12}		x_{22}	
		2000		2200		1800		2000	
		x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}
		1000	800	600	500	1100	700	800	700
Timber Parcels	1	3000	--	800	--	1000	--	--	--
	2	3200	--	1100	--	900	600	800	--
	3	--	1000	--	--	1400	--	1200	--
	4	3500	--	2000	--	--	900	--	1200
	5	600	700	--	--	--	1000	700	900
	6	--	800	--	1200	700	700	700	700

Table 11. STEP 1.4, SECOND PASS.

Cascading Fixed Charges	x_1				x_2			
	18000				16000			
	x_{11}		x_{21}		x_{12}		x_{22}	
	2000		2200		1800		2000	
	x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}
	1000	800	600	500	1100	700	800	700
Timber Parcels 1	3000	--	800	--	1000	--	--	--
2	3200	--	1100	--	900	600	800	--
3	--	1000	--	--	1400	--	1200	--
4	3500	--	2000	--	--	900	--	1200
5	600	700	--	--	--	1000	700	900
6	--	800	--	1200	700	700	700	700
$V_{jk\ell}$	--	+800	$-\infty$	$-\infty$	-16800	-17800	-16900	-18000

↑

$V^*_{jk\ell}$

cause equation [5.2] considers only parcels which have not yet been assigned to some facility. Next, compute the $V_{jk\ell}$ for each column, adding only the $v_{ijk\ell}$ for rows which have not been crossed off. In this case, one facility (including a cableway, yarding system, and landing) has already been assigned. Therefore, for any column affected by that assignment, subtract only the incremental fixed charge which would have to be incurred in order to establish the facility corresponding to the column. In the example, columns affected by the previous assignment are (x_{211}), (x_{121}), and (x_{221}). Two of these, however, correspond to yarding system $(_{21})$, whereas the yarding system currently assigned to landing $(_1)$ is $(_{11})$. Thus, those facilities cannot be added; assign a value of $-\infty$ to their $V_{jk\ell}$. Select $V^*_{jk\ell}$, as before. In Table 11, $V^*_{jk\ell} = +800$, which indicates that cableway $(_{211})$ should be added next.

Assign to cableway $(_{211})$ all of the parcels having values listed in column (x_{211}) and which have not been crossed off. The resulting assignment, including all previous assignments, is shown in Table 12. Next, execute the improvement check.

Improvement Check (Step 1.3)

For each parcel which has been assigned to a facility, select the largest $v_{ijk\ell}$ which corresponds to that parcel and is listed in one of the assigned columns. This is the v^*_i corresponding to parcel i. Enter its value in the rightmost column of Table 12, row i.

Check the circled $v_{ijk\ell}$ in each row against the v^*_i for the same

Table 12. STEP 1.4, SECOND PASS (Continued): PARCEL ASSIGNMENTS AND v_i^*.

Cascading Fixed Charges		x_1				x_2				
		18000				16000				
		x_{11}		x_{21}		x_{12}		x_{22}		
		2000		2200		1800		2000		
		x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}	v_i^*
		1000	800	600	500	1100	700	800	700	
Timber Parcels	1	(3000)	--	800	--	1000	--	--	--	3000
	2	(3200)	--	1100	--	900	600	800	--	3200
	3	--	(1000)	--	--	1400	--	1200	--	1000
	4	(3500)	--	2000	--	--	900	--	1200	3500
	5	(600)	700	--	--	--	1000	700	900	700
	6	--	(800)	--	1200	700	700	700	700	800

row. If for any row the v_i^* is greater than the circled value, then a better assignment exists for that parcel among the currently assigned facilities. Therefore, reassign the parcel to the column corresponding to the v_i^*. In Table 12, the only such reassignment indicated is for parcel 5; it should be reassigned to cableway ($_{211}$).

Table 13 shows the current solution at the end of the improvement check. Note that all of the parcels have been assigned to some facility. Therefore, the initialization process is complete; an initial feasible solution has been obtained.

At this point, the algorithm would proceed to Step 2. The operations in Steps 2 and 3 are simple to perform, but would require considerable space to demonstrate and are therefore not detailed here. For this problem, in fact, the drop and add criteria in Steps 2 and 3 all turn out to be negative. Therefore, no facilities are dropped or added, and the algorithm terminates with the solution in Table 13. Checking Table 7, it is evident that in this case the algorithm found the optimal solution during the initialization step. For small problems, this is often the case. In fact, for all of the (small) problems tested, the initial feasible solution was optimal. This was somewhat of a problem during the testing of the algorithm, as initial feasible solutions which were not optimal had to be input manually in order to create a situation upon which Steps 2 and 3 could act. For large problems, of course, there is no reason to believe that the initial feasible solution would be optimal. At any rate, the algorithm does not recognize optimality as such; it can only recognize the fact that

Table 13. REVISED SOLUTION AFTER THE IMPROVEMENT CHECK.

Cascading Fixed Charges		x_1				x_2			
		18000				16000			
		x_{11}		x_{21}		x_{12}		x_{22}	
		2000		2200		1800		2000	
		x_{111}	x_{211}	x_{121}	x_{221}	x_{312}	x_{412}	x_{322}	x_{422}
		1000	800	600	500	1100	700	800	700
Timber Parcels	1	3000	--	800	--	1000	--	--	--
	2	3200	--	1100	--	900	600	800	--
	3	--	1000	--	--	1400	--	1200	--
	4	3500	--	2000	--	--	900	--	1200
	5	600	700	--	--	--	1000	700	900
	6	--	800	--	1200	700	700	700	700

no apparent further improvement in the objective function is possible. Thus, even if the initial feasible solution is optimal, the algorithm continues through an execution of Steps 2 and 3 before terminating.

Computational Experience

Many publications describing algorithms for solving facilities location problems include the results of extensive computational experience. Recently, in fact, there have been efforts to standardize the test problems which are solved; Geoffrion (1969), for example, has described about 30 all-integer (0-1) programming problems which have been used by numerous authors for computational testing. Certainly there are advantages to such standardization, particularly when generalized algorithms are being tested. In the present case, however, the algorithm has been developed to solve a specific class of problems which has not previously appeared in the literature. To provide extensive computational experience, therefore, numerous problems similar to the example on the preceding pages would have to be generated and solved. Such problems are too small to be of practical use in forest management, however, and the approach here has therefore been to concentrate instead on the solution of a single problem of practical size, which is presented in the next chapter. For the purpose of developmental testing, of course, several small problems similar to the example above were solved with the algorithm; the average computation time on the CDC 3300 for those problems was about 6 seconds. The optimal solution was obtained in all cases. Computation times for the integer programming algorithm described in Chapter IV to verify the optimal solution averaged about 35 seconds. All of the problems were fundamentally similar, and contained between 35 and 45 variables. The number of constraints for such problems is always related to the number of variables by the expression in equation [4.17].

VI. APPLICATION OF THE METHODOLOGY

As this study has been directed primarily at the development of a methodology to assist in the planning of forest harvesting operations, it will be useful to apply the methodology to an actual planning area in order to demonstrate both its capabilities and its limitations. For this purpose a portion of the Harvey Creek watershed on the Siuslaw National Forest, near Reedsport, Oregon, has been selected (Figure 20). The planning area itself consists of two small drainages which are tributary to the North Fork of Harvey Creek (Figure 21). Access to the area, which is about 262 acres in size, is by means of the primary road shown in Figure 21 (F.S. 2138 in Figure 20). Secondary roads indicated in Figure 21 are included in the transportation plan of the Siuslaw National Forest, but have not actually been constructed. The timber on the area, which is entirely unharvested, varies from young-growth to old-growth, with most of the area being occupied by fairly large second-growth Douglas-fir (Figure 22 and Table 14). The area of the Oregon Coast Range in which the planning area resides is commonly called the "Smith-Umpqua Block" as it lies near the confluence of the Smith and Umpqua Rivers (Figure 20). It is characterized by deeply dissected landforms, highly unstable soils, and large, commercially attractive timber (McNutt, 1976). Because of the instability of its soils, all harvest operations in the area were suspended in 1970 subject to the development of an environmentally acceptable harvest plan. Such a plan would limit road construction to a low-density, ridgetop

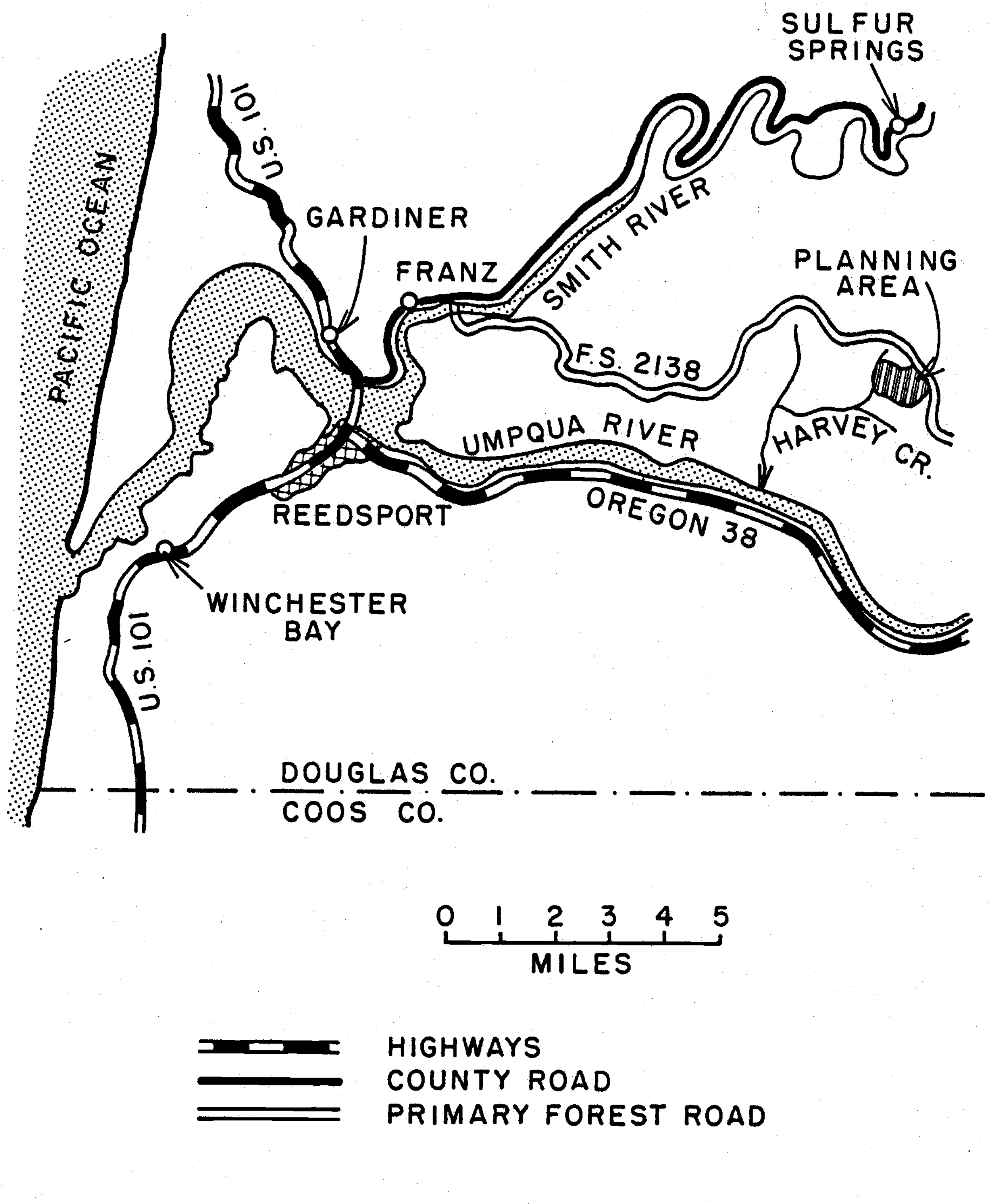

Figure 20. Location of the planning area (Siuslaw National Forest, Oregon).

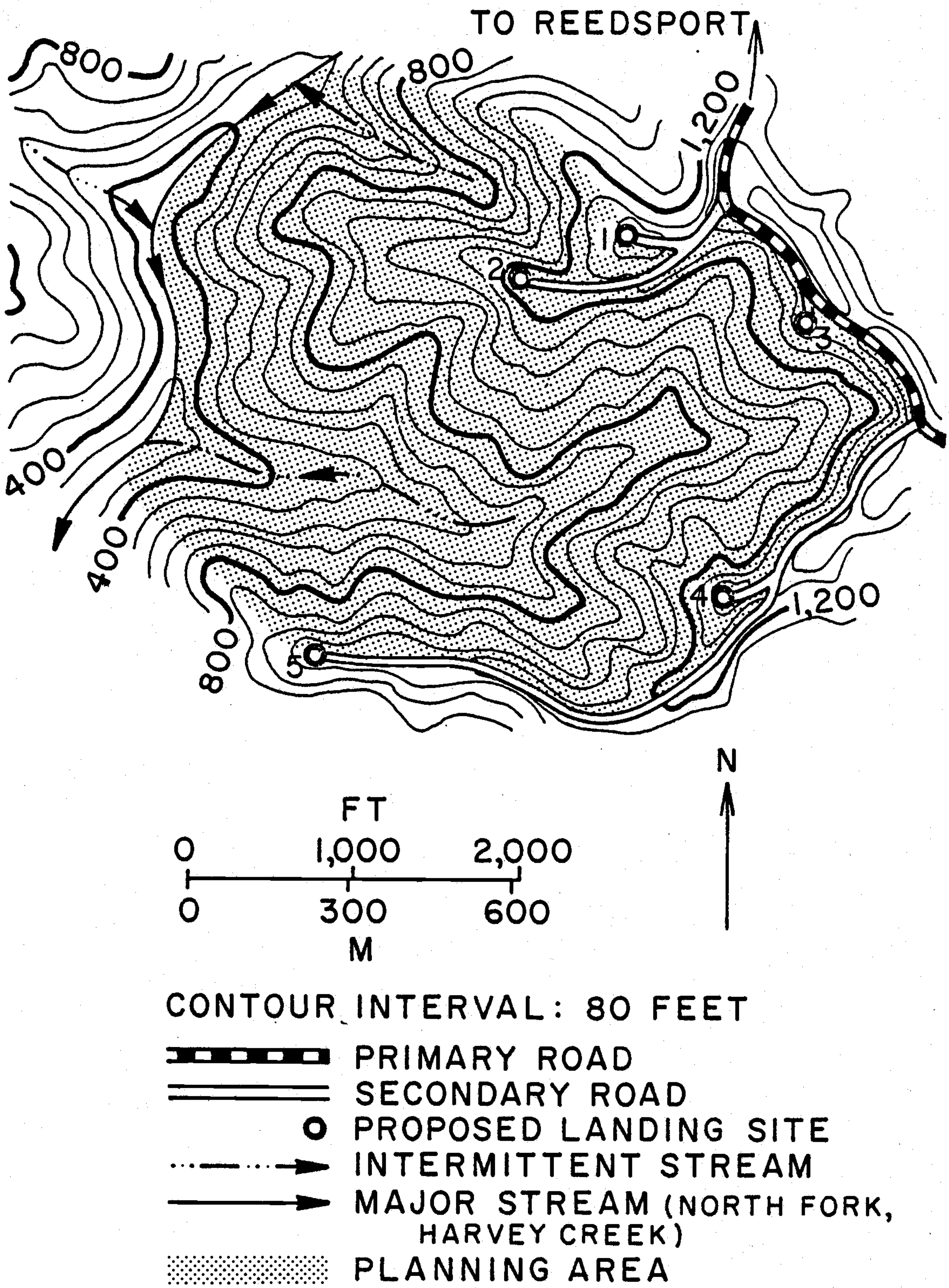

Figure 21. Topographic map of the planning area.

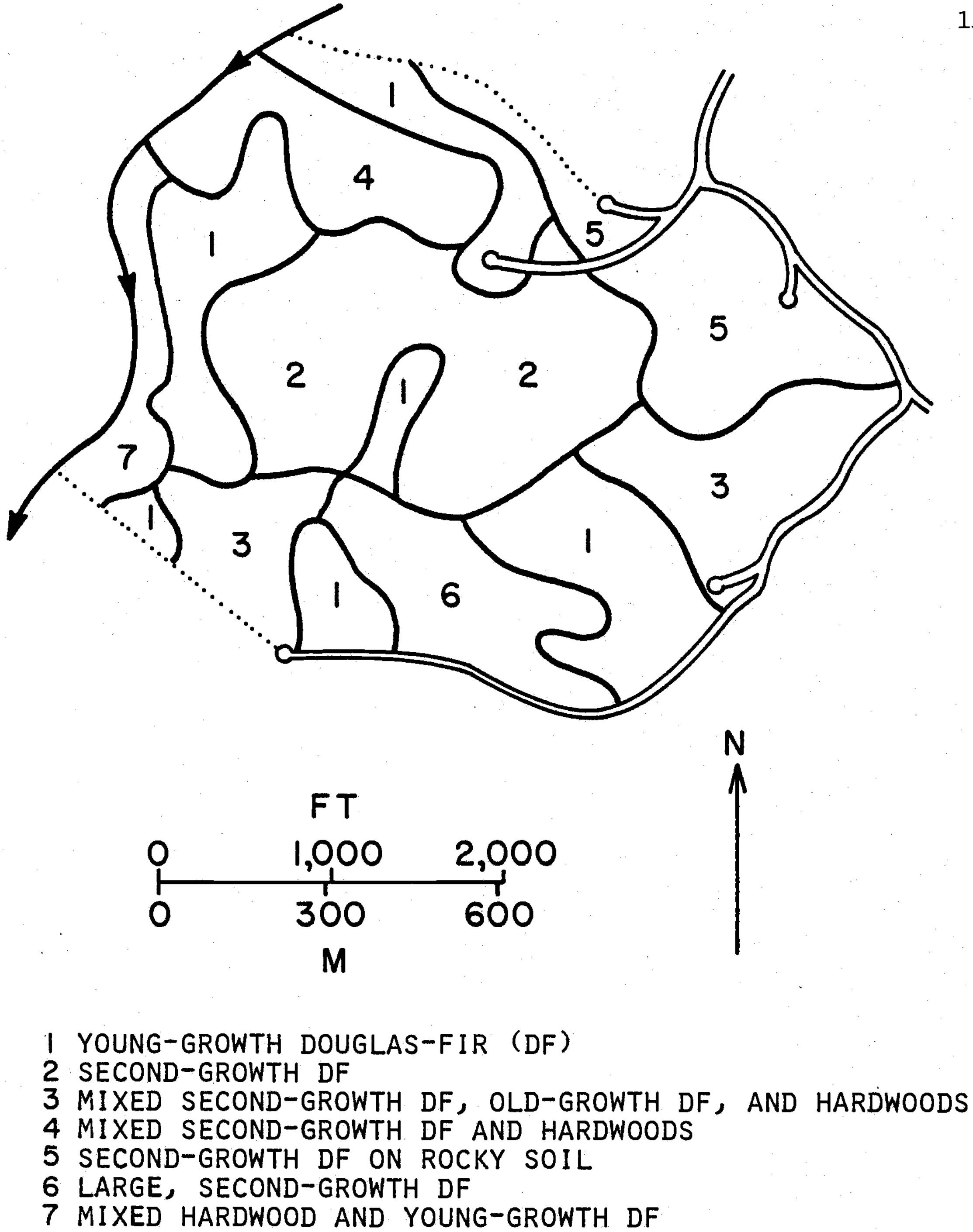

Figure 22. Vegetative type map of the planning area.

Table 14. DESCRIPTION OF VEGETATIVE TYPES ON THE PLANNING AREA.

Attribute	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7
Area Covered (ac)	73	67	37	22	35	21	7
Site Class[1]	III	IV	IV	IV	III	III	V
Stand Age (years)	85	125	125	75	105	75	55
Trees per acre	90	91	52	81	54	79	91
Logs per tree[2]	2.5	3.0	3.5	1.0	3.0	2.5	2.5
Average DBH[3] (inches)	17	22	25	20	20	26	18
Maximum DBH (inches)	40	66	78	60	42	64	76
Volume per acre (fbm/ac)	30500	63200	69600	21500	31500	59200	33800
Volume per log (fbm/log)	140	230	380	260	190	300	150
Wood Density (lbs/fbm)	8.5	8.5	8.5	8.5	8.5	8.5	8.5

[1]Site Class is an index of the relative capacity of an area for timber production. Site I is the highest classification; Site V is the lowest.

[2]A "log" is assumed to be 32 feet in length.

[3]DBH = tree diameter, measured outside the bark, at breast height (about 4-1/2 feet above the ground).

network such as that shown in Figure 21, and would insure that the harvesting systems used would be capable of full or partial suspension of logs, as prescribed, in the vicinity of streams or areas of unstable soils (McNutt, 1976). Thus, the area appears well suited to the kind of analysis developed in the present study. An additional consideration of some importance is the fact that the Siuslaw National Forest has recently completed the collection and organization of a physical data base for the Harvey Creek watershed which is sufficient to provide the kind of information needed for the methodology described in this study.

Fixed Grid Mapping

To describe the planning area digitally, a 100-foot fixed grid was superimposed over the area. The average elevation, vegetative type, and an appropriate physical feature were then recorded for each of the resulting 10,000-square-foot parcels. Figure 23 illustrates this method for the physical features. Note that a buffer strip has been provided along the major stream, and that both full and partial suspension ("restricted yarding") have been specified along portions of the two tributary streams. The rectangular boundary in Figure 23 shows the limits of the fixed grid matrix which was required in order to describe the irregularly shaped planning area. The entire matrix contains 40 rows and 55 columns; part of a summary table from the matrix is given in Table 15. It is interesting to note that the digital map had to be extended several hundred feet to the west of the major stream. This was necessary in order

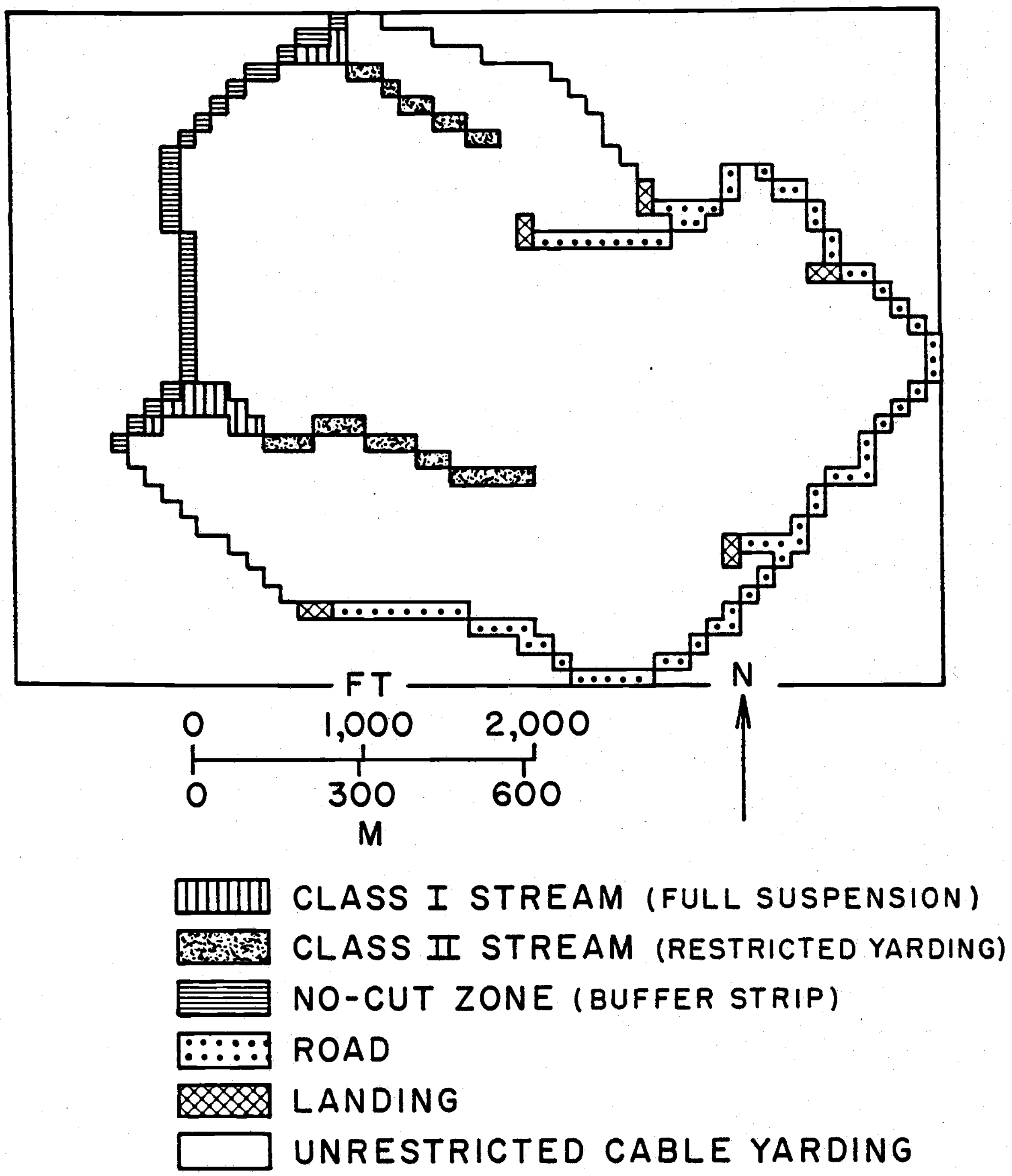

Figure 23. Fixed grid representation of the physical features on the planning area.

Table 15. PORTION OF A SUMMARY TABLE FOR THE PLANNING AREA DATA MATRIX.

Matrix[1]		Elevation	Vegetative Type[2]	Physical Feature[3]
Row	Column			
3	16	430	99	0
3	17	430	4	3
3	18	460	4	1
4	21	500	4	2
5	30	1020	5	99
11	38	1370	5	5
11	43	1300	5	4

[1]Entries have been extracted from the matrix in order to demonstrate nomenclature and convention; they are not in order.

[2]Vegetative type codes correspond to those in Figure 22, except that code 99 indicates that the parcel is outside of the planning area (i.e. it is not to be harvested).

[3]Physical feature codes are as follows:

0 = parcel is outside of the planning area
1 = full-log suspension is required over this parcel
2 = partial suspension of logs is required over this parcel
3 = parcel is a buffer strip or other no-cut area within the planning area
4 = road
5 = landing
99 = ground skidding of logs is permitted

to provide data for tailholds to be located on the hillside above the stream in the manner suggested earlier in Figure 6. As a result, the physical land area which had to be described in order to "cover" the 262-acre planning area is actually 505 acres. Methods exist for reducing the storage requirements occurring in such cases (see, for example, Amidon and Akin, 1971), but these have not been investigated in the present study.

Yarding System Alternatives

The yarding systems selected for study in this application are of three basic configurations: highlead, running skyline, and live skyline. Specifically, the four yarding systems considered are as follows:

1. Madill 071 West Coast Tower[12] (highlead) -- a medium-sized (284 hp), mobile yarder with a vertical, steel tube tower, mounted on a self-propelled crawler. Although the 071 is by design a live skyline yarder, it is frequently operated in highlead configuration.

2. Smith-Berger Marc V (running skyline) -- a medium-sized (300 hp), mobile yarder with an inclined, swinging boom, mounted on a self-propelled, rubber-tired undercarriage.

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[12] The use of trade names in this paper is for information only and does not imply endorsement.

3. Skagit BU-199/T-110HD (live skyline) -- a heavy (556 hp) yarder with a vertical, steel tube tower, mounted on a self-propelled, rubber-tired undercarriage.

4. Skagit BU-90/T-90 (live skyline) -- a heavy (510 hp), trailer-mounted yarder with a vertical, steel tube tower.

The choice of these yarding systems is somewhat arbitrary, as many similar systems could be selected which might operate as well under the conditions specified for the planning area. The four systems selected, however, have recently been the subject of detailed time studies (Dykstra, 1975; Van Winkle, 1976a), and the data which are available for them are therefore more comprehensive than those which are normally available for comparable systems. A summary of the data pertinent to this study is contained in Table 16. Supporting cost information and calculations are included in the Appendix. The yarding regression coefficients listed in Table 16 were adapted from Dykstra (1975) and Van Winkle (1976a). The cableway emplacement parameters and delay coefficients (also in Table 16) are based upon analyses by Van Winkle (1976b) and McGonnagill (1975).

Table 17 summarizes the maximum expected number of logs per turn, which is a function of both yarding system and timber type. These values were estimated by considering the lateral yarding capabilities of each yarding system (Table 16) and the distribution of trees in each timber type (Table 14). Other data in Table 17 relate to the proposed landing sites, which are shown in Figure 21. Detailed calculations

Table 16. YARDING SYSTEM DATA FOR THE ACTUAL APPLICATION.

Attribute	Yarding System			
	1	2	3	4
System Type	Highlead	Running Skyline	Live Skyline	Live Skyline
Maximum Reach (ft)	965	2000	3950	2000
Maximum Lateral Reach (ft)	50	150	200	200
Mainline Unit Weight (lbs/ft)	1.42	2.14	1.85	1.04
Haulback Unit Weight (lbs/ft)	1.04	--	1.04	0.72
Skyline Unit Weight (lbs/ft)	--	1.42	2.89	2.34
Maximum Safe Tension (lbs)	26500	26500	53300	43300
Butt Rigging or Carriage Weight (lbs)	300	850	3500	3500
Spar Height (ft)	50	50	110	90
Maximum Tailtree Height (ft)	0	100	100	100
Full Suspension Clearance (ft)	0	50	50	50
Partial Suspension Clearance (ft)	0	20	20	20
Minimum Acceptable Turn Volume (fbm)	200	200	200	200
Total Yarding System Cost ($/hr)	74.54	92.09	115.51	96.58
System Installation Cost ($)	600	800	3195	925
Cableway Emplacement Parameters:				
α_0(min) } equation [3.26]	5.2	18.1	20	10
α_1(min/ft) } equation [3.26]	0.023	0.015	0.05	0.04
α_2(min/ft) } equation [3.26]	--	0.208	0.166	0.200
α_3(min) } equation [3.26]	10	15	20	20
Yarding Regression Coefficients:				
β_0(min) } equation [3.19]	3.6953	3.1905	2.4973	4.8252
β_1(min/fbm) } equation [3.19]	2.8797×10^{-3}	1.0030×10^{-3}	2.4064×10^{-4}	6.0306×10^{-4}
β_2(min/fbm) } equation [3.19]	-4.0344×10^{-3}	-1.0625×10^{-3}	-1.1453×10^{-4}	1.3634×10^{-4}
β_3(min/ft) } equation [3.19]	1.6996×10^{-3}	2.3369×10^{-3}	1.9075×10^{-3}	1.4618×10^{-3}
β_4(min/ft) } equation [3.19]	0	1.1857×10^{-2}	1.6689×10^{-2}	1.8331×10^{-2}
β_5(min/log) } equation [3.19]	0	0	5.3080×10^{-3}	8.9508×10^{-2}
β_6(min/pct) } equation [3.19]	0	0	7.3780×10^{-3}	0
Delay Coefficient	1.15	1.20	1.25	1.20

Table 17. ADDITIONAL DATA FOR THE ACTUAL APPLICATION.

A. Data Related to Timber Type

	Timber Type						
	1	2	3	4	5	6	7
Maximum Expected Logs Per Turn:							
Yarding System 1	3	3	2	2	2	2	3
Yarding System 2	4	4	2	3	2	3	4
Yarding System 3	6	6	3	5	3	4	6
Yarding System 4	6	6	3	5	3	4	6
Delivered Log Price[1] ($/Mfbm)	125	150	170	125	135	155	125

[1]Estimated after McNutt (1976).

B. Landing Data[2]

	Landing				
	1	2	3	4	5
Landing and Spur Road Construction Cost ($)	18,810	52,260	11,750	14,200	106,850
Estimated Hauling Cost to Mill ($/Mfbm)	11.73	11.87	11.77	12.08	12.60
Location of Spar on Fixed Grid (Row, Column)	(12,38)	(13,31)	(16,48)	(32,43)	(36,18)

[2]Calculations and supporting data are given in the Appendix.

supporting those data are also included in the Appendix.

Logging Feasibility and Cost Analysis

Figure 24 illustrates the feasible cableway alternatives which were isolated as a result of the logging feasibility and cost analysis for this application. Numerous cableway locations in addition to those shown were tested, but proved to be infeasible. The alternatives were initially laid out on a topographic map by considering yarding system capabilities and terrain configuration, and were then appraised for apparent feasibility by field visits to the site. The feasibility and cost analysis programs were then run to confirm or reject feasibility, and to estimate timber parcel values. No claim is made that these are the "best" alternative cableways with which to enter the optimization. Another analyst working from the same data base would most likely compile an entirely different set of alternatives.

