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A TABU SEARCH METHOD FOR A

TACTICAL FOREST PLANNING PROBLEM

BY

EVELYN WINNIFRED RICHARDS

A Thesis Submitted to the

Faculty of Engineering

In Partial Fulfillment of the Requirements for the Degree of

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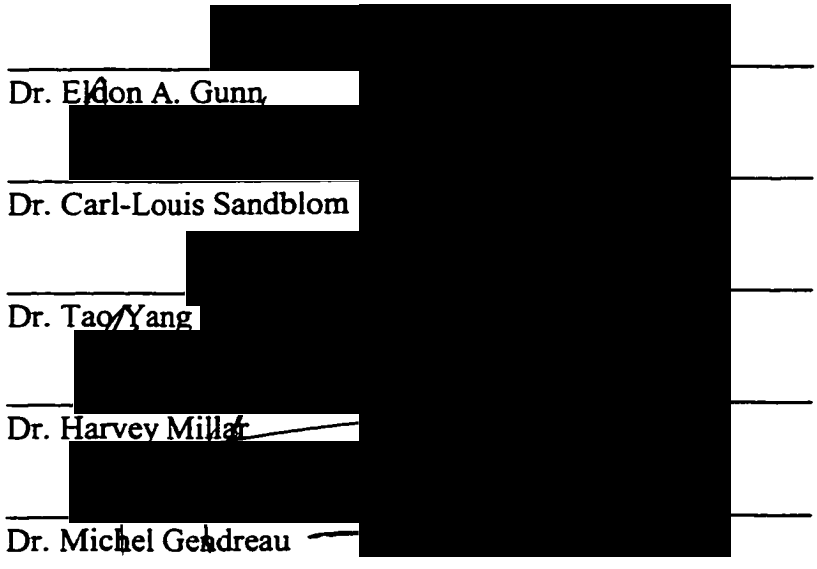

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DEDICATION

This thesis is dedicated to Gerald Bance

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LIST OF ABBREVIATIONS

ac.	acre
dbh	diameter breast height
ft.	feet
ft^3	cubic feet
GIS	Geographic Information System(s)
ha	hectare
HSRBP	Harvest Scheduling and Road Building Problem
IP	Integer Program
IRPM	Integrated Resource Planning Model
km	kilometre
LP	Linear Program
m.	metre
m^3	cubic metre
mai	mean annual increment
MCIP	Monte Carlo Integer Programming
MIP	Mixed Integer Program
PH	Path Heuristic
RISC	Reduced Instruction Set Computer
RNP	Road Network Problem
SA	Simulated Annealing
SAWS	Strategic Analysis of Wood Supply
SRNP	Steiner Road Network Problem
TS	Tabu Search
USDA	United States Department of Agriculture
VRP	Vehicle Routing Problem
WHR	Wildlife Habitat Relationship

ACKNOWLEDGMENTS

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Finally, I will never forget that my family and many friends made it possible for me to complete this work by giving me emotional support and constant encouragement throughout the past four years.

ABSTRACT

At the tactical level of forest planning, decision support systems must deal explicitly with spatial and temporal restrictions on clearcuts and the design of road access to the forest. Formulating and solving optimization models which provide useful decision choices in this context is a serious challenge.

This thesis advances a new model formulation for the harvest scheduling and road building optimization problem. The tactical planning problem is treated in the context of a hierarchical planning system, where a strategic planning process has been first executed. The strategic plan goals of sustainable harvest are inputs to the tactical planning process, where the object is to produce a spatially and temporally explicit schedule of harvesting and road building. The model is designed to produce harvest schedules which minimize both biological productivity losses due to sub-optimal timing of harvests, and the costs of road construction. The objective function to be minimized is a weighted sum of these two opposing cost factors. Solving the optimization problem for a range of weightings produces a spectrum of solutions, from which non-dominated solutions are selected to produce an efficient frontier of roading cost versus lost productivity.

The model uses forest stands as spatial decision units for harvest scheduling, thus avoiding the reduction of the solution space which occurs when stands are pre-blocked. The model produces schedules which are compliant with maximum opening size and adjacency delay requirements, without restricting adjacency delay to one planning period. The configuration of the road system is not restricted to be a tree structure, in that multiple access points and cycles in the proposed network are permitted. As a result, this model can address a wider range of practical road network designs than other models

in the literature. An heuristic algorithm was developed to solve the multi-period road network optimization problem. This algorithm was shown to provide solutions which consistently fall within a small percentage of the optimum solution, and which are optimal in the majority of cases.

Topographical adjacency relationships between stands are represented by a general undirected graph. Openings which are created by harvesting are connected sub-graphs of this forest graph. These sub-graphs are dynamically created throughout the solution process. Spatial feasibility of a proposed schedule is determined by utilizing depth first search and articulation point searches on these sub-graphs.

The combined harvest and road building problem is solved using a tabu search metaheuristic. The search algorithm has a dynamic feedback mechanism to set tabu tenure, and a strategic oscillation strategy to smooth transitions throughout the feasible region. These features of the algorithm essential to ensure solution quality over many problem instances. Computational studies were carried out on a forested region in Cumberland County, Nova Scotia. The study results demonstrate consistent results over the original dataset and five additional datasets. Tradeoff curves which are produced from these solutions provide valuable information, clearly showing the relationship between road building budgets and the range of harvest timing choices available to the decision maker. Thus, this model and solution algorithm represent a significant contribution to the tactical forest management problem.

CHAPTER 1

INTRODUCTION

Forests are a valuable resource. In addition to wood and mineral products which are economically consequential, forests provide habitat for a multitude of animal and plant species, 'facilities' for recreational and sporting activity, and are a carbon sink and a source of oxygen,essential to balance these elements of the earth's atmosphere. Scientific management of our forest resources is an important endeavour, and has in recent years become the focus of operations research activities, aimed at developing better models and solution methods to represent the diverse requirements and concerns of all decision-makers and owners.

1.1. The Planning Problem and Model

This thesis addresses the optimization of harvest and road building schedules in decision support systems for forest management. The problem, a component of the tactical level of the hierarchical planning framework, is to produce an optimal, or near-optimal, and spatially explicit plan that is consistent with management goals derived from a strategic planning process. The optimization model is formulated to determine minimal cost schedules that implement elements of strategic planning (such as harvest levels), and that are in compliance with environmental regulations. Costs include economic factors, such as the expenditures required for road construction. They also include factors which penalize inappropriate timing of harvests, which will negatively impact the future productivity of the forest.

In this hierarchical context, it is assumed that the strategic planning exercise has used a long planning horizon and, amongst other goals, has enforced the requirement that

production levels be consistent with sustained yield. One result of such a process is the recommendation of achievable levels of sustainable wood harvest over some longer planning horizon. The tactical planning problem is to produce a spatially explicit schedule of stand harvests and road building (Figure 1.1). This schedule must meet the strategic goals on volumes. It is further constrained to meet maximum opening size restrictions and adjacency delay constraints.

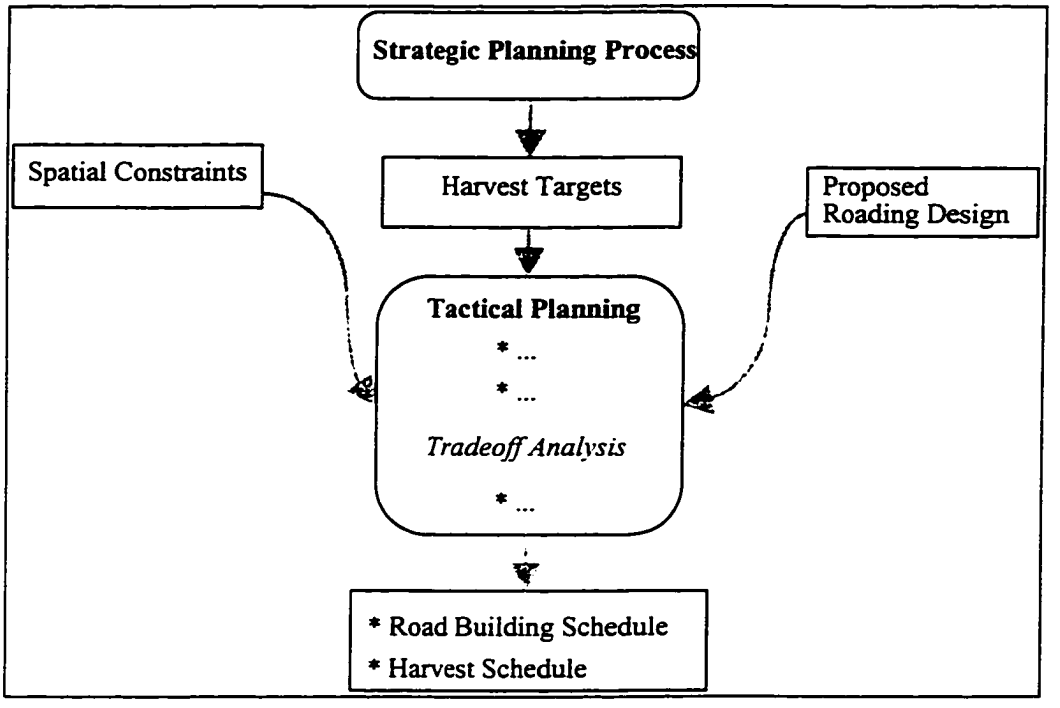


Figure 1.1. Hierarchical Context of the Planning Problem

In many tactical planning optimization models in the literature, the objective function to be maximized is the net present value accruing from the periodic flows of wood products. A different approach is used in this model. It is known that harvest levels, which meet strategic goals, have already been determined in the aspatial model subject to suitable constraints. Thus, levels of production are already optimized. The objective of this model is then restricted to minimizing the costs of road construction and negative impacts on forest productivity due to timing of harvests, while being

constrained to meet the recommended production levels for each period. This approach provides new information to the decision-maker which is not obtained by other models.

Costs in future productivity are induced by harvesting stands at other than their period of peak biological productivity. Roads must be built to gain access to stands and transport timber to main roads. The objective function is a penalty function, comprised of two weighted penalty terms, *lost volume penalty* and *roading cost*. The *lost volume penalty* assesses a cost for timing the harvest of stands at other than their peak productivity. The *roading cost* estimates the cost to access stands scheduled for harvest on a pre-designed set of road links. Clearly, roading costs and lost productivity costs are in opposition: reducing lost productivity involves increasing the cost of road building (See Figures 1.2 and 1.3). Moreover, the units of measure are incompatible. This precludes formulating any one cost function that is meaningful across different problem sets and decision makers. The model objective function is a parameterized sum of the two cost factors, and varying the parameter influences the system to produce solutions across a range of road building costs. The non-dominated solutions then are recorded in two-dimensional attribute space to produce an efficient frontier of choices between road building costs and lost productivity costs. This trade-off curve quantifies the real trade-off relationship between road cost and productivity cost (Figure 1.4).

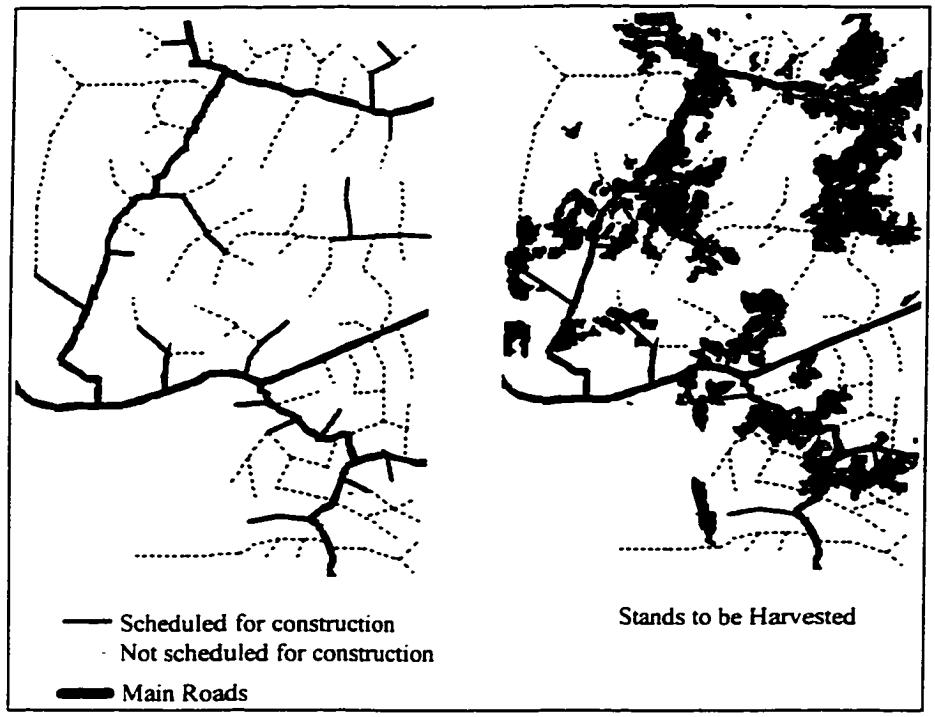


Figure 1.2. Low Road Cost Solution.
RC is \$24, 840 and lost volume 563,444 ft^3.

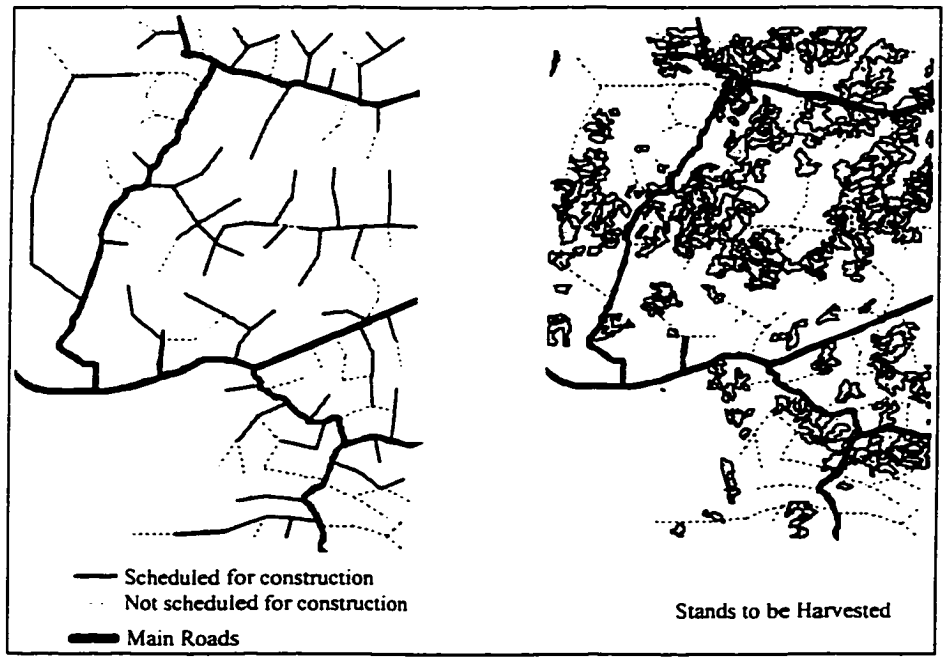


Figure 1.3. High Road Cost Solution.
RC is \$99,132 and lost volume 306,526 ft^3.