Because of its length (more than 100 computer printout pages), the complete feasibility and cost analysis for the application is not included here. A brief summary of the results, however, is as follows:

1. Because of the long spans required to obtain satisfactory deflection for many of the cableway alternatives at landings 2 and 5, only the long-reach system (BU-199) can be installed at either of those landings. Note that many of the cableways for those landings had to be anchored outside of the planning area itself (Figure 24).

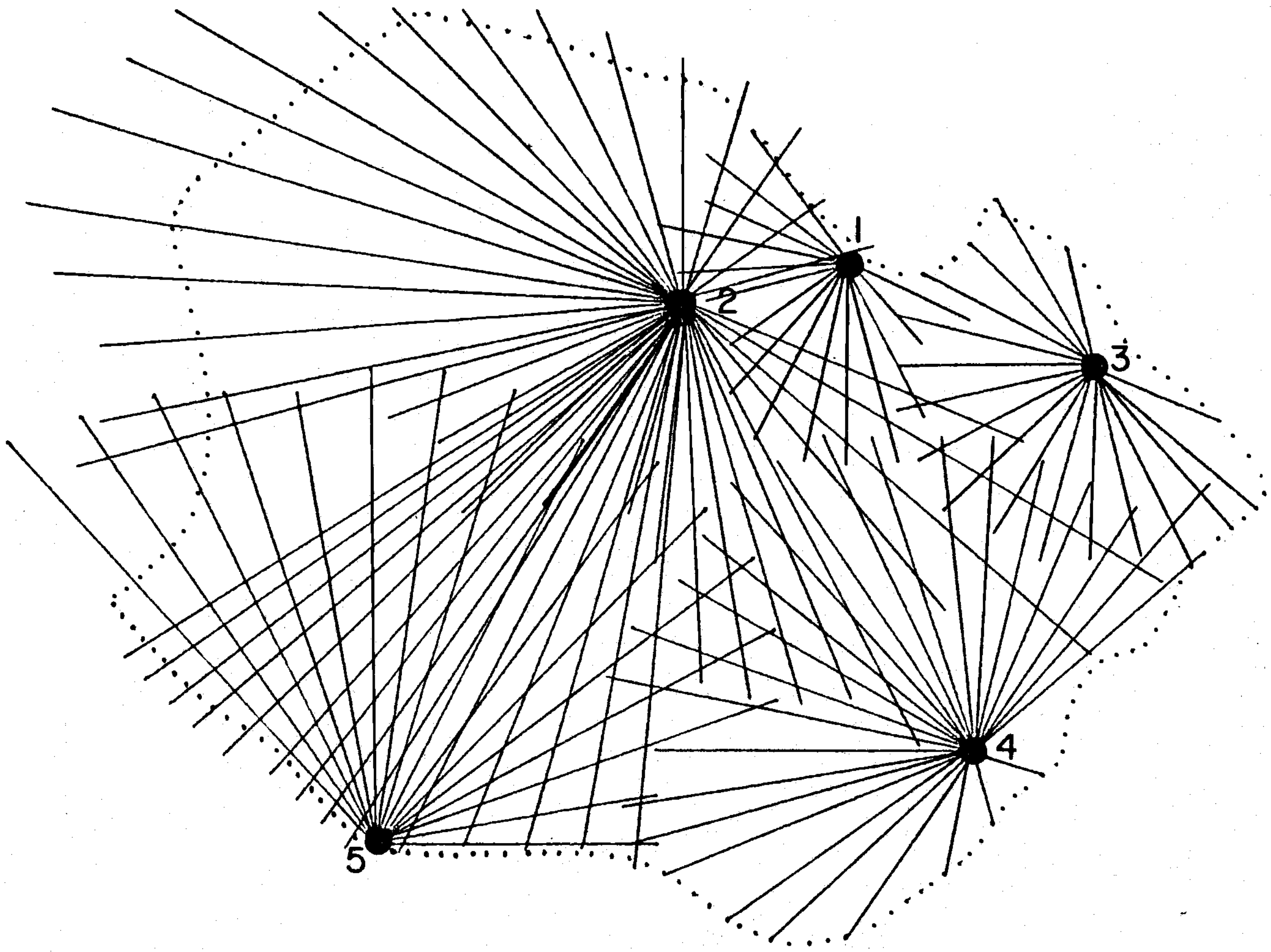

Figure 24. Feasible cableways investigated on the planning area.

2. The cableway alternatives at landings 1, 3, and 4 would be feasible for any of the skyline systems. However, a ground reconnaissance of the area indicated that the terrain at those sites is such that none of those landings could be made large enough to accommodate the BU-199 without a high risk of soil failure. The same is true of landings 1 and 3 for the BU-90, which is somewhat smaller than the BU-199 but still considerably larger than either of the other two systems.

3. Terrain conditions on the planning area are such that the highlead system can only be placed at landings 1 and 3 if the entire planning area is to be harvested. If the highlead system were placed at landing 4, as an example, an area of about 5 acres between landings 4 and 5 could not be harvested at all. This is due primarily to the limited reach of that system, which is less than half the capability of the skyline systems (Table 16).

As a result of this analysis, data prepared for entry into the heuristic optimization procedure were limited to the following alternatives:

1. Landing 1 -- <u>Madill</u> (highlead): 10 feasible cableways;
   <u>Marc V</u> (running skyline): 9 feasible cableways.

2. Landing 2 -- <u>BU-199</u> (live skyline): 48 feasible cableways.

3. Landing 3 -- Madill: 2 feasible cableways;

   Marc V: 13 feasible cableways.

4. Landing 4 -- Marc V: 24 feasible cableways;

   BU-90 (live skyline): 23 feasible cableways.

5. Landing 5 -- BU-199: 15 feasible cableways.

The number of timber parcels which could be harvested over each cableway is a function of cableway length and the lateral yarding capability of the individual yarding system. For this application, as few as 4 and as many as 128 parcels could be harvested over individual cableways. A total of 5350 harvesting alternatives were segregated for the 1048 parcels on this planning area; thus, each parcel could be harvested, on the average, by means of 5 different cableways. As there are 144 feasible cableways, 8 yarding system/landing combinations, and 5 landings, the mathematical programming formulation of this problem would require 5507 decision variables and 6555 constraints (see equations [4.16] and [4.17]).

Total computer time for the feasibility and cost analysis was 15.1 minutes on the CDC 3300. This figure includes time for data entry and line printer output as well as computation time. An additional 6.3 minutes of computation time were required to prepare random access data files for use by the heuristic algorithm (see program RNDFILES in the Appendix).

Improvement Algorithm

Computation Times

An initial feasible solution was obtained with the CASCADE algorithm after 93.3 minutes of computation time. Subsequently the algorithm entered Step 2 (the "drop" step), and during the first pass dropped one cableway from the solution. No landings or yarding systems were dropped. Prior to completing a single pass through Step 2, however, the job was terminated at 26.7 minutes after initiation because all of the computer time budgeted for the project had been expended. Judging from the progress of the algorithm to that point, however, it appears unlikely that any significant improvement would have been made during subsequent passes. The one improvement that was made resulted in only a 0.09 percent increase in the objective function. Because of the way the "drop criterion" is evaluated (see Chapter V), the first change that is made to the initial feasible solution is the one which will cause the greatest total improvement in the objective function. At a rate of less than 0.09 percent per improvement, it would take a great many changes to significantly influence the value of the objective function.

This result was not altogether unexpected. As mentioned earlier, for all of the small test problems the optimal solution was found during initiation. It was very unlikely, of course, that for problems of practical size an initial feasible solution would be found that could not be improved. Because of the fact that the initiation routine was structured to consider not only parcel values but also the cascading effect of fixed charges in the problem, however, it should always find an initial feasible solution that is very good. Furthermore, Cooper (1964) has observed that for location-allocation problems in general, the total cost curve is often very flat in the vicinity of the minimum. Therefore, one would expect that, given an initial feasible solution somewhere on the flat portion of the curve, only small improvements could be made thereafter. Similarly, Pierce (1968) has remarked that for mathematical programming approaches to such problems, a large portion of the total computation time is commonly expended in proving optimality, whereas either the optimal solution, or one quite close to it, may have been obtained at an early stage in the computations.

Case Study Results

The best assignment of timber parcels to landings for the case study area, as computed by the heuristic algorithm, is shown in Figure 25. Also shown are the locations of the 62 cableways which were selected for assignment from among the 144 feasible alternatives considered. A portion of the computer output for the solution is shown in Table 18, and a summary of results is contained in Table 19. Although these results would be most meaningful in the context of alternatives proposed for the same planning area, several useful observations can be made:

1. The cutting units designed by the heuristic algorithm are

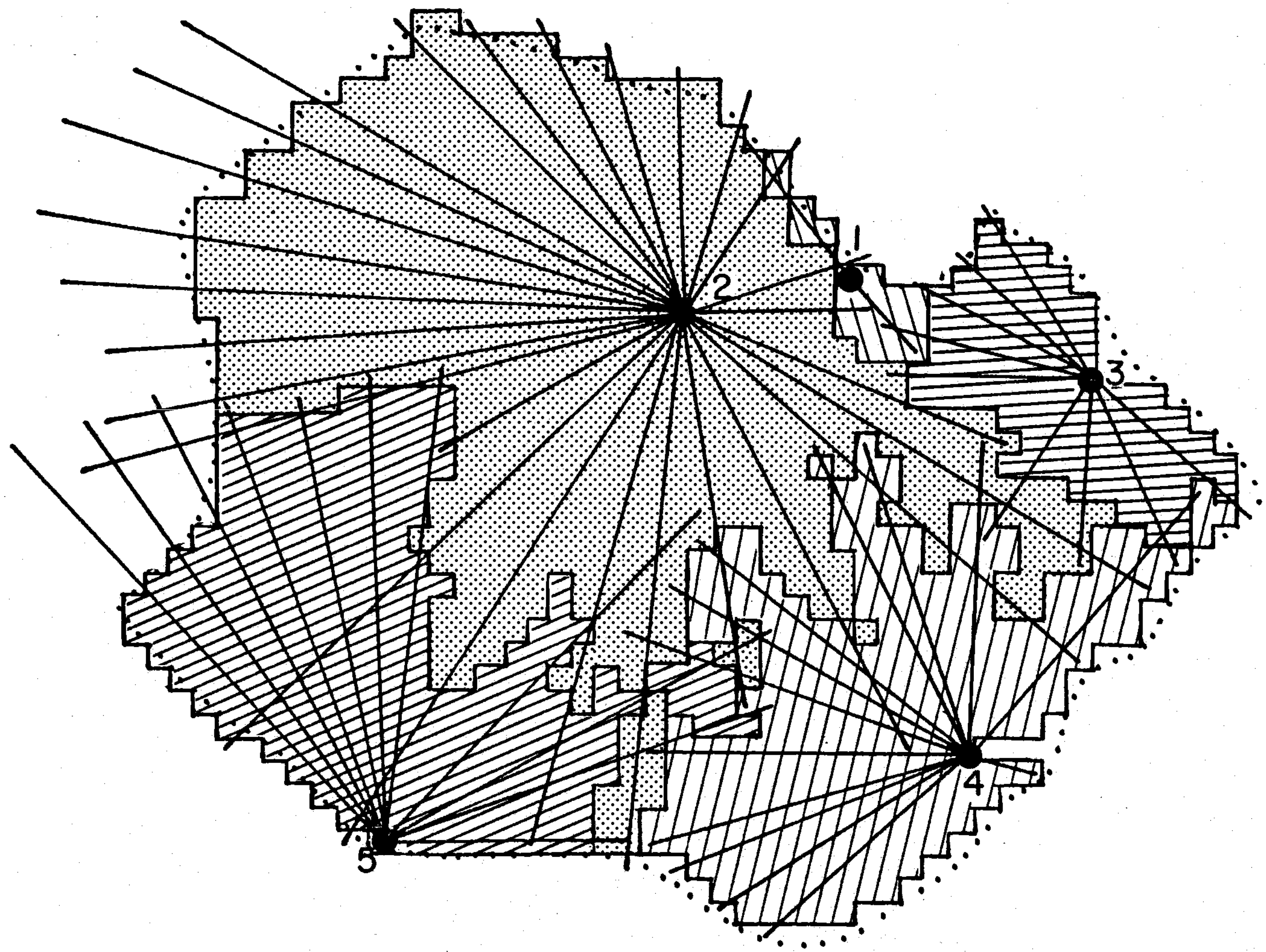

Figure 25. Best assignment of cableways and timber parcels on the case study area as determined by the heuristic algorithm.

Table 18. A PORTION OF THE COMPUTER OUTPUT FROM THE IMPROVEMENT ALGORITHM.

```
CURRENT SOLUTION REPORT -- CASCADE ALGORITHM
============================================

LANDINGS    FIXED     YARDING SYSTEM    FIXED
OCCUPIED    COST         ASSIGNED       COST
--------    -----     --------------    -----

    1       18810           2             800
    2       52260           3            3195
    3       11750           2             800
    4       14200           4             925
    5      106850           3            3195

============================================


SUMMARY OF CABLEWAY/PARCEL ASSIGNMENTS
-----------------------------------------------------------


CABLEWAY   11

    ANCHOR=( 6,34); TAILTREE= 25 FT; EMPLACEMENT COST=$  53
    LANDING= 1; YARDING SYSTEM= 2

    PARCEL    NET VALUE
    ------    ---------

    ( 7,35)      635
    ( 8,35)      703
    ( 9,36)      715
    (10,36)      727
    (10,37)      727
    (11,38)      743

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(similar reports would follow for all other assigned cableways)

Table 19. SUMMARY OF THE HEURISTIC ALGORITHM RESULTS FOR THE CASE STUDY APPLICATION.

Item	Costs $	Costs $/Mfbm[1]
Total mill value of all parcels[2]	1,781,490	147.34
-Estimated yarding costs	241,225	19.95
-Estimated hauling costs	146,085	12.08
-Landing and spur road construction costs	203,870	16.86
Estimated in-place timber value[3]	1,190,310	98.44

[1]Total timber volume on the planning area (calculated from the data in Table 14) is 12,091.4 Mfbm.

[2]Calculated from the data in Tables 14 and 17.

[3]This figure cannot be compared directly with the commonly used "stumpage value" unless other relevant costs are subtracted. These include such items as reforestation, slash disposal, and administration costs.

quite large, even for an industrial forest harvesting operation. The unit at Landing 2, for example (see Figure 25), covers an area of approximately 129 acres; the units at Landings 4 and 5, about 53 and 58 acres, respectively. Cutting unit size, however, is a function of the number of potential landing sites on the planning area. For this application, the existing transportation plan for the area was used without alteration, and only five landing sites were considered available. Thus, it should have been expected a priori that the resulting cutting units would tend to be large.

2. Estimated yarding costs for the solution are surprisingly low, given the long-reach skyline units specified for most of the area. A recent yarding appraisal guide developed by the Bureau of Land Management (1972) lists estimates of \$30/Mfbm to \$45/Mfbm for long-reach skyline yarding under conditions similar to those on the study area. This result has two implications. First, because the analysis considers varying topographic and timber conditions over the entire planning area, much better cost data are developed than is possible with conventional procedures which use estimates of average conditions. Second, the improvement algorithm attempts to find the total assignment of timber parcels to facilities which will maximize the value of those parcels. Often, this will also be the assignment that minimizes yarding costs. For the case study, the algorithm appears to at least have been effective in finding a solution for which yarding costs are far below those that would have been expected.

3. The highlead alternative was not selected for either of the landings at which it could have been emplaced. This is not a judgment on the general applicability of highlead yarding, but rather an observation that for the specific conditions encountered on this study area, expected fixed and variable costs for the running skyline are less than those for the highlead. This could be due to any of a large array of factors, and it is not possible to say with certainty why the running skyline was selected for both landings in spite of its significantly higher hourly cost (Table 16). Inspection of the feasibility and cost analysis results for both systems, however, suggests a slightly higher load capability for the running skyline. In addition, the lateral yarding capability of the running skyline permits a higher expectation of logs per turn for that system than for the highlead (Table 17). The combination of these two factors gives a slightly lower yarding cost estimate for the running skyline on many of the cableways for which both systems were considered. This conclusion should _not_ be generalized, however; to a considerable extent it is undoubtedly dependent upon the capabilities and costs of the specific yarding machinery considered. The Madill 071, for example, is actually a live skyline yarder rather than a highlead yarder. It was used for the highlead alternative in this study because highlead yarding data with that system were available from previous studies (Dykstra, 1975). An analysis involving a more conventional (and cheaper) highlead yarder, however, might give entirely different results.

4. It was somewhat surprising that Landing 1 was assigned at all,

since the cutting unit associated with that landing is too small to recover all of the landing and spur road construction costs. On close inspection of the feasibility and cost analysis results, however, it is evident that two of the 1/4-acre parcels could not be harvested by any other landing. Therefore that landing had to be established in order to obtain an initial feasible solution. Had some other alternative been available for harvesting those two parcels, Landing 1 would not have been established. Therefore, the expenditure of some effort to find such an alternative would pay off in a sizeable reduction in fixed charges.

5. A result which will probably be of considerable interest to forest managers, and to landscape architects as well, is the fact that the cutting units designed by the heuristic algorithm are quite irregular in shape, particularly where the terrain is most dissected. This is a direct refutation of a principle to which foresters have long adhered: that the "most efficient" cutting unit design is geometric (either rectangular or circular) in shape. Again, any temptation to generalize this result should be resisted. Where slopes are uniform, in fact, the cutting boundaries produced by this methodology will almost certainly be uniform themselves; the unit at Landing 3 (Figure 25) is an illustration of this. In areas of uneven terrain, however, the most efficient design is likely to feature irregular boundaries.

Suggestions for Application of the Methodology

Although the solution obtained by applying the CASCADE algorithm may be very near the economic optimum for a given planning area, it should be considered only a "first approximation" to the eventual timber harvest plan for the area. The prescribed plan should be scrutinized closely, realizing that it has been developed by using an abstraction from reality which is admittedly idealized. As an example, the solution may show islands of timber which would have to be yarded through standing trees (see Figure 25). If this is undesirable, or if it is expected to significantly increase yarding costs, then the cutting unit boundaries should be revised. Because of the structure of the methodology, any such revisions can be incorporated easily by changing parcel assignments in the appropriate random access files (see the discussion of file structures in the Appendix). The result of these changes on the total expected value of the planning area can then be computed directly without having to re-run the CASCADE algorithm. Thus, "sensitivity analysis" is greatly facilitated.

Similarly, changes to unit boundaries may be desired in order to enhance aesthetics. Whenever such changes are made, the "value" of the adjusted solution can easily be computed; this revised value will reflect the imputed cost of the improvement in aesthetic quality, and will thus permit economic comparisons of aesthetic tradeoffs. Although this is not a new idea (Rickard, Hughes, and Newport, 1967), it has not previously been successfully incorporated into a harvest planning model.

At current rates, the cost of obtaining the solution in Figure 25 was about $900. This includes computer time for data entry and file preparation, for making the feasibility and cost analysis, for running the improvement algorithm, and for outputting the results on the line printer. It also includes terminal costs, the cost of line printer paper, and file storage charges for one month. For a planning area worth nearly $1.8 million, this amount is insignificant. Many forest areas, however, are not capable of producing revenues on a scale which would justify the expense of this type of analysis. In addition, the lack of suitable data for the analysis could increase the total costs associated with this methodology substantially. On the National Forests, efforts are currently underway to develop a digitized data base which is consistent with the requirements of this methodology (McNutt, 1976). For most other forested areas, however, the appropriate data would have to be obtained before an analysis could be undertaken.

In general, it appears that the gains to be realized by the application of this methodology would more than offset the cost of the additional planning effort for harvest areas which have one or more of the following characteristics:

1. High-value timber.
2. Steep, highly dissected terrain.
3. Unstable soils or other critical environmental problems.
4. High aesthetic impact.

The current version of the feasibility and cost analysis, of course, is limited to only four cable systems (although, among them, these four systems account for a majority of the timber harvested annually in the Douglas-fir region). The improvement algorithm, on the other hand, is general enough to be applied to <u>any</u> cutting unit design problem, regardless of the logging system to be used. Thus, if parcel values can be estimated for harvesting by, say, cable, helicopter, balloon, or tractor systems, then the algorithm can be used to find a satisfactory total assignment of parcels to facilities for those yarding systems. For problems of the type considered in this application, the limited computational experience obtained so far suggests that the initial feasible solution obtained with the CASCADE algorithm may be close enough to the optimum that attempts to improve upon the initial solution are unnecessary. Further research is needed to test this hypothesis, however.

VII. SUMMARY AND CONCLUSIONS

In this study, a two-part methodology has been developed to assist in the design of timber harvest cutting units and the assignment of logging equipment to those units. The first part of this methodology considers the specific topographic and timber conditions on a forest planning area, plus any harvesting restrictions which may be imposed on portions of the area because of expected environmental problems. This information is combined with the known mechanics of the alternative logging systems under consideration to determine the feasibility, and estimate the alternative costs, of harvesting each "parcel" of timber from the area. Thus, a set of feasible harvesting alternatives is developed for each timber parcel; associated with each alternative is a value which represents the worth of the timber on the parcel, net of variable logging and transportation costs, if it were to be harvested by means of that alternative. The second part of the methodology consists of a heuristic optimization algorithm, developed specifically for this study, which seeks to maximize the total value of timber on the planning area, net of both fixed and variable harvesting and transportation costs. The algorithm insures that all parcels on the planning area are assigned to some harvesting facility, and permits each landing site to be occupied by no more than one yarding system.

While the procedures used in both parts of the methodology described above would have to be considered "state-of-the-art", only a few of the procedures themselves are actually new; most are simply applications of existing knowledge to a new area. The most important new development in the feasibility and cost analysis portion of the methodology is the use of a digital model to portray not only topography, which has been done before, but also timber conditions and harvesting restrictions. Thus, harvesting "feasibility" is no longer limited to an assessment of the load carrying capability of the logging system, but also considers the size and distribution of the logs which are to be yarded, and environmental restrictions which may constrain the harvesting methods themselves.

In the optimization portion of the methodology, the CASCADE algorithm developed as part of this study has been based loosely upon several previous algorithms for solving facilities location problems, but differs markedly from those algorithms in two respects. First, it considers problems which exhibit a special "cascading fixed charge" structure; that is, a fixed charge structure in which several levels of fixed charges must be incurred for any complete facility installation. Second, it attempts to find a very good initial feasible solution. Other algorithms usually move quickly to "any" initial feasible solution, and then attempt to improve upon that solution. Because of the cascading structure of fixed charges in the forest harvesting problem, however, experimentation with the algorithm showed that poor initial feasible solutions often stalled without ever approaching the optimal solution. Thus, the strength of the present algorithm appears to depend heavily upon the fact that it finds an initial feasible solution which is often very close to the optimal solution.

This dissertation has been concerned primarily with the development and demonstration of a methodology, rather than with experimentation by which detailed harvest planning guidelines could be derived. Several observations based on experience with the methodology, however, may be of interest:

1. Visits to the site of the case study application emphasized the importance of integrating the planning process with detailed field checking. Had these visits not been made, for example, the large BU-199 yarder might have been specified for installment at Landing 1, which is simply not capable of supporting such a large facility. Similarly, many candidate anchor positions were eliminated during the field visits when it became obvious that the installation of cableways at those positions would have been impossible. This not only saves computation time but also prevents the inadvertent assignment of a cableway which might appear feasible to the model but in actuality could not be emplaced.

2. The most important single factor influencing the shape of cutting unit boundaries appears to be the character of the terrain on the planning area. In areas of uniform slope, relatively uniform boundaries would be expected; in areas of sharply dissected topography, highly irregular boundaries are likely. The specific location and shape of cutting boundaries are highly site-specific, however, and depend not

only upon terrain but also upon timber type and the characteristics of the yarding systems assigned to the opposing cutting units.

3. An important facility of the methodology presented here is the fact that the "cost" of revising a solution can be easily obtained. This means that the solution found by the CASCADE algorithm can effectively be considered a starting point for more detailed planning; adjustments can be made in order to more effectively utilize the assigned yarding systems (from the point of view of a logging engineer), to enhance the aesthetic quality associated with cutting unit design (from the point of view of a landscape architect), or simply to test the sensitivity of the objective function to changes in the solution.

Suggestions for Additional Research

During the development and testing of the methodology considered in this study, several areas in which additional research might provide substantial gains became evident. These include the following:

1. A natural question to ask with regard to any planning methodology is: "how much better can this procedure be expected to perform than a competent analyst using existing guidelines?" Regardless of the philosophical or mathematical value of an operations research approach, its worth to any potential user depends largely upon the answer to this question. The present study, which has been concerned with the development of the methodology itself, has not attempted to

provide insight into this question. Thus, a high priority for additional research would be to measure the quality of harvest plans developed independently by competent logging engineers and by the planning methodology presented in this dissertation. Specifically, such research should consider planning areas which vary in both size and in character, so that conclusions can be drawn with respect to the kind of planning area which is suited to each planning method.

2. The present computer programs by which this methodology has been implemented should be considered experimental. The feasibility and cost analysis program, which is relatively straightforward, appears to be very fast, although a good programmer could undoubtedly improve it. The program which executes the heuristic algorithm, however, is relatively slow. Significant improvements in execution time would almost certainly result if it were reprogrammed. The random access file structure which is used to maintain both the current solution and all potential solutions appears to be cumbersome and may account for a significant amount of computation time. In addition, many of the conventions used in programming the algorithm were arbitrary; during the testing of the program one such convention was changed and the average execution time was cut by a factor of ten. An early priority for additional research involving this algorithm would therefore be to have it reprogrammed by a competent programmer familiar with optimization methodologies.

3. Two of the critical assumptions discussed in Chapter I were

(a) that only clearcut silviculture is considered, and (b) that the forest is presumed to exist in a static condition for the duration of the harvesting period. These assumptions are particularly important as the inventory of old-growth timber becomes depleted and the forest industry comes to rely more and more upon young, vigorous forests. An important research objective would therefore be to generalize the methodology developed here so that changes in prices and costs over time (including the discounting of future costs and revenues), mortality and growth, and alternative silvicultural methods could be investigated. The means for accomplishing this is not straightforward. Applications of facilities location theory over time (Ballou, 1968; Wesolowsky and Truscott, 1975) have typically involved only very small problems because of the combinatorial difficulty encountered in dynamic situations. Perhaps a case study approach could be justified in order to provide guidelines for revising or restructuring the basic "static forest" methodology.

4. As noted in the discussion of exact procedures for solving 0-1 integer programming problems, some very large problems have been solved by Martin (Geoffrion and Marsten, 1972), using an efficient cutting plane algorithm. These problems have been characterized as having a strong tendency toward integer values, with all 1's or 0's on the right-hand side, and usually all 1's or 0's in the matrix. These characteristics also apply to the forest harvesting problem, and it may be that the problem could actually be solved more efficiently by Martin's approach than by the heuristic algorithm. If the exact

procedure were to prove feasible, but too expensive for practical use, a comparison of the exact and approximate solutions would at least provide valuable information as to the worth of the solutions obtained by the heuristic algorithm.

The ability to efficiently solve the integer programming problem which corresponds to the forest harvesting problem is an attractive idea for at least two reasons. First, it would always provide an optimal, rather than approximate, result. Second, it would permit the incorporation of additional constraints without requiring major methodological revisions. The integer programming problem formulated for this study represents (almost) unconstrained optimization, in spite of the fact that a large number of constraints is required in the problem. Most of these constraints are essentially structural; that is, they describe the cascading fixed charge structure of the problem. Only two sets of constraints actually describe resource limitations; one of these requires that each timber parcel be harvested exactly once, and the other insures that no more than one yarding system is assigned to any landing (see Chapter IV, equations [4.6] - [4.15]). It would be interesting in some cases to be able to test many other constraints. As an example, one might want to find the optimal assignment of timber parcels to cableways, subject to limitations on, say, the total number of parcels assigned to any landing (i.e. cutting unit size), or the total volume of timber being hauled over any spur road, or the number of times that any specific yarding system is to be used. Constraints could also be written, after the method of Garfinkel and

Nemhauser (1970), to require that cutting units be contiguous. Any such limitations would be difficult to include in the heuristic algorithm, but could easily be added to an integer programming structure (although doing so might greatly increase the computational difficulty of the problem).

5. Certain of the assumptions made during the feasibility and cost analysis portion of this dissertation should be examined more closely in the context of their impact on the final solution. These include the following:

a. The assumption that cable segments under tension can be approximated by rigid members rather than the true catenaries;

b. Assumption [3.18], that the load capability of a skyline system when a turn of logs is being skidded or partially suspended is approximately equal to 1.5 times the load capability of the same system when the turn is fully suspended.

In addition, a more rigorous procedure should be developed for estimating highlead yarding load capability. The method used in this study represents an initial effort which was developed because no previously published analysis was available.

Concluding Remarks

The methodology developed for this study provides the forest manager with two new tools which can assist in the planning of forest harvesting operations. First, a flexible procedure for evaluating the feasibility and costs of alternative cable yarding systems has been provided; and second, a heuristic algorithm has been developed which seeks to design optimum cutting units by considering the results of the feasibility and cost analysis. It should be emphasized that these procedures only provide information for decisions; they should not be permitted to make decisions. Invariably, it is impossible to fully describe a planning problem in terms of a mathematical model. With the exception of certain soil and water values, for example, the model considered here completely ignores non-timber resources. These resources are always important and may sometimes be critical; therefore, the forest manager himself cannot afford to ignore them. The model formulated for this study, like all models, is an abstraction from reality. If it gives optimum or satisfactory answers to the problem that has been formulated, then it can provide a valuable service to the forest manager by suggesting actions which can be taken and the probable consequences of those actions. No model can foresee the future, nor can it relieve the forest manager of the responsibility of making the very difficult decisions that have to be made in any resource management job. It can, however, provide a stronger foundation on which to make those decisions. Hopefully, the methodology described here will be capable of making that kind of contribution.

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APPENDICES

APPENDIX I

Glossary of Timber Harvesting Terminology[1]

Allowable cut. The quantity of timber which can be harvested during a specific time period such that the perpetuity of the timber stand is assured.

Average yarding distance. Total yarding distance for all turns yarded to a particular landing divided by the total number of turns.

Bucking. The process of cutting felled trees into logs.

Buffer strip. A strip of vegetation left along streams or roadways to improve shading, reduce the entry of residues into the stream or road, or contribute to aesthetic quality.

Cableway. The configuration of one or more cables, stretched between a spar and an anchor, which defines the pathway along which logs are moved during cable yarding.

ccf. The abbreviation for 100 cubic feet of solid wood.

Choker. A noose of wire rope used for attaching logs to the yarding system.

Chord. The slope distance from the top of the spar to the anchor.

Clearcut. A harvesting method in which all of the timber in a cutting area is removed during a single entry.

Cutting unit. An area of timber designated for harvest. As used in this paper, the term is synonomous with "setting": the area logged to one yarder position.

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[1]Many of the definitions in this Glossary have been taken from the following sources:

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McCulloch, W. F. 1958. Woods words. Portland, Oregon Historical Society and The Champoeg Press, 219 p.

Society of American Foresters. 1958. Forestry terminology. Washington, D. C., Society of American Foresters, 97 p.

Deadman. A wooden, concrete, or metal bar buried in the earth for the purpose of anchoring a standing line or guyline.

Deflection. The vertical distance between the chord and the skyline, measured at midspan. Usually expressed as a percentage of the horizontal span length.

External yarding distance. Slope distance from the landing to the most distant point within the cutting unit boundary.

fbm. Feet, board measure: an abbreviation for board feet. A board foot is a measure of the volume of wood contained in a 12"x12"x1" section of log. Large volumes (such as the volume represented by an entire stand of timber) are usually expressed in thousands of board feet, abbreviated Mfbm.

Felling. The act or process of cutting standing trees.

Flyer. A live skyline system composed only of the skyline and a mainline, so that return of the carriage to the timber must be accomplished by gravity. Frequently referred to as a "gravity return", "drift", or "shotgun" system.

Grapple. A hinged mechanism, capable of being opened and closed, which is used to grip logs during grapple yarding or loading.

Ground lead. A method of yarding logs in which the pull of the skidding line is parallel to the ground (i.e. a spar or other means for providing lift is not used, or is ineffective).

Haulback. A wire rope used to pull the mainline back to the timber for the attachment of logs during yarding.

Landing. The area where logs are assembled by the yarding process.

Live skyline. A cable yarding system in which the skyline can be raised or lowered during yarding.

Loading. The act or process of placing logs onto trucks or other vehicles for transport.

Logging. All or any part of the task of converting trees into logs and delivering them to an unloading point; synonomous with the term "lumbering" which is commonly used in eastern forestry.

Mainline. The hauling cable.

Regeneration harvest. Removal of timber in preparation for the establishment of a subsequent timber crop.

Rock bolt. A bolt which may be drilled into rock for the purpose of fixing guylines for anchoring.

Rotation. The period of time required to establish and grow timber crops to a specified condition of maturity.

Running skyline. A system of two or more suspended moving lines, generally referred to as the mainline and haulback, that, when properly tensioned, will provide lift and travel to the carriage.

Shelterwood. A silvicultural method in which mature timber is removed in a series of cuttings which extend over a period of years equal usually to not more than one-quarter and often not more than one-tenth of the rotation.

Silviculture. The science which deals with the theory and practice of controlling forest establishment, composition, and growth.

Skyline. A cableway stretched tautly between a spar and an anchor and used as a track for log carriers.

Skyline anchor. A device used to secure the end of a skyline opposite the spar. Commonly used anchors include stumps, standing trees, tractors, deadmen, and rock bolts.

Slash. Woody residue left after logging.

Span. The horizontal distance from a spar to an anchor.

Spar. The tree or tower on which rigging is hung for use in a cable yarding system.

Standing skyline. A skyline system in which the skyline cable is fixed during the yarding operation (i.e. it cannot be raised or lowered).

Strawline. A light cable used to string heavier lines; synonomous with "haywire".

Tailhold. The anchorage at the outer end of a skyline or highlead yarding system, away from the landing.

Tailtree. A tailhold which has been placed in a tree in order to improve deflection. Synonomous with "tailspar".

Timber type. A descriptive term used to group stands of similar character, by which they may be differentiated from other groups of stands.

Turn. The logs yarded in any one trip.

Type island. A contiguous area on a planimetric map of timber types, within which the timber is considered to be of a single type.

Yarding. The process of conveying felled timber from the stump to a landing, or "yard".

Yarding road. The area bounded by the length and lateral yarding width of any cableway emplacement.

APPENDIX II

Listings of the Logging Feasibility And Cost Analysis Programs

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      PROGRAM CABLYRD
      COMMON NROWS,NCOLS,GRID,CHOSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/CABLE/ PROFILE(35,2),BFMIN(5),DENSTY(10),
     1  IGRIDS,ISYSTM,EL1,EL2,W1(5),W2(5),REACH(5),TMAX(5),
     2  SPAR(5),IBUFF,ITLROW,ITLCOL,DLAST,ELVLST,CUMDIST,
     3  ELEV,TT,TAIL(5),CLEAR(5,2),AVLOG(10),TURNMX(10,5),
     4  ISYS(5),WG(35)
      COMMON/FEAS/ AROW,ACOL,BROW,BCOL,CROW,CCOL,DROW,DCOL
      DIMENSION XLAT(5),TITLE(10),COST(5),CMOVE(5),RDCHG(5,3)
      DIMENSION COEFF(5,7),DELAY(5),CLAND(10),HAUL(10)
      DIMENSION VOLPAC(10),PRICE(10),RIG(5)
C
C          THIS PROGRAM EXAMINES A DIGITIZED PLANNING AREA TO
C     EVALUATE THE FEASIBILITY OF USING CABLE YARDING SYSTEMS
C     AT SPECIFIC LANDINGS AND ANCHORED OVER SPECIFIC CABLEWAYS.
C
C          THE PRESENT CAPABILITIES OF THE PROGRAM ARE LIMITED
C     TO HIGHLEAD, RUNNING SKYLINE, AND LIVE SKYLINE SYSTEMS
C     OVER A SINGLE SPAN.
C
C          IN ADDITION TO THE FEASIBILITY ANALYSIS, THE PROGRAM
C     ESTIMATES THE COST OF YARDING EACH PARCEL ON THE PLANNING
C     AREA WHICH CAN BE ACCESSED FROM ANY OF THE CABLEWAYS.  THIS
C     COST IS THEN ADDED TO THE EXPECTED HAULING COST FROM THAT
C     LANDING TO AN APPRAISAL POINT, AND THE TOTAL IS SUBTRACTED
C     FROM THE EXPECTED APPRAISAL POINT VALUE OF THE TIMBER IN
C     THE PARCEL.  THE RESULT IS THE EXPECTED NET VALUE OF THE
C     TIMBER IN THE PARCEL IF IT WERE TO BE YARDED OVER THAT
C     SPECIFIC CABLEWAY.  EACH CABLEWAY IS UNIQUE: A CABLEWAY
C     MAY BE IDENTIFIED BY A UNIQUE COMBINATION OF LANDING,
C     YARDING SYSTEM, AND ANCHOR POINT.
C
C          HIGHLEAD SYSTEM FEASIBILITY IS ESTABLISHED BY MEANS
C     OF A STATIC ANALYSIS WORKED OUT AS PART OF THIS STUDY.
C
C          LIVE AND RUNNING SKYLINE FEASIBILITY IS EVALUATED
C     BY A PROCEDURE REPORTED IN:  CARSON, W. W., AND C. N. MANN.
C     1971.  AN ANALYSIS OF RUNNING SKYLINE LOAD PATH.  PORTLAND,
C     USDA FOREST SERVICE, PAC. N.W. FOREST & RANGE EXP. STA.,
C     RES. PAP. PNW-120, 9 P.
C
C          PROGRAM CABLYRD SERVES PRIMARILY AS A FRONT-END DEVICE
C     TO PREPARE DATA FOR ANALYSIS BY THE CASCADE ALGORITHM OR BY
C     AN EXACT 0-1 PROGRAMMING ALGORITHM (THE LATTER FOR SMALL
C     PROBLEMS).  OUTPUT FILES WHICH ARE PREPARED BY CABLYRD
C     ARE AS FOLLOWS:  (LUN=LOGICAL UNIT NUMBER)
C
C     LUN 6 -- CABLYRD INPUT DATA SUMMARY AND RUN SUMMARY.
C
C     LUN 7 -- LISTING OF THE VALUE OF EACH PARCEL IF YARDED OVER
C     ANY SPECIFIC CABLEWAY.
C
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C      LUN 8 -- A TABLE WHICH DESCRIBES EACH CABLEWAY.  INCLUDED
C      ARE THE LANDING NUMBER, YARDING SYSTEM NUMBER, ANCHOR GRID
C      LOCATION, ELEVATION OF THE TAILHOLD ABOVE THE CENTROID OF
C      THE GRID, AND CABLEWAY EMPLACEMENT COST.  THIS IS A RANDOM
C      ACCESS FILE: CABLEWAY NUMBER IS ONE GREATER THAN THE LOGICAL
C      RECORD NUMBER, WHERE A LOGICAL RECORD CONTAINS THE FIVE
C      ELEMENTS LISTED ABOVE.
C
C      LUN 9 -- AN INFORMATION FILE FOR USE BY THE CASCADE ALGO-
C      RITHM: CONTAINS THE VALUES OF -NCOLS-, -NSYS-, -CMOVE(I)-,
C      -NLAND-, -CLAND(I)-, AND -ICABL-.  FORMAT IS I7 OR F7.0 AS
C      APPROPRIATE.
C
C           IN ADDITION TO THE ABOVE, CABLYRD USES THE FOLLOWING
C      DATA FILES AS INPUT:
C
C      LUN 1 -- RANDOM-ACCESS DATA FILE CONTAINING THE MATRIX
C      OF ELEVATIONS.  THESE ARE STORED ROW-BY-ROW, FROM THE
C      TOP, AND EACH ELEVATION OCCUPIES FOUR BCD CHARACTER
C      SPACES (I.E. ONE BCD WORD).
C
C      LUN 2 -- RANDOM-ACCESS DATA FILE CONTAINING THE MATRIX
C      OF FOREST TYPE CODES, STORED IN THE SAME WAY AS LUN 1.
C
C      LUN 3 -- RANDOM-ACCESS DATA FILE CONTAINING THE MATRIX
C      OF SPECIAL FEATURE CODES, STORED IN THE SAME WAY AS
C      LUNS 1 AND 2.
C
C      LUN 5 -- RUN DATA FOR CABLYRD.
C
       DO 10 I=1,10
       CLAND(I)=0.
       IF (I .GT. 5) GO TO 10
       CMOVE(I)=0.
    10 CONTINUE
C
C           READ IN THE RUN TITLE.
C
       READ(5,50) TITLE
    50 FORMAT (10A8)
C
C           READ IN RUN DATA.
C
       GRID=FFIN(5)
       NROWS=IFIX(FFIN(5))
       NCOLS=IFIX(FFIN(5))
       WRITE (6,100) TITLE,GRID,NROWS,NCOLS
   100 FORMAT (≠S≠/≠1≠/≠-≠,90(≠*≠)/≠0≠,10X,≠CABLE LOGGING≠,
     1  ≠ SYSTEM FEASIBILITY AND COST ANALYSIS≠/≠0≠,10X,
     2  10A8/≠0≠,90(≠*≠)/
     3  ≠-GRID SIZE=≠,F7.2,≠ FEET≠/≠0DATA MATRIX HAS ≠,I4,
     4  ≠ ROWS AND ≠,I4,≠ COLUMNS.≠//1X,43(≠=≠))
C
C           READ IN YARDING SYSTEM DATA.
```

```
C
      NSYS=0
      N=IFIX(FFIN(5))
      IF (N .GT. 5) GO TO 115
  110 NSYS=NSYS+1
      IF (NSYS .LE. 5) GO TO 120
  115 WRITE (6,9901)
 9901 FORMAT (≠0*****ERROR***** TOO MANY YARDING SYSTEMS:  ≠,
     1  ≠NO MORE THAN 5 ALLOWED.≠//)
      STOP
  120 ISYS(N)=IFIX(FFIN(5))
      REACH(N)=FFIN(5)
      XLAT(N)=FFIN(5)
      W1(N)=FFIN(5)
      W2(N)=FFIN(5)
      TMAX(N)=FFIN(5)
      CARRWT(N)=FFIN(5)
      SPAR(N)=FFIN(5)
      TAIL(N)=FFIN(5)
      CLEAR(N,1)=FFIN(5)
      CLEAR(N,2)=FFIN(5)
      BFMIN(N)=FFIN(5)
      COST(N)=FFIN(5)
      CMOVE(N)=FFIN(5)
      RIG(N)=FFIN(5)
      DO 130 I=1,3
  130 RDCHG(N,I)=FFIN(5)
      N=IFIX(FFIN(5))
      IF (N .EQ. 9999) GO TO 140
      IF (N .GT. 5) GO TO 115
      GO TO 110
  140 WRITE (6,150)
  150 FORMAT (≠-SUMMARY OF YARDING SYSTEM DATA≠/≠0≠,T56,
     1  ≠MAX  SUSPENSN   MIN≠,15X,≠TAILTREE≠/≠ SYS SYS   MAX    ≠,
     2  ≠MAX   SEG1  SEG2   MAX    CARR  SPAR TAIL CARR CLR  FBM/≠,
     3  ≠  COST   MOVE  RIG TIME ROAD CHANGE  BUFFER≠/≠ NO. TYPE ≠,
     4  ≠REACH LATERAL  WT    WT  TENSION WEIGHT  HT   HT  FULL ≠,
     5  ≠PART TURN  $/HR   COST  (MIN/FT) ..A0....A1. AOD TIME≠)
      WRITE (6,155)
  155 FORMAT (≠ --- ---- ----- ------- ----  ---- -------≠,
     1  ≠ ------ ---- ---- ---- ---- ----  -----  ----  --------≠,
     2  ≠ ----  ----  ---------≠/)
      DO 170 I=1,NSYS
      WRITE (6,160) I,ISYS(I),REACH(I),XLAT(I),W1(I),W2(I),
     1  TMAX(I),CARRWT(I),SPAR(I),TAIL(I),(CLEAR(I,J),J=1,2),
     2  BFMIN(I),COST(I),CMOVE(I),RIG(I),(RDCHG(I,J),J=1,3)
  160 FORMAT (2I4,F7.0,F6.0,F7.2,F6.2,2F7.0,F6.0,F4.0,2F5.0,
     1  F6.0,F7.2,F6.0,F9.4,F6.1,F6.3,F6.0)
  170 CONTINUE
      WRITE (6,175)
  175 FORMAT (//,118(≠=≠))
C
C          READ IN YARDING REGRESSION COEFFICIENTS BY SYSTEM.
C
```