Both stand adjacency relationships and road network feasibility are modeled using

graphs. The road network model incorporates multiple access points and a general graph which is not restricted to have a tree structure. Maximum opening size and adjacency delay requirements are represented as conditions on certain specially defined subgraphs of the forest adjacency graph. The combined harvesting and road building model is solved using a Tabu Search metaheuristic method. The road network problem is a sub-problem in the algorithm, and is solved at each step using a custom heuristic method.

An ancillary component of this thesis is the clarification of some issues in integer programming model formulations of the block-based harvest scheduling problem. An algorithm for generating constraints to tighten Linear Programming relaxations for this problem is given, and some empirical results on a well known dataset are reported.

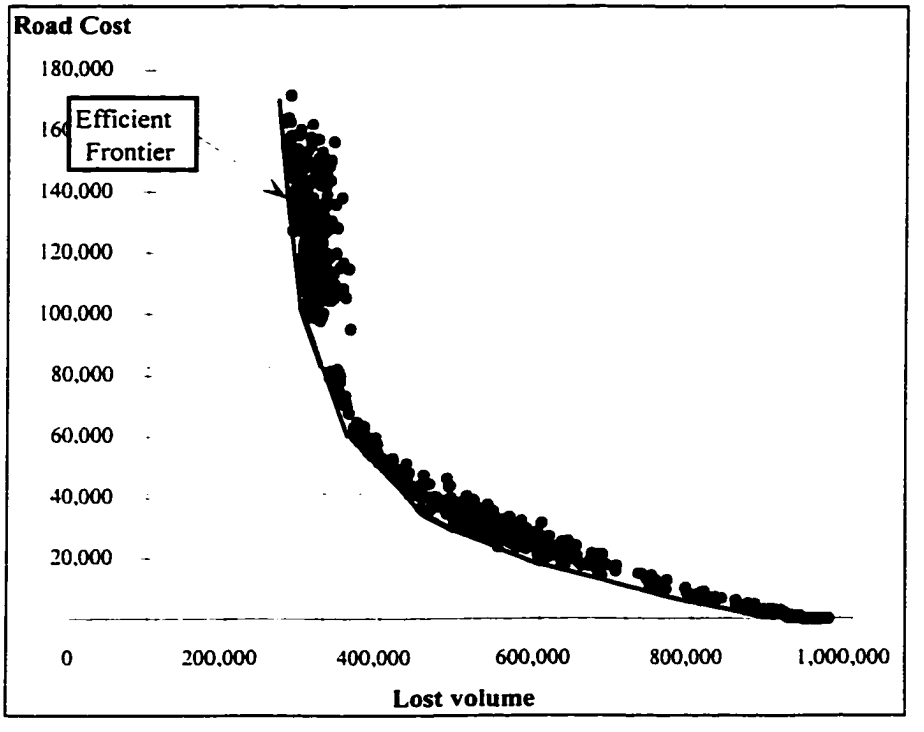


Figure 1.4. Efficient Frontier

1.2. Thesis Organization

To set the context for this work and introduce terminology and relevant technologies, Chapter 2 is an overview of modern forest management planning systems. Some of the unique characteristics of modern forest management planning processes are described. The fitness of forest management for hierarchical organization is well accepted, and this context is assumed in this thesis. Strategic and tactical processes, their inputs and outputs and some of the well-known optimization models for these systems are described in section 2.4. The nature of the feedforward and feedback systems between these two levels is a matter of much concern; these issues are covered in the final section.

Chapter 3 concentrates on tactical planning systems, and particularly on modeling issues which arise when the planning problem is both spatially and temporally specified. Optimization models for forest tactical planning problems are notoriously difficult to solve, hence various heuristic strategies and specialized solution procedures have been developed. The choice of spatial decision units is a well-discussed issue amongst planners and modelers. For models which produce harvest block- or polygon-based schedules, a considerable effort has been made by many researchers to simplify the methods used to specify adjacency constraints. Sections 3.3 is a discussion of the implications of adjacency constraint specification on the solution of such models by branch and bound and cutting planes algorithms. A simple method of specifying some strong inequalities is given in section 3.4, and computational results on a well-known dataset are used to emphasize the usefulness of this formulation.

The model which is proposed in this thesis is solved using a Tabu Search procedure. Accordingly, chapter 4 is devoted to a detailed account of the Tabu Search metaheuristic method, its known successes and some of its more sophisticated

implementations.

Chapter 5 describes the harvest scheduling model. Graph structures are used to model adjacency and maximum opening restrictions. The lost volume penalty function which measures the negative effects of some harvest timing choices is described, and the harvest model parameters and constraints are specified.

The forest road network design problem is documented in Chapter 6. Its mathematical model is based on graphs, and it is shown to be NP-hard by demonstrating equivalency to the Steiner problem in graphs. The Path Heuristic which is used to solve the roading problem is then developed. This heuristic is shown to produce near optimal solutions on some specialized graphs.

Chapter 7 describes the tabu search algorithm for solving the combined harvest scheduling and road building problem. Several tabu search procedures were tested and compared. Chapter 8 contains details of the study area and empirical results. Finally, chapter 9 contains a discussion of the implications of this thesis and some recommendations for further work.

CHAPTER 2

OVERVIEW OF FOREST MANAGEMENT ISSUES

The purpose of this chapter is to provide background in forest management issues to set the context for the tactical planning model of this thesis. The significance of forests and forestry for our society is discussed, and some emerging trends in forest management that encompass the needs and goals of multiple decision makers and forest owners are presented. Technologies which are important in their support of the forest management decision making process include Geographic Information Systems (GIS), growth and yield modeling and simulation. The hierarchical planning system context for forest management is introduced, with an overview of the types of modeling issues which arise in strategic and tactical planning. Finally, a summary of some of the connectivity issues relating to these models is given.

2.1. Economic and Social Importance of Forests

The forest products industries are a cornerstone of the Canadian economy. In 1994, forestry generated $48 billion in shipments, $32 billion of which were exports. In fact, Canada is the world's largest exporter of forest products, having an 18% share of world trade. Forest industries account for 14% of Canadian manufacturing gross domestic product, and are the major or sole employer in more than 350 rural communities [Industry Canada 1996a]. In the maritime provinces, forestry is the most economically consequential sector. Forest industries account for one job in twelve in New Brunswick, and one in twenty-four in Nova Scotia [Industry Canada 1996b, 1996c].

Forests are much more than a source of supply for wood and paper products. Canadian forests account for almost 10% of the earth's forests, which are a vital part of our planet's life support system [Murphy et al 1993]. Forests are the habitat of a multitude of animal and plant species. Healthy forests are required in maintaining a clean water supply. They provide "facilities" for recreational and sporting activity and a carbon sink for the earth's atmosphere.

Continued improvements in technology have increased the efficiency with which forest products are produced, and some recent attention to re-cycling paper products will no doubt result in decreased pressure on raw materials. However, demands for paper and wood products are increasing with a world population that is growing in both size and sophistication. It seems unlikely that improvements in manufacturing technologies will be sufficient to meet the future demand for forest products, without seriously depleting the resource or compromising the environment. Effective management of forest resources is critical to avoid making environmentally or economically catastrophic decisions.

New knowledge of the impact of human actions in forests on the global environment is gained daily. Synthesis of this knowledge into management practices, however, is a much slower and more difficult process. The development of intelligent systems to manage forests so that *both* economic and ecological goals are achieved with any degree of certainty is in its infancy.

2.2. Multiple Owners, Decision-Makers and Goals

A distinguishing and complicating feature in forest management is the existence of multiple "owners" of the forest. In Canada, 91% of the forest area is publicly owned and controlled. The remainder is owned by several hundred thousand private woodlot

owners [Murphy et al 1993]. On public lands, control lies in the jurisdiction of Provincial Governments, although private enterprise may propose and carry out management of these resources [NBGOVT 1994]. In effect, governments act as stewards of the resource for the Canadian people. These governments lose their jurisdiction at national borders; the care and nurturing of the earth does not segregate at these artificial boundaries. Considering the vital importance of forests to the planet's ecological health, one may say that all living species of the earth have title to its forests, and that the management of forest ecosystems is a matter of public trust, regardless of ownership [Davis and Barrett 1992].

Thus, the register of potential participants in forest management ranges from large governmental agencies (national and international) and forest products industries to individual woodlot owners; from communities which depend on the local mill for their economic viability to scientific and environmental advocates for species habitat; from organized industrial lobbies to individual hikers, hunters and campers. The goals and desires of these participants are defined within different frames of reference and are often in conflict. Forest management decision-making processes must be capable of integrating these diverse groups of decision makers with their often conflicting objectives [Weintraub and Davis 1996].

Forest products industries must be economically viable, and thus have a dominant goal which is to maximize profits. Thus, they plan to extract products from the forest to meet their markets and to minimize their operational costs. Governments recognize that local economies may depend on the forest products industry. To maintain a degree of social equilibrium, it is desirable that the industry operate in a sustainable fashion, so that communities are not disrupted by swift depletion of forest resources. This objective has been expressed as the requirement for non-declining yield (harvest in any period must be

at least equal to that from the previous period) and as a reserve margin (a percentage of the final period harvest remaining in inventory). This concept of sustainable forestry is now being expanded or changed to address the sustainability of forest ecosystems [Thompson and Welsh 1993, Booth et al 1993, Dewhurst et al 1995].

Ecological considerations include biodiversity, green cover requirements and water quality and supply. Achieving and maintaining a diverse wildlife population is dependent on, amongst other factors, the availability of forest habitat to support a broad spectrum of plant and animal species. Habitats that are suitable for nesting and breeding, foraging and migration must be available to support wildlife. The choice of interventions (such as clearcutting, shelterwood cutting, thinnings and cleanings), as well as the level and location of such activities, have an obvious impact on habitat. Clearcuts remove mature forest stands, and create edge-type habitat. The spatial arrangement of interventions is important in preserving existing habitat and in creating a diverse environment [Booth et al 1993]. Thus, legislators have initiated restrictions on cutting, such as the maximum opening size and adjacency delay, which are intended to both preserve mature areas and to create new openings which are necessary for foraging and breeding. Appropriate management of waterways and watersheds must be included in planning so as to safeguard the future water supply. Road building causes sedimentation and must therefore be carefully managed so as to preserve the quality of streams and brooks.

Recreational users require hiking and climbing areas, fishing and hunting areas and scenic areas. This is usually achieved by setting aside regions of the forest for recreational use. "Set-asides" are also specified when a particular type of habitat, such as deer wintering yards or old-growth forest, are to be specifically preserved The choice of *what* area and *how much* area to allocate to recreational use and to preservation is a

continuing source of conflict between recreational users, environmental advocates and commercial users.

2.3. Characteristics of Forest Management Models

Scientific management of our forest resources is crucial, and has in recent years become the focus of operations research activities, aimed at developing better models and solution methods to represent the diverse requirements and concerns of all owners of our planet's forests. The forest management problem has many dimensions. Users have diverse and sometimes conflicting goals, ranging from extraction of wood products to preservation of wildlife habitats. Biological scientists strive to understand forest growth and the life patterns of its inhabitants, and to define measures of desirable forest states such as biodiversity. The prediction of forest growth is further complicated by the occurrence of natural events such as fire, pest infestation and disease. Decision makers may be federal, provincial or municipal governments, or individuals who own land. Planning takes place at strategic, tactical and operational levels, requiring telescoping degrees of spatial resolution and detail in planning models.

Early forest management mathematical models concentrated on producing recommendations for harvest levels that would maximize yield while maintaining long-term sustainability of the resource. More comprehensive management models are now needed to address the requirements of all users -- the forest products industry, recreational users, and environmentalists. This presents a significant challenge to researchers to define appropriate model formulations, and to develop new methods of solving these complex models. The availability of a comprehensive and accessible forest inventory is one key to the success of modern management systems.

2.3.1. Forest inventories and GIS Systems

The forest inventory consists of several levels of information. Biological data regarding the forested areas, the location of waterways, roads, and ownership boundaries are all required data for forest management.

The basic spatial unit for forested areas is the *stand*, which is a contiguous region that is homogeneous in species composition and future expected growth characteristics. Stands may be delineated by age; thus "even-aged" stands are also homogeneous in age-class or diameter-breast-height (dbh). "Uneven-aged" stands, inhomogeneous in age-class, are further specified by calculating the distribution of ageclasses (dbh class or basal area class) of trees in the stand area.

A Geographic Information System (GIS) is a spatially referenced database management system. Information is stored as a collection of thematic layers which are geographically referenced [Environmental Systems Research Institute1997]. Forest management has a critical geographic dimension: management choices include not only *what* action is selected but *where* (and when) it is to be implemented [Jordan 1993]. Thus, a GIS is a natural choice for gathering, maintaining, updating and displaying inventory for the forest management process. (Figure 2.1) GIS, a relatively new technology, has had a real impact on forest management in improving the speed, flexibility and accuracy with which such data can be stored and manipulated.

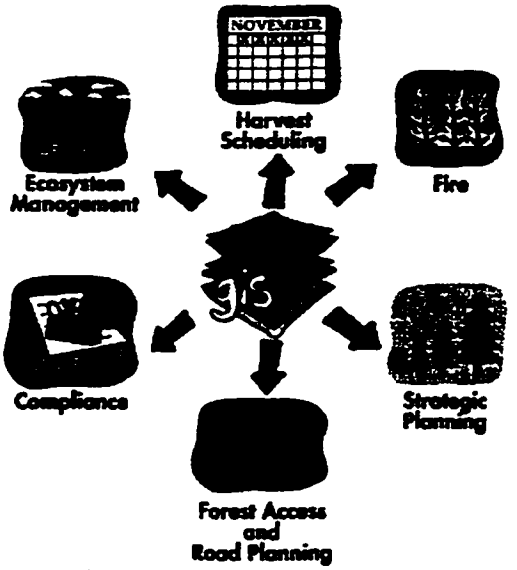


Figure 2.1. Using GIS in Forestry (Figure courtesy of ESRI Inc.)

A GIS includes a set of generic tools which can be customized for forest management purposes [Jordan 1993]. Relational database functionality allows selection and grouping of spatial features by attributes which are stored in tables. For example, Figure 2.2 shows the distribution of budworm damaged stands in a forested area. This figure was generated by querying a forestry GIS for stands matching this classification. Spatial analysis, such as proximity analysis, allows the user to extract information on stands based on their spatial relationship to other features. As an example, Figure 2.3 shows stands which are adjacent to main roads, and was generated using ARCVIEW™'s spatial analysis capability. Use of the database and analysis tools ranges from simple "point and click" usage to complex programmed algorithms.

GIS has had a large impact on forestry planning because of its visual nature: mapped "what - if" management scenarios or their predicted results provide a common meeting point for decision-makers from widely varying backgrounds. Thus, GIS systems

allow disparate groups of users to communicate effectively and, for that reason alone, are advantageous to the planning process.

Forest management is having to adapt to radically different groups of decision makers, new goals and an evolving science. Moreover, GIS is a relatively new technology. Thus there are of course some challenges in implementing GIS technology. First, the effort in generating the initial database is enormous. Second, the database must be well designed so as to be comprehensive, flexible and extensible, since the nature of future demands on the system for information are not known in advance. Finally, a well managed system of updates is critical, since forest interventions are almost continuously changing the landscape.

Figure 2.2. Relational Database Query. Dark areas are Budworm Damaged Stands (ARCVIEW™ Image Source: Nova Scotia Dept. Lands & Forests GIS Database)

Figure 2.3. Spatial Analysis Using ARCVIEW™
Selection of Stands Adjacent to Main Roads
(Source: Nova Scotia Dept. Lands & Forests GIS Database)

Despite some problems, it is fair to say that GIS has had a major positive impact on forest planning systems and has removed several impediments to modern forestry management endeavours. It has provided the capability to develop a comprehensive spatially referenced database, an excellent communications tool and significantly increased analysis functionality [Davis and Barrett 1992, Ball 1994, Dewhurst et al 1993].

2.3.2. Growth Models: Predicting Future Inventory.

Models which predict the growth of trees are essential to forest management [Brack 1996a]. The goal of growth modeling is to predict the future condition of a stand using the current composition (i.e. the species, age, and stocking or density), any previous or planned silvicultural treatments and a measure of site capability or site quality. Due to the length of crop rotations in forestry, these predictions must be made decades into the future [Province of Nova Scotia 1993]. The value of a growth and yield

model lies in its ability to provide the best possible prediction of the relative outcomes of various management alternatives [Edwards and Christie 1981]. Data for growth and yield models may come from permanent sample plots, temporary sample plots and stem analysis [Brack 1996a]. Growth and yield models are thus location specific, since climate, soil and topology strongly affect forest growth. In Nova Scotia, the Department of Lands and Forests has developed growth and yield models for first and second rotation unmanaged stands and for managed stands. Data have been obtained from hundreds of permanent and temporary sample plots in plantations, pre-commercial thinnings, commercial thinnings, shelterwoods and unmanaged stands [Province of Nova Scotia 1993]. The future inventory is predicted in terms of total, merchantable and sawlog stand averages for each diameter, height and basal area class. The model is limited to eight softwood species: mixedwood and hardwood stand predictions are calculated as for softwood growth and are adjusted by volume factors.

The growth and yield model forms the basis for growth simulation, which is used to evaluate the effect of different management scenarios on the forest. In Nova Scotia, for example, the Strategic Analysis of Wood Supply (SAWS) system is a simulation model of even-aged forest management [Gunn 1994b]. Inputs to the simulation are the current inventory, levels for each potential treatment (including harvesting and silvicultural activities), as well as ending period inventory restrictions, the number of planning periods and the discount rate. The spatially explicit stand-based inventory is aggregated into "macro-stands", thus losing geographic representation in order to reduce the number of decision variables to a manageable size. The outputs from SAWS are the number of acres which were assigned to each treatment, and the volumes of merchantable hardwood and softwood which are thus extracted in each planning period.

Thus, SAWS is a strategic planning tool, intended for use on large areas without being spatially explicit.

2.4. Hierarchical Planning

Forest management has all the classical elements of a hierarchical problem -- differing levels of decision making, elements of uncertainty in forecasts, and a rolling planning horizon [Hax and Golovin 1978, Gunn and Rai 1987]. It has become established practice to adopt a hierarchical planning framework for forest management, and to structure decision support systems or mathematical models to conform to the requirements of each phase [Vertinsky et al 1994, Gunn and Rai 1987, Barros and Weintraub 1982, Weintraub and Cholaky 1991]. The hierarchical framework is appropriate to integrate groups of decision makers, with different and often conflicting objectives, at different hierarchical levels into decision making processes [Weintraub and Davis 1996].

2.4.1. Forest Management Hierarchy

An example of a forest management hierarchy is illustrated in Figure 2.4.

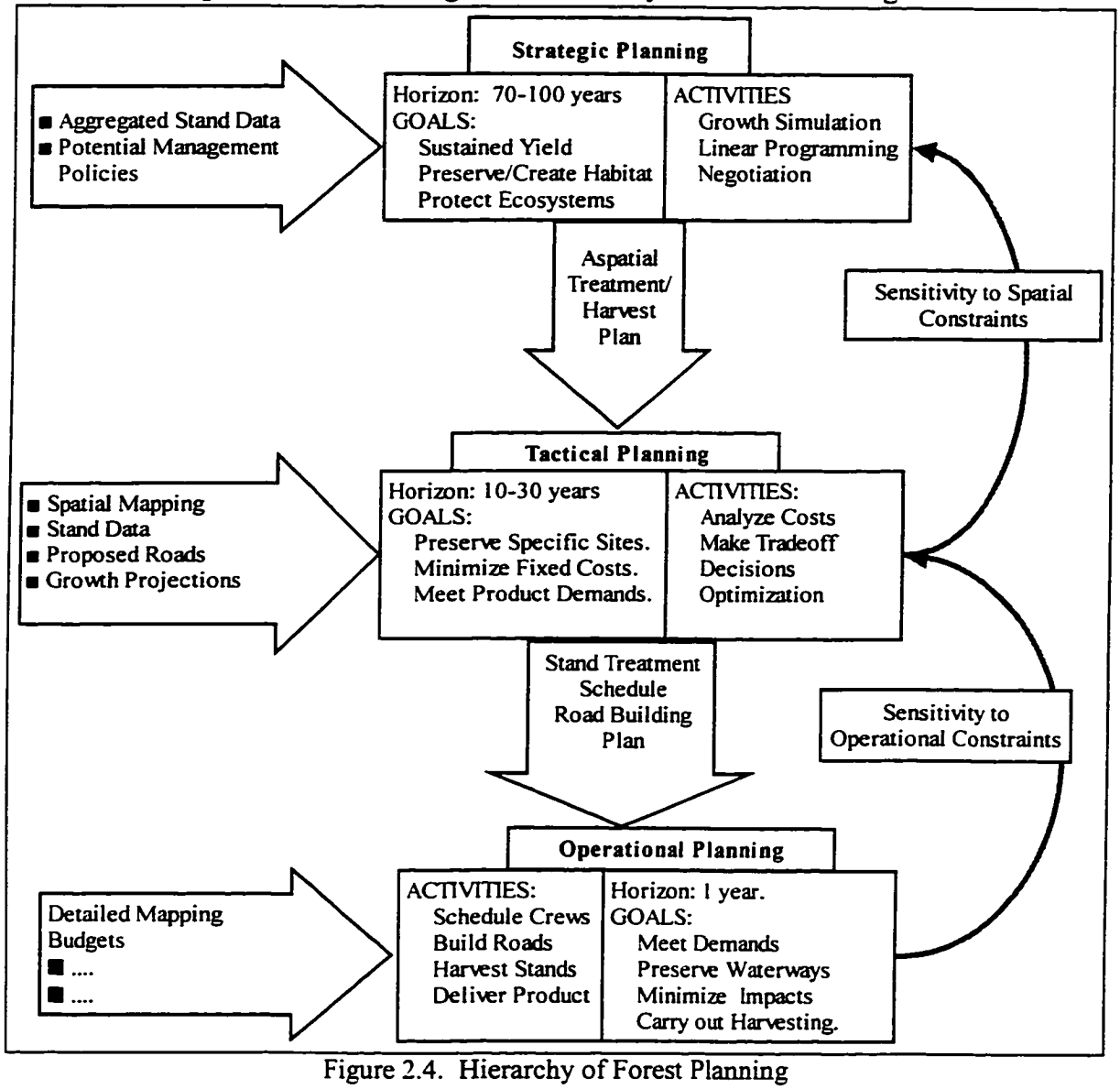


Figure 2.4. Hierarchy of Forest Planning

Hierarchical decision support systems for forest management must resolve multiple and often conflicting objectives of decision makers. Different levels of spatial detail are required at strategic, tactical and operational planning stages, and appropriately designed feedforward and feedback mechanisms must link models at each level. Each planning level demands appropriately designed mathematical models to support the decision-

making process. These models differ in the planning horizon used, the level of decision-maker to be "satisfied", and the refinement of spatial detail in the inputs and output of the model.

Strategic planning addresses the allocation of forest resources amongst multiple and competing demands [Weintraub and Cholaky 1991]. At this stage, the planning horizon is long, encompassing at least one crop rotation. Examples of strategic goals are the creation or preservation of habitat and ensurance of a perpetual supply of timber products. Large forests may be divided into zones, stands are aggregated into "macro-stands" or strata and recommendations for interventions are developed. These recommendations include an estimate of the amount of timber product that may be extracted (annual allowable cut) and levels (acreage, volume) of silvicultural activities that are required to sustain the annual allowable cut. The strategic planning horizon usually encompasses more than one crop rotation. The aspatial outputs of the strategic planning phase are input goals or constraints to the tactical planning phase.

The overall goal of the tactical planning process is to produce a spatially and temporally viable schedule of activities. In this phase a shorter horizon, usually less than or equal to one rotation, and shorter time periods are used. For example, in New Brunswick, the tactical planning horizon is thirty-five years, with five year planning periods. [NBGOVT 1994] One critical feature of tactical planning is the requirement to produce spatially explicit recommendations. Decisions become discrete (whether or not to cut a given stand) rather than continuous (the percentage of a given stand-type to be assigned to a particular activity). This introduces non-linearities into the models, and increases the difficulty of solving them to optimality [Weintraub and Davis 1996]. The output of tactical planning is a mapped schedule of interventions (harvesting, silvicultural activities) on stands or blocks of stands, and schedules of other activities

such as road building, setting aside special areas for special habitats (deer wintering, shelterwood, water and stream buffers, wildlife corridors etc.).

In the operational planning phase, a tactical plan for one period is implemented in the best possible way. This phase of "on-the-ground" planning requires fine levels of detail in constructing roads, scheduling personnel and equipment. Operational planning horizons are typically very short -- for example, a one year horizon with bi-weekly planning periods may be suitable for planning the detail of "on-the-ground" operations.

2.4.2. Hierarchy of Planning Models

In forest management, the difficulties in solving models which span the strategic and tactical planning phases has, to some extent, motivated the pursuit of hierarchical planning [Weintraub and Cholaky 1991]. The structure of forest harvest/treatment models in the literature may be broadly categorized into two types, strata-based models and area-based or spatial models, depending on whether the stands are aggregated aspatially by type or not. This delineation coincides with the strategic and tactical phases of the hierarchical planning process.

Strata-based models are amenable to Linear Programming methods, since decision variables are continuous. Area-based or spatial models are not, since decisions to chose from management options or road building projects require binary or integer decision variables. There is considerable debate over the value of Mixed Integer formulations due to the considerable computational burden which occurs when problems of realistic size are dealt with. Some methods of improving formulations by adding inequalities which tighten the LP relaxation of the integer program have been applied to this problem [Barahona, Weintraub and Epstein 1992]. In many cases, however, researchers have turned to heuristic and metaheuristic methods to solve area-based models.

2.4.2.1. Strata-Based Models

Strata-based models are used to develop long term plans for forest industries and governments. They are used to determine the potential harvest of forest products from large areas over long time frames, perhaps encompassing several rotations. These are strategic planning models, in which the goal is usually to determine the level of periodic product flows which are sustainable. Constraints on the levels of harvest in these models are designed to ensure the sustainability of the resource. These constraints may include the non-declining yield requirement and an ending reserve margin. In addition to sustainability issues, environmental considerations such as the maintenance of a diverse age composition of the forest, or the creation of a given age-class structure in the forest, are appropriate in these strategic planning models The strata model will develop a capacity plan subject to corporate strategy, but may not provide spatially feasible solutions [Nelson, Brodie and Sessions 1991].

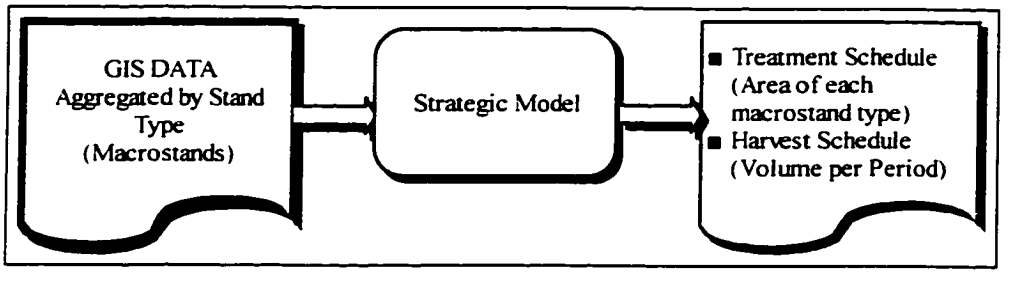


Figure 2.5 Strata-Based Model

Linear Programming is especially suitable for formulating and solving strata-based plans when stochastic effects are ignored. Decision variables such as the volume or area to harvest (or treat) from a stand type are continuous and constraints are easily specified. Timber RAM [Navon 1971] has been used extensively in the1970s in the United States for strata-based planning. FORPLAN (FORest PLANning), developed for the US Forest Service, is a well-known LP model for forest wide harvest scheduling and has served as the primary analysis system for the USDA Forest Service Land Management Planning.

LP strata-based models may be further classified as Model I [Navon 1971] and Model II [Johnson and Scheurman 1977] formulations. In the Model I formulation, candidate schedules of potential treatments over the planning horizon are enumerated for each stand type. Each sequence differs from the others in the number of harvests over the time horizon and/or the age at time of harvest, and will produce a different pattern of outputs (wood products) over time [Johnson and Scheurman 1977, Gunn and Rai 1987]. The decision variables x_{lq} are the amount (area) of each stand type l to be assigned to each possible schedule of treatments q. This formulation removes time variables from the model equations, at the expense of the specification and computation of the coefficients for a large number of treatment schedules. In the Model II formulation, treatment schedules over time are not pre-specified for each stand type. Rather, the decision variables are linked to the periods in the planning horizon. TimberRAM [Navon 1971] is a well-known modeling system that is based on Model I formulation. FORPLAN is a Model I formulation, and both FORPLAN and Musyc systems can accommodate Model II-type decision variables [Field 1984].