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```
      N=IFIX(FFIN(5))
  176 IF (N .GT. 5) GO TO 115
      DO 177 I=1,7
  177 COEFF(N,I)=FFIN(5)
      DELAY(N)=FFIN(5)
      N=IFIX(FFIN(5))
      IF (N .NE. 9999) GO TO 176
      WRITE (6,178)
  178 FORMAT (≠-SUMMARY OF YARDING REGRESSION COEFFICIENTS≠/
     1  ≠0≠,8X,≠CONSTANT    VOL/TURN     VOL/LOG    YARD ≠,
     2  ≠DIST   LAT DIST    LOGS/TURN  CHORDSLOPE  DELAY≠/
     3  ≠ SYSTEM    (MIN)      (MIN/FBM)    (MIN/FBM)   ≠,
     4  ≠(MIN/FOOT)  (MIN/FOOT)   (MIN/LOG)   (MIN/PCT)≠,
     5  ≠ FACTOR≠)
      WRITE (6,185)
  185 FORMAT (≠ ------ ---------- ----------- -----------≠,
     1  ≠ ----------- ----------- ----------- -----------≠,
     2  ≠ ------≠/)
      DO 181 I=1,NSYS
      WRITE (6,179) I,(COEFF(I,J),J=1,7),DELAY(I)
  179 FORMAT (I5,1X,7(1X,F11.4),F6.2)
  181 CONTINUE
      WRITE (6,186)
  186 FORMAT (//≠ ≠,96(≠=≠))
C
C           READ IN LANDING DATA.
C
      NLAND=0
      N=IFIX(FFIN(5))
      IF (N .GT. 10) GO TO 190
  180 NLAND=NLAND+1
      IF (NLAND .LE. 10) GO TO 200
  190 WRITE (6,9902)
 9902 FORMAT (≠0*****ERROR***** TOO MANY LANDINGS: NO MORE  ≠,
     1  ≠THAN 10 ALLOWED.≠//)
      STOP
  200 IHDROW(N)=IFIX(FFIN(5))
      IHDCOL(N)=IFIX(FFIN(5))
      IF (IHDROW(N) .LE. NROWS .AND. IHDCOL(N) .LE. NCOLS)
     1  GO TO 205
      WRITE (6,9905) IHDROW(N),IHDCOL(N)
 9905 FORMAT (≠0*****ERROR***** ATTEMPT TO PLACE A LANDING≠,
     1  ≠ AT (≠,I9,≠,≠,I9,≠)≠//)
      STOP
  205 CLAND(N)=FFIN(5)
      HAUL(N)=FFIN(5)
      N=IFIX(FFIN(5))
      IF (N .EQ. 9999) GO TO 210
      IF (N .GT. 10) GO TO 190
      GO TO 180
  210 WRITE (6,220)
  220 FORMAT (≠-SUMMARY OF LANDING DATA≠/≠0≠,T14,≠SPAR      ≠,
     1  ≠LANDING   HAUL≠/≠ LANDING   LOCATION  AND SPUR   ≠,
     2  ≠COST≠/≠   NO.      ROW   COL  CONSTR.   $/M≠)
```

```
      WRITE (6,225)
  225 FORMAT (≠ -------     ---     --- --------     -----≠/)
      DO 240 I=1,NLAND
      WRITE (6,230) I,IHDROW(I),IHDCOL(I),CLAND(I),HAUL(I)
  230 FORMAT (2X,I3,6X,I3,3X,I3,2X,F7.0,F8.2)
  240 CONTINUE
      WRITE (6,245)
  245 FORMAT (//≠ ≠,36(≠=≠))
C
C            READ IN FOREST TYPE DATA.
C
      NTYPES=0
      N=IFIX(FFIN(5))
      IF (N .GT. 10) GO TO 270
  260 NTYPES=NTYPES+1
      IF (NTYPES .LE. 10) GO TO 280
  270 WRITE (6,9903)
 9903 FORMAT (≠0*****ERROR***** TOO MANY FOREST TYPES:  ≠,
     1  ≠NO MORE THAN 10 ALLOWED.≠//)
      STOP
  280 VOLPAC(N)=FFIN(5)
      AVLOG(N)=FFIN(5)
      DENSTY(N)=FFIN(5)
      PRICE(N)=FFIN(5)
      DO 285 J=1,NSYS
      I=IFIX(FFIN(5))
      IF (I .LE. 5) GO TO 285
      WRITE (6,9907) J,I
 9907 FORMAT (≠0*****ERROR***** ATTEMPT TO ENTER A MAXIMUM TURN≠,
     1  ≠ SIZE FOR SYSTEM ≠,I3,≠, FOREST TYPE ≠,I2//)
      STOP
  285 TURNMX(N,I)=FFIN(5)
      N=IFIX(FFIN(5))
      IF (N .EQ. 9999) GO TO 290
      IF (N .GT. 10) GO TO 270
      GO TO 260
  290 WRITE (6,300)
  300 FORMAT (≠-SUMMARY OF FOREST TYPE DATA≠/≠0≠,T10,
     1  ≠AVG      AVG     DENSITY    .MAX TURN.    MILL≠/≠ TYPE≠,
     2  ≠  VOL/AC  VOL/LOG  LBS/FBM    SYSTM.LOGS    PRICE≠)
      WRITE (6,305)
  305 FORMAT (≠ ----  ------  -------  -------    ----- ----≠,
     1  ≠  ------≠/)
      DO 320 I=1,NTYPES
      DO 315 J=1,NSYS
      IF (J .EQ. 1) WRITE (6,310) I,VOLPAC(I),AVLOG(I),
     1  DENSTY(I),J,TURNMX(I,J),PRICE(I)
  310 FORMAT (I4,F9.0,F7.0,F10.1,5X,I3,F6.1,F8.2)
      IF (J .GT. 1) WRITE (6,311) J,TURNMX(I,J)
  311 FORMAT (T36,I3,F6.1)
  315 CONTINUE
      WRITE (6,316)
  316 FORMAT (≠ ≠)
  320 CONTINUE
```

```
      WRITE (6,325)
  325 FORMAT (//≠ ≠,51(≠=≠))
C
C           READ AND PROCESS CABLEWAY ALTERNATIVES.
C
      WRITE (6,370)
  370 FORMAT (≠-CANDIDATE ANCHOR POINT SUMMARY≠)
      IFEAS=1
      ICABL=0
  380 LANDG=IFIX(FFIN(5))
      IF (EOF(5)) GO TO 1000
      IF (LANDG .LE. NLAND) GO TO 390
      WRITE (6,9904) LANDG,NLAND
 9904 FORMAT (≠0*****ERROR***** ATTEMPT TO PROCESS CABLEWAYS FOR ≠,
     1  ≠LANDING≠,I9,≠; ONLY ≠,I3,≠ LANDINGS IN THIS ANALYSIS.≠//)
      STOP
C
C           GET YARDING SYSTEM.
C
  390 ISYSTM=IFIX(FFIN(5))
      IF (ISYSTM .LE. NSYS) GO TO 410
      WRITE (6,9906) ISYSTM,LANDG,NSYS
 9906 FORMAT (≠0*****ERROR***** ATTEMPT TO PLACE SYSTEM ≠,I9,
     1  ≠ AT LANDING ≠,I3,≠; ONLY ≠,I3,≠ SYSTEMS IN THIS ANALYSIS.≠//)
      STOP
C
C           GET CANDIDATE ANCHOR POSITION.
C
  410 ITLROW=IFIX(FFIN(5))
      IF (EOF(5)) GO TO 1000
      IF (ITLROW .EQ. 8888) GO TO 390
      IF (ITLROW .EQ. 9999) GO TO 380
      ITLCOL=IFIX(FFIN(5))
      IF (ITLROW .GT. 0 .AND. ITLROW .LE. NROWS .AND.
     1    ITLCOL .GT. 0 .AND. ITLCOL .LE. NCOLS) GO TO 415
      WRITE (6,9908) ITLROW,ITLCOL,ISYSTM,LANDG
 9908 FORMAT (≠0*****ERROR***** ATTEMPT TO PLACE A TAILHOLD AT (≠,
     1  I9,≠,≠,I9,≠) FOR SYSTEM ≠,I3,≠, LANDING ≠,I3//)
      STOP
C
C           PREPARE THE RUN SUMMARY.
C
  415 IF (IFEAS .EQ. 0) WRITE (6,416)
  416 FORMAT (≠+≠,T42,≠*** CABLEWAY DISCARDED ***≠/)
      WRITE (6,417) LANDG,ISYSTM,ITLROW,ITLCOL
  417 FORMAT (≠0  LANDING ≠,I2,≠ SYSTEM ≠,I2,≠ ANCHOR (≠,
     1  I2,≠,≠,I2,≠):  ≠)
C
C           DETERMINE THE GEOMETRY NECESSARY FOR THE
C       FEASIBILITY AND COST ANALYSES.
C
      EL1=XMATRIX(IHDROW(LANDG),IHDCOL(LANDG),1)+SPAR(ISYSTM)
      EL2=XMATRIX(ITLROW,ITLCOL,1)
      IFEAS=1
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```
      IF (EL2 .LT. 0.) WRITE (6,416)
      IF (EL2 .LT. 0.) GO TO 410
      IFEAS=0
C
C          THE VALUE OF -EAST- IS POSITIVE IF THE ANCHOR
C     IS LOCATED EAST OF THE LANDING; THE VALUE OF -XNORTH-
C     IS POSITIVE IF THE ANCHOR IS LOCATED NORTH
C     OF THE LANDING.
C
      EAST=FLOAT(ITLCOL-IHOCOL(LANDG))
      XNORTH=FLOAT(IHOROW(LANDG)-ITLROW)
      SPAN=SQRT(XNORTH**2 + EAST**2)*GRID
      CHORD=SQRT(SPAN*SPAN + (EL1-EL2)**2)
C
C          REJECT THIS CABLEWAY IF THE DISTANCE ALONG THE
C     CHORD EXCEEDS THE CAPABILITY OF THE SYSTEM.
C
      IF (CHORD .GE. REACH(ISYSTM) .AND. ISYS(ISYSTM) .NE. 1)
     1  GO TO 410
      CHDSLP=(EL2-EL1)/SPAN
      THETA=ATAN(CHDSLP)
      IF (ABS(EAST) .LT. 1E-10) TANPHI=.6E300
      IF (ABS(EAST) .GE. 1E-10) TANPHI=ABS(XNORTH/EAST)
      PHI=ATAN(TANPHI)
C
C          MAKE UP A TERRAIN PROFILE UNDER THE CABLEWAY.
C
      IGRIDS=0
      D=0.
  420 D=D+GRID
      IF (D .GE. SPAN) GO TO 430
      IGRIDS=IGRIDS+1
      IF (ABS(XNORTH) .LT. 1E-10) ROW=FLOAT(IHDROW(LANDG))+.5
      IF (ABS(XNORTH) .GE. 1E-10) ROW=(FLOAT(IHDROW(LANDG))+.5)-
     1  (SIN(PHI)*(D/GRID)*(XNORTH/ABS(XNORTH)))
      IF (ABS(EAST) .LT. 1E-10) COL=FLOAT(IHOCOL(LANDG))+.5
      IF (ABS(EAST) .GE. 1E-10) COL=(FLOAT(IHOCOL(LANDG))+.5)+
     1  (COS(PHI)*(D/GRID)*(EAST/ABS(EAST)))
      PROFILE(IGRIDS,1)=D
      PROFILE(IGRIDS,2)=PTELEV(ROW,COL)
      GO TO 420
C
C          CALL THE FEASIBILITY ANALYSIS SUBROUTINES.
C
  430 IF (ISYS(ISYSTM) .EQ. 1) CALL HILEAD
      IF (ISYS(ISYSTM) .GE. 2) CALL SKYLINE
      IF (XMYD .LE. 1E-10) GO TO 410
C
C          A FEASIBLE CABLEWAY IS INDICATED; WRITE OUT
C     THE CABLEWAY IDENTIFICATION AND FIXED EMPLACEMENT
C     COST.
C
      IF (ISYS(ISYSTM) .EQ. 1) TT=0.
      CWCOST=(RDCHG(ISYSTM,1) + RDCHG(ISYSTM,2)*CHORD +
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     1  ROCHG(ISYSTM,3)*FLOAT(IBUFF) + TT*RIG(ISYSTM))*
     2  COST(ISYSTM)/60.
      ICABL=ICABL+1
      WRITE (8,8801) ISYSTM,LANDG,ITLROW,ITLCOL,
     1  TT,CWCOST
 8801 FORMAT (4I4,2F4.0)
      WRITE (6,440) CWCOST
  440 FORMAT (≠+≠,T42,≠CABLEWAY EMPLACEMENT=$≠,F7.2/≠0≠,
     1  3X,≠AVE     AVE     AVE     AVE     AVE      YARD≠/
     2  4X,≠HOR  SLOPE     LAT   LOGS     VOL      COST≠/
     3  3X,≠YARD   YARD    YARD     PER     PER      PER≠,
     4  17X,≠EXP≠/3X,≠DIST    DIST    DIST   TURN   TURN≠,
     5  ≠      M FBM      PARCEL     VALUE≠)
      WRITE (6,445)
  445 FORMAT (≠   ----    ----    ----    ----    ----    -----≠,
     1  ≠     -------     ------≠/)
      IFEAS=1
C
C          CONSTRUCT A RECTANGLE ENCLOSING THE CABLEWAY AND
C     ITS LATERAL YARDING DISTANCE.  FIND THE ROWS AND COLUMNS
C     TO BE SEARCHED IN ORDER TO DETERMINE WHICH GRIDSQUARES
C     ARE FULLY ENCLOSED WITHIN THAT RECTANGLE.
C
      CALL BIGSQ(LOWROW,LOWCOL,IHIROW,IHICOL,XLAT(ISYSTM))
C
C          SEARCH THE INDICATED LOCAL AREA OF THE MATRIX
C     AND IDENTIFY THOSE GRIDSQUARES WHICH ARE FULLY
C     ENCLOSED BY THE LATERAL YARDING AREA/MAXIMUM
C     YARDING AREA RECTANGLE.
C
      DO 510 I=LOWROW,IHIROW
      DO 500 J=LOWCOL,IHICOL
      ROW1=FLOAT(I)
      ROW2=ROW1+1.
      COL1=FLOAT(J)
      COL2=COL1+1.
      CALL FEAS(ROW1,ROW2,COL1,COL2,IRES)
      IF (IRES .EQ. 0) GO TO 500
      ITYPE=XMATRIX(I,J,2)
      IFEAT=XMATRIX(I,J,3)
      IF (IFEAT .EQ. 3 .OR. IFEAT .EQ. 4 .OR. IFEAT .EQ. 5)
     1  GO TO 500
      IF (ITYPE .EQ. 99) GO TO 500
C
C          A FEASIBLE GRIDSQUARE (I,J) HAS BEEN ISOLATED.
C     COMPUTE ITS VALUE NET OF HAULING AND YARDING COSTS.
C
C          FIRST COMPUTE -AYD- (AVERAGE YARDING DISTANCE
C     ALONG THE CABLEWAY) AND -ALD- (AVERAGE LATERAL
C     YARDING DISTANCE PERPENDICULAR TO THE CABLEWAY).
C
C          NOTE THAT 90 DEGREES IS APPROXIMATELY EQUAL TO
C     1.5707963 RADIANS.
C
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      IF (IHDCOL(LANDG) .EQ. J) BETA1=1.5707963
      IF (IHDCOL(LANDG) .NE. J) BETA1=ABS(ATAN(FLOAT(IHDROW(LANDG)
     1  -I)/FLOAT(IHDCOL(LANDG)-J)))
      BETA2=ABS(PHI-BETA1)
      IF (XNORTH .GT. 0. .AND. I .GT. IHDROW(LANDG)) BETA2=
     1  BETA1+PHI
      IF (XNORTH .LT. 0. .AND. I .LT. IHDROW(LANDG)) BETA2=
     1  BETA1+PHI
      IF (EAST .GT. 0. .AND. J .LT. IHDCOL(LANDG)) BETA2=
     1  3.1415926-BETA1-PHI
      IF (EAST .LT. 0. .AND. J .GT. IHDCOL(LANDG)) BETA2=
     1  3.1415926-BETA1-PHI
      XL=SQRT(FLOAT(IHDROW(LANDG)-I)**2 + FLOAT(IHDCOL(LANDG)-J)**2)
      ALD=XL*SIN(BETA2)*GRID
      HYD=XL*COS(BETA2)*GRID
      AYD=YDIST(HYD)
C
C          IF ALD<(GRID/2), THE ABOVE UNDERESTIMATES
C     LATERAL YARDING DISTANCE.  THE APPROXIMATION BELOW
C     GIVES BETTER RESULTS, ALTHOUGH IT IS BASED UPON
C     A CIRCULAR SEGMENT.  IT IS VERY CLOSE FOR PHI NEAR
C     45 DEGREES, AND OVERESTIMATES -ALD- FOR PHI NEAR 0
C     OR 90 DEGREES (WHEN -ALD- APPROACHES GRID/2).
C
      IF (ALD .LT. GRID/2.) ALD=2.*GRID/3.
      IF (ISYS(ISYSTM) .GE. 2) GO TO 465
C
C          GET ADDITIONAL PARAMETERS NECESSARY FOR THE
C     COST CALCULATION.
C
      N=IFIX(AYD/GRID)
      XLOGS=TURNMX(ITYPE,ISYSTM)
      TURN=XLOGS*AVLOG(ITYPE)
C
C          FIND THE LARGEST FEASIBLE TURN THAT CAN BE
C     YARDED FROM PARCEL (I,J) OVER THIS HIGHLEAD
C     CABLEWAY.
C
      H=EL1-EL2
      DO 460 K=1,N
      D=PROFILE(K,1)
      Y=EL1-PROFILE(K,2)
  450 WL=TURN*DENSTY(ITYPE)
      TENSION=TENSN(WL)
      IF (TENSION .LE. TMAX(ISYSTM)) GO TO 460
C
C          THE ABOVE TURN IS TOO BIG: REDUCE IT BY A
C     HALF LOG.
C
      XLOGS=XLOGS-.5
      TURN=XLOGS*AVLOG(ITYPE)
      IF (TURN .GT. BFMIN(ISYSTM)) GO TO 450
C
C          THE FEASIBILITY OF A TURN OF SIZE BFMIN(ISYSTM)
```

```
C     HAS PREVIOUSLY BEEN ESTABLISHED FOR THIS CABLEWAY, OR
C     WE WOULD NOT HAVE GOTTEN THIS FAR IN THE PROGRAM.
C     THEREFORE, CONSTRAIN THE LOWER LIMIT ON TURN SIZE
C     TO THAT VALUE.
C
      TURN=BFMIN(ISYSTM)
      GO TO 470
  460 CONTINUE
      GO TO 470
C
C           SKYLINE LOAD CAPACITY HAS ALREADY BEEN
C     COMPUTED IN THE SKYLINE SUBROUTINE; CONVERT
C     TO VOLUME AND LOGS/TURN.  TRUNCATE XLOGS TO THE
C     NEAREST ONE-HALF LOG.
C
  465 II=IFIX(HYD/GRID)
      IF (II .EQ. 0) II=1
      TURN=WG(II)/DENSTY(ITYPE)
      XLOGS=FLOAT(IFIX(TURN/(AVLOG(ITYPE)*0.5)))*0.5
      IF (XLOGS .LE. TURNMX(ITYPE,ISYSTM)) GO TO 470
      XLOGS=TURNMX(ITYPE,ISYSTM)
  470 TURN=XLOGS*AVLOG(ITYPE)
C
C           COMPUTE EXPECTED YARDING COST.
C
      YTIME=(COEFF(ISYSTM,1) + COEFF(ISYSTM,2)*TURN +
     1  COEFF(ISYSTM,3)*TURN/XLOGS + COEFF(ISYSTM,4)*
     2  AYD + COEFF(ISYSTM,5)*ALD + COEFF(ISYSTM,6)*XLOGS
     3  + COEFF(ISYSTM,7)*CHOSLP*100.)*DELAY(ISYSTM)
      VOL=((GRID*GRID)/43560.)*VOLPAC(ITYPE)
      YTIME=(VOL/TURN)*YTIME/60.
      YCOST=YTIME*COST(ISYSTM)
C
C           COMPUTE THE EXPECTED VALUE OF THE TIMBER IN
C     PARCEL (I,J) IF IT IS YARDED OVER THIS HIGHLEAD
C     CABLEWAY.
C
      VALUE=VOL*PRICE(ITYPE)/1000. - HAUL(LANDG)*VOL/1000.
     1  -YCOST
C
C           WRITE OUT THE RESULT.
C
      IPARCL=J+(NCOLS*(I-1))-1
      WRITE (7,8802) ICABL,IPARCL,VALUE
 8802 FORMAT (2(I5,1X),F11.2)
      CPM=YCOST/(VOL/1000.)
      WRITE (6,480) HYD,AYD,ALD,XLOGS,TURN,CPM,I,J,VALUE
  480 FORMAT (3F7.0,F7.1,F7.0,F9.2,4X,≠(≠,I2,≠,≠,I2,≠)≠,
     1  F10.2)
      IF (IFEAT .EQ. 1) WRITE (6,490)
  490 FORMAT (≠+≠,T70,≠**FULL SUSPENSION**≠)
      IF (IFEAT .EQ. 2) WRITE (6,495)
  495 FORMAT (≠+≠,T70,≠**PARTIAL SUSPENSION**≠)
  500 CONTINUE
```