In the basic FORPLAN model, land is allocated to general management objectives and treatments and product flows are scheduled. The following description of the FORPLAN model was taken from Field [1984].In this model, the decision variables x_{lq} are the number of acres of land type l to be assigned to management strategy q. Given T land types, S_l possible management strategies for land type l, N planning periods and M possible inputs outputs and other responses. A_l is the number of acres in land type l, D_{lq} is the discounted net value per acre of land type l under management strategy q, P_{lgik} the response level k (per acre) in time period j, land type l and management strategy q, V_{lqj} the timber harvest volume. B_{jk} is the desired level of input, output or response in period j. The LP model is then

$$\text{Max} \sum_{l=1}^{T} \sum_{q=1}^{S_l} D_{lq} x_{lq}$$

subject to

$\sum_{q=1}^{S_l} x_{lq} = A_l$	$l = 1, \ldots, T$	Area constraints
$\sum_{l=1}^{T} \sum_{q=1}^{S_l} V_{lqj} x_{lq} - \sum_{l=1}^{T} \sum_{q=1}^{S_l} V_{lqj+1} x_{lq} \leq 0$	$j = 1, \ldots, N-1$	Nondeclining timber harvest
$\sum_{l=1}^{T} \sum_{q=1}^{S_l} P_{lqjk} x_{lq} \leq, =, \geq B_{jk}$	$j = 1, \ldots, N, k = 1, \ldots, M$	Input, output and response
$x_{lq} \geq 0$	$\forall l, q$	Non – negativity

Figure 2.6 FORPLAN Model

Recently, the Ecosystem Management Analysis center (Fort Collins, Co.) has developed a more comprehensive modeling system (SPECTRUM) which, building on FORPLAN capability, provides a Graphic User Interface to define decision variables, constraints and objectives. In SPECTRUM, goal programming models allow the user to address conflicting multiple use objectives. SPECTRUM is foremost a linear programming system, although some integer variables are used in defining cost functions [Schuster, Leefers and Thompson 1993].

Figure 2.7 shows the Model II formulation, as taken from [Gunn and Rai 1987]. In this formulation, in contrast to Model I, decision variables x_{ij} and w_{jN} represent both the timing and magnitude of harvest choices for each stand type at each period. Gunn and Rai [1987] observed that Model II can be formulated as an acyclic network, where the nodes correspond to initial regeneration periods and planning horizon periods ($i = -M, \ldots, 0$ *and* $i = 1, \ldots, N$) and arcs represent the flow of products from a regeneration period to a harvest period. At each period in the horizon, stand types (i.e. age-classes) are aggregated and the initial delineation of the forest into stand types (by age-class) is lost.

$$Max \sum_i \sum_j D_{ij} x_{ij} + \sum_i E_{iN} w_{iN}$$

Subject to

$$\sum_j x_{ij} + w_{iN} = A_i \; i = -M, 0$$

$$\sum_k x_{jk} + w_{jN} = \sum_j x_{ij} \; , j = 1, N$$

where

x_{ij}	*ha regenerated in period i and regeneration harvested in period j*
w_{iN}	*ha regenerated in period i and left as ending inventory in period N*
A_i	*ha in period 1 that were regenerated in period i (i = -M,0)*
M	age of the *oldest age - class present in period 1*
D_{ij}, E_{ij}	*Discounted net revenue coefficients*

Figure 2.7. Model II Formulation

In summary, strata-based optimization models typically have an objective function which is to maximize the net present value of product flows over time. The models are aspatial, since stands are aggregated into strata or macro-stands. These models are relatively easy to formulate as linear programs, and although there may be many variables, are computationally tractable. The aspatial model output is usually a schedule of harvest levels (in area or volume) and possibly a schedule of silvicultural treatments over the planning horizon. These outputs are the inputs to the tactical planning problem.

2.4.2.2. Spatially Explicit Models for Tactical Planning

Area-based models address the tactical issues in medium range planning horizons, (usually less than one crop rotation), while attempting to achieve harvest levels as specified in the long range plan. Transportation requirements (road networks) and spatial concerns such as access over time, adjacency over time, habitat dispersion and fragmentation, requirements for habitat and riparian corridors are normally addressed in area based models [Brodie and Sessions 1991]. Area-based models provide input to the short term operational planning systems and may be used to provide feedback to the

strata-based strategic model . The output from these models is a mapped schedule of forest treatments, and possibly road-building, for each period in the tactical planning horizon (Figure 2.8).

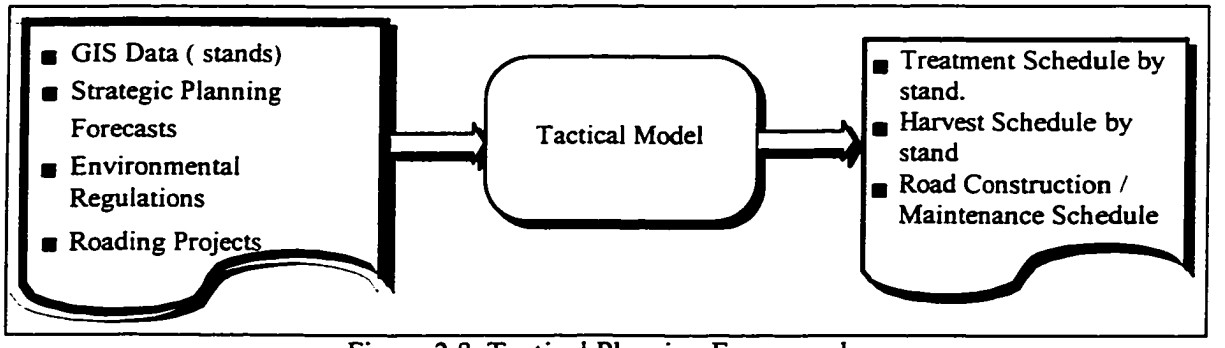


Figure 2.8 Tactical Planning Framework

Decisions regarding the choice of resource projects include both the type of project (silvicultural activity, harvest) and the timing. Transportation issues such as construction, maintenance, upgrading or removing roads must be dealt with in the tactical model, since a large proportion of management costs is spent on road construction or upgrading, especially in natural forests. One strategy of modeling access to forested areas is to pre-select a limited number of routes to be considered. This strategy not only requires preliminary work but results in a model in which there is no guarantee of optimality since the best route may not have been included. In order to determine the best (i.e. cheapest) routes for accessing stands and transporting products to market, road construction decisions must be represented explicitly in the optimization model along with timber resource management options [Weintraub and Navon 1986]. In a mathematical program, this results in the inclusion of integer decision variables for road projects, and can significantly increase solution difficulties.

The Integrated Resource Planning Model (IRPM) is a well known mixed integer model that simultaneously considers land allocation and scheduling with a transportation

network model. Land is divided into areas (polygons) on which fractions of resource projects are allocated. The model was developed by Kirby and others [Kirby et al 1980, Kirby, Hager and Wong 1986], and combines resource project selection with a transportation network subject to road capacity constraints. Many others have used variants of the IRPM model.

Protection of habitat, preservation of or convergence to an age-class structure, insuring of water quality -- these are some of the many expressions of environmental requirements in forest management. The most commonly specified environmental constraints are the maximum opening size and adjacency delay requirements. The maximum opening size constraint limits the area of any clearcut. In New Brunswick at this time this limit is 100 ha. [NBGOVT 1994], in Nova Scotia 50 ha. [Province of Nova Scotia 1990]. Adjacency delay constraints specify that area bordering clearcuts may not be scheduled for harvest for a fixed length of time, say 10 or 20 years. The effect of adjacency delay is to allow a "green-up" period for the stand which has been clearcut. In the case of an even-aged forest, this would prevent the execution of a progressive clearcut, which would cause a forced migration of the large animals out of their habitat with no likely means to return. Adjacency delay means (roughly) that a harvest pattern such as Figure 2.9(a) is appropriate, but Figure 2.9(b) is not. Another regulation which has been imposed to avoid this effect is the requirement for wildlife corridors -- strips of forest of a prescribed minimum width which allow animals to travel "through" cut over areas. These goals may be found in LP, IP, MIP and non-linear mathematical models as constraints, or as terms in objective functions of goal programming and heuristic search formulations.

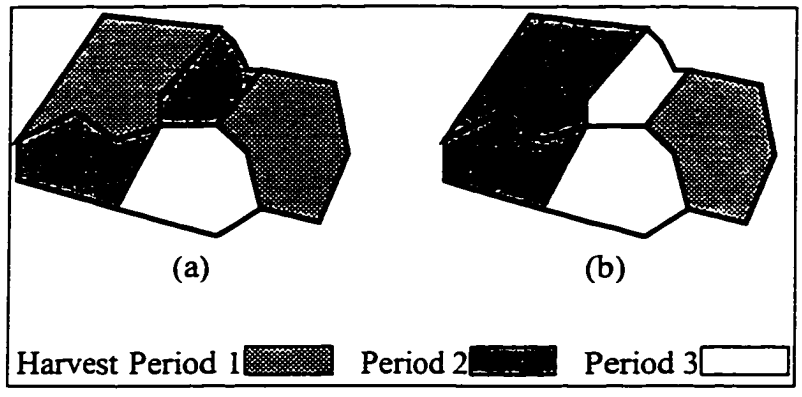


Figure 2.9. Adjacency Requirement

Special habitat protection is often a requirement. For example, in New Brunswick, designated land areas are set aside from harvesting to provide deer wintering yards. Other pre-specified "set-asides" may occur when a particular species is deemed to be in danger of extinction due to loss of habitat, or when an area is to be reserved for a recreational use such as a park. These restrictions remove the affected stands from consideration for clearcut harvesting, although other methods such as shelterwood cutting may be allowed [Province of Nova Scotia 1990, NBGOVT 1994].

In an effort to directly include the objectives of diversity and habitat availability, Hof and Joyce [1992] present a non-linear model to optimize two types of wildlife habitat, edge-type and dense-type, combined with forest harvest optimization. This is further developed by Hof and Joyce [1993] to model edge effects, fragmentation effects and habitat area threshold with integer variables. In Hof and Rafael [1993], approaches for finding optimum allocation of forest age-classes to meet multi-species conservation objectives are investigated.

Davis and Barrett (1992) have developed a model to examine the long-term effects of forest practice on habitats. The model predicts the effect on habitat of even-aged management by large clear-cuts, small group selection planting, selection cutting, hardwood type conversions to conifer management, shelterwood and reserves. The

California Wildlife Habitat Relationship (WHR) system is used to measure the suitability of habitat type for different species. This "measurement" includes expert scoring of the each suitability of each WHR cover type for reproduction, food and shelter for each vertebrate species (Davis and Barrett 1992). The first phase (a linear program) produces a prediction of economic outputs (revenues, costs, net present worth) based on an aspatial allocation of different forest management practices (an assignment of areas of each WHR type to different management prescriptions). This aggregate plan is then allocated spatially, manually allocating ("by expert judgment") areas using the GIS. The model then "grows" the GIS polygons into the future, and evaluates each future state of the forest in terms wildlife habitat suitability for three vertebrate species.

2.5. Cohesion Between Strategic And Tactical Models.

Some of the technical and philosophical issues with regard to these mathematical models are the effects of aggregation and disaggregation on treatment schedule feasibility, the choice of appropriate measures to feed sensitivity information upwards in the hierarchy, and the choice of spatial decision units. For example, the output of the strategic phase, the aspatial treatment schedule, may not be attainable when constrained by spatial restrictions such as adjacency delay.

Whether or not a "gap" exists between the level of timber harvests produced by the strategic and tactical phase has been discussed in Daust and Nelson [1993], Nelson and Finn [1990], Nelson and Errico [1993], Yoshimoto1994, Yoshimoto and Brodie [1994]. If there is indeed a gap, it is important to identify the tactical level factors which cause the discrepancy, and to feed this sensitivity information back to the strategic planning process.

At tactical planning, the existence or the perception of the existence of significant setup and capitalization costs has encouraged planners to group stands into harvest blocks of a minimum size [Clements, Dallain and Jamnick 1990, Jamnick and Walters 1993, 1991, Hokans 1984]. This has the effect of reducing the number of decision variables and thus making models more computationally tractable. It has the negative effect of limiting the set of scheduling choices and thus potentially excluding better schedules. (This issue is discussed in more detail in Chapter 3.) This is a relevant factor in considering the so-called gap between the aspatial and spatial forecasts. The significant effects observed by Nelson and Finn [1990], Daust and Nelson [1993], Yoshimoto [1994] and Yoshimoto and Brodie [1994] are estimated using blocked stands, and these may in some measure be due to the blocking as well as to real impacts of spatial constraints. Observe for example, in Lockwood and Moore [1992], that the spatially constrained tactical schedule produced harvest volumes that had less than one percent deviation from the strata-based (aspatial) solution.

An additional complication to the process of determining the cost of spatial constraints is the fact that the magnitude of the effect of adjacency delay and maximum opening size is definitely location dependent -- there will obviously be a larger impact in forests that contain large homogeneous tracts of land. Thus, these case studies should be carefully examined in this respect.

CHAPTER 3

TACTICAL PLANNING MODELS AND SOLUTION METHODS

The framework for forest management tactical planning models was outlined in chapter 2. The desired output of these models is a good or optimal schedule of harvesting and road building. These problems are characterized by the requirement for discrete decision variables, and a complicated constraint structure due to spatial and temporal constraints on harvesting. Hence, the models are difficult to solve exactly using integer programming methods, and, although some efforts in that direction have been made, there has been a considerable direction of energy towards heuristic and metaheuristic methods of solution.

Tactical planning models are constrained spatially and temporally to meet environmental regulations which limit the size of clearcuts and prescribe adjacency conditions on areas near to clearcuts. Road networks are based on a pre-determined set of potential road links which give full access to the forested area. In this thesis, several modeling issues will be addressed. These include the design of an appropriate objective function, the selection of spatial decision units, and the inclusion of a more general road network. The model which is proposed will be solved using a metaheuristic method; however some attention to the solution methods employed by other researchers on other models is appropriate to set the context for the new model.

The first section of this chapter contains a summary of some of the methods which have been used to solve tactical planning models. Section 3.2 deals with the choice of spatial decision units, and section 3.3 the issues in modeling adjacency constraints. An

improved formulation for adjacency constraints is presented, and in section 3.4 results from implementing the improved formulation on a small study area in BC are given.

3.1. Solving Tactical Planning Models

Integer and mixed integer programming (MIP), Monte Carlo Integer Programming (MCIP), dynamic programming, heuristic and metaheuristic methods have been used to solve tactical forest management problems. Adjacency and road building requirements, requiring discrete decision variables, create the main difficulty in solving these polygon-based models using linear programming with branch-and-bound techniques. For example, Murray and Church [1995] solved a 431-block problem (excluding roading) on a 486/50 personal computer, but the solution time exceeded 24 hours. [Also, see Nelson and Brodie 1990.] Although some efforts have been made to solve such models exactly [see Weintraub et al 1994, Barahona, Weintraub and Epstein 1992, Guignard, Zhu and Chajakis 1995], it is not surprising that heuristic and simulation methods have been the tools of choice for large problems. The disadvantage of using heuristics, of course, is that optimality of the solution is not known or expected and only probabilistic measures of deviation from true optimum can be presented. However, given the lack of exactness in forest growth simulation, and the hierarchical nature of the management setting, the ability to provide several good solutions in reasonable time is very useful [Gunn and Rai 1987].

Integer and mixed integer programming models simultaneously consider roading decisions and land use decisions. These models are generally variations on the IRPM model [Kirby et al 1980], where binary decision variables are used to model land use decisions and road construction decisions. Some improvements on the formulation of the traffic capacity constraints in IRPM have been reported in Guignard et al [1995].

Monte Carlo Integer Programming (MCIP) has been used to solve area-based models including adjacency constraints [Nelson and Brodie 1990, Nelson, Brodie and Sessions 1991]. In this method, acceptable schedules are produced by generating harvest patterns over blocks randomly, then discarding those that do not meet adjacency requirements. MCIP has the advantage of simplicity, and the ability to generate a large number of feasible schedules easily for consideration by planners. Its disadvantage is that it is inefficient compared to other random heuristic search methods such as interchange, simulated annealing and Tabu Search [Murray and Church 1995].

Specialized heuristic methods have been developed for this problem. Weintraub, Jones and others [1994] describe a heuristic system for solving the IRPM model of Kirby [Kirby, et al 1980, Kirby et al1986]. Weintraub et al [1991] used simulation techniques combined with heuristic scheduling rules to solve a truck scheduling and short term timber cutting problem. The PASS system [Tanke 1985] is a tool for analyzing alternative harvest schedules under alternative road networks. This is essentially a data management system where harvest schedules are exogenously supplied.

Lockwood and Moore [1992] used Simulated Annealing (SA) to solve a harvest scheduling problem, based on a stand-based model. They produced spatially explicit harvest schedules on test data of 6148 and 27,548 stands, which conformed to maximum and minimum opening restrictions, 20 year adjacency delays, and met even-flow harvest targets over minimum area. This is the only stand-based model in the literature which addresses all of the above constraints. The authors used a penalty function method to impose constraints and to drive the solution towards the desired harvest characteristics. Harvest blocks were formed at each stage of the procedure using a depth first graph search method. The model did not include any roading considerations. The main difficulty in the solution procedure appears to be in the specification of the penalty

functions. The shape of the functions was easily determined from the nature of the constraint that they represented. However, experimentation with several runs was necessary to adjust coefficients so that no one function dominated over others early in the SA procedure, yet the "hard" adjacency and opening size constraints were satisfied in the final solution.

Murray and Church [1994] developed a Tabu Search (TS) method to solve the operational planning formulation based on that of Nelson and Brodie [1990]. Their TS method achieved near optimal solutions in relatively short computing times. The model included road building and adjacency constraints, with stands pre-blocked. This study was relatively small, consisting of 45 blocks and 52 road links. With an improved IP formulation, this problem can be solved to optimality in reasonable time. This is discussed fully in section 3.4.

3.2. Spatial Decision Units

A basic concern in tactical model formulation is the choice of spatial decision units. From a spatial and biological perspective, the stand is the logical decision unit. This is because the stand represents a contiguous area which is homogeneous in terms of its current state and future growth potential. Stands which are too large may be sub-divided without losing this homogeneity. Results of decisions based on stands may be mapped using a GIS, and thus present a "picture" of the model results which is meaningful to the decision maker. On the other hand, stands tend to vary widely in size, and there may be many small stands. This makes problems awkward to formulate, and in the case of integer programming, exponentially harder to solve.

Aside from modeling issues, economic reasons may influence the decision to create aggregated blocks of stands for decision units. A minimum opening size (harvest

block) has been imposed in many models [Wightman and Baskent 1994, Baskent and Jordan 1991, Lockwood and Moore 1992]. In cases where large fixed costs of harvest are of concern, (for example, where hillside terrain is being harvested as is common in British Columbia), a large production volume is required to make the operation economically viable. High capital costs may dictate maximizing utilization of harvesting equipment. This may require a minimum block size to reduce time spent in moving and setting up equipment. Other considerations, apart from polygon area, influence the design of blocks. In some situations, an economically suitable block has a minimum value of merchantable timber product. Block shape can have an impact on harvesting costs -- long, thin wedge shaped areas are often more expensive to work. The ratio of perimeter to area can be used to evaluate the quality of a block shape.

Most of the models proposed in the literature [Barahona, Weintraub and Epstein 1992, Barros and Weintraub 1982, Jones et al 1991, Nelson et al 1991, Weintraub and Cholaky 1991,Yoshimoto et al 1994] assume pre-defined harvest blocks as spatial decision units. Others [Baskent and Jordan 1991, Jamnick and Walters 1993, Jordan and Baskent 1992] form blocks or neighborhoods by random seed search methods combined with block formation rules. BLOCK [Clements, Dallain and Jamnick 1990] and CRYSTAL [Jamnick and Walters 1993] are examples of such systems for forming harvest blocks. Hokans [1984] proposes the use of artificial intelligence to select stands for harvest by constructing a discriminant function that simulates the spatial criteria used by experienced foresters. The computer support system speeds the process by calculating important measures such as distance to roads and recency of harvest of adjacent areas. Their proposed "expert" system would "learn" the rules that experts use to select cutting units.

There are some distinct disadvantages to using blocks as decision units. First, there is some effort involved in creating these blocks. Pre-blocking implies a reduction in the number of stand-harvest timing choices that are available, and may eliminate many good solutions from consideration. Aggregating stands of different ageclass or growth potential means that some stands will be scheduled at other than their peak production period. Thus, blocking may be expected to lead to less than optimal solutions since the feasible solution space of the problem has been restricted.

Solving stand-based models is not always too difficult. Lockwood and Moore [1992] successfully solved a problem of significant size using stands as input units without pre-blocking, using simulated annealing (SA). Blocks were dynamically created as the procedure progressed, using a cost function to penalize clusters of stands (that are assigned harvest in the same period) which are either too small or too large. Thus, within the limitations of the simulated annealing procedure, their model addresses all possible configurations of stands into harvest blocks. This thesis presents a similar "dynamic" blocking algorithm using graph structures, and a solution method which produces good solutions in reasonable computation time.

3.3. Adjacency Constraints

This section deals with effective formulation of adjacency constraints for tactical planning models based on pre-aggregated polygons or blocks. Let x_S = *1 (0)* be the decision variable representing harvest (not harvest) polygon s. The most obvious formulation for adjacency constraints is the dis-aggregated form: $x_i + x_j \leq 1$ for each pair of adjacent polygons i and j. The number of such constraints can be large (one for each pair of adjacent polygons and for each planning period) however, and this has led several researchers to investigate methods of aggregating these constraints.

Various attempts at aggregating these pair-wise adjacencies into a smaller set of constraints have been made. These are generally based on recognizing that different patterns of adjacent polygons can be identified, and that constraints can be derived which cover several adjacent polygon pairs. [See Jones, Meneghin and Kirby 1991, Murray and Church 1996a and 1996b, Torres-Rojo and Brodie 1990] The difficulty with these aggregations is that although a smaller constraint set may be generated, they may not be the best formulations for models which are to be solved using integer programming methods. Murray and Church [1996] noted this problem, and recognize the importance of identifying cliques (a set of mutually adjacent polygons). The Type I constraints of Jones et al [1991] in fact identify such cliques of cardinality 2, 3 and 4, although they did not recognize these as clique constraints in a general graph theoretic framework. Moreover, they stated that cliques of order 5 or more are a physical impossibility. This is not true when adjacency is defined by polygons being a minimum distance apart as opposed to the stricter condition of sharing a common edge. They then went on to aggregate these "Type I" constraints into further aggregated Type II constraints. Torres-Rojo and Brodie [1990] provide heuristic rules to create one adjacency constraint for each polygon (the T-B method) and produce a different set of constraints than do Jones, Meneghin and Kirby [1991]. In Yoshimoto and Brodie [1994], a third method which utilizes matrix algebra produces yet another set of adjacency constraints.

Better formulations, which involve less constraints and which sharpen the bound achieved by the Linear Programming relaxation of integer programs, are possible. Moreover, in the sparse adjacency graphs for these forest planning problems, it is relatively easy to generate the set of clique constraints which are known to represent a tight LP formulation [Padberg 1973, Nemhauser and Wolsey 1988, Nemhauser and Trotter 1974]. To explore this concept, some integer programming results are required.

The next sub-section summarizes the fundamental theory of strong valid inequalities and cutting planes methods for solving integer programs. For a comprehensive description, see Nemhauser and Wolsey [1988].

3.3.1. Strong Valid Inequalities and Cutting Planes Algorithms

Given the discrete (binary) integer programming problem *IP:* $\max\{cx: Ax \le b, x \in B^n_+\}$, with feasible region $S = B^n \cap P$, where $P = \{x \in R^n_+: Ax \le b, 0 \le x_i \le 1\}$. The linear programming relaxation of *IP*, *ILP*, is $\max\{cx: x \in P\}$. This is the problem obtained by *relaxing* the integrality constraints. In other words, the binary variables x_i are replaced by continuous bounded real variables $0 \le x_i \le 1$. The feasible region of *ILP*, *P*, contains *S*, and the optimal solution to *ILP* is greater than or equal to that of *IP*. A valid inequality for *ILP*, $\alpha x \le \pi$, is one which satisfied at all points in *S*. In theory, the integer program *IP* can be reduced to a linear program wherein a system of valid inequalities completely defines conv(*S*), the convex hull of *S*. Thus, the integer programming problem can be replaced by a linear programming problem. Although in theory this can always be done, the problem of finding such an inequality system for conv(*S*) is hard.

For an integer problem *IP* and its relaxation *ILP*, let z_{ip} be the optimal solution to *IP* and z_{ilp} the optimal solution to *ILP*. The *cutting planes method* is to find valid inequalities which reduce the gap between z_{ip} and z_{ilp}, sharpening the bound Z_{ilp}, and, consequently, forcing variables to attain integral values in *ILP*. Strong valid inequalities are those which define facets or high order faces of the polyhedron conv(*S*). The idea is to start with the inequality system $\{Ax \le b, 0 \le x_i \le 1\}$ and, if this does not define conv*(S)*, then to progressively construct stronger valid inequalities to create a more complete description of conv(*S*). If it is practical to complete this process, a linear program which

is equivalent to the integer program is defined, meaning that the optimal solution to the linear program is also the optimal solution to the integer program. Alternately, one can generate enough inequalities so that the "gap" $\left[z_{ilp} - z_{lp}\right]$ is small, and then use branch and bound from that point forward to find the optimal integer solution.

It is not always necessary to generate the complete inequality system which describes conv(*S*) to solve *IP*. Also, from a problem-solving practical point of view, at some point the effort involved in locating further inequalities may outweigh the effort in completing the solution using branch and bound. Thus, the cutting planes algorithms involve an iterative procedure as follows:

1. Solve *ILP* with minimal formulation. If the solution is integer, the optimum solution to conv*(S)* has been found. Otherwise,
2. Find a set of (strong) valid inequality which is violated by the current fractional solution. (This is called the separation problem). Add these inequalities to the current problem and go to 1.

Many hard integer problems have been successfully approached with this method. Bretthauer and Cabot [1994], Clark and Armentano [1995], Corberan and Sanchis [1994], Dijkhuizen and Faigle [1993], Magnanti, Mirchandani and Vachani [1995], Pochet and Wolsey [1991 and 1986] and Weintraub and Vera [1991] are only a few examples. Nemhauser and Sigismondi [1992] have developed a cutting planes algorithm for the node packing problem which is of direct relevance to this work. See also Barahona, Weintraub and Epstein [1992], and Weintraub, Barahona and Epstein [1994], wherein these methods are used to solve the adjacency problem as part of a column generation algorithm for solving forest planning problems.

3.3.2. The Adjacency Problem: Node Packing

For simplicity of notation, omit the time dimension. Let *A(i)* be the list of

polygons which are adjacent to polygon i, and $x_i = 1$ if stand i is scheduled for harvest.

Definition 1: The *adjacency graph* of the forest $AG(V,E)$ is a simple graph (a graph with no loops) with one node v for each polygon and one edge $e=\{v,w\}$ for each pair of adjacent polygons v and w. See figure 3.1.

Definition 2: A *node packing* (stable set, independent set, vertex packing) in a graph $G=(V,E)$ is a subset S of V such that the subgraph induced by S has no edges. (The subgraph induced by S is the graph with node set S and the edges of E which have both their end nodes in S.) In a weighted graph, the maximal independent set is one of maximum weight.

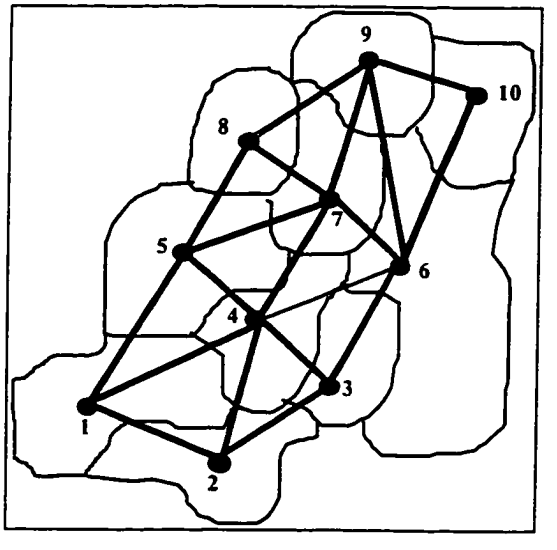


Figure 3.1. Adjacency Graph

A harvest solution is *feasible* with respect to adjacency rules if $X = \{i: x_i = 1\} \subseteq V$ is an independent set or *node packing* in the graph AG. For example, in figure 3.1, two feasible solutions are {1,3,7,10} and {2, 5, 6,9}. The problem of finding *node packings* of maximum weight is an NP-hard problem [Garey and Johnson 1979, Nemhauser and Wolsey 1988]. Nonetheless, recognition of the nature of the adjacency constraints as node packing conditions leads immediately to some known strong valid inequalities which define facets for the *node packing* problem. These inequalities significantly

strengthen the disaggregated representation of the adjacency constraints. Although a complete description of the *node packing* polytope is not known, the maximal clique, odd hole, odd anti-hole and web (claw) facet-defining inequalities are very strong in sharpening the LP bound for this problem [Nemhauser and Trotter 1974].

3.3.2.1. Clique Inequalities

A clique in a graph is a complete subgraph -- that is, each node is joined by an edge to every other node. A maximal clique is a clique which is not a proper subset of any other clique, and *clique,* when unqualified, will mean maximal clique in this discussion. Clearly, the constraint $\sum_{i \in C} x_{ij} \leq 1$, where C is a clique in AG, is a valid inequality for this problem. In fact, this is a facet-defining inequality for the *node packing* problem [Nemhauser and Trotter 1974]. In figure 3.1, there are several cliques of cardinality 3. (For example {1,2,3}, {1,4,5}.) For some graphs, called *perfect* graphs, clique inequalities give a complete description of the *node packing* integer polytope. In general, however, other inequalities are needed. These are the (lifted) odd hole constraints, odd anti-hole constraints and web or claw constraints [Nemhauser and Trotter 1974].