```
PAGE 11   OSU FORTRAN        PROGRAM CABLYRO

      510 CONTINUE
          IFLAG=0
          D=0.
          EL=EL1-SPAR(ISYSTM)
          CUMDIST=CUMDIST-(2.*SPAR(ISYSTM))-(2.*TT)
          WRITE (6,515) CUMDIST
      515 FORMAT (≠0  ESTIMATED GROUND DISTANCE, SPAR TO ≠,
         1  ≠ANCHOR:  ≠,F5.0,≠ FEET≠)
          IF (ISYS(ISYSTM) .EQ. 1) GO TO 560
C
C              WRITE OUT THE GROUND AND LOAD PROFILES
C         FOR THE SKYLINE.
C
          WRITE (6,520) D,EL
      520 FORMAT (≠0≠,T32,≠DIST≠/T32,≠FROM   GROUND    LOAD≠/
         1  ≠    CABLEWAY PROFILE:  POINT   SPAR    ELEV    ≠,
         2  ≠CAPAC≠/T24,≠-----    ----     ----     -----≠//,T25,
         3  ≠SPAR≠,F7.0,F8.0)
          DO 540 I=1,IGRIDS
          WRITE (6,530) I,PROFILE(I,1),PROFILE(I,2),WG(I)
      530 FORMAT (T25,I4,F7.0,F8.0,F9.0)
          IF (IFLAG .EQ. 0 .AND. PROFILE(I,1) .GE. XMYD) WRITE
         1  (6,535)
      535 FORMAT (≠+≠,T55,≠**MAXIMUM YARDING DISTANCE**≠)
          IF (PROFILE(I,1) .GE. XMYD) IFLAG=1
      540 CONTINUE
          WRITE (6,550) SPAN,EL2,TT
      550 FORMAT (T25,≠TAIL≠,F7.0,F8.0,T55,≠  TAIL TREE ≠,
         1  ≠HEIGHT=≠,F3.0,≠ FEET≠//≠ ≠,81(≠=≠))
C
C              GET THE NEXT CANDIDATE ANCHOR POSITION.
C
          GO TO 410
C
C              WRITE OUT THE GROUND PROFILE FOR THE HIGHLEAD.
C
      560 WRITE (6,570) D,EL
      570 FORMAT (≠0≠,T32,≠DIST≠/T32,≠FROM   GROUND≠/≠     ≠,
         1  ≠CABLEWAY PROFILE:  POINT   SPAR    ELEV≠/T24,
         2  ≠-----    ----    ------≠//T25,≠SPAR≠,F7.0,F8.0)
          DO 590 I=1,IGRIDS
          WRITE (6,580) I,PROFILE(I,1),PROFILE(I,2)
      580 FORMAT (T25,I4,F7.0,F8.0)
          IF (IFLAG .EQ. 0 .AND. PROFILE(I,1) .GE. XMYD)
         1  WRITE (6,585)
      585 FORMAT (≠+≠,T46,≠**MAXIMUM YARDING DISTANCE**≠)
          IF (PROFILE(I,1) .GE. XMYD) IFLAG=1
      590 CONTINUE
          WRITE (6,600) SPAN,EL2
      600 FORMAT (T25,≠TAIL≠,F7.0,F8.0//≠ ≠,69(≠=≠))
C
C              GET THE NEXT CANDIDATE ANCHOR POSITION.
C
          GO TO 410
```

```
PAGE 12  OSU FORTRAN        PROGRAM CABLYRD

 1000 IF (IFEAS .EQ. 0) WRITE (6,416)
C
C          WRITE OUT INFORMATION DATA.
C
      WRITE (9,1010) NCOLS,NSYS,(CMOVE(I),I=1,5),NLAND
     1  ,(CLAND(I),I=1,10),ICABL
 1010 FORMAT (I7/I7,5F7.0/I7,10F7.0/I7)
      STOP
      END
```

```
PAGE  1  OSU FORTRAN       SUBROUTINE HILEAD

      SUBROUTINE HILEAD
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/CABLE/ PROFILE(35,2),BFMIN(5),DENSTY(10),
     1  IGRIDS,ISYSTM,EL1,EL2,W1(5),W2(5),REACH(5),TMAX(5),
     2  SPAR(5),IBUFF,ITLROW,ITLCOL,DLAST,ELVLST,CUMDIST,
     3  ELEV,TT,TAIL(5),CLEAR(5,2),AVLOG(10),TURNMX(10,5),
     4  ISYS(5),WG(35)
C
C          THE HIGHLEAD FEASIBILITY ANALYSIS CHECKS FOR THE
C     FOLLOWING:  (1) SLOPE DISTANCE TO A PROFILE POINT
C     GREATER THAN THE SPECIFIED MAXIMUM: (2) BLIND LEAD
C     AREAS: (3) STREAM CROSSINGS, BUFFER STRIPS, ROADS,
C     LANDINGS, OR THE CUTTING AREA BOUNDARY; AND (4)
C     PROFILE POINTS AT WHICH THE MINIMUM ACCEPTABLE USER-
C     SPECIFIED TURN VOLUME WILL CAUSE EXCESSIVE TENSION
C     IN THE MAINLINE.  IF AN INFEASIBILITY IS DISCOVERED,
C     THEN THE MAXIMUM YARDING DISTANCE -XMYD- IS FIXED AT
C     THE PREVIOUS PROFILE POINT.  IF THIS DISTANCE IS
C     LESS THAN 500 FEET, HOWEVER, THE CABLEWAY IS DISCARDED
C     (UNLESS THE USER-ENTERED TAILHOLD LOCATION IS LESS THAN
C     500 FEET FROM THE LANDING).
C
      IBUFF=0
      XMYD=SPAN
      CUMDIST=SPAR(ISYSTM)*2.
      DLAST=0.
      ELVLST=EL1-SPAR(ISYSTM)
      DO 130 J=1,IGRIDS
      JL=J-1
      IF (JL .EQ. 0) GO TO 105
      DLAST=PROFILE(JL,1)
      ELVLST=PROFILE(JL,2)
  105 D=PROFILE(J,1)
      ELEV=PROFILE(J,2)
      CUMDIST=CUMDIST+SQRT((D-DLAST)**2 + (ELEV-
     1  ELVLST)**2)
      IF (CUMDIST .LE. REACH(ISYSTM)) GO TO 100
C
C          MAINLINE LENGTH EXCEEDED.
C
      XMYD=D-GRID
      GO TO 140
  100 ELDIFF=PROFILE(J,2)-(EL1-(D*CHDSLP))
      IF (ELDIFF .LE. 0.) GO TO 110
C
C          BLIND LEAD AREA DISCOVERED.
C
      XMYD=D-GRID
      GO TO 140
  110 IF (ABS(XNORTH) .LT. 1E-10) IROW=IHDROW(LANDG)
      IF (ABS(XNORTH) .GE. 1E-10) IROW=IFIX((FLOAT(IHDROW(LANDG))+
     1  .5)-(SIN(PHI)*(D/GRID)*(XNORTH/ABS(XNORTH))))
```

```
      IF (ABS(EAST) .LT. 1E-10) ICOL=IHDCOL(LANDG)
      IF (ABS(EAST) .GE. 1E-10) ICOL=IFIX((FLOAT(IHDCOL(LANDG))+
     1 .5)+(COS(PHI)*(D/GRID)*(EAST/ABS(EAST))))
      ITYPE=IFIX(XMATRIX(IROW,ICOL,2))
      IFEAT=IFIX(XMATRIX(IROW,ICOL,3))
      IF (ITYPE .NE. 99 .AND. IFEAT .EQ. 99) GO TO 120
C
C          STREAM CROSSING, BUFFER STRIP, ROAD, LANDING,
C     OR AREA BOUNDARY ENCOUNTERED.
C
      ITYPE=IFIX(XMATRIX(ITLROW,ITLCOL,2))
      IFEAT=IFIX(XMATRIX(ITLROW,ITLCOL,3))
      IF (IFEAT .EQ. 3 .OR. ITYPE .EQ. 99) IBUFF=1
      XMYD=D-1.
      GO TO 140
C
C          VARIABLE NAMES USED IN THE FOLLOWING SECTION ARE
C     REFERENCED TO THOSE USED IN THE HIGHLEAD TENSION ANALYSIS
C     PORTION OF THE PAPER.
C
C          COMPUTE THE TENSION IN THE MAINLINE IF A MINIMUM
C     LOAD WERE TO BE APPLIED AT THE PROFILE POINT.
C
  120 WL=BFMIN(ISYSTM)*DENSTY(ITYPE)
      TENSION=TENSN(WL)
      IF (TENSION .LE. TMAX(ISYSTM)) GO TO 130
C
C          MAXIMUM SAFE MAINLINE TENSION EXCEEDED.
C
      XMYD=D-GRID
      GO TO 140
  130 CONTINUE
  140 IF (XMYD .GE. 500.) GO TO 150
      IF (SPAN .LE. 500.) GO TO 150
C
C          MAXIMUM FEASIBLE YARDING DISTANCE IS LESS THAN 500
C     FEET FOR A PROPOSED SPAN OF GREATER THAN 500 FEET;
C     THEREFORE, DISCARD THE CABLEWAY.
C
      XMYD=0.
      RETURN
C
C          COMPLETE THE CHECK ON MAINLINE RIGGING LENGTH
C     CAPACITY.
C
  150 J=J+1
      IF (J .GT. IGRIDS) GO TO 170
      DO 160 I=J,IGRIDS
      JL=I-1
      DLAST=PROFILE(JL,1)
      ELVLST=PROFILE(JL,2)
      D=PROFILE(I,1)
      ELEV=PROFILE(I,2)
      CUMDIST=CUMDIST+SQRT((D-DLAST)**2 + (ELEV-
```

```
        1  ELVLST)**2)
    150 CONTINUE
    170 CUMDIST=CUMDIST+SQRT((SPAN-D)**2 + (EL2-
       1  ELEV)**2)
        IF (CUMDIST .LE. REACH(ISYSTM)) GO TO 180
C
C            MAINLINE RIGGING LENGTH CAPACITY EXCEEDED.
C
        XMYD=0.
        RETURN
C
C            THE PROPOSED CABLEWAY (OR THE PORTION OF IT
C       BETWEEN THE TOWER AND THE MAXIMUM FEASIBLE YARDING
C       DISTANCE) IS ACCEPTED.
C
    180 RETURN
        END
```

```
PAGE  1  OSU FORTRAN       SUBROUTINE SKYLINE

      SUBROUTINE SKYLINE
      COMMON NROWS,NCOLS,GRID,CHOSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/CABLE/ PROFILE(35,2),BFMIN(5),DENSTY(10),
     1  IGRIDS,ISYSTM,EL1,EL2,W1(5),W2(5),REACH(5),TMAX(5),
     2  SPAR(5),IBUFF,ITLROW,ITLCOL,DLAST,ELVLST,CUMDIST,
     3  ELEV,TT,TAIL(5),CLEAR(5,2),AVLOG(10),TURNMX(10,5),
     4  ISYS(5),WG(35)
C
C          THE SKYLINE FEASIBILITY ANALYSIS CHECKS FOR THE
C     FOLLOWING:  (1) GROUND PROFILE DISTANCE TO THE ANCHOR
C     POINT (PLUS TWICE THE HEIGHT OF THE SPAR AND TAILTREE)
C     GREATER THAN SYSTEM CAPABILITY: (2) LOAD CAPABILITY
C     AT ANY PROFILE POINT LESS THAN THE MINIMUM ACCEPTABLE
C     TURN VOLUME; (3) THE OCCURRENCE OF BUFFER STRIPS,
C     ROADS, LANDINGS, OR THE CUTTING BOUNDARY ALONG
C     THE CABLEWAY (ANY OF THESE FIXES THE MAXIMUM YARDING
C     DISTANCE AT LESS THAN THE SPAN).
C
C          IF (1) IS DISCOVERED, THE CABLEWAY IS DISCARDED;
C     IF (2), THEN THE TAILTREE HEIGHT (INITIALLY SET AT ZERO)
C     IS RAISED BY 25 FEET AND THE LOAD CAPABILITY RECALCULATED.
C     IF STILL INFEASIBLE, THE TAILTREE HEIGHT IS AGAIN RAISED
C     AND SO ON UP TO A MAXIMUM OF -TAIL(ISYSTM)- FEET.  IF
C     LOAD CAPABILITY IS BELOW THE MINIMUM FOR THE HIGHEST
C     TAILTREE, THEN THE CABLEWAY IS DISCARDED.  IF
C     (3) IS ENCOUNTERED, THEN -XMYD- IS FIXED AT THE PRESENT
C     LOCATION.  UNLESS THE CANDIDATE ANCHOR POSITION IS LESS
C     THAN 500 FEET FROM THE LANDING, HOWEVER, A CABLEWAY WITH
C     -XMYD- LESS THAN 500 FEET WILL BE DISCARDED.
C
      IBUFF=0
      XMYD=SPAN
      CUMDIST=SPAR(ISYSTM)*2
      DLAST=TT=0.
      ELVLST=EL1-SPAR(ISYSTM)
      DO 160 J=1,IGRIDS
      JL=J-1
      IF (JL .EQ. 0) GO TO 105
      DLAST=PROFILE(JL,1)
      ELVLST=PROFILE(JL,2)
  105 D=PROFILE(J,1)
      ELEV=PROFILE(J,2)
      CUMDIST=CUMDIST+SQRT((D-DLAST)**2 + (ELEV-ELVLST)**2)
      IF (CUMDIST .LE. REACH(ISYSTM)) GO TO 110
C
C          SKYLINE RIGGING LENGTH CAPACITY EXCEEDED.
C
      XMYD=0.
      RETURN
  110 IF (ABS(XNORTH) .LT. 1E-10) IROW=IHDROW(LANDG)
      IF (ABS(XNORTH) .GE. 1E-10) IROW=IFIX((FLOAT(IHDROW(LANDG))
     1  + .5) - (SIN(PHI)*(D/GRID)*(XNORTH/ABS(XNORTH))))
```

```
PAGE  2  OSU FORTRAN        SUBROUTINE SKYLINE

      IF (ABS(EAST) .LT. 1E-10) ICOL=IHDCOL(LANDG)
      IF (ABS(EAST) .GE. 1E-10) ICOL=IFIX((FLOAT(IHDCOL(LANDG))
     1 + .5) + (COS(PHI)*(D/GRID)*(EAST/ABS(EAST))))
      ITYPE=IFIX(XMATRIX(IROW,ICOL,2))
      IFEAT=IFIX(XMATRIX(IROW,ICOL,3))
      IF (ITYPE .NE. 99 .AND. IFEAT .EQ. 99) GO TO 120
      IF (IFEAT .EQ. 1 .OR. IFEAT .EQ. 2) GO TO 120
C
C          BUFFER STRIP, ROAD, LANDING, OR AREA BOUNDARY
C     ENCOUNTERED.
C
      XMYD=D-1.
      IF (ITYPE .EQ. 99 .OR. IFEAT .EQ. 3) IBUFF=1
C
C          THE PROCEDURE IN THE FOLLOWING SECTION IS ESSENTIALLY
C     THAT OF CARSON AND MANN (1971).  NOTE THAT WHEN GROUND
C     SKIDDING IS PERMITTED (IFEAT EQUAL TO 99), A CARRIAGE
C     CLEARANCE OF 5 FEET IS ASSUMED.
C
  120 Y=EL1-ELEV-5.
C
C          ADJUST FOR FULL SUSPENSION IF NECESSARY.
C
      IF (IFEAT .EQ. 1) Y=Y-CLEAR(ISYSTM,1)+5.
      IF (IFEAT .EQ. 2) Y=Y-CLEAR(ISYSTM,2)+5.
      T1=Y/D
      H=EL1-(EL2+TT)
      T3=(Y-H)/(SPAN-D)
      R1=W1(ISYSTM)*D*SQRT(1.+T1*T1)
      R2=W1(ISYSTM)*(SPAN-D)*SQRT(1.+T3*T3)
      R3=W2(ISYSTM)*D*SQRT(1.+T1*T1)
      H2=((W1(ISYSTM)*(SPAN-D))/(2.*SQRT(1.+T3*T3)))
     1  *(T3+SQRT((4.*((TMAX(ISYSTM)/(W1(ISYSTM)*(SPAN-D)))
     2  -(Y/(SPAN-D))))**2)-1.))
C
C          ISYS(ISYSTM)=2 FOR A LIVE SKYLINE AND 3 FOR A
C     RUNNING SKYLINE.
C
      WG(J)=FLOAT(ISYS(ISYSTM)-1)*H2*(T1+T3)-0.5*(R1+(FLOAT(
     1  ISYS(ISYSTM)-1)*R2)+R3)-CARRWT(ISYSTM)
C
C          THE FOLLOWING ASSUMES THAT THE SKYLINE LOAD
C     CAPACITY IS 1.5 TIMES GREATER FOR A PARTIALLY SUSPENDED
C     LOAD THAN FOR A FULLY SUSPENDED LOAD.
C
      IF (IFEAT .NE. 1) WG(J)=WG(J)*1.5
      IF (WG(J) .GE. BFMIN(ISYSTM)*DENSTY(ITYPE)) GO TO 150
C
C          LOAD CAPACITY EXCEEDED; INCREASE TAILTREE HEIGHT
C     IF POSSIBLE.
C
      IF (TT .LT. TAIL(ISYSTM)) GO TO 140
  130 XMYD=0.
      RETURN
```

```
PAGE   3  OSU FORTRAN        SUBROUTINE SKYLINE

   140 TT=TT+25.
       IF (TT .GT. TAIL(ISYSTM)) GO TO 130
       GO TO 120
   150 IF (XMYD .LT. SPAN) GO TO 170
   160 CONTINUE
   170 IF (XMYD .GE. 500.) GO TO 180
       IF (SPAN .LE. 500.) GO TO 180
       XMYD=0.
       RETURN
C
C            COMPLETE THE CHECK ON SKYLINE RIGGING LENGTH
C      CAPACITY.
C
   180 J=J+1
       IF (J .GT. IGRIDS) GO TO 200
       DO 190 I=J,IGRIDS
       JL=I-1
       DLAST=PROFILE(JL,1)
       EVLST=PROFILE(JL,2)
       ELEV=PROFILE(I,2)
       D=PROFILE(I,1)
       CUMDIST=CUMDIST+SQRT((D-DLAST)**2 + (ELEV-
      1  ELVLST)**2)
   190 CONTINUE
   200 CUMDIST=CUMDIST+SQRT((SPAN-D)**2 + (EL2-
      1  ELEV)**2) + 2.*TT
       IF (CUMDIST .LE. REACH(ISYSTM)) GO TO 210
C
C            SKYLINE RIGGING LENGTH CAPACITY EXCEEDED.
C
       XMYD=0.
       RETURN
C
C            THE CABLEWAY IS ACCEPTED.
C
   210 DO 220 J=2,IGRIDS
       JL=J-1
       IF (WG(JL) .LT. WG(J)) WG(J)=WG(JL)
   220 CONTINUE
       RETURN
       END
```

PAGE 1 OSU FORTRAN FUNCTION TENSN

```
      FUNCTION TENSN(WL)
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/CABLE/ PROFILE(35,2),BFMIN(5),DENSTY(10),
     1 IGRIDS,ISYSTM,EL1,EL2,W1(5),W2(5),REACH(5),TMAX(5),
     2 SPAR(5),IBUFF,ITLROW,ITLCOL,DLAST,ELVLST,CUMDIST,
     3 ELEV,TT,TAIL(5),CLEAR(5,2),AVLOG(10),TURNMX(10,5),
     4 ISYS(5),WG(35)
C
C         THIS FUNCTION COMPUTES THE TENSION IN THE
C     HIGHLEAD MAINLINE WHEN A LOAD OF WEIGHT WL IS
C     IMPOSED UPON IT.
C
      R=W1*SQRT(D*D + Y*Y)
      FWL=WL*SIN(THETA)
      XMUNL=0.5*WL*COS(THETA)
      WHB=W2*SQRT((SPAN-D)**2 + (Y-H)**2)
      FWHB=WHB*SIN(THETA)
      XMUNHB=0.6*WHB*COS(THETA)
      TENSN=R/4.
      TENSN=TENSN+((FWL+XMUNL)*SIN(THETA))
      TENSN=TENSN+(0.5+((SPAN-D)/(4.*D)))*(FWHB+XMUNHB)*
     1 SIN(THETA)
      TENSN=TENSN+(CHDSLP/2. + (H-Y)/(4.*D))*(FWHB +
     1 XMUNHB)*COS(THETA)
      TENSN=TENSN+CARRWT(ISYSTM)
      TENSN=TENSN/SIN(THETA)
      RETURN
      END
```

```
PAGE   1   OSU FORTRAN        FUNCTION YDIST

         FUNCTION YDIST(AYD)
         COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
         COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
         COMMON SPAN,D,Y,H,LANDG
         COMMON/CABLE/ PROFILE(35,2),BFMIN(5),DENSTY(10),
        1  IGRIDS,ISYSTM,EL1,EL2,W1(5),W2(5),REACH(5),TMAX(5),
        2  SPAR(5),IBUFF,ITLROW,ITLCOL,DLAST,ELVLST,CUMDIST,
        3  ELEV,TT,TAIL(5),CLEAR(5,2),AVLOG(10),TURNMX(10,5),
        4  ISYS(5),WG(35)
   C
   C            THIS FUNCTION CONVERTS AVERAGE HORIZONTAL YARDING
   C     DISTANCE INTO AN AVERAGE YARDING DISTANCE MEASURED
   C     ALONG THE GROUND PROFILE.
   C
         SDIST=0.
         DLAST=0.
         ELVLST=EL1-SPAR(ISYSTM)
         J=0
     100 J=J+1
         JL=J-1
         IF (J .EQ. 1) GO TO 105
         DLAST=PROFILE(JL,1)
         ELVLST=PROFILE(JL,2)
     105 D=PROFILE(J,1)
         ELEV=PROFILE(J,2)
         IF (J .GT. IGRIDS) D=SPAN
         IF (J .GT. IGRIDS) ELEV=EL2
         IF (J .GT. IGRIDS) GO TO 110
         IF (D .GT. AYD) GO TO 110
         SDIST=SDIST+SQRT((D-DLAST)**2 + (ELEV-ELVLST)**2)
         GO TO 100
     110 IF (ABS(AYD-DLAST) .LT. 1E-10) GO TO 120
         ELEV=(ELEV-ELVLST)*(AYD-DLAST)/(D-DLAST)
         SDIST=SDIST+SQRT((AYD-DLAST)**2 + ELEV**2)
     120 YDIST=SDIST
         RETURN
         END
```

```
PAGE  1  OSU FORTRAN        SUBROUTINE BIGSQ

      SUBROUTINE BIGSQ(LOWROW,LOWCOL,IHIROW,IHICOL,OLAT)
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/FEAS/ AROW,ACOL,BROW,BCOL,CROW,CCOL,DROW,DCOL
      INTEGER XMAX1F,XMIN1F
C
C          THIS SUBROUTINE FINDS THE COORDINATES OF A
C     RECTANGLE ENCLOSING THE CABLEWAY AND ITS LATERAL
C     YARDING AREA.  IT ALSO FINDS THE ROWS AND COLUMNS
C     TO BE SEARCHED IN ORDER TO DETERMINE WHICH GRID-
C     SQUARES ARE FULLY ENCLOSED WITHIN THAT RECTANGLE
C     (AND THUS CAN BE COMPLETELY YARDED FROM THE CABLEWAY).
C
C
C          ADJUST FOR THE AZIMUTH OF THE CABLEWAY.  NOTE THAT
C     45 DEGREES IS APPROXIMATELY EQUAL TO 0.78539816 RADIANS.
C
      IF (PHI .LE. .78539816) GO TO 100
      OLAT1=OLAT/SIN(PHI)
      G=GRID/SIN(PHI)
      GO TO 110
  100 OLAT1=OLAT/COS(PHI)
      G=GRID/COS(PHI)
  110 IF (G .GT. OLAT1) OLAT1=G
C
C          FIND THE CORNERS OF THE RECTANGLE.
C
      IF (ABS(XNORTH)  .LT.  1E-10)  SIGN1=0.
      IF (ABS(XNORTH)  .GE.  1E-10)  SIGN1=XNORTH/ABS(XNORTH)
      IF (ABS(EAST)    .LT.  1E-10)  SIGN2=0.
      IF (ABS(EAST)    .GE.  1E-10)  SIGN2=EAST/ABS(EAST)
      AROW=FLOAT(IHDROW(LANDG))+.5+((OLAT1/GRID)*COS(PHI)*SIGN2)
      ACOL=FLOAT(IHDCOL(LANDG))+.5+((OLAT1/GRID)*SIN(PHI)*SIGN1)
      BROW=FLOAT(IHDROW(LANDG))+.5-((OLAT1/GRID)*COS(PHI)*SIGN2)
      BCOL=FLOAT(IHDCOL(LANDG))+.5-((OLAT1/GRID)*SIN(PHI)*SIGN1)
      CROW=AROW-((XMYD/GRID)*SIN(PHI)*SIGN1)
      CCOL=ACOL+((XMYD/GRID)*COS(PHI)*SIGN2)
      DROW=BROW-((XMYD/GRID)*SIN(PHI)*SIGN1)
      DCOL=BCOL+((XMYD/GRID)*COS(PHI)*SIGN2)
C
C          FIND THE ROW AND COLUMN LIMITS FOR THE SEARCH.
C
      IHIROW=XMAX1F(AROW,BROW,CROW,DROW)
      LOWROW=XMIN1F(AROW,BROW,CROW,DROW)
      IHICOL=XMAX1F(ACOL,BCOL,CCOL,DCOL)
      LOWCOL=XMIN1F(ACOL,BCOL,CCOL,DCOL)
      IF (IHIROW .GT. NROWS) IHIROW=NROWS
      IF (LOWROW .LT. 1) LOWROW=1
      IF (IHICOL .GT. NCOLS) IHICOL=NCOLS
      IF (LOWCOL .LT. 1) LOWCOL=1
      RETURN
      END
```

PAGE 1 OSU FORTRAN SUBROUTINE FEAS

```
      SUBROUTINE FEAS(ROW1,ROW2,COL1,COL2,IRES)
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
      COMMON/FEAS/ AROW,ACOL,BROW,BCOL,CROW,CCOL,DROW,DCOL
      DIMENSION ROW(2),COL(2)
C
C          THIS SUBROUTINE DETERMINES WHETHER A GRIDSQUARE
C     DEFINED BY (ROW1,ROW2,COL1,COL2) IS FULLY ENCLOSED
C     IN THE RECTANGLE (AROW,ACOL),(BROW,BCOL),(CROW,CCOL),
C     (DROW,DCOL).
C
      IRES=0
C
C          CHECK THE INTERSECTIONS OF THE SIDES OF THE
C     RECTANGLE WITH THE COLUMNS OF THE GRIDSQUARE BEING
C     CONSIDERED.
C
C          IF THE CABLEWAY POINTS DUE EAST OR WEST, THERE
C     ARE NO INTERSECTIONS BETWEEN SEGMENTS AB OR CD AND
C     THE COLUMNS OF THE GRIDSQUARE.
C
      IF (ABS(XNORTH) .LT. 1E-10) GO TO 120
C
C          CHECK THE INTERSECTION OF LINE AB AND THE LOWER
C     COLUMN OF THE GRIDSQUARE.
C
      ROW(1)=AROW-(ACOL-COL1)*(AROW-BROW)/(ACOL-BCOL)
C
C          LINE AB AND THE UPPER COLUMN OF THE GRIDSQUARE.
C
      ROW(2)=AROW-(ACOL-COL2)*(AROW-BROW)/(ACOL-BCOL)
C
C          TEST THE INTERSECTIONS.
C
      DO 100 I=1,2
      IF (XNORTH .LT. 0. .AND. ROW(I) .GT. ROW1) RETURN
      IF (XNORTH .GT. 0. .AND. ROW(I) .LT. ROW2) RETURN
  100 CONTINUE
C
C          LINE CD AND THE COLUMNS.
C
      ROW(1)=CROW-(CCOL-COL1)*(CROW-DROW)/(CCOL-DCOL)
      ROW(2)=CROW-(CCOL-COL2)*(CROW-DROW)/(CCOL-DCOL)
      DO 110 I=1,2
      IF (XNORTH .LT. 0. .AND. ROW(I) .LT. ROW2) RETURN
      IF (XNORTH .GT. 0. .AND. ROW(I) .GT. ROW1) RETURN
  110 CONTINUE
C
C          IF THE CABLEWAY IS ORIENTED DUE NORTH OR SOUTH,
C     THERE ARE NO INTERSECTIONS BETWEENS LINES AC OR BD AND
C     THE COLUMNS OF THE GRIDSQUARE.
C
  120 IF (ABS(EAST) .LT. 1E-10) GO TO 170
```

```
C
C              LINE AC AND THE COLUMNS.
C
          ROW(1)=AROW-(ACOL-COL1)*(AROW-CROW)/(ACOL-CCOL)
          ROW(2)=AROW-(ACOL-COL2)*(AROW-CROW)/(ACOL-CCOL)
          DO 130 I=1,2
          IF (EAST .LT. 0. .AND. ROW(I) .GT. ROW1) RETURN
          IF (EAST .GT. 0. .AND. ROW(I) .LT. ROW2) RETURN
      130 CONTINUE
C
C              LINE BD AND THE COLUMNS
C
          ROW(1)=BROW-(BCOL-COL1)*(BROW-DROW)/(BCOL-DCOL)
          ROW(2)=BROW-(BCOL-COL2)*(BROW-DROW)/(BCOL-DCOL)
          DO 140 I=1,2
          IF (EAST .LT. 0. .AND. ROW(I) .LT. ROW2) RETURN
          IF (EAST .GT. 0. .AND. ROW(I) .GT. ROW1) RETURN
      140 CONTINUE
C
C              CHECK THE INTERSECTIONS OF THE SIDES OF THE
C         RECTANGLE AND THE ROWS OF THE GRIDSQUARE.
C
C              LINE AB AND THE ROWS.
C
          COL(1)=ACOL-(AROW-ROW1)*(ACOL-BCOL)/(AROW-BROW)
          COL(2)=ACOL-(AROW-ROW2)*(ACOL-BCOL)/(AROW-BROW)
          DO 150 I=1,2
          IF (EAST .LT. 0. .AND. COL(I) .LT. COL2) RETURN
          IF (EAST .GT. 0. .AND. COL(I) .GT. COL1) RETURN
      150 CONTINUE
C
C              LINE CD AND THE ROWS.
C
          COL(1)=CCOL-(CROW-ROW1)*(CCOL-DCOL)/(CROW-DROW)
          COL(2)=CCOL-(CROW-ROW2)*(CCOL-DCOL)/(CROW-DROW)
          DO 160 I=1,2
          IF (EAST .LT. 0. .AND. COL(I) .GT. COL1) RETURN
          IF (EAST .GT. 0. .AND. COL(I) .LT. COL2) RETURN
      160 CONTINUE
C
C              IF THE CABLEWAY IS ORIENTED DUE EAST OR WEST,
C         THERE ARE NO INTERSECTIONS BETWEEN LINES AC OR
C         BD AND THE ROWS.
C
      170 IF (ABS(XNORTH) .LT. 1E-10) GO TO 200
C
C              LINE AC AND THE ROWS.
C
          COL(1)=ACOL-(AROW-ROW1)*(ACOL-CCOL)/(AROW-CROW)
          COL(2)=ACOL-(AROW-ROW2)*(ACOL-CCOL)/(AROW-CROW)
          DO 180 I=1,2
          IF (XNORTH .LT. 0. .AND. COL(I) .GT. COL1) RETURN
          IF (XNORTH .GT. 0. .AND. COL(I) .LT. COL2) RETURN
      180 CONTINUE
```

```
PAGE  3  OSU FORTRAN        SUBROUTINE FEAS

C
C            LINE BD AND THE ROWS.
C
       COL(1)=BCOL-(BROW-ROW1)*(BCOL-DCOL)/(BROW-DROW)
       COL(2)=BCOL-(BROW-ROW2)*(BCOL-DCOL)/(BROW-DROW)
       DO 190 I=1,2
       IF (XNORTH .LT. 0. .AND. COL(I) .LT. COL2) RETURN
       IF (XNORTH .GT. 0. .AND. COL(I) .GT. COL1) RETURN
   190 CONTINUE
C
C            IF WE GET HERE, THE GRIDSQUARE IS FULLY ENCLOSED
C      IN THE RECTANGLE.
C
   200 IRES=1
       RETURN
       END
```

```
PAGE  1  OSU FORTRAN        FUNCTION PTELEV

      FUNCTION PTELEV(ROW,COL)
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
C
C          THIS FUNCTION DETERMINES THE APPROXIMATE ELEVATION
C     OF A REAL POINT WITHIN THE GRIDSQUARE (IROW, ICOL).
C
      PTELEV=-.6E300
C
C          TEST TO SEE WHETHER A FULL UNIT SQUARE CAN BE CON-
C     STRUCTED AROUND THE POINT FOR WHICH THE ELEVATION IS TO
C     BE FOUND.
C
      IROW=IFIX(ROW)
      ICOL=IFIX(COL)
      RROW=ROW-FLOAT(IROW)
      CCOL=COL-FLOAT(ICOL)
      IF (IROW .EQ. 1 .AND. RROW .LE. .5) GO TO 100
      IF (IROW .EQ. NROWS .AND. RROW .GE. .5) GO TO 110
      IF (ICOL .EQ. 1 .AND. CCOL .LE. .5) GO TO 130
      IF (ICOL .EQ. NCOLS .AND. CCOL .GE. .5) GO TO 130
C
C          IF WE GET HERE, THEN A FULL UNIT SQUARE CAN BE
C     CONSTRUCTED AROUND THE POINT.
C
      GO TO 140
C
C          THE POINT IS IN THE TOP HALF OF ROW 1.
C
  100 IF (ICOL .EQ. 1 .AND. CCOL .LE. .5) PTELEV=
     1  XMATRIX(IROW,ICOL,1)
      IF (ICOL .EQ. NCOLS .AND. CCOL .GE. .5) PTELEV=
     1      XMATRIX(IROW,ICOL,1)
      IF (PTELEV .LT. -.5E300) GO TO 120
      RETURN
C
C          THE POINT IS IN THE BOTTOM HALF OF ROW NROWS.
C
  110 IF (ICOL .EQ. 1 .AND. CCOL .LE. .5) PTELEV=
     1  XMATRIX(IROW,ICOL,1)
      IF (ICOL .EQ. NCOLS .AND. CCOL .GE. .5) PTELEV=
     1      XMATRIX(IROW,ICOL,1)
      IF (PTELEV .LT. -.5E300) GO TO 120
      RETURN
C
C          FIND THE ELEVATION FOR THE POINT IN THE TOP (OR
C     BOTTOM) HALF OF THE FIRST (OR LAST) ROW.
C
  120 DELTA=COL-(FLOAT(ICOL)+.5)
      IF (DELTA .GE. 0.) ICOL1=ICOL+1
      IF (DELTA .LT. 0.) ICOL1=ICOL-1
      IF (DELTA .LT. 0.) DELTA=DELTA*(-1.)
      PTELEV=XMATRIX(IROW,ICOL,1)+(DELTA*(
```

PAGE 2 OSU FORTRAN FUNCTION PTELEV

```
     1  XMATRIX(IROW,ICOL1,1)-XMATRIX(IROW,ICOL,1)))
      RETURN
C
C          IF WE GET HERE, THEN THE POINT IS IN EITHER THE
C     LEFT HALF OF THE LEFTMOST COLUMN, OR IN THE RIGHT HALF
C     OF THE RIGHTMOST COLUMN, BUT NOT IN THE TOP OR BOTTOM
C     ROW.
C
  130 DELTA=ROW-(FLOAT(IROW)+.5)
      IF (DELTA .GE. 0.) IROW1=IROW+1
      IF (DELTA .LT. 0.) IROW1=IROW-1
      IF (DELTA .LT. 0.) DELTA=DELTA*(-1.)
      PTELEV=XMATRIX(IROW,ICOL,1)+(DELTA*(
     1  XMATRIX(IROW1,ICOL,1)-XMATRIX(IROW,ICOL,1)))
      RETURN
C
C          THE FOLLOWING PROCEDURE CONSTRUCTS A UNIT SQUARE
C     AROUND THE POINT FOR WHICH THE ELEVATION IS TO BE FOUND.
C     THE CORNERS OF THE SQUARE ARE AT THE CENTROIDS OF
C     GRIDSQUARES (IROW,ICOL), (IROW1,ICOL), (IROW,ICOL1),
C     AND (IROW1,ICOL1).
C
C          BEGIN BY PROJECTING A LINE SEGMENT FROM THE CENTROID
C     OF GRIDSQUARE (IROW,ICOL) THROUGH POINT (ROW,COL);
C     COMPUTE THE ELEVATION OF THE POINT WHERE THAT LINE
C     SEGMENT INTERSECTS A SIDE OF THE UNIT SQUARE.  THEN COM-
C     PUTE A PROJECTED ELEVATION BACK TO THE POINT ITSELF.
C
  140 DELTA1=COL-(FLOAT(ICOL)+.5)
      IF (DELTA1 .GE. 0.) ICOL1=ICOL+1
      IF (DELTA1 .LT. 0.) ICOL1=ICOL-1
      DELTA2=ROW-(FLOAT(IROW)+.5)
      IF (DELTA2 .GE. 0.) IROW1=IROW+1
      IF (DELTA2 .LT. 0.) IROW1=IROW-1
      PTELEV=0.
      CALL AVELEV(DELTA1,DELTA2,IROW,IROW1,ICOL,ICOL1,EL2)
      IF (EL2 .LT. 0.) EL2=XMATRIX(IROW,ICOL,1)
      PTELEV=PTELEV+EL2
C
C          PROJECT THE LINE FROM THE CENTROID OF GRIDSQUARE
C     (IROW,ICOL1).
C
      IF (ABS(DELTA1) .EQ. 0.) DEL1=1.
      IF (ABS(DELTA1) .NE. 0.) DEL1=(1.-ABS(DELTA1))*(-1.)*
     1   (DELTA1/(ABS(DELTA1)))
      CALL AVELEV(DEL1,DELTA2,IROW,IROW1,ICOL1,ICOL,EL2)
      IF (EL2 .LT. 0.) EL2=XMATRIX(IROW,ICOL,1)
      PTELEV=PTELEV+EL2
C
C          PROJECT THE LINE FROM THE CENTROID OF GRIDSQUARE
C     (IROW1,ICOL).
C
      IF (ABS(DELTA2) .EQ. 0.) DEL2=1.
      IF (ABS(DELTA2) .NE. 0.) DEL2=(1.-ABS(DELTA2))*(-1.)*
```

PAGE 3 OSU FORTRAN FUNCTION PTELEV

```
     1   (DELTA2/(ABS(DELTA2)))
      CALL AVELEV(DELTA1,DEL2,IROW1,IROW,ICOL,ICOL1,EL2)
      IF (EL2 .LT. 0.) EL2=XMATRIX(IROW,ICOL,1)
      PTELEV=PTELEV+EL2
C
C          PROJECT THE LINE FROM THE CENTROID OF GRIDSQUARE
C     (IROW1,ICOL1).
C
      CALL AVELEV(DEL1,DEL2,IROW1,IROW,ICOL1,ICOL,EL2)
      IF (EL2 .LT. 0.) EL2=XMATRIX(IROW,ICOL,1)
      PTELEV=PTELEV+EL2
C
C          COMPUTE THE MEAN OF THE FOUR ESTIMATES.
C
      PTELEV=PTELEV/4.
      RETURN
      END
```

```
PAGE  1  OSU FORTRAN        SUBROUTINE AVELEV

      SUBROUTINE AVELEV(DELTA1,DELTA2,IROW,IROW1,ICOL,ICOL1,EL2)
      COMMON NROWS,NCOLS,GRID,CHOSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
C
C          THIS SUBROUTINE ESTIMATES THE ELEVATION AT ANY POINT
C     BY CONSTRUCTING A UNIT SQUARE AROUND THE POINT.  THE
C     CORNERS OF THE UNIT SQUARE ARE AT THE CENTROIDS OF THE
C     CLOSEST FOUR GRIDSQUARES, ONE OF WHICH CONTAINS THE POINT
C     ITSELF.  EACH TIME THIS SUBROUTINE IS CALLED, A LINE
C     SEGMENT IS CONSTRUCTED FROM THE CORNER OF THE UNIT SQUARE
C     AT (IROW, ICOL) THROUGH THE POINT OF INTEREST.  THIS LINE
C     SEGMENT INTERSECTS ONE OF THE SIDES OF THE UNIT SQUARE.
C     FROM KNOWN ELEVATIONS AT THE CORNERS OF THE UNIT SQUARE,
C     AN ESTIMATE OF THE ELEVATION AT THE POINT IS COMPUTED.
C
      IF (ABS(DELTA1) .LT. ABS(DELTA2)) GO TO 110
C
C          A LINE SEGMENT PROJECTED FROM (IROW,ICOL) THROUGH THE
C     POINT OF INTEREST WILL INTERSECT THE LINE SEGMENT BETWEEN
C     THE CENTROIDS OF (IROW,ICOL1) AND (IROW1,ICOL1).  FIND THE
C     ELEVATION AT THAT INTERSECTION.
C
      IF (XMATRIX(IROW,ICOL1,1) .LT. -7E6 .OR.
     1   XMATRIX(IROW1,ICOL1,1) .LT. -7E6) GO TO 120
      EL1=XMATRIX(IROW,ICOL1,1)-(ABS(DELTA2/DELTA1)*
     1   (XMATRIX(IROW,ICOL1,1)-XMATRIX(IROW1,ICOL1,1)))
C
C          FIND THE DISTANCE TO THE INTERSECTION.
C
      DIST=SQRT((DELTA2/DELTA1)**2 + 1.)
C
C          ESTIMATE THE ELEVATION AT THE POINT OF INTEREST.
C
  100 EL2=XMATRIX(IROW,ICOL,1)-((SQRT(DELTA1*DELTA1 +
     1  DELTA2*DELTA2)/DIST)*(XMATRIX(IROW,ICOL,1)-EL1))
      RETURN
C
C          A LINE SEGMENT PROJECTED FROM (IROW,ICOL) THROUGH THE
C     POINT OF INTEREST WILL INTERSECT THE LINE SEGMENT BETWEEN THE
C     CENTROIDS OF (IROW1,ICOL) AND (IROW1,ICOL1).  FIND THE
C     ELEVATION AT THAT INTERSECTION.
C
  110 IF (XMATRIX(IROW1,ICOL,1) .LT. -7E6 .OR.
     1   XMATRIX(IROW1,ICOL1,1) .LT. -7E6) GO TO 120
      EL1=XMATRIX(IROW1,ICOL,1)-(ABS(DELTA1/DELTA2)*
     1   (XMATRIX(IROW1,ICOL,1)-XMATRIX(IROW1,ICOL1,1)))
C
C          FIND THE DISTANCE TO THE INTERSECTION.
C
      DIST=SQRT((DELTA1/DELTA2)**2 + 1.)
      GO TO 100
C
C          IF WE GET HERE, THE GRIDSQUARE INTO WHICH THE
```

PAGE 2 OSU FORTRAN SUBROUTINE AVELEV

```
C     LINE SEGMENT FROM (IROW,ICOL) IS PROJECTED THROUGH
C     THE POINT IN QUESTION HAS AN ELEVATION WHICH WAS NOT
C     ENTERED VIA THE DATA MATRIX.  THEREFORE, ESTIMATE
C     THE ELEVATION OF THE POINT AS BEING EQUAL TO THAT OF
C     THE CENTROID OF (IROW,ICOL).
C
  120 EL2=XMATRIX(IROW,ICOL,1)
      RETURN
      END
```

```
PAGE   1  OSU FORTRAN         FUNCTION XMATRIX

      FUNCTION XMATRIX(I,J,K)
      COMMON NROWS,NCOLS,GRID,CHDSLP,PHI,THETA,CARRWT(5)
      COMMON IHDCOL(10),IHDROW(10),EAST,XNORTH,XMYD
      COMMON SPAN,D,Y,H,LANDG
C
C           THIS FUNCTION READS A RANDOM-ACCESS FILE
C     EQUIPPED TO LOGICAL UNIT K, AND RETURNS A SINGLE
C     FLOATING POINT VALUE.  IF K=1, THE VALUE RETURNED
C     IS THE ELEVATION OF POINT (I,J), IN FEET; IF K=2,
C     IT IS THE FOREST TYPE OF THE POINT; AND IF K=3,
C     IT IS THE SPECIAL FEATURE CODE OF THE POINT.
C
      IP=J+(NCOLS*(I-1))-1
      CALL SEEK(K,IP)
      READ (K,100) X
  100 FORMAT (F4.0)
      XMATRIX=X
      RETURN
      END
```

APPENDIX III

USER'S GUIDE TO THE LOGGING FEASIBILITY AND COST ANALYSIS PROGRAMS

Data required are of four types:

1. Elevation matrix -- the average elevation of each matrix parcel must be recorded on a word-addressable, random-access file equipped to logical unit number 1. Each elevation must be right adjusted on a single BCD word (maximum elevation = 9999).

2. Forest type matrix -- a vegetative type code corresponding to each matrix parcel must be recorded on a word-addressable, random-access file equipped to logical unit number 2. Each code must be right adjusted on a single BCD word. Codes should be numbered from 1 to N, where there are N vegetative types on the area. Code number 99 signifies that the parcel is outside of the planning area.

3. Physical feature matrix -- a code signifying the physical feature corresponding to each matrix parcel must be recorded on a word-addressable, random-access file equipped to logical unit number 3. Each code must be right adjusted on a single BCD word. Codes which are currently recognized by the programs are as follows:

Code	Interpretation
1	Full suspension of logs over this parcel is required.
2	Partial suspension of logs over this parcel is required.
3	This parcel is a buffer strip or other reserved timber.
4	Road
5	Landing
99	Ground skidding of timber is permitted.

4. Run data -- a free-format BCD file pertaining to an individual run, as described below. This file must be equipped to logical unit number 5.

   a. Run title -- any descriptive title of 80 BCD characters or less.

   b. Matrix data -- the grid length, in feet, which has been superimposed over the area; the number of rows in the grid; and the number of columns. The grid length is the length of one side of an individual gridsquare, or parcel.

   The format for this data line is as follows:

Grid Length	No. Rows	No. Columns
______,	______,	______

c. Yarding system data -- this is a set of lines, one for each yarding system to be analyzed. Information listed below must be entered for each yarding system. If the data for any system is too long to fit on a single line (or data card), it may be continued onto additional lines or cards.

After data for all yarding systems to be considered (up to a maximum of 5) has been entered, the number 9999 is used to terminate input of this data type.

The format for entering yarding system data is as follows:

Sys No.	Sys Type	Max Reach	Max Lat.	Seg1 Wt	Seg2 Wt	Max. T	Carr. Wt	Spar Ht	Tail Ht	Carr. Full	Clr. Part	Min. fbm/turn
___,	___,	___,	___,	___,	___,	___,	___,	___,	___,	___,	___,	___

Cost $/hr	Move Cost	Rig Tail Road (min/ft)	Change α_0	α_1	Add Time Through Buffer
___,	___,	___,	___,	___,	___

9999

Following is an explanation of these entries:

System number -- a number which identifies each yarding system to the programs. The maximum system number presently available is 5.

System type -- 1=highlead
2=live skyline with or without haulback
3=running skyline

Maximum reach -- the effective limit, along the ground surface, in feet, of the distance between the landing and the anchor.

Maximum lateral -- an estimate of the greatest slope distance, perpendicular to the cableway, from which logs may be yarded laterally. This may be set according to either physical limits or what is desired. Note, however, that the actual resolution of the model is dependent upon parcel size, and for larger grid lengths the number entered here may have to be ignored if the program is to be able to analyze the yarding system at all. As an example, the lateral resolution for a 100-foot grid length is between 50 and $50\sqrt{2}$ feet, depending upon the orientation of the cableway relative to the axes of the grid. Smaller entries in this space will therefore be ignored. Knowing this fact, it is possible to simulate closer spacing of yarding roads by increasing the cost of cableway emplacement.

Segment 1 weight -- the unit weight (lbs/lineal foot) of the mainline (for highlead systems), the skyline (for live skyline systems), or the haulback (for running skyline systems).

Segment 2 weight -- the unit weight (lbs/lineal foot) of the haulback (for highlead systems) or the combined main and slackpulling lines (for skyline systems). Weight of the carriage dropline is not included.

Maximum tension -- the maximum safe tension permitted in the controlling line, in pounds. The controlling line is assumed to be the mainline (for highlead systems), the skyline (for live skylines), and the haulback (for running skylines).

Carriage weight -- total weight, in pounds, of the carriage or butt rigging.

Spar height -- vertical height of the tower, in feet, above the centroid of the grid at which the spar is located.

Tailtree height -- maximum height of the tailhold in a rigged tailtree, above the elevation of the ground. This is dependent primarily upon the size and quality of trees available for use as tailtrees. It is always equal to zero for highlead systems.

Carriage clearance (full) -- the minimum distance, in feet, by which the carriage is suspended above the ground in order to permit full suspension of logs at any point. Includes allowance for chokers and log length.

Carriage clearance (partial) -- same as above, but for partial suspension of logs.

Minimum volume/turn -- the minimum acceptable average volume, in fbm, for this yarding system. It is important that some volume greater than zero always be entered in this space. If harvesting priority is high, and the importance of yarding cost is small, then the actual entry can be made quite small.

Cost per hour -- the estimated total of fixed and operating costs of the yarding system, including both machinery and crew costs for yarding and loading. The cost of equipment necessary for yarding but not actually used during yarding, such as fire fighting equipment or crew vehicles, should be included.

Moving cost -- the estimated fixed cost, in $, of rigging down at the previous setting, moving, and rigging up. Includes moving charges for all personnel and equipment necessary for yarding and loading.

Tailtree rigging time -- an estimate of the time required to rig a tailtree, in minutes per foot of tailtree height. This time is used to estimate cableway emplacement cost. As that cost is based upon an estimate of emplacement time (see equation [3.26]), this coefficient should be adjusted so that it reflects only yarding system time. As an example, suppose that tailtree rigging time is estimated to take two men 1.6 minutes per foot of tailtree height, and that the tailtree will be pre-rigged. If the cost of the two men is $12 per hour, the total cost of rigging the tailtree is estimated to be $16 for a 50-foot tailtree. If the yarding system costs $100 per hour, then the equivalent time which should be entered here is (16/100)(60)/50 = 0.192 system-minutes/foot of tailtree height. This is then α_2 in equation [3.26].

Road change coefficients -- α_0 and α_1 in equation [3.26]. If it does not seem appropriate to assume that road changing time is a function of external yarding distance or distance to the tailhold, then enter α_0 as the expected road changing time, in minutes, and α_1 as zero.

Add time through buffer -- α_3 in equation [3.26]. This is the time, in minutes, by which road changing time should be increased when the lines are to be threaded through a buffer strip or other standing timber.

d. Yarding regression coefficients -- this is a set of lines, each of which describes the seven linear regression coefficients β_0 through β_6, and the delay factor, δ, as described in equation [3.19], for each yarding system to be considered.

After regression coefficients for all yarding systems to be considered have been entered, the number 9999 is used to terminate input of this data type.

The format for entering yarding regression data is as follows:

System No.	β_0	β_1	β_2	β_3	β_4	β_5	β_6	δ
____,	____,	____,	____,	____,	____,	____,	____,	____

9999

Following is an explanation of these entries:

β_0 -- the regression constant, in minutes.

β_1 -- the regression coefficient corresponding to volume per turn, in minutes/fbm.

β_2 -- the regression coefficient corresponding to volume per log, in minutes/fbm.

β_3 -- the regression coefficient corresponding to slope yarding distance, in minutes/foot.

$\underline{\beta_4}$ -- the regression coefficient corresponding to slope lateral yarding distance, in minutes/foot.

$\underline{\beta_5}$ -- the regression coefficient corresponding to logs per turn, in minutes/log.

$\underline{\beta_6}$ -- the regression coefficient corresponding to chordslope, in minutes/percent. Note that chordslope is assumed to be in percent as measured from the horizontal and from the point of view of the landing. Thus, it will always be negative for uphill yarding, and positive for downhill yarding.

$\underline{\delta}$ -- the delay factor. δ=1.15 indicates that delays will increase total expected yarding time by 15 percent.

Note that if a regression equation is to be used which has only some subset of the above, then any missing coefficients should be entered as zeroes. Similarly, if a regression equation is to be used which contains additional independent variables, then the average of those variables multiplied by their regression coefficients should be added to β_0.

e. Landing data -- this is another set of lines, one line for each landing site which is to be considered.

After data for all landings (up to a maximum of 10) has been entered, the number 9999 is used to terminate landing data entry.

The format for entering landing data is as follows:

Landing No.	Parcel of Spar Row	Parcel of Spar Column	Fixed Cost	Haul Cost
____,	____,	____,	____,	____

9999

Following is an explanation of these entries:

Parcel location of spar -- the row and column in the data matrix in which the yarder will be located if this landing is used. For computation purposes, the yarder is assumed to be centered in this parcel.

Fixed cost -- the total estimated fixed cost associated with establishing the landing, including any spur road construction which would otherwise not be required.

Haul cost -- the estimated cost, in $/Mfbm, of hauling logs from this landing to the mill or appraisal point.

f. Forest type data -- a set of lines which describe the forest types which reside on the planning area.

After data for all forest types (up to a maximum of 10) has been entered, the number 9999 is used to terminate entry of this data.

The format for entering forest type data is as follows:

Type Code	Volume per ac	Volume per log	Wood Density	Expected Mill Price	System Code	No. Logs	...	System Code	No. Logs
___,	___,	___,	___,	___,	___,	___,	...,	___,	___

9999

Repeats for all yarding systems

Following is an explanation of these entries:

Type code -- a two-digit code which identifies a particular vegetative type to the user.

Volume per acre -- an estimate of the average volume per acre in the timber type, in fbm/ac.

Volume per log -- an estimate of the average volume per 32-foot log in the timber type, in fbm/log.

Wood density -- estimated density, in lbs/fbm, of the wood in the timber type.

Expected mill price -- the estimated price which logs from this timber type will bring at the mill or appraisal point, in $/Mfbm.

System code -- the number of one of the yarding systems for which data were entered in step c (above).

Number of logs -- an estimate of the maximum average number of logs per turn which this system can be expected to yard from this timber type. This estimate is based upon the distribution of trees in the type and the capabilities of the yarding system for reaching widely dispersed logs. It has nothing to do with the lifting capacity of the yarding system, as that is evaluated internally.

If data for N yarding systems were entered in step c, then N sets of yarding system and number of logs must be entered here.

g. Cableway data -- this section of the data file is used to enter all of the candidate anchor positions which are to be examined for each landing and yarding system combination. This is the final section of the data file, and there is no limit to the number of anchor positions which can be entered here; the program will continue analyzing such alternatives until it either runs out of data or is stopped for some other reason.

After all of the candidate anchor positions for one yarding system at any landing have been entered, the number 8888 is used to signal that the program is to begin analyzing candidate anchor positions for another yarding system at the same landing. When the analysis is to proceed to a new landing, the number 9999 is used instead. This procedure continues until the entire data file is exhausted. At least one candidate anchor position must be examined for each yarding system which is to be considered for emplacement at any landing.

The format for entering this data is as follows:

Landing No.

Yarding System

Candidate Anchor Position		...	Candidate Anchor Position	
Row	Column	...	Row	Column
______ ,	______	...	______ ,	______

Repeats for all candidate anchor positions for this landing and yarding system combination.

8888

Yarding System

⋮

9999

Example -- Run Data File

The data file listed below was used for the example problem in Chapter III. see Tables 1 and 2 for summaries of the data. Also, Table 3 summarizes the results for one of the candidate anchor positions, (3,5), for both yarding systems.

Circled letters to the left of the data file reference the data types described on the preceding pages.

ⓐ	EXAMPLE PROBLEM -- HIGHLEAD AND RUNNING SKYLINE
ⓑ	100,5,5
ⓒ	1,1,950,75,1.42,1.04,26500,300,50,0,0,0,200,75,650,0,20,.01,40 2,3,2000,200,1.42,2.14,26500,1000,50,50,50,20,300,95,1000,.2 30,.05,20 9999
ⓓ	1,3. 95,2.880E-3,-4.034E-3,1.7E-3,0,0,0,1.15 2,3.191,1.003E-3,-1.063E-3,2.337E-3,1.186E-2,0,0,1.2 9999
ⓔ	1,5,2,18000,11.00 2,4,5,16000,10.00 9999
ⓕ	1,30200,140,8.5,125,1,3,2,5 2,63800,230,8,175,1,2,2,4 9999
ⓖ	1 1 1,3,3,5 8888 2 1,3,3,5 9999 2 1 2,2,4,1 8888 2 2,2,4,1 9999

Output Files

In addition to the summary output (see Tables 2 and 3) which is written onto logical unit number 6 (usually equipped to a line printer), output files are also written onto logical units number 7 and 8. These are used as input files for the CASCADE optimization processor. Their format is as follows:

a. LUN 7 -- each record contains a cableway number, parcel number, and the value of the parcel if it is harvested over that cableway. The FORTRAN format of this file is (I5,1X,I5,1X,F11.2).

   The parcel number is a single integer which identifies the row and column of the parcel in the rectangular, fixed grid digital map.

   Let I = the row of the parcel, where row 1 is the topmost row;
   J = the column, where column 1 is the leftmost column;
   NCOLS = the total number of columns in the map;
   IPRCL = the index number of the parcel.

   Then IPRCL = J+(NCOLS*(I-1))-1

   Conversely, if IPRCL is known, I and J can be found as follows:

```
TEMP = FLOAT(IPRCL+1)/FLOAT(NCOLS)
I=IFIX(TEMP)+1
J=IFIX(((TEMP-FLOAT(I-1))*FLOAT(NCOLS))+.5)
```

b. LUN 8 -- this is a word-addressable random-access file which contains cableway identification data. Each cableway can be fully identified by a unique combination of:

   1 -- yarding system
   2 -- landing
   3,4 -- anchor position (row,column)
   5 -- tailtree height
   6 -- estimated cableway emplacement cost

   Each of these six items is right adjusted on a single BCD word. Thus, the effective FORTRAN format is (4I4,2F4.0).

   The cableway number is one greater than the record number, where the six items above are all contained on one "record". Records are numbered from 0; cableways, from 1.

Following are listings of LUN 7 and 8 from the example problem in Chapter III (Tables 1-3, Figures 14 and 15).

LUN 7

1	16	2207.14
2	17	2203.79
2	18	2197.10
3	7	689.97
3	11	695.63
3	12	694.47
3	13	675.73
3	16	2254.17
3	17	2249.97
4	11	677.85
4	12	686.41
4	13	695.10
4	17	2251.13
4	18	2245.05
6	16	2204.94
6	17	2213.32
6	18	2221.25
7	7	701.82
7	12	701.77
7	13	705.50
7	16	2221.59
7	17	2247.45
7	18	2273.42
8	11	680.32
8	12	695.44
8	13	699.92
8	16	2253.51
8	17	2261.12
8	18	2268.33

LUN 8

1	1	1	3	0	80
1	1	3	5	0	30
2	1	1	3	50	130
2	1	3	5	25	85
1	2	2	2	0	80
1	2	4	1	0	30
2	2	2	2	50	93
2	2	4	1	0	79

APPENDIX IV

Listings of the Heuristic Optimization Programs

```
PAGE  1.  OSU FORTRAN        PROGRAM CASCADE

      PROGRAM CASCADE
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
      DIMENSION OL(10)
C
C          THIS PROGRAM ATTEMPTS TO FIND, FOR SOME FOREST
C     PLANNING AREA, THE OPTIMUM ASSIGNMENT OF TIMBER
C     PARCELS (I) TO CABLE YARDING FACILITIES WHICH ARE
C     AVAILABLE TO HARVEST THEM.  THE FACILITIES CON-
C     SIDERED IN THIS CONTEXT ARE:
C
C          LANDINGS (L), AT EACH OF WHICH NO MORE THAN
C     ONE OF SEVERAL ALTERNATIVE YARDING SYSTEMS MAY
C     BE EMPLACED;
C
C          YARDING SYSTEMS (K); AND
C
C          CABLEWAYS (J).  EACH CABLEWAY IS DEFINED BY
C     A UNIQUE COMBINATION OF LANDING, YARDING SYSTEM,
C     AND ANCHOR LOCATION.
C
C
C          PROGRAM CASCADE IS ENTERED WITH THE FOLLOWING
C     DATA:
C
C          LUN 7 (SEQUENTIAL ACCESS FILE) -- A LISTING OF
C     NCOLS, NSYSTMS, CMOVE(I), NLNDGS, CLAND(I), AND
C     NCABLS.  FORMAT IS (I7/I7,5F7.0/I7,10F7.0/I7).  THIS
C     IS OUTPUT FROM PROGRAM -CABLYRD-.
C
C          LUN 8 (RAF) -- A LIST OF ALL CABLEWAYS TO BE
C     CONSIDERED FOR HARVESTING THE PLANNING AREA.  EACH
C     CABLEWAY IS DESCRIBED BY SIX ADDRESSABLE RECORDS:
C
C               RECORD 1 -- SYSTEM NUMBER:
C               RECORD 2 -- LANDING NUMBER:
C               RECORD 3 -- ROW OF ANCHOR LOCATION;
C               RECORD 4 -- COLUMN OF ANCHOR LOCATION;
C               RECORD 5 -- HEIGHT OF TAILTREE;
C               RECORD 6 -- EXPECTED CABLEWAY EMPLACEMENT
C                           COST.
C
C     GIVEN A CABLEWAY, J, THE RECORD IN LUN 8 ON WHICH
C     THE SYSTEM NUMBER IS STORED (I.E. RECORD 1 FOR
C     THAT CABLEWAY) IS EQUAL TO  (J*6)-6.
C
C     LUN 8 CORRESPONDS INITIALLY TO THE LIST -CAPITAL U-
C     WHICH IS USED IN THE DESCRIPTION OF THE CASCADE ALGORITHM.
C
C
C          LUN 10 (RAF) -- A LIST OF CABLEWAYS WHICH HAVE
C     BEEN (TEMPORARILY) EMPLACED.  RECORD J CORRESPONDS TO
C     CABLEWAY (J+1).  IF ITS VALUE = 1, THEN THE CABLEWAY
C     HAS BEEN EMPLACED; IF 0, THEN IT HAS NOT.
```

```
C
C
C          LUN 11 (RAF) -- THIS FILE CONTAINS RECORD NUMBERS
C     WHICH ARE USED TO ENTER LUN 12.  RECORD I IN LUN 11
C     CORRESPONDS TO CABLEWAY (I+1).  THE CONTENT OF RECORD
C     I IS A NUMBER INDICATING THE FIRST RECORD IN LUN 12 ON
C     WHICH DATA PERTAINING TO CABLEWAY (I+1) HAS BEEN
C     STORED.  THIS DATA (SEE LUN 12) RELATES TO PARCELS WHICH
C     COULD BE HARVESTED BY MEANS OF CABLEWAY (I+1).  THE
C     TOTAL NUMBER OF FEASIBLE PARCELS FOR THAT CABLEWAY IS
C     EQUAL TO:  (THE ENTRY ON RECORD (I+1) MINUS THE ENTRY
C     ON RECORD I)/3.  THE FINAL RECORD ON THIS FILE CONTAINS
C     AN INDEX NUMBER WHICH IS 1 GREATER THAN THE TOTAL
C     NUMBER OF RECORDS IN LUN 12.  EACH RECORD IS TWO BCD WORDS
C     IN LENGTH.
C
C          LUN 12 (RAF) -- THIS FILE CONSISTS OF RECORDS
C     WHICH ARE GROUPED IN THREES AND REFERENCED BY LUN
C     11.  THE FIRST RECORD OF EACH GROUP IS A PARCEL
C     NUMBER; THE SECOND IS THE EXPECTED VALUE OF THAT
C     PARCEL IF IT IS HARVESTED VIA THE CABLEWAY IN LUN 11
C     WHICH REFERENCES IT; AND THE VALUE OF THE
C     THIRD ENTRY = 1 IF THE ASSIGNMENT IS MADE, AND
C     0 OTHERWISE.
C
C     TOGETHER, LUNS 11 AND 12 ARE EQUIVALENT TO LISTS
C     -PHI.PRIME(JKL)- AND -PHI(JKL)- WHICH ARE USED
C     IN THE DESCRIPTION OF THE CASCADE ALGORITHM.
C
C
C          LUN 13 (RAF) -- THIS FILE CONTAINS PAIRS OF RECORDS,
C     THE CONTENTS OF WHICH ARE USED (A) TO ENTER LUN 14, AND
C     (B) TO FIND THE LUN 13 RECORD CORRESPONDING TO THE NEXT
C     HIGHER NUMBERED PARCEL SCHEDULED FOR HARVEST.  RECORDS
C     I AND (I+1) IN LUN 13, WHERE I IS AN EVEN-NUMBERED
C     INTEGER, CORRESPOND TO PARCEL (I+2)/2.  IN PROBLEMS
C     INVOLVING NON-RECTANGULAR PLANNING AREAS, SOME (OR MANY)
C     RECORDS IN THIS FILE WILL NORMALLY BE EMPTY, BECAUSE
C     THOSE PARCELS ARE NOT CONSIDERED IN THE HARVEST PLANNING.
C     EVEN-NUMBERED EMPTY RECORDS ARE INITIALIZED TO -1, AND
C     ODD-NUMBERED EMPTY RECORDS ARE INITIALIZED TO 0.  RECORD I
C     (I AN EVEN INTEGER) CONTAINS THE NUMBER OF THE FIRST RECORD
C     IN LUN 14 ON WHICH DATA PERTAINING TO PARCEL (I+2)/2 HAS
C     BEEN STORED.  THIS DATA (SEE LUN 14) RELATES TO CABLEWAYS
C     WHICH COULD BE USED TO HARVEST THAT PARCEL.  RECORD
C     (I+1) CONTAINS THE NUMBER OF THE NEXT NON-EMPTY RECORD
C     PAIR IN LUN 13.  THUS, THE ODD-NUMBERED RECORDS ARE USED
C     TO DEFINE A PATHWAY THROUGH LUN 13 WHICH AVOIDS HAVING TO
C     READ ANY OF THE EMPTY RECORDS.  THE TOTAL NUMBER OF FEASIBLE
C     CABLEWAYS FOR THE PARCEL CORRESPONDING TO RECORDS I AND (I+1)
C     IS EQUAL TO:  (THE ENTRY ON THE LUN 13 RECORD REFERENCED BY
C     RECORD (I+1), MINUS THE ENTRY ON RECORD I)/3.  EVEN-
C     NUMBERED RECORDS ARE TWO BCD WORDS IN LENGTH; ODD-
C     NUMBERED RECORDS ARE ONE BCD WORD.
```