3.3.2.2. Odd Hole, Odd Anti-Hole Inequalities

An *odd hole* in a graph is, by definition, a chordless cycle of odd length. The existence of an odd hole H gives rise to the valid inequality $\sum_{i \in H} x_i \leq \frac{1}{2}[|H|-1]$. This inequality can be *lifted* to form a stronger inequality $\sum_{i \in H} x_i + \sum_{j \in N(H)} a_j x_j \leq \frac{1}{2}[|H|-1]$ by considering all nodes which are adjacent to H (those in $N(H)$) [Nemhauser and Trotter 1974]. Both clique and odd hole inequalities were used by Barahona et al [1992] in their column generation algorithm. In Figure 3.1, {4,6,9,8,5} is an odd hole, and its inequality is $x_4 + x_6 + x_9 + x_8 + x_5 \leq 2$. This is "lifted" by including node 7 (and finding the largest possible value of a_7 to be 2) to derive the inequality $x_4 + x_6 + x_9 + x_8 + x_5 + 2x_7 \leq 2$.

A *anti-hole* is the edge complement of a hole. That is, an anti-hole of cardinality n is a graph which is formed by removing the edges of an *n-hole* from K_n, the complete graph on n nodes. Odd holes and anti-holes are illustrated in Figure 3.2. If a graph contains an odd anti-hole G, then the inequality $\sum_{i \in G} x_i \leq 2$ is a facet defining inequality for the node packing problem.

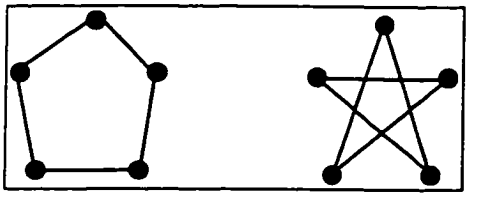


Figure 3.2. Odd hole and Anti-Hole

3.4. Generating Clique Constraints

The number of cliques in a given graph can be very large, and hence difficult to enumerate completely [Bron and Kerbosch 1973]. However, for these adjacency problems, the graphs are of low density, resulting in a small number of cliques of cardinality greater than three. The following procedure was developed to locate cliques in a graph. It is suitable for sparse graphs.

3.4.1. Generation Procedure

Let $A = \left\{ a_{ij} \middle| (i,j) \in E \rightarrow a_{ij} = 1 \right\}$ be the adjacency matrix of $G=(V,E)$, and calculate the degree of each node, $deg(i) = \sum_j a_{ij}$, and the maximum degree $M = max(deg(i), i \in V)$. Observe that a node i can be an element of a clique of order n only if $deg(i) \geq n$. Then, the procedure is to build cliques of order $(n+1)$ from cliques of order n. Denote by *n-clique* a clique of cardinality n. First, the *2-cliques* are identified directly from A and stored as ordered pairs $\left\{ a_{ij} \middle| a_{ij} = 1, j > i \right\}$. Then, higher order cliques

are built successively, discarding the lower cardinality dominated cliques as new ones are found. See Figure 3.3.

This algorithm is relatively efficient since the degree of the nodes is used to exclude many of the cliques from consideration. Also, each sub-clique is automatically discarded in step (3) and only the non-dominated or maximal cliques are output at the end in step (5). The computational effort in generating these maximal cliques should be no greater than that spent in aggregating constraints into other, less efficient forms.

```
For n = 3 to M                                                        (1)
    For each clique k={k1, k2,..., kn} of order n                     (2)
        If deg(k1),deg(k2), ..., deg(kn) ≥ (n+1) then:
            For b = 1 to |V|
                If a_{b,k1} = a_{b,k2} = a_{b,k3} = ... = a_{b,kn} = 1 then
                    Mark clique n dominated                           (3)
                Endif
                If b > kn then
                    Store new clique {k1, k2,..., kn, b}              (4)
                Endif
            Next b
        Endif
    Next clique
Next n
Output each maximal clique which is not marked dominated.             (5)
```

Figure 3.3 Algorithm to Generate all Cliques in a Sparse Graph

3.4.2. Bloedel Farm Case Study

The MacMillan Bloedel tree farm in Vancouver, British Columbia consists of 45 forest polygons. A potential road network of 52 links has been defined for the area [Nelson and Brodie 1990]. The planning problem is taken from Murray and Church [1994], who based it on the work of Nelson and Brodie [1990]. There are 3 planning periods, and the planning problem is to schedule harvests on the given polygons which meet upper and lower bounds on harvest in each time period, and undiscounted revenue

bounds for each period. Adjacency delay of one period is imposed on adjoining polygons. The potential road network is a tree structure -- that is, it contains no cycles. Thus, the road network feasibility constraints are relatively simple to specify since each link either requires one predecessor in the tree or none at all. Each stand has a set of road links, one of which is required if that stand is to be harvested. Decision variables x_{it} are to harvest polygon i in period t and z_{jt} to build link j in period t. Discounted and undiscounted revenues from harvesting polygon i in period t are a_{it} and $\tilde{a}_{it}$, and discounted (,respectively undiscounted) costs to build each road link are c_{rt} and $\tilde{c}_{rt}$. M_r is the set of links from which one must be built if link r is built, and S_i is the set of road links from which one must be built if stand i is to be harvested. (Note that each M_r has only one element for this road network, since it contains no cycles.)

The IP formulation of the problem used by Murray and Church [1994] is:

$\max \sum_t \sum_i a_{it} x_{it} - \sum_t \sum_r c_{rt} z_{rt}$		*Discounted revenues - discounted road costs*
Subject to:		
$\sum_t x_{it} \le 1$	*for each i*	*Harvest each polygon at most once.*
$\sum_t z_{rt} \le 1$	*for each r*	*Build each link at most once.*
$z_{rt} \le \sum_{l=1}^{t} z_{kl}$	*for all r, t, k* $\in M_r$	*Road Connectivity*
$x_{it} \le \sum_{r \in S_i} \sum_{l=1}^{t} z_{rl}$	*for all i,t*	*Link required to harvest stand i*
$\sum_i v_{it} x_{it} \ge L_t$	*for all t*	*Lower bound on volume*
$\sum_i v_{it} x_{it} \le U_t$	*for all t*	*Upper bound on volume*
$\sum_i \tilde{a}_{it} x_{it} - \sum_r \tilde{c}_{it} z_{rt} \ge LR_t$	*for all t*	*Bound on undiscounted profit*
$n_i x_{it} + \sum_{s \in N_i} x_{st} \le n_i$	*for all i,t*	*Adjacency Requirements*
$x_{it}, z_{rt} \in \{0,1\}$	*all i, t, r*	*Binary Variables*

The optimal solution to this problem is 5,953.20 [Murray and Church 1995]. Note

that the adjacency requirements are expressed in aggregated form of Torres and Brodie [1990], where N_i is the set of polygons adjacent to i. This problem is suitable for pre-generating clique constraints since it is a relatively small study area. To illustrate the effectiveness of generating maximal clique constraints, three formulations are solved. The first (DISAGG) is with the disaggregated form of clique constraints

$$x_{it} + x_{jt} \leq 1, \textit{ for each pair of adjacent polygons } i, j \textit{ and } t = 1,2,3.$$

The second (MURRAY) is the above formulation with aggregated adjacency constraints. The third (MAXCLIQ) is the above problem with the aggregated adjacency constraints replaced by maximal clique constraints. Table 3.1 summarizes results from implementing these three formulations, using LINDO on a 486/33 personal computer.

The maximum cardinality of the cliques was 4, and there were no maximal *2-cliques*, 20 *3-cliques* and 17 *4-cliques*. Thus, with three time periods, this resulted in 111 clique constraints in MAXCLIQ. There are 112 adjacent pairs which resulted in 336 constraints in DISSAG. MURRAY used 135 constraints to specify adjacency. Thus, MAXCLIQ is efficient in reducing the number of clique constraints. The constraints were generated using a QBASIC program, which took less than 2 seconds (elapsed) time to compute the maximal cliques.

Running the program in LINDO with the disaggregated cliques was unsuccessful. The program ran for more than 24 hours and terminated when the pivot limit of 1210599 was exceeded. This formulation was included to underline the importance of generating tight constraints for the problem.

Table 3.1. Bloedel Problem Results

	LP OPTIMUM	Number of Branches	Time to Solution (HR:MIN:SEC)	Number of Adjacency Constraints
DISSAG	6767.596	>4842	>24 hrs	336
MURRAY	6394.120	1227	1:16:37.53	135
MAXCLIQ	6076.102	533	0:17:42.04	111

Although it is dangerous to infer a lot from one case study, this does show that it is easy to generate clique constraints for small problems, and that the clique representation is relatively compact. Since it has been proven that the maximal clique constraints form facets of the node packing problem, they are a logical choice to represent the adjacency requirements in these problems.

For large problems, it may be impractical to generate all the maximal cliques in the adjacency graph. In this case, a cutting planes algorithm which finds violated clique and other (odd hole, odd anti-hole, web) violated strong inequalities [Nemhauser and Sigismondi 1992] for this problem could be used.

CHAPTER 4

TABU SEARCH

A Tabu Search strategy was chosen to solve the tactical forest planning problem because of its record of success on hard optimization problems. Since the algorithms presented in chapter 7 of this thesis are based on this metaheuristic, this chapter is devoted to describing the principle ideas behind the tabu search method, the basic algorithm and some of its more sophisticated variants. Amongst the more advanced implementations of tabu search, those algorithms which use dynamic parameter assignments and the self-tuning, feedback-based Reactive Tabu Search method (R-TABU) [Battiti and Tecchiolli1994] are especially important in the context of this thesis.

Tabu search (TS) belongs to the *metaheuristic* class of algorithms, where local optimization (local neighbourhood search) is enhanced with strategies which enable the search process to go beyond local minima. Simulated annealing, genetic algorithms and evolutionary algorithms are also included in this category. (See Reeves [1996] for a comprehensive description of these and other metaheuristic methods.) The seminal ideas behind tabu search were first developed by Glover [1986], and independently by [Hansen 1986]. Tabu search is a history-based or memory-based strategy; information from previous phases of the search is used to direct future phases.

4.1. Basic Tabu Search Algorithm

Consider an optimization problem P, which is to find a solution x which minimizes

some function $z(x)$; P: $\min z(x) | x \in F \subseteq X$. If x is a solution to P, and if a set of moves M which perturb x to form new solutions in X can be defined, then the *neighbourhood* of x is the set of these perturbed solutions. That is, denoting the set of all allowed moves by M, $N(x) = \{x' \in X | x' = x \oplus m, m \in M\}$. In constrained optimization problems, moves which produce an infeasible solution $x' \notin F$ are called infeasible moves, and neighbourhoods may or may not be restricted to the feasible region F.

Moves are relatively simple operators on the current solution, that is, those which perturb the solution slightly. For example, in a job shop scheduling problem, a solution is a sequencing of n jobs $x(j_k) = t_k$, $t_k \in [1,n]$. A move can be defined as a swap of the ordering of two jobs k and l, $x(j_k) \leftrightarrow x(j_l)$, thus permuting the previous solution. In this case, the neighbourhood of a solution is the set of all permutations of x obtained by swapping any two elements of x. As another example, in the Vehicle Routing Problem [Gendreau, Hertz and Laporte 1994], a commonly used move is the insertion of a city into a route. The neighbourhood of a given route is the set of all new routes formed by all possible insertions into the current route. As a third example, in solving the Maximum Clique problem using tabu search, moves are to add or drop vertices from the current clique solution [Battiti and Protasi 1995, see also Gendreau, Soriano and Salvail 1993].

Tabu search is based on neighbourhood or local search, where, starting with an initial solution, each possible move is evaluated and the best improving move chosen. Local search ceases when no improving move can be found; that is, local search stops when a local optimum is found. In tabu search, when no improving moves can be found, a best non-improving move is selected. This serves to lead the search away from the current local optimum, to where a different neighbourhood has new possibilities for improving on the current best solution.

4.1.1. Strict and Fixed TS, Tabu Tenure

Used without restriction, the inclusion of non-improving moves in local search could result in endless cycling back to the same local optima. Thus, TS incorporates a prohibition strategy to avoid returning to previously encountered solutions. The prohibition scheme can be to explicitly forbid moves which lead to previously encountered solutions, the so-called *strict* tabu search. An indirect method, the *tabu tenure* or *move prohibition* approach, is to forbid the reversal of *recently* taken moves. Strict tabu search explicitly rejects the repetition of previous solutions at all phases of the search, while move prohibition is temporal in nature, and may allow the search to progress back to a previous solution in time.

Strict tabu search requires the ability to determine whether a move would in fact give rise to repetition of a previous solution. The difficulty with testing for this condition directly is that storage and indexing to all solutions which have been encountered in the search is, computationally, both time and memory intensive. A common strategy is to store only a list of the moves which have been taken, the *reverse elimination* method [Dammeyer and Voss 1993, Glover 1990a and 1990b]. As each candidate move is evaluated in the neighbourhood search, the sequence of previous moves is traced in reverse order to determine whether the candidate move should be prohibited. This method avoids the large storage and indexing costs to access previous solutions, but incurs an increasing computational cost as the search progresses. Recently, data structures for storing past solutions which are efficient in terms of both space and computational effort have been investigated [Battiti 1996, Woodruff 1993]. However, most work in the literature has focused on the second prohibition strategy, the move prohibition method, since it is simple in concept and is relatively trivial in computational effort to implement.

The major issue in developing algorithms which use move prohibition to direct the search process is to define appropriate rules to restrict or forbid a small sub-set of moves, the so-called *tabu* moves. The length of time (number of iterations of neighbourhood search) for which a move is forbidden is called the *tabu tenure* or *prohibition period.* Tabu tenure is often referred to as the *tabu list* size; this expression is derived from a common implementation of tabu status as a list of forbidden moves. The most basic of the TS rules is to exogenously determine the tabu tenure. This is called *fixed tabu search,* since, once a move is taken, its reversal is forbidden for a fixed number of iterations. There is no universal "good" value for tabu tenure, although some empirically determined guidelines for certain problem types have been published [Glover 1989]. Thus, if a fixed tabu search algorithm is to be attempted on a given problem, an experimentation phase to determine an effective setting for tabu tenure is usually required. This empirical investigation will often involve "expert" feedback from the algorithm designer. Thus, this investigation, in addition to being costly, may be difficult to reproduce, and may be instance-specific. That is, the choice of tabu tenure which is arrived at through experimentation on one problem instance may not be a good choice for other cases of the same problem [Battiti 1995].

4.1.2. Aspiration Criteria

In addition to tabu considerations, moves are accepted or rejected with regard to *aspiration* criteria. An aspiration can over-ride the tabu status of a move -- when this happens, the move is said to be *aspirated.* While a suite of aspirations may be defined for any given problem, most TS algorithms include the *aspiration by default*, which is to choose the "least tabu" move when all possible moves are tabu. This ensures that the process does not terminate arbitrarily. *Aspiration by objective* is always included. This

aspiration over-rides tabu status for any move which yields a solution better than any encountered thus far in the search, ensuring that optimum solution, if it is encountered, is not lost.