```
C
C            LUN 14 (RAF) -- THIS FILE IS A ONE-TO-ONE ANALOG FOR
C       LUN 12, BUT THE FIRST RECORD OF EACH GROUP IS A CABLEWAY
C       NUMBER RATHER THAN A PARCEL NUMBER.
C
C       TOGETHER, LUNS 13 AND 14 ARE ESSENTIALLY CROSS-
C       REFERENCES FOR LUNS 11 AND 12: THEY ARE USED TO
C       SIGNIFICANTLY SPEED UP THE EXECUTION OF THE
C       CASCADE ALGORITHM.
C
C
C            IN ADDITION TO THE ABOVE, LUNS 9 AND 15 ARE REQUIRED
C       AS SEQUENTIAL ACCESS SCRATCH FILES.  ALSO, LUN 6 IS
C       USED FOR RECORDING RUN SUMMARY INFORMATION.
C
C
C
C
C            READ INFORMATION FROM LUN 7.
C
        READ (7,90) NCOLS,NSYSTMS,(CMOVE(I),I=1,5),NLNDGS,
       1  (CLAND(I),I=1,10),NCABLS
     90 FORMAT (I7/I7,5F7.0/I7,10F7.0/I7)
        IGMAJKL=IGMAPJKL=IGMAKL=IGMAPKL=IGMAL=IGMAPL=0
C
C *******  INITIALIZATION STEP.  FIRST, ASSIGN ANY PARCELS
C       FOR WHICH ONE AND ONLY ONE CABLEWAY IS FEASIBLE.
C
        CALL ITIME (INIT)
        IPARCL1=1
    100 CALL SEEK (13,(IPARCL1*3)-3)
        READ (13,105) NRCD1
    110 FORMAT (I4)
    105 FORMAT (I8)
        CALL SEEK (13,(IPARCL1*3)-1)
        READ (13,110) NXTRCD
        IF (NRCD1 .GE. 0) GO TO 120
C
C            THE RECORDS JUST READ WERE EMPTY: GET ANOTHER PAIR.
C
        IPARCL1=IPARCL1+1
        GO TO 100
C
C            THE RECORDS JUST READ WERE NOT EMPTY: -IPARCL1-
C       IS THE LOWEST NUMBERED PARCEL SCHEDULED FOR HARVEST.
C
    120 CALL SEEK (13,NXTRCD)
        IPARCL2=(NXTRCD+3)/3
        READ (13,105) NRCD2
        CALL SEEK (13,NXTRCD+2)
        READ (13,110) NXTRCD
        IF ((NRCD2-NRCD1) .LE. 3) GO TO 130
        IF (NXTRCD .EQ. 0) GO TO 170
        NRCD1=NRCD2
```

```
      IPARCL1=IPARCL2
      GO TO 120
  130 IF (NRCD2 .GT. NRCD1) GO TO 150
C
C          NO CABLEWAY IS LISTED FOR -IPARCL1-.  THEREFORE,
C     IT CANNOT BE HARVESTED AND THE PROBLEM IS INFEASIBLE.
C
      WRITE (6,140) IPARCL1
  140 FORMAT (≠0*****ERROR*****  PARCEL ≠,I4,≠ CANNOT BE ≠,
     1  ≠HARVESTED.≠//)
      CALL EXIT
C
C          EXACTLY ONE CABLEWAY IS INDICATED FOR -IPARCL1-.
C     ASSIGN THAT CABLEWAY.
C
  150 CALL SEEK (14,NRCD1)
      BUFFER IN (14,0) (ICABL,ICABL)
      DECODE (4,110,ICABL) ICABL
      CALL ASSIGN1(ICABL,NRCD1,NRCD2,14,IERR,1)
      CALL SEEK (11,(ICABL*2)-2)
      READ (11,105) NRCD3
      CALL SEEK (11,ICABL*2)
      READ (11,105) NRCD4
      CALL ASSIGN1(IPARCL1,NRCD3,NRCD4,12,IERR,1)
      CALL ASSIGN2(ICABL,1)
      IPARCL1=IPARCL2
      IF (NXTRCD .EQ. 0) GO TO 170
      NRCD1=NRCD2
      GO TO 120
C
C          CONSTRUCT -LAMBDA- FROM THE LIST OF ASSIGNED CABLE-
C     WAYS.  THE ARRAY -LAMBDA- IS EQUIVALENT TO THE LISTS
C     -LAMBDA- AND -PI(L)- WHICH ARE REFERENCED IN THE
C     DESCRIPTION OF THE CASCADE ALGORITHM.
C
  170 DO 175 I=1,10
  175 LAMBDA(I)=0
      ICABL=1
  180 CALL SEEK (10,ICABL-1)
      READ (10,110) IASGN
      IF (EOF(10)) GO TO 220
      IF (IASGN .EQ. 1) GO TO 190
      ICABL=ICABL+1
      GO TO 180
  190 CALL SEEK (8,(ICABL*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(ICABL*6)-5)
      READ (8,110) LANDG
      IF (LAMBDA(LANDG) .NE. 0 .AND. LAMBDA(LANDG) .NE.
     1  ISYSTM) GO TO 200
      LAMBDA(LANDG)=ISYSTM
      ICABL=ICABL+1
      GO TO 180
C
```

```
C           IF -LAMBDA(LANDG)- HAS ALREADY BEEN ASSIGNED
C       TO SOME SYSTEM OTHER THAN -ISYSTM-, THEN THE PROBLEM
C       IS INFEASIBLE.
C
  200 WRITE (6,210) ISYSTM,LAMBDA(LANDG),LANDG
  210 FORMAT (≠0*****ERROR*****  AT LEAST ONE PARCEL ≠,
     1  ≠CANNOT BE HARVESTED UNLESS SYSTEMS ≠,I2,≠ AND ≠,I2/
     2  18X,≠ARE BOTH INSTALLED AT LANDING ≠,I2//)
      CALL EXIT
C
C           EXECUTE THE IMPROVEMENT CHECK.
C
  220 CALL IMPROVE
C
C           COMPLETE THE INITIALIZATION BY ADDING FACILITIES
C       AS NECESSARY TO OBTAIN AN INITIAL FEASIBLE SOLUTION.
C
      JKLADD=0
      XMXVAL=-.6E300
      ICABL=1
  230 CALL SEEK (10,ICABL-1)
      READ (10,110) IASGN
      IF (EOF(10)) GO TO 250
      IF (IASGN .EQ. 0) GO TO 240
      ICABL=ICABL+1
      GO TO 230
C
C           EVALUATE THE POSSIBILITY OF ADDING -ICABL-.
C
  240 CALL ADDJKL(ICABL,IADD,VALUE)
      ICABL=ICABL+1
      IF (IADD .EQ. 0) GO TO 230
      IF (VALUE .LE. XMXVAL) GO TO 230
C
C           SAVE THE INDEX AND VALUE OF THE BEST FACILITY TO
C       ADD.  ALSO, COPY THE LIST OF PARCELS TO ASSIGN TO THE
C       BEST FACILITY FROM LUN 9 ONTO LUN 15.
C
      XMXVAL=VALUE
      JKLADD=ICABL-1
      CALL COPY
      GO TO 230
C
C           IF NO FACILITY WAS FOUND TO ADD, ALL PARCELS MUST
C       HAVE BEEN PREVIOUSLY ASSIGNED TO FACILITIES AND WE HAVE
C       AN INITIAL FEASIBLE SOLUTION.
C
  250 IF (JKLADD .EQ. 0) GO TO 270
C
C           A FACILITY WAS FOUND TO ADD; DO SO.
C
      CALL SEEK (11,(JKLADD*2)-2)
      READ (11,105) NRCD1
      CALL SEEK (11,JKLADD*2)
```

```
          READ (11,105) NRCO2
          CALL ASSIGN2(JKLADD,1)
C
C              UPDATE -LAMBDA-.
C
          CALL SEEK (8,(JKLADD*6)-6)
          READ (8,110) ISYSTM
          CALL SEEK (8,(JKLADD*6)-5)
          READ (8,110) LANDG
          LAMBDA(LANDG)=ISYSTM
C
C              ASSIGN THE PARCELS ON LUN 15 TO -JKLADD-.
C
          REWIND 15
      260 READ (15,110) IPARCL
          IF (EOF(15)) GO TO 220
          CALL SEEK (13,(IPARCL*3)-3)
          READ (13,105) NRCD3
          CALL SEEK (13,(IPARCL*3)-1)
          READ (13,110) NXTRCD
          CALL SEEK (13,NXTRCD)
          READ (13,105) NRCD4
          CALL ASSIGN1(IPARCL,NRCD1,NRCD2,12,IERR,1)
          CALL ASSIGN1(JKLADD,NRCD3,NRCD4,14,IERR,1)
          GO TO 260
C
C ******** INITIALIZATION IS COMPLETE.  COMMENCE THE IMPROVE-
C         MENT ALGORITHM BY FIRST EXECUTING STEP 2.
C
      270 CALL ITIME(ISTEP2)
          TIME=(ISTEP2-INIT)/1000.
          WRITE (6,280) TIME
      280 FORMAT (≠0ELAPSED INITIATION TIME =≠,F9.3,≠ SECONDS.≠/)
          CALL REPORT
          IPASS3=0
      300 CALL ITIME(ISTEP2)
C
C              DECIDE ON THE ORDER IN WHICH LANDINGS SHOULD BE
C         EVALUATED FOR DROPPING.
C
          IGMAL=0
          LDROP=0
C
C              -OL- IS THE ORDER CRITERION IN EQUATION [5.9].
C
          DO 340 L=1,NLNDGS
          OL(L)=.6E300
C
C              SEE IF THIS LANDING WAS THE LAST ONE ADDED; IF SO,
C         DO NOT DROP IT.  -IGMAPL- CORRESPONDS TO THE LIST -GAMMA.
C         PRIME(L)- WHICH IS USED IN THE DESCRIPTION OF THE
C         ALGORITHM.
C
          IF (IGMAPL .EQ. L) GO TO 340
```

```
C
C           IF LAMBDA(L) IS EQUAL TO ZERO, THEN THE LANDING -L-
C       HAS NOT BEEN ASSIGNED: DO NOT DROP IT.
C
        IF (LAMBDA(L) .EQ. 0) GO TO 340
C
C           SUM OVER -L- FOR EQUATION [5.9].
C
        OL(L)=-CLAND(L)
C
C           SUM OVER -K- FOR EQUATION [5.9].
C
        K=LAMBDA(L)
        OL(L)=OL(L)-CMOVE(K)
        DO 320 J=1,NCABLS
        CALL SEEK(8,(J*6)-6)
        READ (8,110) ISYSTM
        CALL SEEK (8,(J*6)-5)
        READ (8,110) LANDG
        CALL SEEK (8,(J*6)-1)
        READ (8,310) EMPLACE
    310 FORMAT (F4.0)
C
C           ACCUMULATE THE SUM OVER -J- FOR EQUATION [5.9].
C
        IF (LANDG .NE. L .OR. ISYSTM .NE. K) GO TO 320
        CALL SEEK(10,J-1)
        READ (10,110) IASGN
        IF (IASGN .EQ. 0) GO TO 320
        OL(L)=OL(L)+DSUMI(J)-EMPLACE
    320 CONTINUE
    340 CONTINUE
C
C           THE LOOP ON 350 CHECKS ALL OF THE LANDINGS FOR DROPPING,
C       IN ORDER OF LEAST -OL-.
C
    350 XMIN=.5E300
        REWIND 9
        IL=0
        DO 360 L=1,NLNDGS
        IF (OL(L) .GE. XMIN) GO TO 360
        XMIN=OL(L)
        IL=L
    360 CONTINUE
        IF (IL .EQ. 0) GO TO 440
C
C           EVALUATE LANDING -IL- FOR DROPPING.
C
        K=LAMBDA(IL)
C
C           THE EVALUATION PROCEEDS BY TESTING EVERY CABLEWAY
C       WHICH IS PRESENTLY ASSIGNED TO LANDING -IL-.
C
        DELTA=0.
```

```
      DO 370 J=1,NCABLS
      CALL SEEK (8,(J*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(J*6)-5)
      READ (8,110) LANDG
      IF (LANDG .NE. IL .OR. ISYSTM .NE. K) GO TO 370
      CALL SEEK (10,J-1)
      READ (10,110) IASGN
      IF (IASGN .EQ. 0) GO TO 370
      CALL EVALII(J,0,IL,IDROP,1,SUM)
      DELTA=DELTA+SUM
C
C          IF IDROP=0, THEN CABLEWAY -J- CANNOT BE DROPPED
C     AND THE LANDING MUST REMAIN ASSIGNED.
C
      IF (IDROP .EQ. 1) GO TO 365
  364 CALL UPLAMBDA
      OL(IL)=.6E300
      GO TO 350
  365 LDROP=1
  370 CONTINUE
      IF (LDROP .EQ. 0) GO TO 364
C
C          THERE IS NOW A LIST, ON LUN 9, WHICH INDICATES
C     THE BEST CABLEWAY (NOT AT LANDING -IL-) TO WHICH EACH
C     PARCEL ASSIGNED TO LANDING -IL- COULD BE REASSIGNED.
C     FIND OUT WHAT INCREASE IN VALUE WOULD RESULT IF THESE
C     REASSIGNMENTS WERE MADE AND THEN THE IMPROVEMENT CHECK
C     WERE EXECUTED.
C
      REWIND 9
  380 READ (9,390) I,JOLD,JNEW
  390 FORMAT (3I4)
      IF (EOF(9)) GO TO 395
      CALL EVALI(I,JOLD,JNEW,SAVING)
      DELTA=DELTA+SAVING
      GO TO 380
C
C          FINALLY, COMPLETE EQUATION [5.7] BY ADDING THE
C     FIXED COSTS SAVED BY CLOSING LANDING -IL-, YARDING
C     SYSTEM -K-, AND ALL OF THE CABLEWAYS PRESENTLY
C     ASSIGNED TO LANDING -IL-.
C
  395 DELTA=DELTA+CMOVE(K)+CLAND(IL)
      DO 400 J=1,NCABLS
      CALL SEEK (8,(J*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(J*6)-5)
      READ (8,110) LANDG
      CALL SEEK (8,(J*6)-1)
      READ (8,310) EMPLACE
      IF (LANDG .NE. IL .OR. ISYSTM .NE. K) GO TO 400
      CALL SEEK (10,J-1)
      READ (10,110) IASGN
```

```
      IF (IASGN .EQ. 0) GO TO 400
      DELTA=DELTA+EMPLACE
  400 CONTINUE
C
C            IF DELTA>0, EXECUTE THE REASSIGNMENTS INDICATED
C     ON LUN 9 AND THEN UPDATE -LAMBDA-.  OTHERWISE, GO
C     ON TO THE EVALUATION OF THE NEXT LANDING.
C
      IF (DELTA .GT. 0.) GO TO 410
      CALL UPLAMBDA
      OL(IL)=.6E300
      GO TO 350
  410 REWIND 9
  420 READ (9,390) I,JOLD,JNEW
      IF (EOF(9)) GO TO 430
      CALL ASSIGN3(I,JOLD,JNEW)
      GO TO 420
  430 CALL UPLAMBDA
      CALL IMPROVE
      IGMAL=IL
      OL(IL)=.6E300
      GO TO 350
C
C ******** CONTINUING WITH STEP 2, EVALUATE THE DROPPING
C     OF YARDING SYSTEMS.  FIRST, DECIDE ON THE ORDER IN
C     WHICH YARDING SYSTEMS SHOULD BE EVALUATED.
C
  440 CALL ITIME(ISTEP2L)
      TIME=(ISTEP2L-ISTEP2)/1000.
      WRITE (6,450) TIME
  450 FORMAT (≠0ELAPSED TIME, LANDING PORTION OF STEP 2=≠,
     1  F9.3,≠ SECONDS.≠/)
      CALL REPORT
      CALL ITIME(ISTEP2L)
      IGMAKL=0
      KLDROP=0
C
C            HERE, -OL- IS THE ORDER CRITERION IN EQUATION [5.8].
C     RECALL THAT THERE IS EXACTLY ONE YARDING SYSTEM AT EACH
C     ASSIGNED LANDING.  IN THIS SECTION, WE USE THE FACT THAT
C     THERE ARE AT MOST 10 LANDINGS TO PERMIT THE USE OF AN
C     INDEX, -KL-, TO IDENTIFY THE YARDING SYSTEM EMPLACED AT
C     ANY LANDING.  KL=(10*L)+K, WHERE K<=5.
C
      DO 465 L=1,NLNDGS
      OL(L)=.6E300
      IF (LAMBDA(L) .EQ. 0) GO TO 465
C
C            SEE IF -KL- WAS THE LAST YARDING SYSTEM ADDED; IF SO,
C     DO NOT DROP IT.  -IGMAPKL- CORRESPONDS TO THE LIST -GAMMA.
C     PRIME(KL)- WHICH IS USED IN THE DESCRIPTION OF THE ALGORITHM.
C
      K=LAMBDA(L)
      KL=(L*10)+K
```

PAGE 10   OSU FORTRAN   PROGRAM CASCADE

```
          IF (IGMAPKL .EQ. KL) GO TO 465
    C
    C          SUM OVER -K- FOR EQUATION [5.9].
    C
          OL(L)=-CMOVE(K)
          DO 460 J=1,NCABLS
          CALL SEEK (8,(J*6)-6)
          READ (8,110) ISYSTM
          CALL SEEK (8,(J*6)-5)
          READ (8,110) LANDG
          CALL SEEK (8,(J*6)-1)
          READ (8,310) EMPLACE
    C
    C          SUM OVER -J- FOR EQUATION [5.8].
    C
          IF (LANDG .NE. L .OR. ISYSTM .NE. K) GO TO 460
          CALL SEEK (10,J-1)
          READ (10,110) IASGN
          IF (IASGN .EQ. 0) GO TO 460
          OL(L)=OL(L)+DSUMI(J)-EMPLACE
      460 CONTINUE
      465 CONTINUE
    C
    C          THE LOOP ON 470 CHECKS ALL OF THE PRESENTLY
    C     ASSIGNED YARDING SYSTEMS FOR DROPPING, IN ORDER
    C     OF LEAST -OL-.
      470 XMIN=.5E300
          REWIND 9
          IL=0
          DO 480 L=1,NLNDGS
          IF (OL(L) .GE. XMIN) GO TO 480
          XMIN=OL(L)
          IL=L
      480 CONTINUE
          IF (IL .EQ. 0) GO TO 560
    C
    C          EVALUATE THE YARDING SYSTEM AT LANDING -IL-
    C     FOR DROPPING.
    C
          K=LAMBDA(IL)
    C
    C          TEST EACH CABLEWAY CURRENTLY ASSIGNED TO YARDING
    C     SYSTEM -K- AT LANDING -IL-.
    C
          DELTA=0.
          KADD=0
          DO 490 J=1,NCABLS
          CALL SEEK (8,(J*6)-6)
          READ (8,110) ISYSTM
          CALL SEEK (8,(J*6)-5)
          READ (8,110) LANDG
          IF (LANDG .NE. IL .OR. ISYSTM .NE. K) GO TO 490
          CALL SEEK (10,J-1)
          READ (10,110) IASGN
```

PAGE 11 OSU FORTRAN   PROGRAM CASCADE

```
          IF (IASGN .EQ. 0) GO TO 490
          CALL EVALI1(J,K,0,IDROP,KADD,SUM)
          DELTA=DELTA+SUM
          IF (IDROP .EQ. 1) GO TO 485
      484 CALL UPLAMBDA
          OL(IL)=.6E300
          GO TO 470
      485 KLDROP=1
      490 CONTINUE
          IF (KLDROP .EQ. 0) GO TO 484
          IF (LAMBDA(IL) .EQ. K) LAMBDA(IL)=0
C
C              THERE IS NOW A LIST, ON LUN 9, WHICH INDICATES
C         THE BEST CABLEWAY (NOT AT LANDING -IL-) TO WHICH EACH
C         PARCEL ASSIGNED TO LANDING -IL- COULD BE REASSIGNED.
C         FIND OUT WHAT INCREASE IN VALUE WOULD RESULT IF THESE
C         REASSIGNMENTS WERE MADE AND THEN THE IMPROVEMENT
C         CHECK WERE EXECUTED.
C
          REWIND 9
      500 READ (9,390) I,JOLD,JNEW
          IF (EOF(9)) GO TO 510
          CALL EVALI(I,JOLD,JNEW,SAVING)
          DELTA=DELTA+SAVING
          GO TO 500
C
C              COMPLETE EQUATION [5.6].
C
      510 DELTA=DELTA+CMOVE(K)
          IF (LAMBDA(IL) .EQ. 0) DELTA=DELTA+CLAND(IL)
          DO 520 J=1,NCABLS
          CALL SEEK (8,(J*6)-6)
          READ (8,110) ISYSTM
          CALL SEEK (8,(J*6)-5)
          READ (8,110) LANDG
          CALL SEEK (8,(J*6)-1)
          READ (8,310) EMPLACE
          IF (LANDG .NE. IL .OR. ISYSTM .NE. K) GO TO 520
          CALL SEEK (10,J-1)
          READ (10,110) IASGN
          IF (IASGN .EQ. 0) GO TO 520
          DELTA=DELTA+EMPLACE
      520 CONTINUE
          IF (DELTA .GT. 0) GO TO 530
          CALL UPLAMBDA
          OL(IL)=.6E300
          GO TO 470
      530 REWIND 9
      540 READ (9,390) I,JOLD,JNEW
          IF (EOF(9)) GO TO 550
          CALL ASSIGN3(I,JOLD,JNEW)
          GO TO 540
      550 CALL UPLAMBDA
          CALL IMPROVE
```

```
      IGMAKL=KL
      OL(IL)=.6E300
      GO TO 470
C
C ******** TO COMPLETE STEP 2, EVALUATE THE DROPPING OF
C     INDIVIDUAL CABLEWAYS.  FIRST, DECIDE THE ORDER IN
C     WHICH CABLEWAYS SHOULD BE EVALUATED.
C
  560 CALL ITIME(I2KL)
      TIME=(I2KL-ISTEP2L)/1000.
      WRITE (6,570) TIME
  570 FORMAT (≠0ELAPSED TIME, YARDING SYSTEM PORTION OF ≠,
     1  ≠STEP 2=≠,F9.3,≠ SECONDS.≠/)
      CALL REPORT
      CALL ITIME(I2KL)
      REWIND 15
      IGMAJKL=0
      IWRITE=0
C
C           -O- IS THE ORDER CRITERION IN EQUATION [5.4], AND
C     -JKL- IS THE CABLEWAY TO WHICH IT CORRESPONDS.
C
  575 O=.6E300
      REWIND 9
      DO 610 J=1,NCABLS
      CALL SEEK (10,J-1)
      READ (10,110) IASGN
      IF (IASGN .EQ. 0) GO TO 610
      CALL SEEK (8,(J*6)-1)
      READ (8,310) EMPLACE
      OTEMP=DSUMI(J)-EMPLACE
      IF (OTEMP .GE. 0) GO TO 610
      IF (IWRITE .EQ. 0) GO TO 600
C
C           THE LIST ON LUN 15 CONSISTS OF CABLEWAYS WHICH
C     HAVE BEEN CONSIDERED IN THIS PASS BUT CANNOT BE DROPPED.
C
      REWIND 15
  590 READ (15,110) JJ
      IF (EOF(15)) GO TO 600
      IF (JJ .EQ. J) GO TO 610
      GO TO 590
  600 O=OTEMP
      JKL=J
  610 CONTINUE
      IF (O .GT. .5E300) GO TO 670
C
C           A CABLEWAY HAS BEEN SELECTED FOR WHICH -O- IS
C     MINIMIZED AND WHICH HAS NOT BEEN CONSIDERED FOR
C     DROPPING IN THIS PASS.  EVALUATE IT FOR DROPPING,
C     UNLESS IT WAS THE LAST CABLEWAY PREVIOUSLY ADDED.
C
      IF (JKL .EQ. IGMAPJKL) GO TO 615
      CALL EVALII(JKL,0,0,IDROP,1,DELTA)
```

```
          IF (IDROP .EQ. 1) GO TO 620
      C
      C          -JKL- CANNOT BE DROPPED.
      C
        615 IF (IWRITE .EQ. 1) CALL SEFF(15)
            IF (IWRITE .EQ. 1) CALL SEFB(15)
            IWRITE=1
            CALL UPLAMBDA
            WRITE (15,110) JKL
            GO TO 575
      C
      C          -JKL- CAN BE DROPPED: COMPLETE EQUATION [5.3] BY
      C     ADDING -I(JKL)- AND -F(JKL)-.
      C
        620 REWIND 9
        630 READ (9,390) I,JOLD,JNEW
            IF (EOF(9)) GO TO 640
            CALL EVALI(I,JKL,JNEW,SAVING)
            DELTA=DELTA+SAVING
            GO TO 630
        640 CALL SEEK (8,(JKL*6)-1)
            READ (8,310) EMPLACE
            DELTA=DELTA+EMPLACE
            IF (DELTA .LE. 0.) GO TO 615
      C
      C          IT IS WORTHWHILE DROPPING JKL: DO SO.
      C
            REWIND 9
        650 READ (9,390) I,JOLD,JNEW
            IF (EOF(9)) GO TO 660
            CALL ASSIGN3(I,JKL,JNEW)
            GO TO 650
        660 CALL IMPROVE
            IGMAJKL=JKL
            GO TO 615
      C
      C ********** STEP 2 IS COMPLETE: EXECUTE STEP 3 OR EXIT.
      C
        670 CALL ITIME(ISTEP3)
            TIME=(ISTEP3-I2KL)/1000.
            WRITE (6,680) TIME
        680 FORMAT (≠0ELAPSED TIME, CABLEWAY PORTION OF STEP 2=≠,
           1  F9.3,≠ SECONDS.≠/)
            CALL REPORT
            CALL ITIME(ISTEP3)
            IF (IPASS3 .EQ. 0) GO TO 690
      C
      C          EXIT IF STEP 3 HAS BEEN EXECUTED AT LEAST ONCE AND NO
      C     FACILITIES WERE DROPPED OR ADDED DURING THE MOST RECENT
      C     PASS THROUGH STEPS 2 AND 3.
      C
            IF (IGMAL    .EQ. 0 .AND. IGMAKL   .EQ. 0 .AND.
           1    IGMAJKL .EQ. 0 .AND. IGMAPL   .EQ. 0 .AND.
           2    IGMAPKL .EQ. 0 .AND. IGMAPJKL .EQ. 0) CALL EXIT
```

```
  690 IPASS3=1
      IGMAPL=IGMAPKL=IGMAPJKL=0
C
C            FOR EACH UNASSIGNED CABLEWAY, COMPUTE THE -ADD
C     CRITERION-.  DO NOT, HOWEVER, CONSIDER ADDING A CABLEWAY
C     IF IT WOULD REQUIRE A SECOND YARDING SYSTEM AT SOME LANDING
C     OR IF IT WAS THE CABLEWAY MOST RECENTLY DROPPED.
C
      DO 740 J=1,NCABLS
      IF (J .EQ. IGMAJKL) GO TO 740
      CALL SEEK (10,J-1)
      READ (10,110) IASGN
      IF (IASGN .EQ. 1) GO TO 740
      CALL SEEK (8,(J*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(J*6)-5)
      READ (8,110) LANDG
      IF (LAMBDA(LANDG) .NE. 0 .AND. LAMBDA(LANDG) .NE.
     1  ISYSTM) GO TO 740
      CALL ADDEVAL(J,SUM)
C
C            ADD -I(JKL)- TO EQUATION [5.10].
C
      REWIND 9
  695 READ (9,715) I,JOLD
      IF (EOF(9)) GO TO 696
      CALL EVALI(I,JOLD,J,SAVING)
      SUM=SUM+SAVING
      GO TO 695
  696 CALL SEEK (8,(J*6)-1)
      READ (8,310) EMPLACE
      SUM=SUM-EMPLACE
      IF (LAMBDA(LANDG) .EQ. 0) SUM=SUM-CLAND(LANDG)-
     1  CMOVE(ISYSTM)
      IF (SUM .LE. 0) GO TO 740
C
C            ADD CABLEWAY -J-.  NOTE THAT LUN 9 CONTAINS A
C     LIST OF PARCELS TO BE ASSIGNED TO -J-.
C
      REWIND 9
      IGMAPJKL=J
      IF (LAMBDA(LANDG) .NE. 0) GO TO 700
      IGMAPKL=ISYSTM
      IGMAPL=LANDG
  700 CALL ASSIGN2(J,1)
      CALL SEEK (11,(J*2)-2)
      READ (11,105) NRCD1
      CALL SEEK (11,J*2)
      READ (11,105) NRCD2
  710 READ (9,715) I,JOLD
  715 FORMAT (2I4)
      IF (EOF(9)) GO TO 740
      CALL ASSIGN1(I,NRCD1,NRCD2,12,IERR,1)
      CALL SEEK (11,(JOLD*2)-2)
```

```
      READ (11,105) NRCD1A
      CALL SEEK (11,JOLD*2)
      READ (11,105) NRCD2A
      CALL ASSIGN1(I,NRCD1A,NRCD2A,12,IERR,0)
      CALL SEEK (13,(I*3)-3)
      READ (13,105) NRCD3
      CALL SEEK (13,(I*3)-1)
      READ (13,110) NXTRCD
      CALL SEEK (13,NXTRCD)
      READ (13,105) NRCD4
      CALL ASSIGN1(J,NRCD3,NRCD4,14,IERR,1)
      CALL ASSIGN1(JOLD,NRCD3,NRCD4,14,IERR,0)
C
C           CHECK TO SEE IF ALL OF THE PARCELS PREVIOUSLY
C     ASSIGNED TO CABLEWAY -JOLD- HAVE BEEN RE-ASSIGNED.
C     IF SO, CLOSE IT.
C
      I21=NRCD2A-NRCD1A
      DO 720 II=1,I21
      CALL SEEK (12,NRCD1A+II-1)
  720 READ (12,110) IBUF(II)
      IALL=0
      DO 730 II=1,I21,3
      II2=II+2
      IF (IBUF(II2) .EQ. 0) GO TO 730
      IALL=1
  730 CONTINUE
      IF (IALL .EQ. 1) GO TO 735
      CALL ASSIGN2(JOLD,0)
      IGMAJKL=JOLD
      CALL SEEK (8,(JOLD*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(JOLD*6)-5)
      READ (8,110) LANOG
      CALL IMPROVE
      CALL UPLAMBDA
      IF (LAMBDA(LANOG) .NE. 0) GO TO 740
      IGMAKL=ISYSTM
      IGMAL=LANOG
      GO TO 710
  735 CALL IMPROVE
      CALL UPLAMBDA
      GO TO 710
  740 CONTINUE
C
C ******** STEP 3 IS COMPLETE.  IF NO FACILITIES WERE ADDED,
C     EXIT.  OTHERWISE, MAKE ANOTHER PASS.
C
      CALL ITIME(IEND)
      TIME=(IEND-ISTEP3)/1000.
      WRITE (6,750) TIME
  750 FORMAT (≠0ELAPSED TIME FOR STEP 3=≠,F9.3,≠ SECONDS.≠/)
      CALL REPORT
      IF (IGMAL   .EQ. 0 .AND. IGMAKL   .EQ. 0 .AND.
```

```
        1    IGMAJKL .EQ. 0 .AND. IGMAPL   .EQ. 0 .AND.
        2    IGMAPKL .EQ. 0 .AND. IGMAPJKL .EQ. 0) CALL EXIT
         GO TO 300
         END
```

```
PAGE   1  OSU FORTRAN        SUBROUTINE IMPROVE

          SUBROUTINE IMPROVE
          COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
          COMMON LAMBDA(10)
      C
      C        THIS SUBROUTINE EXECUTES AN IMPROVEMENT CHECK
      C   DESIGNED TO IMPROVE THE CURRENT ASSIGNMENT OF PARCELS
      C   TO CABLEWAYS, IF POSSIBLE.  IT DOES NOT ADD CABLEWAYS;
      C   RATHER, IT SEEKS TO ADD AS MANY PARCELS AS POSSIBLE TO
      C   EACH OF THE CURRENTLY ASSIGNED CABLEWAYS.  IF ANY PARCEL
      C   CAN BE ASSIGNED TO MORE THAN ONE EMPLACED CABLEWAY, IT
      C   IS ASSIGNED TO THE ONE WHICH MAXIMIZES ITS VALUE (FIXED
      C   COSTS ARE NOT CONSIDERED BECAUSE ALL FACILITIES EVALUATED
      C   ARE ALREADY IN PLACE).  THIS PROCEDURE MAY RESULT IN
      C   SOME CABLEWAYS BEING DROPPED.
      C
          ICABL=0
      100 CALL SEEK (10,ICABL)
      105 FORMAT (I8)
          READ (10,110) IASGN
      110 FORMAT (I4)
          IF (EOF(10)) RETURN
          ICABL=ICABL+1
          IF (IASGN .EQ. 0) GO TO 100
          CALL SEEK (11,(ICABL*2)-2)
          READ (11,105) NRCD1
          CALL SEEK (11,ICABL*2)
          READ (11,105) NRCD2
          I21=NRCD2-NRCD1
          CALL SEEK (12,NRCD1)
          BUFFER IN (12,0) (IBUF(1),IBUF(I21))
          I=-2
      140 I=I+3
          I2=I+2
          IF (I2 .GT. I21) GO TO 100
          DO 150 J=I,I2
      150 DECODE (4,110,IBUF(J)) IBUF(J)
      C
      C        IF PARCEL -IBUF(I)- IS ALREADY ASSIGNED TO CABLEWAY
      C   -ICABL-, GO GET THE NEXT PARCEL.
      C
          IF (IBUF(I2) .EQ. 1) GO TO 140
          CALL SEEK (13,(IBUF(I)*3)-3)
          READ (13,105) NRCD3
          CALL SEEK (13,(IBUF(I)*3)-1)
          READ (13,110) NXTRCD
          CALL SEEK (13,NXTRCD)
          READ (13,105) NRCD4
          I43=NRCD4-NRCD3
      C
      C        IF I43=3, THE PARCEL CAN ONLY BE HARVESTED OVER ONE
      C   CABLEWAY.  THEREFORE, THAT ASSIGNMENT SHOULD ALREADY HAVE
      C   BEEN MADE, AND WE LEAVE IT ALONE.
      C
          IF (I43 .EQ. 3) GO TO 140
```

```
PAGE  2  OSU FORTRAN       SUBROUTINE IMPROVE

C
C           GET THE LIST OF ALL POSSIBLE CABLEWAYS (-IBUF1-)
C     OVER WHICH PARCEL -IBUF(I)- CAN BE HARVESTED.
C
      CALL SEEK (14,NRCD3)
      BUFFER IN (14,0) (IBUF1(1),IBUF1(I43))
      DO 160 J=1,I43
  160 DECODE (4,110,IBUF1(J)) IBUF1(J)
C
C           ASSIGN PARCEL -IBUF(I)- TO CABLEWAY -ICABL- IF:
C
C           (A) THE PARCEL IS NOT CURRENTLY ASSIGNED TO ANY
C               CABLEWAY:
C
C           (B) THE PARCEL WOULD HAVE A GREATER VALUE IN THE
C               NEW ASSIGNMENT THAN IN ITS PRESENT ASSIGNMENT.
C
      DO 170 J=1,I43,3
      J2=J+2
      IF (IBUF1(J2) .EQ. 1) GO TO 180
  170 CONTINUE
C
C           THE PARCEL IS NOT CURRENTLY ASSIGNED TO ANY
C     CABLEWAY.  NOTE THAT IT IS NOT NECESSARY TO CALL
C     SUBROUTINE -ASSIGN2- BECAUSE WE ALREADY KNOW THAT
C     -ICABL- IS LISTED ON LUN 10 AS AN ASSIGNED CABLEWAY.
C
      CALL ASSIGN1(ICABL,NRCD3,NRCD4,14,IERR,1)
      IPARCL=IBUF(I)
      CALL ASSIGN1(IPARCL,NRCD1,NRCD2,12,IERR,1)
      GO TO 140
C
C           THE PARCEL IS CURRENTLY ASSIGNED TO CABLEWAY
C     -IBUF1(J)-.  SEE IF RE-ASSIGNMENT TO -ICABL- WOULD
C     GIVE IT A HIGHER VALUE.
C
  180 J1=J+1
      I1=I+1
      IF (IBUF1(J1) .GE. IBUF(I1)) GO TO 140
C
C           RE-ASSIGN THE PARCEL TO -ICABL-.
C
      ICABL1=IBUF1(J)
      IPARCL=IBUF(I)
      CALL ASSIGN1(ICABL,NRCD3,NRCD4,14,IERR,1)
      CALL ASSIGN1(IPARCL,NRCD1,NRCD2,12,IERR,1)
      CALL ASSIGN1(ICABL1,NRCD3,NRCD4,14,IERR,0)
      CALL SEEK (11,(ICABL1*2)-2)
      READ (11,105) NRCD5
      CALL SEEK (11,ICABL1*2)
      READ (11,105) NRCD6
      CALL ASSIGN1(IPARCL,NRCD5,NRCD6,12,IERR,0)
C
C           CHECK TO SEE IF ANY OTHER PARCELS ARE
```

```
C      ASSIGNED TO CABLEWAY -ICABL1-.  IF NOT, RECORD
C      ITS CLOSURE ON LUN 10.
C
       DO 190 JJ=NRCD5,NRCD6,3
       IF ((JJ+2) .GE. NRCD6) GO TO 190
       CALL SEEK (12,JJ+2)
       BUFFER IN (12,0) (IASGN,IASGN)
       DECODE (4,110,IASGN) IASGN
       IF (IASGN .EQ. 1) GO TO 140
   190 CONTINUE
       CALL ASSIGN2(ICABL1,0)
C
C           UPDATE -LAMBDA- TO INCORPORATE THE CLOSURE OF -ICABL-.
C
       CALL UPLAMBDA
       GO TO 140
       END
```

PAGE 1 OSU FORTRAN SUBROUTINE ADDJKL

```
      SUBROUTINE ADDJKL(ICABL,IADD,VALUE)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE IS DESIGNED TO EVALUATE THE ADVANTAGE OF
C     ADDING FACILITY -ICABL-, GIVEN EXISTING ASSIGNMENTS.
C
C          FIRST, FIND OUT IF THE YARDING SYSTEM REPRESENTED BY
C     -ICABL- IS ALREADY IN PLACE, OR, IF IT IS NOT, WHETHER IT
C     CAN BE ADDED WITHOUT DESTROYING FEASIBILITY.
C
      CALL SEEK (8,(ICABL*6)-6)
      READ (8,100) ISYSTM
  100 FORMAT (I4)
      CALL SEEK (8,(ICABL*6)-5)
      READ (8,100) LANDG
      CALL SEEK (8,(ICABL*6)-1)
      READ (8,105) EMPLACE
  105 FORMAT (F4.0)
      IF (LAMBDA(LANDG) .EQ. 0 .OR. LAMBDA(LANDG) .EQ. ISYSTM)
     1  GO TO 110
      IADD=0
      RETURN
C
C          THE YARDING SYSTEM IS EITHER ALREADY IN PLACE OR CAN
C     BE ADDED.
C
  110 IADD=1
      REWIND 9
      IF (LAMBDA(LANDG) .EQ. 0) EMPLACE=EMPLACE+CMOVE(ISYSTM)+
     1  CLAND(LANDG)
      CALL SEEK (11,(ICABL*2)-2)
      READ (11,115) NRCD1
  115 FORMAT (I8)
      CALL SEEK (11,ICABL*2)
      READ (11,115) NRCD2
      I21=NRCD2-NRCD1
      CALL SEEK (12,NRCD1)
      BUFFER IN (12,0) (IBUF(1),IBUF(I21))
      DO 140 I=1,I21
      DECODE (4,100,IBUF(I)) IBUF(I)
  140 CONTINUE
C
C          SUM THE VALUE OF ALL PARCELS WHICH COULD BE HARVESTED
C     BY -ICABL- AND ARE NOT CURRENTLY ASSIGNED TO SOME OTHER
C     CABLEWAY.
C
      VALUE=0.
      DO 160 I=1,I21,3
      CALL SEEK(13,(IBUF(I)*3)-3)
      READ (13,115) NRCD3
      CALL SEEK (13,(IBUF(I)*3)-1)
      READ (13,100) NXTRCD
      CALL SEEK (13,NXTRCD)
```

```
PAGE  2  OSU FORTRAN         SUBROUTINE ADDJKL
        READ (13,115) NRC04
        I43=NRCD4-NRCD3
        CALL SEEK (14,NRCD3)
        BUFFER IN (14,0) (IBUF1(1),IBUF1(I43))
        DO 150 J=1,I43,3
        J2=J+2
        DECODE (4,100,IBUF1(J2)) IBUF1(J2)
        IF (IBUF1(J2) .EQ. 1) GO TO 160
    150 CONTINUE
C
C             PARCEL -IBUF(I)- IS NOT ASSIGNED TO ANY OTHER CABLEWAY.
C
        I1=I+1
        VALUE=VALUE+IBUF(I1)
        WRITE (9,100) IBUF(I)
    160 CONTINUE
C
C             IF, AT THE END OF THIS ROUTINE, -VALUE- IS STILL EQUAL
C       TO ZERO, THEN EVEN THOUGH -ICABL- COULD BE ADDED, NO
C       PARCELS WOULD BE ASSIGNED TO IT BECAUSE THEY HAVE ALL BEEN
C       PREVIOUSLY ASSIGNED.
C
        IF (VALUE .GT. 0) GO TO 170
        IADD=0
        RETURN
C
C             RETURN THE SUM OF THE VALUES OF PARCELS WHICH COULD
C       BE ASSIGNED TO -ICABL-, MINUS THE CASCADED FIXED
C       COSTS.
C
    170 VALUE=VALUE-EMPLACE
        RETURN
        END
```

```
      SUBROUTINE ASSIGN1(I,NRCD1,NRCD2,LUN,IERR,IASGN)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE RECORDS OR ERASES ASSIGNMENTS
C     OF PARCELS TO CABLEWAYS ON LUN 12 OR LUN 14.
C
      IERR=0
      I1=NRCD2-NRCD1
      IF (I1 .GT. 450) GO TO 150
      CALL SEEK(LUN,NRCD1)
      BUFFER IN (LUN,0) (IBUF1(1),IBUF1(I1))
      DO 110 J=1,I1,3
      DECODE (4,100,IBUF1(J)) IBUF1(J)
  100 FORMAT (I4)
      IF (IBUF1(J) .EQ. I) GO TO 120
  110 CONTINUE
C
C          IF WE GET HERE, AN ERROR WAS MADE BECAUSE THE
C     INDEX NUMBER -I- WAS NOT FOUND BETWEEN RECORDS
C     -NRCD1- AND -NRCD2- ON FILE -LUN-.
C
      IERR=1
      WRITE (6,115) I,NRCD1,NRCD2,LUN
  115 FORMAT (≠0*****ERROR*****  ITEM ≠,I4,≠ NOT FOUND ≠,
     1  ≠BETWEEN RECORDS ≠,I5,≠ AND ≠,I5,≠ IN LUN ≠,I2//)
      CALL EXIT
C
C          RECORD THE ASSIGNMENT OR ERASURE.
C
  120 J2=J+2
      IBUF1(J2)=IASGN
      ENCODE (4,130,IBUF1(J2)) IBUF1(J2)
  130 FORMAT (I4)
      CALL SEEK (LUN,NRCD1+J2-1)
      BUFFER OUT (LUN,0) (IBUF1(J2),IBUF1(J2))
      RETURN
C
C          THERE ARE MORE THAN 150 PARCELS ENTERED FOR
C     THIS CABLEWAY (THIS EXCEEDS THE DIMENSION SIZE).
C
  150 IERR=1
      WRITE (6,160)
  160 FORMAT (≠0*****ERROR*****  ATTEMPT TO ASSIGN A CABLE≠,
     1  ≠WAY FOR WHICH MORE THAN 150 PARCELS ARE FEASIBLE.≠//)
      CALL EXIT
      END
```

```
PAGE   1  OSU FORTRAN         SUBROUTINE ASSIGN2

      SUBROUTINE ASSIGN2(ICABL,IASGN)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE RECORDS OR ERASES CABLEWAY
C     ASSIGNMENTS ON LUN 10.
C
      CALL SEEK(10,ICABL-1)
      ENCODE (4,100,IJ) IASGN
  100 FORMAT (I4)
      BUFFER OUT (10,0) (IJ,IJ)
      RETURN
      END
```

PAGE 1 OSU FORTRAN SUBROUTINE ASSIGN3

```
      SUBROUTINE ASSIGN3(I,JOLD,JNEW)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE REASSIGNS PARCEL I FROM CABLEWAY -JOLD-
C     TO CABLEWAY -JNEW-.  IT ALSO REMOVES THE ASSIGNMENT OF
C     CABLEWAY -JOLD- AND ADDS CABLEWAY -JNEW-.
C
      CALL ASSIGN2(JOLD,0)
      CALL ASSIGN2(JNEW,1)
      CALL SEEK (11,(JNEW*2)-2)
      READ (11,110) NRCD1
  110 FORMAT (I8)
      CALL SEEK (11,JNEW*2)
      READ (11,110) NRCD2
      CALL SEEK (13,(I*3)-3)
      READ (13,110) NRCD3
      CALL SEEK (13,(I*3)-1)
      READ (13,120) NXTRCD
  120 FORMAT (I4)
      CALL SEEK (13,NXTRCD)
      READ (13,110) NRCD4
      CALL ASSIGN1 (I,NRCD1,NRCD2,12,IERR,1)
      CALL ASSIGN1 (JNEW,NRCD3,NRCD4,14,IERR,1)
      CALL SEEK (11,(JOLD*2)-2)
      READ (11,110) NRCD1
      CALL SEEK (11,JOLD*2)
      READ (11,110) NRCD2
      CALL ASSIGN1 (I,NRCD1,NRCD2,12,IERR,0)
      CALL ASSIGN1 (JOLD,NRCD3,NRCD4,14,IERR,0)
      RETURN
      END
```

```
PAGE   1  OSU FORTRAN        SUBROUTINE UPLAMBDA

      SUBROUTINE UPLAMBDA
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE UPDATES THE LIST -LAMBDA- FROM THE
C     CONTENTS OF LUN 8 AND THE REVISED LUN 10.
C
      DO 100 I=1,10
  100 LAMBDA(I)=0
      ICABL=1
  110 CALL SEEK (10,ICABL-1)
      READ (10,120) IASGN
  120 FORMAT (I4)
      IF (EOF(10)) RETURN
      IF (IASGN .EQ. 1) GO TO 130
      ICABL=ICABL+1
      GO TO 110
  130 CALL SEEK (8,(ICABL*6)-6)
      READ (8,120) ISYSTM
      CALL SEEK (8,(ICABL*6)-5)
      READ (8,120) LANDG
      LAMBDA(LANDG)=ISYSTM
      ICABL=ICABL+1
      GO TO 110
      END
```

```
PAGE   1  OSU FORTRAN        SUBROUTINE COPY

              SUBROUTINE COPY
              COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
              COMMON LAMBDA(10)
      C
      C             THIS SUBROUTINE COPIES THE CONTENTS OF LUN 9 ONTO LUN 15.
      C
              REWIND 9
              REWIND 15
          100 READ (9,110) I
          110 FORMAT (I4)
              IF (EOF(9)) GO TO 120
              WRITE (15,110) I
              GO TO 100
          120 RETURN
              END
```

```
PAGE   1  OSU FORTRAN        SUBROUTINE EVALI

          SUBROUTINE EVALI(I,J1,J2,SAVING)
          COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
          COMMON LAMBDA(10)
C
C              THIS SUBROUTINE PERFORMS AN IMPROVEMENT CHECK IN THE
C         MANNER OF SUBROUTINE -IMPROVE-, BUT DOES NOT ACTUALLY MAKE
C         ANY REVISIONS.  RATHER, IT EVALUATES THE SAVINGS WHICH
C         WOULD RESULT FROM AN EXECUTION OF SUBROUTINE -IMPROVE-
C         AFTER PARCEL -I- WERE REASSIGNED FROM CABLEWAY -J1- TO
C         CABLEWAY -J2-.
C
          SAVING=0.
          CALL SEEK (11,(J2*2)-2)
          READ (11,110) NRCD1
          CALL SEEK (11,J2*2)
          READ (11,110) NRCD2
          I21=NRCD2-NRCD1
          DO 100 II=1,I21
          CALL SEEK (12,NRCD1+II-1)
          READ (12,115) IBUF(II)
      100 CONTINUE
      110 FORMAT (I8)
      115 FORMAT (I4)
          DO 150 II=1,I21,3
          II1=II+1
          II2=II+2
C
C              TO AVOID DOUBLE COUNTING OF IMPROVEMENTS DURING
C         SUCCESSIVE CALLS TO -EVALI- FOR ANY CABLEWAY, CONSIDER
C         ONLY THOSE IMPROVEMENTS DUE TO MOVING PARCELS NUMBERED
C         GREATER THAN -I-.
C
          IF (IBUF(II) .LE. I .OR. IBUF(II2) .EQ. 1) GO TO 150
          CALL SEEK (13,(IBUF(II)*3)-3)
          READ (13,110) NRCD3
          CALL SEEK (13,(IBUF(II)*3)-1)
          READ (13,115) NXTRCD
          CALL SEEK (13,NXTRCD)
          READ (13,110) NRCD4
          I43=NRCD4-NRCD3
          IF (I43 .EQ. 3) GO TO 150
          DO 119 K=1,I43
          CALL SEEK (14,NRCD3+K-1)
      119 READ (14,115) IBUF1(K)
          DO 120 K=1,I43,3
          K1=K+1
          K2=K+2
          IF (IBUF1(K2) .EQ. 1) GO TO 140
      120 CONTINUE
C
C              IF WE GET HERE, AN ERROR HAS BEEN MADE BECAUSE
C         PARCEL -IBUF(II)- IS NOT LISTED AS BEING ASSIGNED TO
C         ANY CABLEWAY.
C
```

```
      WRITE (6,130) I,J1,J2,IBUF(II)
  130 FORMAT (≠0*****ERROR*****  DURING ATTEMPT TO RE-ASSIGN ≠,
     1  ≠PARCEL ≠,I2,≠ FROM CABLEWAY ≠,I2,≠ TO ≠,I2,≠,≠/
     2  T19,≠PARCEL ≠,I2,≠ IS LISTED AS UNASSIGNED.≠//)
      CALL EXIT
C
C             COMPUTE THE EXPECTED SAVINGS DUE TO A POTENTIAL
C     SHIFT OF -IBUF(II)- FROM CABLEWAY -IBUF1(K)- TO CABLEWAY -J2-.
C
  140 IF (IBUF1(K1) .GE. IBUF(II1)) GO TO 150
      SAVING=SAVING+FLOAT(IBUF(II1)-IBUF1(K1))
  150 CONTINUE
      RETURN
      END
```

PAGE 1 OSU FORTRAN SUBROUTINE EVALII

```
      SUBROUTINE EVALII(J,KSYS,L,IDROP,KADD,SUM)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE COMPUTES THE PORTION OF THE -DROP
C     CRITERION- WHICH IS WITHIN THE SUMMATION OVER PARCELS,
C     FOR CABLEWAY J.  IF KSYS>0, THEN WE ARE CONSIDERING
C     DROPPING YARDING SYSTEM KSYS: IF L>0, WE ARE CONSIDERING
C     DROPPING LANDING L.  IF KADD=0, THE ROUTINE IS FREE
C     TO ADD ONE OTHER YARDING SYSTEM AT THE LANDING OF J;
C     OTHERWISE, NOT.
C
      SUM=0.
      IDROP=1
      CALL SEEK (11,(J*2)-2)
      READ (11,115) NRCD1
      CALL SEEK (11,J*2)
      READ (11,115) NRCD2
      I21=NRCD2-NRCD1
      DO 100 I=1,I21
      CALL SEEK (12,NRCD1+I-1)
  100 READ (12,110) IBUF(I)
  115 FORMAT (I8)
  110 FORMAT (I4)
C
C          FIND OUT THE LANDING OF -J-.
C
      CALL SEEK (8,(J*6)-5)
      READ (8,110) LANDGO
C
C          SUMMATION OVER THE PARCELS CURRENTLY ASSIGNED TO -J-.
C
      DO 160 I=1,I21,3
      I1=I+1
      I2=I+2
      IF (IBUF(I2) .EQ. 0) GO TO 160
      CALL SEEK (13,(IBUF(I)*3)-3)
      READ (13,115) NRCD3
      CALL SEEK (13,(IBUF(I)*3)-1)
      READ (13,110) NXTRCD
      CALL SEEK (13,NXTRCD)
      READ (13,115) NRCD4
      I43=NRCD4-NRCD3
C
C          SEE IF ONLY ONE CABLEWAY CAN BE USED TO HARVEST
C     PARCEL -IBUF(I)-.  IF SO IT CANNOT BE DROPPED.
C
      IF (I43.LE. 3) GO TO 145
      DO 119 K=1,I43
      CALL SEEK (14,NRCD3+K-1)
  119 READ (14,110) IBUF1(K)
C
C          FIND THE MAXIMUM-VALUE REASSIGNMENT FOR EACH PARCEL.
C
```

```
      XMAX=-.6E300
      DO 140 K=1,I43,3
      K1=K+1
      K2=K+2
      IF (IBUF1(K2) .EQ. 1) GO TO 140
      VALUE=FLOAT(IBUF1(K1)-IBUF(I1))
C
C           SEE IF THIS CABLEWAY IS AFFIXED TO A YARDING SYSTEM
C     OR LANDING BEING EVALUATED FOR DROPPING.
C
      CALL SEEK (8,(IBUF1(K)*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(IBUF1(K)*6)-5)
      READ (8,110) LANDG
      CALL SEEK (8,(IBUF1(K)*6)-1)
      READ (8,120) EMPLACE
  120 FORMAT (F4.0)
      IF (ISYSTM .EQ. KSYS .AND. LANDG .EQ. LANDG0) GO TO 140
      IF (LANDG.EQ. L) GO TO 140
      CALL SEEK (10,IBUF1(K)-1)
      READ (10,110) IASGN
      IF (IASGN .EQ. 1) GO TO 130
C
C           CABLEWAY -IBUF1(K)- WILL HAVE TO BE ADDED IF PARCEL
C     -IBUF(I)- IS TO BE ASSIGNED TO IT.
C
C
C           MAKE SURE THE ONE-YARDING SYSTEM-PER-LANDING
C     RULE PERMITS ESTABLISHING -IBUF1(KSYS)-.  NOTE THAT IF KSYS>0,
C     WE ARE EVALUATING DROPPING THE ENTIRE YARDING SYSTEM
C     AND CAN THUS ADD ONE OTHER SYSTEM AT THAT LANDING.  IF
C     L>0, WE ARE EVALUATING DROPPING THE ENTIRE LANDING.
C
      IF (KADD .EQ. 1 .AND. LAMBDA(LANDG) .NE. 0 .AND.
     1  LAMBDA(LANDG) .NE. ISYSTM) GO TO 140
      IF (LANDG .NE. LANDG0 .AND. LAMBDA(LANDG) .NE. 0 .AND.
     1  LAMBDA(LANDG) .NE. ISYSTM) GO TO 140
      IF (LANDG .EQ. LANDG0 .AND. L .GT. 0) GO TO 140
      VALUE=VALUE-EMPLACE
C
C           FIGURE IN THE COST OF LANDING CONSTRUCTION AND
C     YARDING SYSTEM INSTALLATION IF NECESSARY.
C
      IF (LAMBDA(LANDG) .EQ. 0) VALUE=VALUE-CMOVE(ISYSTM)-
     1  CLAND(LANDG)
C
C           ACCOUNT FOR ADDING A NEW SYSTEM AT THE LANDING
C     OF -KSYS-.
C
      IF (LANDG .EQ. LANDG0 .AND. LAMBDA(LANDG) .NE.
     1  ISYSTM) VALUE=VALUE-CMOVE(ISYSTM)
  130 IF (VALUE .LE. XMAX) GO TO 140
      XMAX=VALUE
      JNEW=IBUF1(K)
```

PAGE 3 OSU FORTRAN SUBROUTINE EVALII

```
  140 CONTINUE
      IF (XMAX .GT. -.5E300) GO TO 146
C
C          A FEASIBLE ALTERNATIVE HAS NOT BEEN FOUND; THEREFORE,
C     THE CABLEWAY CANNOT BE DROPPED.
C
  145 IDROP=0
      RETURN
C
C          THE FOLLOWING RESETS -LAMBDA- FOR (A) THE CASE WHERE
C     WE ARE DROPPING A CABLEWAY ONLY AND -LAMBDA(LANDG)- = 0,
C     (B) THE CASE WHERE WE ARE DROPPING A SYSTEM AND WANT
C     TO ADD A NEW SYSTEM AT THE SAME LANDING (THE FIRST SUCH
C     OPPORTUNITY ENCOUNTERED IS ACCEPTED; THEN WE CANNOT, OF
C     COURSE, ADD ANY MORE SYSTEMS AT THAT LANDING, SO WE SET
C     KADD=1).
C
  146 CALL SEEK (8,(JNEW*6)-6)
      READ (8,110) ISYSTM
      CALL SEEK (8,(JNEW*6)-5)
      READ (8,110) LANDG
C
C          THE FOLLOWING JUMP STEP IS PUT HERE SO THAT IF WE
C     HAVE NOT ADDED A NEW SYSTEM AT LANDING L FOR CASE (B),
C     KADD IS STILL EQUAL TO 0 SO WE CAN DO SO IN ANOTHER
C     STEP IF NECESSARY.
C
      IF (LAMBDA(LANDG) .EQ. ISYSTM) GO TO 147
      LAMBDA(LANDG)=ISYSTM
      IF (LANDG .EQ. LANDG0) KADD=1
C
C          STORE THE INDICES OF THE PARCEL TO BE REASSIGNED,
C     THE OLD CABLEWAY TO WHICH IT WAS ASSIGNED, AND THE
C     NEW CABLEWAY TO WHICH IT SHOULD BE REASSIGNED.
C
  147 WRITE (9,150) IBUF(I),J,JNEW
  150 FORMAT (3I4)
C          ACCUMULATE THE SUM OVER ALL PARCELS CURRENTLY ASSIGNED
C     TO THE OLD CABLEWAY.
C
      SUM=SUM+XMAX
  160 CONTINUE
      RETURN
      END
```

```
PAGE  1  OSU FORTRAN        FUNCTION DSUMI

      FUNCTION DSUMI(J)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS FUNCTION COMPUTES THE SUM OF THE VALUES OF
C     TIMBER PARCELS CURRENTLY ASSIGNED TO CABLEWAY -J-.
C
      DSUMI=0.
      CALL SEEK (11,(J*2)-2)
      READ (11,100) NRCD1
      CALL SEEK (11,J*2)
      READ (11,100) NRCD2
  100 FORMAT (I8)
      I21=NRCD2-NRCD1
      DO 110 I=1,I21
      CALL SEEK (12,NRCD1+I-1)
  110 READ (12,115) IBUF(I)
  115 FORMAT (I4)
      DO 120 I=1,I21,3
      I1=I+1
      I2=I+2
      IF (IBUF(I2) .EQ. 0) GO TO 120
      DSUMI=DSUMI+FLOAT(IBUF(I1))
  120 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE ADDEVAL(J,SUM)
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C          THIS SUBROUTINE COMPUTES THE PORTION OF THE -ADD
C     CRITERION- WHICH IS WITHIN THE SUMMATION OVER PARCELS,
C     FOR CABLEWAY -J-.
C
      SUM=0.
      REWIND 9
      CALL SEEK (11,(J*2)-2)
      READ (11,101) NRCD1
  100 FORMAT (I4)
  101 FORMAT (I8)
      CALL SEEK (11,J*2)
      READ (11,101) NRCD2
      I21=NRCD2-NRCD1
C
C          FIND OUT WHICH PARCELS COULD BE ASSIGNED TO CABLEWAY
C     -J-.
C
      DO 110 I=1,I21
      CALL SEEK (12,NRCD1+I-1)
  110 READ (12,100) IBUF(I)
C
C          ACCUMULATE THE SUM.
C
      DO 150 I=1,I21,3
      I1=I+1
      I2=I+2
      IF (IBUF(I2) .NE. 1) GO TO 130
      WRITE (6,120) J,IBUF(I)
  120 FORMAT (≠0***** ERROR *****  DURING ATTEMPT TO ADD CABLEWAY≠,
     1  1X,I4,≠ (STEP 3), PARCEL ≠,I4,≠ IS ALREADY LISTED≠/T21,
     2  ≠AS BEING ASSIGNED TO THAT CABLEWAY.≠/)
      CALL EXIT
  130 CALL SEEK (13,(IBUF(I)*3)-3)
      READ (13,101) NRCD3
      CALL SEEK (13,(IBUF(I)*3)-1)
      READ (13,100) NXTRCD
      CALL SEEK (13,NXTRCD)
      READ (13,101) NRCD4
      I43=NRCD4-NRCD3
      DO 140 K=1,I43
      CALL SEEK (14,NRCD3+K-1)
  140 READ (14,100) IBUF1(K)
      DO 150 K=1,I43,3
      K1=K+1
      K2=K+2
      IF (IBUF1(K2) .EQ. 0) GO TO 150
C
C          IF THE VALUE OF PARCEL -IBUF(I)- WOULD BE GREATER
C     UNDER ASSIGNMENT TO CABLEWAY -J- THAN UNDER ITS PRESENT
C     ASSIGNMENT (TO CABLEWAY -IBUF1(K)-), THEN ADD THE
```

```
PAGE  2  OSU FORTRAN        SUBROUTINE ADDEVAL

      C      DIFFERENCE TO -SUM-.
      C
             IF (IBUF1(K1) .GE. IBUF(I1)) GO TO 150
             SUM=SUM+FLOAT(IBUF(I1)-IBUF1(K1))
      C
      C           ON LUN 9, MAKE UP A LIST OF THE PARCELS (AND THE
      C      CABLEWAYS TO WHICH THEY ARE PRESENTLY ASSIGNED) WHICH
      C      WOULD IMPROVE IN VALUE IF RE-ASSIGNED TO CABLEWAY -J-.
      C
             WRITE (9,145) IBUF(I),IBUF1(K)
         145 FORMAT (2I4)
         150 CONTINUE
         160 CONTINUE
             RETURN
             END
```

PAGE 1 OSU FORTRAN SUBROUTINE REPORT

```
      SUBROUTINE REPORT
      COMMON IBUF(450),IBUF1(450),CMOVE(5),CLAND(10),NROWS,NCOLS
      COMMON LAMBDA(10)
C
C            PRINT OUT A SUMMARY OF THE CURRENT SOLUTION.
C
      CVAL=CCLAND=CCMOVE=CCBL=0.
      WRITE (6,100)
  100 FORMAT (≠S≠/≠1CURRENT SOLUTION REPORT -- CASCADE ≠,
     1  ≠ALGORITHM≠/≠ ≠,45(≠=≠)///≠ LANDINGS     FIXED      ≠,
     2  ≠YARDING SYSTEM    FIXED≠/≠ OCCUPIED    COST≠,9X,
     3  ≠ASSIGNED≠,7X,≠COST≠/≠ ≠,8(≠-≠),4X,≠------≠,5X,14(≠-≠),
     4  4X,5(≠-≠)/)
      DO 120 L=1,10
      IF (LAMBDA(L) .EQ. 0) GO TO 120
      K=LAMBDA(L)
      WRITE (6,110) L,CLAND(L),K,CMOVE(K)
  110 FORMAT (I6,6X,F6.0,7X,I6,8X,F6.0)
      CCLAND=CCLAND+CLAND(L)
      CCMOVE=CCMOVE+CMOVE(K)
  120 CONTINUE
      WRITE (6,130)
  130 FORMAT (≠0≠,45(≠=≠)///≠ SUMMARY OF CABLEWAY/PARCEL ≠,
     1  ≠ASSIGNMENTS≠/≠ ≠,59(≠-≠)//)
      IC=1
  140 CALL SEEK (10,IC-1)
      READ (10,150) IASGN
  150 FORMAT (I4)
      IF (EOF(10)) GO TO 220
      IF (IASGN .EQ. 1) GO TO 160
      IC=IC+1
      GO TO 140
  160 CALL SEEK (8,(IC*6)-6)
      READ (8,150) K
      CALL SEEK (8,(IC*6)-5)
      READ (8,150) L
      CALL SEEK (8,(IC*6)-4)
      READ (8,150) IR
      CALL SEEK (8,(IC*6)-3)
      READ (8,150) ICL
      CALL SEEK (8,(IC*6)-2)
      READ (8,150) ITT
      CALL SEEK (8,(IC*6)-1)
      READ (8,170) CBL
  170 FORMAT (F4.0)
      CCBL=CCBL+CBL
      WRITE (6,180) IC,IR,ICL,ITT,CBL,L,K
  180 FORMAT (≠ CABLEWAY ≠,I4//5X,≠ANCHOR=(≠,I2,≠,≠,I2,≠); ≠,
     1  ≠TAILTREE=≠,I3,≠ FT: EMPLACEMENT COST=$≠,F4.0/5X,
     2  ≠LANDING=≠,I2,≠: YARDING SYSTEM=≠,I2//5X,≠PARCEL    ≠,
     3  ≠NET VALUE≠/5X,≠------    ---------≠/)
      CALL SEEK (11,(IC*2)-2)
      READ (11,190) NRCD1
  190 FORMAT (I8)
```

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```
      CALL SEEK (11,IC*2)
      READ (11,190) NRCD2
      I21=NRCD2-NRCD1
      DO 210 I=1,I21,3
      I1=I+1
      I2=I+2
      CALL SEEK (12,NRCD1+I2-1)
      READ (12,150) IASGN
      IF (IASGN .EQ. 0) GO TO 210
      CALL SEEK (12,NRCD1+I-1)
      READ (12,150) IP
      CALL SEEK (12,NRCD1+I1-1)
      READ (12,170) V
      A1=FLOAT(IP)/FLOAT(NCOLS)
      IPR=IFIX(A1)+1
      IPC=IFIX(((A1-FLOAT(IPR-1))*FLOAT(NCOLS))+.5)
      WRITE (6,200) IPR,IPC,V
  200 FORMAT (5X,≠(≠,I2,≠,≠,I2,≠)≠,4X,F4.0)
      CVAL=CVAL+V
  210 CONTINUE
      WRITE (6,215)
  215 FORMAT (≠0≠,59(≠-≠)//)
      IC=IC+1
      GO TO 140
  220 TOTAL=CVAL-CCLAND-CCMOVE-CCBL
      WRITE (6,230) CVAL,CCLAND,CCMOVE,CCBL,TOTAL
  230 FORMAT (≠-≠,59(≠=≠)//≠ TOTAL ESTIMATED VALUE OF ≠,
     1  ≠THE SOLUTION≠≠/≠0≠,4X,≠TOTAL OF PARCEL VALUES≠,
     2  15X,≠= $≠,F8.0//4X,≠-LANDING AND SPUR CONSTRUCTION≠,
     3  ≠ COSTS   =≠,F10.0//4X,≠-YARDING SYSTEM INSTALLA≠,
     4  ≠TION COSTS     =≠,F10.0//4X,≠-CABLEWAY EMPLACE≠,
     5  ≠MENT COSTS≠,11X,≠=≠,F10.0//44X,9(≠-≠)/≠0     =≠,
     6  ≠TOTAL ESTIMATED VALUE≠,16X,≠= $≠,F8.0)
      RETURN
      END
```

APPENDIX V

LISTINGS OF THE RANDOM ACCESS DATA FILES USED BY THE HEURISTIC PROCESSOR TO SOLVE THE EXAMPLE PROBLEM IN CHAPTERS IV AND V (see Table 4).