4.1.3. Summary of the Basic TS Structure

Denote by *z(x,H)* the move evaluation function. (The notation *(x,H)* means that this evaluation function may change throughout the course of the search algorithm as a function of the recorded history of the search, *H*. See section 4.3.) The TS algorithm may be outlined as follows:

1. Initialization
- 1.1 Find a solution $cur\_sol = x$
- 1.2 Set $best\_sol = x$
  Set $best\_z = z(x)$

2. Neighbourhood Search
- 2.1 For each move m, evaluate $z(x', H)$, where $x' = x \oplus m$.
- 2.2 Choose $best\_move = m$ *such that* $z(x \oplus m, H)$ *is minimized*
  Set $x' = x \oplus best\_move$

3. Update and save best solution
- 3.1 Set $cur\_sol = x'$
- 3.2 Update tabu status of moves and *z(x,H)*
- 3.3 if ($z(x') < best\_z$) then
  $best\_z = z(x')$
  $best\_sol = x'$
  endif

4. Termination
If stopping condition is not met, go to Step 1. Otherwise, terminate and report results.

Figure 4.3. Tabu Search Algorithm

The cost function *z* and constraints defining the feasible region can be non-linear, discontinuous and even stochastic. Thus, tabu search provides a framework which is flexible in that it can be applied to a wide variety of problems. For many problems, the method has an inherent computational efficiency since only the incremental change to

values of the objective function z need be calculated at each iteration. Tabu search has been applied successfully to many hard combinatorial optimization problems [Barnes and Laguna 1993, Barnes, Laguna and Glover 1995, Costa 1995, Friden 1990, Garcia 1993, Gendreau et al 1996a and 1996b, Gendreau, Soriano and Salvail 1993, Glover 1990, Hertz and de Werra 1987, Hertz, Laporte and Mittaz 1997, Laguna and Glover 1993, Sharaiha et al 1997, Widmer 1993]. To date, only one application to the forest harvesting problem has been reported, that of Murray and Church [1995].

4.2. Reduced Neighborhood Search

For large problems, evaluation of every possible move in the neighbourhood may be computationally prohibitive. In this case, a suitable subset of the neighbourhood must be identified for move evaluation. Candidate list strategies [Glover et al 1974, Frendewey 1983] are used to create the reduced neighbourhood.

The reduced neighbourhood may be chosen by drawing a random sample of moves from M. If the result, i.e. the quality or composition of new solutions attained by executing these moves, is unsatisfactory, the process can be repeated. Another candidate list strategy is to decompose the neighbourhood into "critical" subsets. This method requires a system of "remembering" which subsets have been used in the past, so as to systematically cover all different critical sub-regions during the search process. Another random sampling method is to draw a small random sample of moves for most iterations, yet periodically evaluating a much larger sample of moves.

4.3. Move Evaluation, Intensification, Diversification

In a simplistic algorithm, tabu moves are those which would reverse recently taken moves, while the evaluation function is the original objective function z. The essence of Tabu search is to add principles of intelligent problem solving to the basic search

mechanism. TS enhances the subsequent stages of the search by acting on the information gleaned from the results of the search so far. Tabu schemes are based on knowledge of the history of the search, H, and a set of rules or principles which act on that knowledge to determine tabu status, aspiration conditions and move evaluation functions. Thus, the move evaluation function is denoted by $z(x,H)$. Differing evaluations of moves may be done at different phases of the search, depending on whether intensification or diversification is required.

Intensification means to search for better solutions near a known good solution. To effect intensification in the neighbourhood of a solution, the best improving moves are chosen until a local optimum is found. Intensification is also achieved by searching about solutions with known good attributes. In this case, the evaluation function $z(x,H)$ is changed to favour solutions with these characteristics over those which lack them.

Diversification means to move the search trajectory away from the current solution, that is, to change the structure of the current solution so that the new neighbourhood search leads to exploration of a different region of the search space. Diversification is necessary when an intensification phase fails to further improve the solution, that is, when intensification finds a local optimum. In memoryless search algorithms such as pure local search, diversification is effected by re-starting the process with a new randomly generated initial solution. In contrast, tabu search uses its memory of previous solutions and moves to create diversification in a systematic and largely deterministic manner.

Thus, diversifying moves are (usually non-improving) moves that lead away from a current local minimizer, or moves which specifically change the structure of the current solution. For example, in the packing problem, the goal is to place unequally weighted objects into boxes so that the total weight is distributed evenly across the boxes. In this

problem, a diversifying move is to swap two objects which are very different in weight, thus significantly changing the composition of two of the boxes' contents. [Dowsland and Dowsland1992, Dowsland 1993] In the harvesting and road building problem for forest planning, (Chapter 7 of this thesis), choosing moves which reduce the number of road links required effects one type of diversification.

The basic method for achieving diversification in tabu search is the enforcement of tabu tenure, creating a restricted neighbourhood derived from the set of allowed moves. This forces the process to look for moves which do not reverse recently taken moves, thus leading the search to new feasible regions. Because tabu tenure is typically small, the imposition of tabu status is often referred to the use of short-term memory, or recency-based memory. In the medium to long-term phases of the search, diversification can be implemented by discouraging or penalizing moves which have occurred frequently in the past. This is often accomplished by augmenting the cost function with a penalty term which is proportional to the frequency of the move, for example:

$$z(x \oplus m, H) = z(x) + \frac{aF_m}{t}, \text{where}$$

$t =$ *current iteration*

$F_m =$ *number of times move m has been chosen*

$a =$ *a suitable constant*

Stochastic diversification schemes may be designed by selecting a series of random moves -- this is akin to a random re-start method. The choice of the number of random moves may be a free parameter (i.e. fixed but determined prior to search) or may be determined dynamically by examining the history of the search [Battiti 1995]. Stochastic diversification adds robustness to the algorithm, and is thus desirable, especially when the solution space is highly non-convex or discontinuous.

Intensification and diversification strategies interact and oppose each other to form the fundamental cornerstones of longer term memory in tabu search. [Glover 1991a] At each stage of the search, an appropriate choice of intensification or diversification is made by examining the state of the search. For example, at the initial or startup phase, intensification is required. Once a local minimizer is found, diversification by tabu status (short term memory) is used to force the search into new areas, hopefully finding new minimizers. In the mid-range and later stages of the search, diversification which encourages moving to new local minima by changing the solution structure is appropriate. These are long-term memory processes, and often involve penalizing frequently taken moves or solutions with key elements that have occurred frequently in the past. Thus, the design of tabu search algorithms that effectively balance intensification and diversification is a major challenge to researchers. The most effective schemes use dynamic rules to modify tabu tenure and $z(x,H)$ throughout the search duration. [Glover, Taillard and de Werra 1993, Soriano and Gendreau 1996

4.4. Dynamic Rules for Evaluation and Prohibition

Tabu search algorithms in which the evaluation function is not changed and the tabu tenure is fixed have been classified as fixed tabu search in Battiti [1995]. Fixed TS has been found to be quite successful in getting good solutions to many hard problems. The difficulty with fixed TS is in determining a good value for tabu tenure. Its magnitude determines the effectiveness of the algorithm in escaping from the "attraction basin" of a local minimizer [Battiti 1995]. If tenure is too small, not enough moves are prohibited and the search will return again and again to the same minimum point. If the tenure is too large, the search is over-constrained and is likely to miss other good minimizers.

Often, an extensive period of experimentation with problem instances is required to find a good value for tabu tenure. Since this is an empirical determination, the value found may be dependent on problem instance -- that is, it may depend on the magnitude (or relative magnitude) of cost function coefficients, or on the constraint structure. This experimentation period can constitute a lengthy trial and error process, sometimes with intervention by the designer of the algorithm. Moreover, if the statistical properties of the search space vary widely in different regions, a tabu tenure that is suitable for one region may be unsuitable for another [Battiti and Protasi 1995].

In the quest for more robust and more generally applicable TS procedures, researchers have developed methodologies and data structures to incorporate dynamic rules for move evaluation. These rules include modifying parameters which define the extent to which the search history H is used in move evaluation, and the introduction of different move selection rules at different stages in the search progression. In addition to deterministic rules, randomness is often incorporated into the algorithm, in a controlled way, to increase the robustness of the algorithm. For example, researchers have found that a relatively straightforward modification of fixed TS which is to vary tabu tenure randomly within a range improves the search performance for some problems [Dell"Amico and Trubian 1993, Gendreau et al 1994].

Intelligent dynamic choice rules have been used by Gendreau et al [1994, 1992] to solve vehicle routing and traveling salesman problems. They chose a tabu tenure θ, drawn randomly from the interval [5,10]. Others [for example, Dell'Amico and Trubian 1993] allow tabu tenure to vary on an interval $[t_{min}, t_{max}]$, and then invoke diversification and intensification strategies by increasing (respectively, decreasing) t_{min} and t_{max}. Woodruff and Spearman [1992] studied TS formulations with varying levels of diversity, and found that better results were always found when some level of diversity is

incorporated. Mooney and Rardin (1992) postulated that relatively high diversification is a necessary condition for finding good solutions using TS for complex problems. Battiti and Tecchiolli [1995] have gone even farther in determining the appropriate tabu tenure dynamically as the tendency of the search process to cycle back to known solutions is detected. Their self-tuning framework for tabu search is called the Reactive Tabu Search.

4.5. Reactive Tabu Search

A group of researchers at Trento University in Italy, led by Dr. Roberto Battiti, have developed the Reactive Tabu Search framework. The system is described in detail in [Battiti and Tecchiolli 1994, 1995]. This section summarizes the main ideas of reactive tabu search.

Reactive Tabu Search (R-TABU) is a self-tuning heuristic, integrating simple feedback schemes to determine the value of tabu tenure at each iteration. R-TABU is aimed at providing a framework which is applicable to a wide range of discrete optimization problems, while avoiding the trial and error adjustment of tabu tenure. The R-TABU process uses the past history of the search to dynamically tune parameters (tabu tenure), and to automate the balance of diversification and intensification in the search process. Let L be the number of possible moves, and denote by $T^{(t)}$ the tabu tenure at iteration t. The search trajectory at iteration t is the set of visited solutions $\{x^{(1)}, x^{(2)}, \ldots, x^{(t)}\}$. R-TABU is based on detecting the repetition of previously visited solutions in the search trajectory.

In R-TABU, tabu tenure T is always less than $(L-2)$, ensuring that at least two moves are allowed at each iteration. The level of diversification is controlled by T: the larger T is, the longer the distance (i.e. the length of the search trajectory) must be before

the trajectory will cycle back to a previously visited solution, and hence the greater the diversity. In some applications, the minimum cycle length can be determined from L and T. For example, in the case where the solution space is the set of binary strings of length L, and moves are to complement one entry in the string, the minimum repetition interval is $2(T+1)$. That is, $x^{(t+r)} = x^{(t)} \Rightarrow r \geq 2(T+1)$.

In R-TABU, T is set equal to one at the beginning of the search. If solutions are repeated, T is increased to an amount proportional to the moving average of the length of short cycles. After an increase has been made, if no repetitions occur for a sufficiently long period, T is decreased by a constant factor. This scheme is designed to "break" short cycles. Long cycles, for example those longer than $2L$ in the binary string problem, are not prevented by this mechanism. Battiti [1995] also recognizes that the search trajectory may be trapped in a restricted region of the solution space even though no limit cycle exists. In analogy with the chaotic attractors of dynamical systems, this type of behaviour is called chaotic cycling, and also is not prevented by the above scheme. To break long cycles, exit from a "chaotic attractor" and to increase robustness, R-TABU uses an "escape" mechanism, which is to execute a random number of randomly selected moves. The escape system is triggered when too many solutions are repeated too often, indicating that chaotic cycling has occurred.

The ability to detect the repetition of previous solutions easily is essential to the R-TABU framework. Cycling is checked at each iteration, and thus it is critical that a time and space efficient method be available to include this information in the search history. The reverse elimination method, used in strict tabu search, is space efficient but excessively taxing computationally. In R-TABU [Battiti and Tecchiollli 1995], hashing vectors and digital tree structures are used to store the incidence of solutions. In Battiti [1996], persistent dynamic sets implemented on red-black trees are proposed to store

previous solutions, using hashing techniques [Knuth 1973, Woodruff and Zemel 1993] to provide search indexes. This method is efficient with respect to computation time (*O(L)* in the worst case) and space (*O(1)*).

The authors have shown that R-TABU outperforms other algorithms for the Quadratic Assignment problem [Battiti and Tecchiolli 1995] and the Maximal Clique problem [Battiti and Protasi 1995]. R-TABU, augmented with strategic oscillation, forms the basis of the algorithm presented in this thesis to solve the forest harvest scheduling problem.

4.6. Strategic Oscillation

A substantial proportion of the reported TS algorithms restrict the neighbourhood of a solution to the feasible region. However, complex constraint structures may tend to trap the search trajectory in a subspace of the feasible region. That is, it is not obvious how to select a sequence of feasible moves that cause the search to transition from one region to another. Glover [1990a] proposed the idea of "strategic oscillation", where the search trajectory is first moved away from a certain solution, then drawn back towards it. This concept is applied to oscillating through the boundaries of the feasible region. The concept is that allowing infeasible moves may result in the search process more quickly transitionning to new local minima. The infeasible move or moves become a "stepping stone" to a previously unexplored feasible region. [Woodruff and Spearman 1992, Glover 1990a, Mooney and Rardin 1992, Gendreau et al 1991].

If the moves and the structure of the problem *P* are such that we can categorize moves that lead into and out of the infeasible region, oscillation can be achieved by executing a series of such moves. For example, in the knapsack problem, the constraint is an upper bound on the total weight or cost of the items placed in the knapsack. Moves

which add items "push" the solution into the infeasible region, and moves which delete items will lead the solution back to the feasible region.

For more complex problems with more complicated constraints, specifying oscillating by defining move type sequences may not be possible. One way to achieve oscillating behaviour (on any problem) is to add penalty terms to the evaluation function, with coefficients that are dynamically updated depending on the feasibility of a recent set of accepted solutions. Specifically, suppose that there are *m* constraint sets in the problem to define the feasible region *X*. We add *m* penalty terms $F_j(x)$ to *z(x)*, each of which measures the deviation of a solution from the feasible region with respect to that constraint set. Each penalty term is multiplied by a positive coefficient ρ_j, and each $F_j(x)$ is non-negative.

$$z(x,H) = z(x) + \sum_{j=1}^{m} \rho_j F_j(x), \rho_j > 0, and$$

$$F_j(x)\begin{cases} = 0 & \text{for } x \in X \\ > 0 & \text{for } x \notin X \end{cases}$$

The coefficients ρ_j are modified throughout the search to encourage the acceptance of a mixture of feasible and infeasible solutions. If feasible solutions are to be encouraged, the coefficients are increased. Otherwise, if infeasible solutions are required, the coefficients are decreased. In this way, a systematic oscillation through boundaries of the feasible region is effected. Gendreau et al [1991] used this approach in solving the vehicle routing problem. They showed that, for the VRP, their penalty function approach was far superior to tabu search methods which maintained feasibility at each step. This method is used in the TS algorithm for solving the forest harvesting problem (Chapter 7).