Format

The logical unit number (LUN) associated with each file is indicated. Columns to the left of the double vertical line are for information only and are not physically part of the data file. Assignments shown in LUNs 10, 12, and 14 are for the optimal solution; initial assignments in all cases would be 0 (i.e. unassigned).

The logical record length for each file is equal to one BCD word (four characters).

Remarks

1. LUNs 8, 11, and 13 are read-only files; LUNs 10, 12, and 14 are read-write files.

2. LUN 11 always contains two more records than twice the number of cableways being considered in the problem. The entry on the last two records is an 8-digit number which is one larger than the maximum record number in LUN 12.

3. LUN 13 always contains three times as many records as there are parcels in the original data matrix, plus three additional records. The entry on the first two records of the last group of three is an

8-digit number which is one larger than the maximum record number in LUN 14; the entry on the final record is a 0. For a non-rectangular planning area, some (or many) of the records in LUN 13 are usually "empty" because the parcels corresponding to those records are outside of the planning area and are thus not actually being considered for harvest (this is not the case for the example shown; all parcels are to be harvested). Empty "first feasible cableway" records contain a -1, and empty "next parcel to be harvested" records contain a 0.

4. Every parcel represented in LUN 14 will have exactly one cableway assigned to it after optimization.

Listings

See the two pages following.

LUN 8

Cableway Number	Record Number	File Entries: Yarding System	Landing	Anchor Row	Anchor Column	Tailtree Height	Emplacement Cost
1	0-5	1	1	1	3	0	1000
2	6-11	1	1	3	5	25	800
3	12-17	2	1	1	3	0	600
4	18-23	2	1	3	5	50	500
5	24-29	1	2	2	2	75	1100
6	30-35	1	2	4	1	25	700
7	36-41	2	2	2	2	100	800
8	42-47	2	2	4	1	0	700

Each entry requires 4 BCD characters

LUN 10

Cableway Number	Record Number	Optimal Assignment
1	0	1
2	1	1
3	2	0
4	3	0
5	4	0
6	5	0
7	6	0
8	7	0

4 BCD characters

LUN 11

Cableway Number	Record Number	Record of First Feasible Parcel in LUN 12
1	0	0
2	2	12
3	4	21
4	6	30
5	8	33
6	10	45
7	12	57
8	14	69
-	16	78

8 BCD characters

LUN 12

Cableway Number	Record Number	File Entries: Parcel	Value	Optimal Assignment
1	0-2	1	3000	1
	3-5	2	3200	1
	6-8	4	3500	1
	9-11	5	600	0
2	12-14	3	1000	1
	15-17	5	700	1
	18-20	6	800	1
3	21-23	1	800	0
	24-26	2	1100	0
	27-29	4	2000	0
4	30-32	6	1200	0
5	33-35	1	1000	0
	36-38	2	900	0
	39-41	3	1400	0
	42-44	6	700	0
6	45-47	2	600	0
	48-50	4	900	0
	51-53	5	1000	0
	54-56	6	700	0
7	57-59	2	800	0
	60-62	3	1200	0
	63-65	5	700	0
	66-68	6	700	0
8	69-71	4	1200	0
	72-74	5	900	0
	75-77	6	700	0

4 BCD characters (each entry)

LUN 13

Parcel Number	Record Number	Record of First Feasible Cableway in LUN 14	Record of Next Parcel to be Harvested (LUN 13)
1	0-2	0	3
2	3-5	9	6
3	6-8	24	9
4	9-11	33	12
5	12-14	45	15
6	15-17	60	18
-	18-20	78	0
		8 BCD characters	4 BCD characters

LUN 14

Parcel Number	Record Number	File Entries: Cableway	File Entries: Value	File Entries: Optimal Assignment
1	0-2	1	3000	1
	3-5	3	800	0
	6-8	5	1000	0
2	9-11	1	3200	1
	12-24	3	1100	0
	15-17	5	900	0
	18-20	6	600	0
	21-23	7	800	0
3	24-26	2	1000	1
	27-29	5	1400	0
	30-32	7	1200	0
4	33-35	1	3500	1
	36-38	3	2000	0
	39-41	6	900	0
	42-44	8	1200	0
5	45-47	1	600	0
	48-50	2	700	1
	51-53	6	1000	0
	54-56	7	700	0
	57-59	8	900	0
6	60-62	2	800	1
	63-65	4	1200	0
	66-68	5	700	0
	69-71	6	700	0
	72-74	7	700	0
	75-77	8	700	0

4 BCD characters (each entry)

APPENDIX VI

Listing of a Program to Create the Random Access Files For Use by the Heuristic Algorithm

```
PAGE  1  OSU FORTRAN        PROGRAM RNDFILES

      PROGRAM RNDFILES
C
C          USING THE OUTPUT FROM PROGRAM -CABLYRD-, MAKE
C     UP THE RANDOM ACCESS FILES FOR -CASCADE-.  NOTE THAT
C     THE DIMENSION STATEMENT AND SOME CONSTANTS HAVE
C     BEEN SET ASSUMING THAT THE PLANNING AREA CONSISTS OF
C     2200 PARCELS OF TIMBER.
C
      DIMENSION IPARCL(2200),ICUML(2200)
      DO 50 I=1,2200
      ICUML(I)=0
   50 IPARCL(I)=0
C
C ******** LUN 10.
C
      READ (9,100) NCOLS,NSYS,NLAND,NCABLS
  100 FORMAT (I7/I7/I7/I7)
      L=0
      L1=-1
      DO 120 I=1,NCABLS
      CALL SEEK (10,I-1)
      WRITE (10,110) L
  110 FORMAT (I4)
  120 CONTINUE
C
C ******** LUNS 11 AND 12.
C
      IFIRST=0
      ICABL=0
  130 READ (7,140) IC,IP,V
      IF (EOF(7)) GO TO 161
  140 FORMAT (2(I5,1X),F11.2)
      IP1=IP+1
      IPARCL(IP1)=IPARCL(IP1)+1
      IF (V .GE. 1E4 .OR. V .LE. -1E3) WRITE (6,141) IC,
     1  IP1,V
  141 FORMAT (≠ *** FOR CABLEWAY ≠,I2,≠, THE VALUE OF PARCEL ≠,
     1  I2,≠ IS ≠,F11.2)
      IF (IC .NE. ICABL) GO TO 160
  145 CALL SEEK (12,IFIRST)
      WRITE (12,150) IP1,V,L
  150 FORMAT (I4,F4.0,I4)
      IFIRST=IFIRST+3
      GO TO 130
  160 CALL SEEK (11,ICABL*2)
      WRITE (11,155) IFIRST
  155 FORMAT (I8)
      ICABL=ICABL+1
      GO TO 145
  161 CALL SEEK (11,NCABLS*2)
      WRITE (11,155) IFIRST
C
C ******** LUNS 13 AND 14.  FIRST, RECORD CABLEWAYS ON
C     SCRATCH FILE 15, WHICH IS A RAF.  THE NUMBER OF
```

```
C       CABLEWAYS FOR PARCEL -IP- IS STORED IN -IPARCL(IP1)-:
C       BEGIN BY CONVERTING THAT TO A CUMULATIVE.
C
        REWIND 7
        ICUM=0
        DO 180 I=1,2200
        IF (IPARCL(I) .EQ. 0) GO TO 180
        ICUML(I)=ICUM
        ICUM=ICUM+IPARCL(I)
        WRITE (6,1000) IPARCL(I),ICUML(I)
 1000   FORMAT (2I8)
  180   CONTINUE
        WRITE (6,1100) ICUM
 1100   FORMAT (16X,I8)
C
C            INITIALIZE LUN 15.
C
        DO 200 I=1,ICUM
        WRITE (15,190) L,L
  190   FORMAT (2I4)
  200   CONTINUE
        REWIND 15
C
C            RECORD DATA ON LUN 15.
C
  202   READ (7,140) IC,IP,V
        IF (EOF(7)) GO TO 205
        ENCODE (4,110,IC) IC
        ENCODE (4,203,IV) V
  203   FORMAT (F4.0)
        IP1=IP+1
        IADDR=ICUML(IP1)*2
        CALL SEEK (15,IADDR)
        READ (15,190) ICBL,IV2
        IF (ICBL .GT. 0) GO TO 204
        CALL SEEK (15,IADDR)
        BUFFER OUT (15,0) (IC,IC)
        CALL SEEK (15,IADDR+1)
        BUFFER OUT (15,0) (IV,IV)
        GO TO 202
  204   IADDR=IADDR+2
        CALL SEEK (15,IADDR)
        READ (15,190) ICBL,IV2
        IF (ICBL .GT. 0) GO TO 204
        CALL SEEK (15,IADDR)
        BUFFER OUT (15,0) (IC,IC)
        CALL SEEK (15,IADDR+1)
        BUFFER OUT (15,0) (IV,IV)
        GO TO 202
C
C            ALL OF THE CABLEWAYS HAVE BEEN RECORDED.  NOW,
C       COPY THIS INFORMATION ONTO LUNS 13 AND 14 AND PUT IT
C       IN ORDER.
C
```

PAGE 3 OSU FORTRAN PROGRAM RNOFILES

```
  205 REWIND 15
      IFIRST=0
      DO 220 I=1,2200
      IF (IPARCL(I) .GT. 0) GO TO 208
      CALL SEEK (13,(I*3)-3)
      WRITE (13,206) L1,L
  206 FORMAT (I8,I4)
      GO TO 220
  208 CALL SEEK (13,(I*3)-3)
      WRITE (13,206) IFIRST,L1
      IADDR=ICUML(I)*2
      K=IPARCL(I)
      DO 212 IK=1,K
      CALL SEEK (15,IADDR)
      READ (15,190) IC,IV
      IADDR=IADDR+2
      CALL SEEK (14,IFIRST)
      WRITE (14,210) IC,IV,L
  210 FORMAT (3I4)
      IFIRST=IFIRST+3
  212 CONTINUE
  220 CONTINUE
      CALL SEEK (13,6597)
      WRITE (13,206) IFIRST,L
C
C          LUNS 13 AND 14 HAVE BEEN INITIALIZED.  NOW, GO BACK
C     AND FILL IN THE -RECORD OF NEXT PARCEL TO BE HARVESTED-
C     ENTRIES IN LUN 13.
C
      REWIND 13
      DO 250 I=1,2200
      CALL SEEK (13,(I*3)-1)
      READ (13,110) L
      IF (L .NE. -1) GO TO 250
      J=I+1
  230 CALL SEEK (13,(J*3)-3)
      READ (13,206) L1
      IF (L1 .EQ. -1) GO TO 240
      CALL SEEK (13,(I*3)-1)
      IJ=(J-1)*3
      ENCODE (4,110,IJ) IJ
      BUFFER OUT (13,0) (IJ,IJ)
      GO TO 250
  240 J=J+1
      GO TO 230
  250 CONTINUE
      CALL EXIT
      END
```

APPENDIX VII

Landing and Spur Road Construction Cost Calculations

Reference: McNutt, J. A. 1976. A stochastic analysis or erosion and economic impacts associated with timber harvests and forest roads. Ph.D. dissertation. Corvallis, Oregon State University, 206 p.

All roads to be constructed are secondary roads, for which the following characteristics are assumed:

1 lane, 12-foot gravel-surfaced width plus ditch, turnouts every 750 feet and on blind corners, 35-foot right-of-way.

According to McNutt, recent Forest Service experience for ridgetop roads of this type in the Smith-Umpqua Block has averaged $192,000 per mile, total in-place cost.

Landings are assumed to be of the same character as the spur roads, except that 75-foot by 20-foot dimensions are used. This gives a total in-place cost of $224,000 per mile.

Timber in the right-of-way is netted against the road or landing construction cost to give a cost net of timber value.

Landing 1

Road: (0.09 mi)($192000/mi)	=	$17280
Landing: (75 ft/5280 ft/mi)($224000/mi)	=	3200
Timber value	=	1670
Net cost	=	$18810

Landing 2

Road: (0.28 mi)($192000/mi)	=	$53760
Landing	=	3200
Timber value	=	4700
		$52260

Landing 3

Road: (0.05)(192000)	=	$ 9600
Landing	=	3200
Timber value	=	1050
		$ 11750

Landing 4

Road: (0.08)(192000)	=	$ 15360
Landing	=	3200
Timber value	=	4360
		$ 14200

Landing 5

Road: (0.63)(192000)	=	$120960
Landing	=	3200
Timber value	=	17310
		$106850

APPENDIX VIII

Hauling Cost Calculations

Reference: Byrne, J. J., R. J. Nelson, and P. H. Googins. 1960. Logging road handbook: the effect of road design on hauling costs. Washington, D. C. U. S. Dept. of Agric., Handbook No. 183. 65 p.

Assumptions

65,000-lb GVW, 200-hp truck

$$B_\ell = \frac{(200)(0.72)(1000)}{65000} = 2.22 \text{ (loaded)}$$

[p. 4, Byrne et al.]

$$B_e = \frac{(200)(0.72)(1000)}{26750} = 5.38 \text{ (empty)}$$

Average load = 4500 fbm = 38250 lbs

Traffic intensity = 10 vehicles per hour

Turnout spacing = 750 feet

Expected delay times per trip:

Waiting to be loaded	20 min
Loading time	35
Tighten binders, check brakes	10
Wait at scale station	15
Scaling time	10
Wait to be unloaded	10
Unloading time	5
	105 min

Maximum hauling hours per day = 12

Straight-time costs:

Truck	\$5.12/hr
Driver	6.76
Truck operating costs	6.50
	\$18.38/hr

Overtime costs:

Truck	\$5.12/hr	
Driver	10.14	
Truck operating costs	6.50	
	\$21.76/hr	

Delay time costs:

Truck	\$5.12/hr	
Driver	6.76	or 10.14 (ot)
Truck operating costs	0	
	\$11.88/hr	or \$15.26/hr

Amortization and maintenance charges on the Forest Service roads and PUC charges on other public roads are assumed to be assessed equally against the timber hauled from any of the five landings, and are therefore not considered in the analysis.

Amortization of spur road construction costs are not considered here because those costs are handled as fixed charges in the formulation of the mathematical model.

Road segments A, A1, A2, B, C, C1, and C2 are shown on the accompanying figure. Segments M1, M2, M3, M4, and M5 are on the main haul road; segment CTY is along the county road; segment HWY is on U. S. Highway 101 (see Figure 20).

Cost Calculations

The accompanying table gives estimated controlling times for each road segment, both loaded and empty. Using the method of Byrnes *et al.*, estimated hauling costs can be calculated as follows:

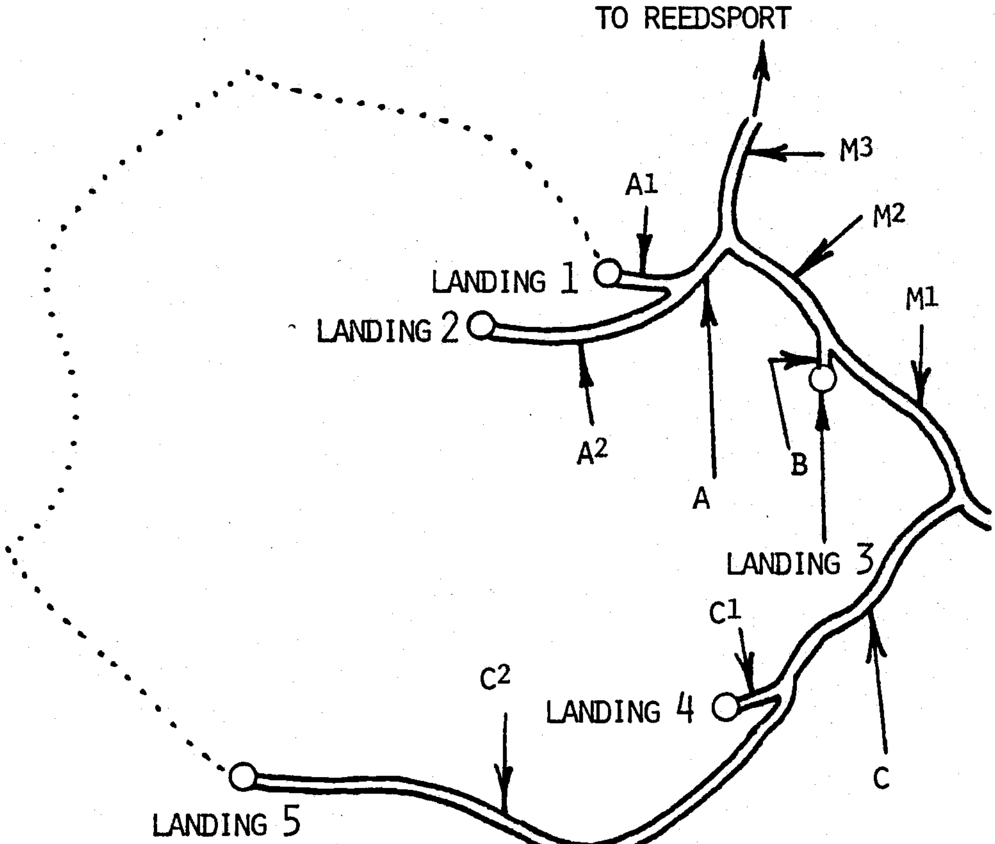
Landing 1:	total estimated hauling time	= 92.2 min
	estimated delay times	= 105.0
	total estimated time/trip	= 197.2 min
	straight-time trips per day	= (480 min)/(197.2 min) = 2.43
	overtime trips per day	= (240 min)/(197.2 min) = 1.22

ROAD SEGMENT HAULING TIME TABLES
(after Byrne et al. -- see page 17)

Road Sgmt	Road Type[1]	Avg Grade	Avg Curves per Mile	Curve Radius	Dist (mi)	Controlled by Grade Loaded	Controlled by Grade Empty	Controlled by Alignmt Loaded	Controlled by Alignmt Empty
LANDING 1						Haul Time per Mile (minutes)			
A1	S	-20%	--	--	0.09	5.5*	6.0*	--	--
A	S	-5	--	--	.05	2.0*	2.3*	--	--
M3	P	-5	10	300	2.0	2.0	2.3	3.0*	2.8*
M4	P	+10	10	300	.5	8.8*	3.2*	3.0	2.8
M5	P	-5	10	300	8.2	2.0	2.3	3.0*	2.8*
CTY	2L	-1	5	500	2.9	1.3	1.3	2.4*	2.1*
HWY	2L	-1	1	1000	3.7	1.3	1.3	1.5*	1.4*
LANDING 2									
A2	S	+12	1	800	.23	9.9*	3.8*	2.2	1.9
Segments A, M3, M4, M5, CTY, and HWY are the same as for Landing 1.									
LANDING 3									
B	S	-10	1	200	.05	3.2	3.7	4.2*	4.1*
M2	P	-2	2	150	.21	1.3	1.5	3.7*	3.4*
Segments M3, M4, M5, CTY, and HWY are the same as for Landing 2.									
LANDING 4									
C1	S	-10	1	200	.08	3.2	3.7*	3.9*	3.6
C	S	+10	4	150	.24	9.0*	3.2	4.7	4.4*
M1	P	-2	1	800	.21	1.3	1.8*	2.0*	1.8
Segments M2, M3, M4, M5, CTY, and HWY are the same as for Landing 3.									
LANDING 5									
C2	S	+10	4	350	.63	8.8*	3.3*	3.0	2.8
Segments C, M1, M2, M3, M4, M5, CTY, and HWY are the same as for Landing 4.									

[1]S=secondary road; P=primary haul road; 2L=two-lane, paved highway.

Grades, curvature, and distances were estimated for existing roads by driving the roads. For planned roads, they were established by means of a ground reconnaissance.



HAUL ROAD SEGMENTS WITHIN OR ADJACENT TO THE PLANNING AREA
(M4, M5, CTY, AND HWY NOT SHOWN)

costs:

	Delays	Haul	Total
straight time	\$50.60	\$68.63	\$119.23
overtime	32.58	40.79	73.37
	\$83.18	\$109.42	\$192.60

At the estimated 4500 fbm/trip and (2.43 + 1.22 =) 3.65 trips/day, this gives

$$\frac{\$192.60}{(3.65)(4.5)} = \$11.73/\text{Mfbm}$$

The same procedure is followed for the other landings; estimated haul costs are summarized in Table 17 (Chapter VI).

APPENDIX IX. YARDING SYSTEM COSTS

References

Costs and methodology used in computing the equipment, labor, and wire rope cost estimates in this Appendix have been taken from the following source:

Forest Service, USDA. 1974. Timber appraisal handbook (Chapters 410 and 415.82). Portland, USDA Forest Service, Region 6. Various paging.

Procedures used to estimate yarding system installation costs are described in the following publication:

Bureau of Land Management, USDI. 1972. Timber appraisal production cost schedule 18. Portland, USDI Bureau of Land Management, Oregon State Office. Release 9-109. 283 p.

Estimated Hourly Yarding System Costs

Equipment Item	Hourly Cost Dollars
MADILL 071 WEST COAST TOWER (Highlead) -- Yarding System 1	
Depreciation	
Yarder-tower ($112,500 initial cost, depreciated to 20% salvage value, estimated useful life of 8 years) . .	7.03
Radios ($4200, 10%, 4-year life)	0.59
Butt rigging ($500, no salvage, 1-year life)	0.31
Tail and corner rigging ($2000, 10%, 4 years)	0.28
Guylines ($1271, no salvage, 4 years)	0.20
Landing tractor (used, $8000, no salvage, 8 years)	0.63
Loader ($82,000, 20%, 8 years)	5.13
Crew vehicles ($15,000, no salvage, 8 years)	1.17
Miscellaneous equipment ($10,000, no salvage, 4 years) . .	1.56
Subtotal	16.12
Maintenance and repair costs	
Yarder, tractor, loader, and crew vehicle (50% of depreciation)	6.98
Radios (60% of depreciation)	0.35
Subtotal	7.33
Fuel and lubricants	5.51
Total equipment costs	$28.96
Labor	
Yarder operator	7.56
Loader operator	7.96
Rigging slinger	7.23
Chaser	6.39
Choker setters (2)	12.44
Supervision	4.00
Total labor costs	$45.58
TOTAL ESTIMATED HOURLY COSTS	$74.54

Equipment Item	Hourly Cost Dollars
SMITH-BERGER MARC V (Running Skyline) -- Yarding System 2	
Depreciation	
Yarder-tower ($278,000, 20%, 8 years)	17.38
Radios ($4200, 10%, 4 years)	0.59
Carriage ($4830, 10%, 4 years)	0.68
Tailtree rigging equipment ($4400, 10%, 4 years)	0.62
Guylines ($833, no salvage, 4 years)	0.13
Landing tractor ($8000, no salvage, 8 years)	0.63
Loader ($82,000, 20%, 8 years)	5.13
Crew vehicles ($15,000, no salvage, 8 years)	1.17
Miscellaneous equipment ($10,000, no salvage, 4 years) . .	1.56
Subtotal	27.11
Maintenance and repair costs	
Yarder, tractor, loader, and crew vehicles (50% of depreciation)	12.16
Carriage (20% of depreciation)	0.14
Radios (60% of depreciation)	0.35
Subtotal	12.65
Fuel and lubricants	6.75
Total equipment costs	$46.51
Labor costs (same as Madill 071)	45.58
TOTAL ESTIMATED HOURLY COSTS	$92.09

Equipment Item	Hourly Cost Dollars
SKAGIT BU-199/T-110 (Live Skyline) -- Yarding System 3	
Depreciation	
Yarder-tower ($408,400, 20%, 8 years)	25.53
Radios ($4200,10%, 4 years)	0.59
Carriage ($22,500, 10%, 8 years)	1.58
Tailtree rigging equipment ($7100, 10%, 4 years)	1.00
Guylines ($6050, no salvage, 4 years)	0.95
Landing tractor ($8000, no salvage, 8 years)	0.63
Loader ($82,000, 20%, 8 years)	5.13
Crew vehicles ($15,000, no salvage, 8 years)	1.17
Miscellaneous equipment ($10,000, no salvage, 4 years)	1.56
Subtotal	38.14
Maintenance and repair costs	
Yarder, carriage, tractor, loader, and crew vehicles (50% of depreciation)	17.02
Radios (60% of depreciation)	0.35
Subtotal	17.37
Fuel and lubricants	9.63
Total equipment costs	$65.14
Labor	
Hooktender	8.79
Yarder operator	7.56
Loader operator	7.96
Rigging slinger	7.23
Chaser	6.39
Choker setters (2)	12.44
Total labor costs	$50.37
TOTAL ESTIMATED HOURLY COSTS	$115.51

Equipment Item	Hourly Cost Dollars
SKAGIT BU-90/T-90 (Live Skyline) -- Yarding System 4	
Depreciation	
Yarder-tower($210,000, 20%, 8 years)	13.13
Radios ($4200, 10%, 4 years)	0.59
Carriage ($22,500, 10%, 8 years)	1.58
Tailtree rigging equipment ($7100, 10%, 4 years)	1.00
Guylines ($5313, no salvage, 4 years)	0.75
Landing tractor ($8000, no salvage, 8 years)	0.63
Loader ($82,000, 20%, 8 years)	5.13
Crew vehicles ($15,000, no salvage, 8 years)	1.17
Miscellaneous equipment ($10,000, no salvage, 4 years) . .	1.56
Subtotal	25.54
Maintenance and repair costs	
Yarder, carriage, tractor, loader, and crew vehicles (50% of depreciation)	10.82
Radios (60% of depreciation)	0.35
Subtotal	11.17
Fuel and lubricants	9.50
Total equipment costs	$46.21
Labor costs (same as BU-199)	50.37
TOTAL ESTIMATED HOURLY COSTS	$96.58

Estimated Wire Rope Costs per Mfbm, Gross

Wire Rope Item	Rope Diameter Inches	Quantity Required Feet	Total Cost Dollars	Estimated Life MMfbm	Cost $/Mfbm
MADILL 071					
Mainline	7/8	965	883	5	0.18
Haulback	3/4	1870	1384	10	0.14
Strawline	3/8	1900	550	10	0.06
Chokers	5/8	60	41	0.2	0.20
Total					$0.58
SMITH-BERGER MARC V					
Skyline	7/8	4400	4026	5	0.81
Mainline	7/8	2200	2013	10	0.20
Skidding line	5/8	2300	1156	10	0.12
Strawline	7/16	4500	1575	20	0.08
Chokers	5/8	20	22	0.2	0.11
Total					$1.32
SKAGIT BU-199/T-110					
Skyline	1-1/4	3970	6392	10	0.64
Mainline	1	4890	5526	15	0.37
Haulback	3/4	8470	6268	20	0.31
Straw + Utility	7/16	9500	2850	20	0.14
Tagline	7/8	300	255	5	0.05
Chokers	5/8	20	22	0.2	0.11
Total					$1.62
SKAGIT BU-90/T-90					
Skyline	1-1/8	2030	2822	10	0.28
Mainline	3/4	2220	1643	15	0.11
Haulback	5/8	6600	3320	20	0.17
Strawline	7/16	4800	1680	20	0.08
Tagline	3/4	300	222	5	0.04
Chokers	5/8	20	22	0.2	0.11
Total					$0.80

Estimated Costs of Yarding System Installation

MADILL 071 WEST COAST TOWER (Highlead) -- Yarding System 1

1 hour to rig down at previous location	74.54
4 hours to move yarding system	298.16
Logging truck for hauling yarder and loader--4 hours	73.52
Flag car	80.00
1 hour to rig up at new location	74.54
	$600.76

SMITH-BERGER MARC V (Running Skyline) -- Yarding System 2

1 hour to rig down at previous location	92.09
4 hours to move yarding system	368.36
Logging truck for hauling yarder and loader--4 hours	73.52
Flag car	80.00
2 hours to rig up at new location	184.18
	$798.15

SKAGIT BU-199/T-110 (Live Skyline) -- Yarding System 3

2 hours to rig down at previous location	231.02
9 hours to move yarding system	1039.59
Lowboy rental to move yarding system	1360.50
Flag car	100.00
4 hours to rig up at new location	462.04
	$3193.15

SKAGIT BU-90/T-90 (Live Skyline) -- Yarding System 4

1 hour to rig down at previous location	96.58
4 hours to move yarding system	386.32
Logging truck for hauling yarder and loader--4 hours	73.52
Flag car	80.00
3 hours to rig up at new location	289.74
	$926.16