CHAPTER 5

HARVEST SCHEDULING AND ROAD BUILDING PROBLEM (HSRBP)

In this chapter, definitions and data structures to formulate the tactical harvest scheduling and road building problem *HSRBP* are developed. This model can be used to analyze the tradeoffs between lost biological productivity and the costs of road building, while meeting timber volume goals and conforming to environmental restrictions.

Section 5.1 is a general description of the purpose of the model and the assumptions on which it is based. In section 5.2 the spatial decision units, stands and openings, are defined. In section 5.3, the lost volume function which is used to penalize inappropriate timing of harvests is described. Section 5.4 describes the harvest volume constraints which originate in the strategic planning process.

5.1. Model Assumptions

Assume a hierarchical planning structure such as the one described in chapter 1, where a strategic planning process has been completed. The model is intended for tactical planning horizons of approximately fifteen to twenty-five years, with planning periods of length in the order of five years. Although many different tactical level goals are worth considering, this work will be restricted to minimizing negative impacts on forest productivity caused by timing of harvests, and minimizing the costs of road construction. The model is then constrained to meet harvest volume bounds for each planning period and for the total harvest, these target bounds having been derived from the strategic planning process. These bounds represent a harvesting goal which is

consistent with long-term sustained yield requirements, where the objective was to maximize the economic benefits of timber harvesting. Thus, unlike most of the tactical models in the literature, this model does not have an objective to maximize volumes or net present value of timber products. The model is further constrained to meet spatial and temporal environmental restrictions for green-up periods and maximum clearcut size.

Harvest decision units for this model are the forest stands, that is, contiguous areas of the forest which are homogeneous in cover type, age and expected future growth potential. Only one method of harvest is employed (clearcutting), and other silvicultural activities are not considered. Negative effects of the timing of harvests on forest productivity are measured by the Lost Volume Function as described in Section 5.2.

Both stand scheduling and road building are required elements of tactical harvest planning problems. A network of road links that covers the area has been designed and represents the input to the road network selection problem, discussed in detail in Chapter 6, section 6.1. For the purpose of defining the model generally, it is sufficient to note that the road building costs are assumed to constitute the major costs of accessing stands in the forest. Other costs, such as skidding/hauling costs are omitted, as are any restrictions on transportation flows over the road network. The management of the forest stands is assumed to be under a single "owner", such as a provincial government, for which road maintenance is an on-going activity. Thus, road maintenance costs are not a cost factor in the model and the roads are permanent for the duration of the tactical planning horizon. No upper limit was placed on the amount of road construction which may be scheduled for any period, and any effects on wood volumes or opening sizes due to road construction are ignored.

The primary decision variables in this model are the stand harvest decisions. The model treats road building as a consequence of a harvest schedule. There are (at least)

two other ways to look at this problem. First, it is conceivable that roading and harvest decisions be considered simultaneously. The implication of using such a model is that, when a search algorithm is used, moves could be taken which render the road network infeasible with respect to its own connectivity and with respect to covering access to all stands scheduled. Thus this strategy was discarded, and it was decided that a model which separated roading decisions from harvest decisions was more likely to be successful. Since the roading sub-problem can easily be made feasible for any harvest, it was decided to have roading be a consequence of harvest decisions.

There is no commensurable unit of measure for the lost volume penalty and the costs of road construction. Lost volume represents a loss of productivity, the difference between the volume which could be obtained under best timing for each stand and that which is expected under the proposed schedule. Road link construction costs are estimated in dollars, depending on the length of the road link and, possibly, topological factors. This cost is discounted across the planning horizon to include a "hedge" against uncertainty. It is not at all clear that a sensible method of assigning dollar values to lost volume could be derived. Even if a conversion factor or method was clearly indicated, the question of the appropriate way to discount the "lost volume dollars" arises. Yet, clearly, the cost of roading and the cost of harvest timing are opposing factors in *HSRBP*. For these reasons, a tradeoff analysis to compare the effects of different weightings of the two cost factors is recommended.

To summarize, the *HSRBP* is to generate a schedule of stand harvests and road construction that:

Minimizes: Lost Volume Costs + Road Building Costs
Subject to:
Harvest volumes being within bounds for each period;
Total harvest volume being within bounds for the planning horizon;
Maximum clearcut sizes and green-up period requirements being met;
Road Network feasibility (operational feasibility).

5.2. Stands and Openings

Stand characteristics include the species composition, age of trees, stocking and site capability classification. Geographically, stands have defined boundaries and known area.

Definition 5.1 A *stand* is a contiguous area of the forest which is homogeneous in cover type, age of trees and site capability.

Suppose that the forest area under consideration is composed of S stands, and that the planning horizon consists of J periods.

Definition 5.2 A *harvest schedule* is a vector $\boldsymbol{x}$ with elements $x_s = j,\ s = 1,\ldots,S,\ j \in [0, J+1]$, where the value assigned to each element of $\boldsymbol{x}$ is the harvest period for that stand.

Stands which begin period 1 in a clearcut state are assigned $x_s = 0$; stands which are not scheduled for harvest within the planning horizon are assigned period $j=J+1$.

Definition 5.3 The *forest adjacency graph* or forest graph $FG=(S,E)$ is a set of nodes S, one for each stand, and an edge e in E for each pair of stands which share a common boundary.

The forest graph may consist of a set of connected subgraphs. This happens when the region under consideration includes non-forested areas which then "disconnect" the forest graph. It is also worth noting that adjacency may, in some jurisdictions, be defined by the proximity of one stand to another. That is, stands are deemed to be adjacent if

they are within a minimum distance of each other. The adjacency graph has the same definition regardless of which method is used to define stand to stand adjacency, but the "proximity" definition of adjacency results in a denser adjacency graph.

An opening in the forest is a contiguous area which has been clearcut and not regenerated. Most jurisdictions impose a maximum acreage on the size of openings (*maxopen*), and require that areas adjacent to openings be left forested for a period known as the "green-up" period. Openings are determined by the harvest schedule x, the adjacency delay time, and the forest adjacency graph *FG*.

Definition 5.4 The *adjacency delay time ADT* is the number of planning periods for which green-up period is required on adjacent openings.

In many jurisdictions, *ADT* is set at 10 years, or 2 planning periods in the context of this tactical model. The NS Forest/Wildlife Guidelines specify adjacency delay and maximum opening restrictions as "Where total area would exceed 50 hectares (125 acres) avoid clearcutting stands adjoining a clearcut area, until the regeneration in the original clearcut is at least two metres (six feet) or else provide appropriate wildlife corridors." [Province of Nova Scotia 1990] For most stands in Nova Scotia, this translates to an adjacency delay of approximately ten years.

Now, if stands are pre-blocked so that the combined acreage of any two stands is greater than *maxopen*, the imposition of the maximum opening and adjacency delay requirements is effected by prohibiting harvest of adjacent blocks in consecutive periods. Since this model is stand based, requiring adjacency delay on neighbouring stands imposes a more restrictive condition than that specified in the guidelines, since most stands are significantly smaller than *maxopen*. These guidelines can be interpreted to mean that openings can be increased to the maximum size over the number of periods in the adjacency delay time. Since openings are not pre-blocked, a different method of

specifying these conditions is needed. This is done by first defining multi-period openings, and then imposing conditions on these openings.

Definition 5.5 The set of stands which, under schedule x, would be clearcut within one green-up interval ending at period p is $S_p(x) = \{s | x_s \in \{p - ADT + 1, ..., p\}$.

Definition 5.6 $E_p(x)$ is the set of edges of E with both end-nodes in $S_p(x)$.

Definition 5.7 $F_p(x) = (S_p(x).E_p(x))$ is the subgraph of FG induced by $S_p(x)$ and $E_p(x)$.

Definition 5.8 The *opening period p* is the maximum of the periods assigned to nodes in an opening.

Definition 5.9 An *opening* with opening period p $O_k^p(x)$ is a connected subgraph of $F_p(x)$.

Thus, openings are induced by a harvest schedule and the adjacency delay time, and each stand in an opening of period p is assigned to a harvest period within the adjacency delay time window terminating at period p. For example, if the number of planning periods is four and the adjacency delay time is two, openings of period one include stands already clearcut and those scheduled for period one, period two those scheduled for periods one or two, and so on. Thus, each stand which is scheduled for harvest may be a member of as many as two openings. Figure 5.1 illustrates multi-period openings for an ADT of two periods.

With this definition of openings, both the adjacency delay and maximum opening size constraints are imposed by the condition that every opening (as defined above) be of size not exceeding *maxopen*. Thus the spatial constraints on the harvest schedule are given by :

$$\sum_{s \in O_k^p(x)} a_s \leq maxopen, k = 1,..,K^p(x),\ p = 1,...,j \qquad (1)$$

Since openings are derived from a given harvest schedule **x**, there is no convenient method of specifying these constraints in an integer programming formulation. Enumeration of all potential openings which could cause a *maxopen* violation is possible, but not practical since the number of possible openings is exponential in the number of stands. However, the computational complexity of graph searches to calculate these openings is rather trivial in this application, since the forest graph will be sparse. Thus, although this is not a useful model for integer programming methods, it will prove to be workable for our heuristic search methods.

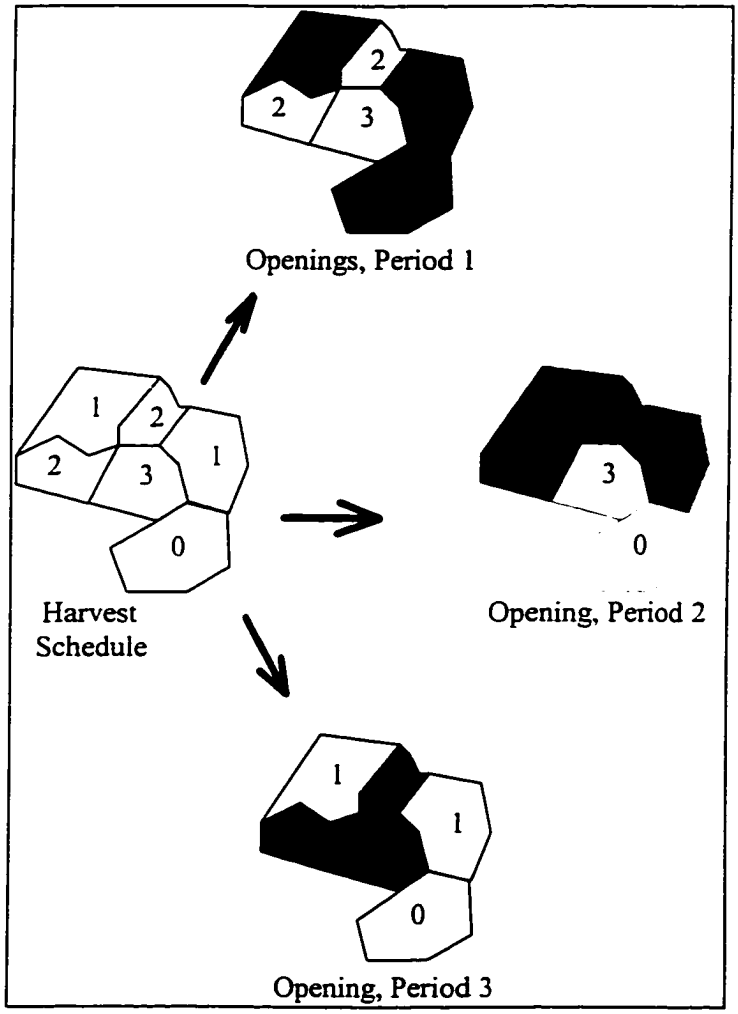


Figure 5.1. Multi-period Openings

5.3. Lost Volume Penalty

Appropriate timing of stand harvests is of major importance in realizing long-term sustainablity of the forest resource and in maximizing its productivity. In this model, a lost volume penalty function is used to differentiate between effective and ineffective timing of harvests. This penalty function, as a factor in the objective function to be minimized, also favours solutions that attempt to recover from existing inefficient conditions (over abundance of old stands and dead stands). It also discourages those solutions which would incur losses in the future, i.e. outside the planning horizon for which the model is solved.

Definition 5.10 The mean annual increment, *mai(g)*, of a stand at age g is the average wood volume increase per unit area per year at full stocking.

Mai depends on the existing covertype, age and site capability of the stand [Gunn 1994b]. Figure 5.2 shows *mai* curves for stands of site index 3 - 8 for Nova Scotia softwoods (a higher numbered site index indicates better growth potential). If the biological production potential of the forest is to be maximized, then stands should be scheduled for harvest when they have reached their maximum *mai*. The lost volume penalty function was developed to form a proxy measure for negative effects on potential productivity which can be attributed to decisions made within the planning horizon. The lost volume penalty induced from harvesting stand s in period j is a function of the stand size, age, stocking, *mai* and its current growth state (growing or moribund). For *growing* stands the contribution to lost volume from assigning stand s to harvest in period j is :

$$LV_{growing}(s,j) = \left[mai\_max(s) - mai(s,j)\right] \times a_s \times age(j) \times stocking \qquad (2)$$

If stand s is harvested at its period of maximum productivity, *mai_max_age(s)*, the penalty is zero. Suppose that a stand is harvested at period j, before its peak productivity period. Then, the incurred penalty is equal to the difference between the volume which

is achieved at that harvest and the maximum volume which could be achieved by harvesting at *mai_max_age(s)*. If the stand has reached its peak productivity at some period *k* in the planning horizon or prior to the inception of the first planning period, then a decision to delay harvest of that stand results in the land being kept in a declining state of productivity. Suppose that the stand is eventually harvested at period *j*. Then, the penalty is derived from observing that, for *age(j)* years, the land has been occupied by a stand producing at the rate *mai(s,j)*, which is less than *mai_max(s)*. Assuming that the next rotation harvest for the stand occurs at maximum productivity, the appropriate penalty is the volume corresponding to the difference in *mai_max(s)* and *mai(s,min[j,J+1])*. The lost volume penalty, being the sum of all stand penalties, will evaluate to zero only if the scheduling of all stands is such that productivity has not been harmed. Therefore, minimizing the lost volume penalty is a sensible proxy for maximizing forest productivity.

In figure 5.3, the stand is at ageclass 7 in period 1 of the planning horizon, and reaches maximum *mai* at ageclass 10. The figure illustrates the penalties for harvest in period 1 (early) and in period 5 (late).

For stands which have a significant amount of dead timber, the lost volume function is defined differently. The presumption is that the stand will resume normal growth after the inhibiting deadwood is removed and some remedial silvicultural action taken. Thus, for *dead* stands, the penalty is based on the number of periods into the planning horizon that no intervention is taken.

$$LV_{dead}(s,j) = \begin{cases} 0 & \text{if } j = 1 \\ \text{mai\_max(s)} \times (j-1) \times a_s \times \text{stocking} & \text{if } j \in [2, J+1] \end{cases} \quad (3)$$

Thus, if the stand is cleared in the first planning period, no penalty is applied, since this is the best action that can be taken. Otherwise, the delay to future periods incurs a

penalty calculated from the stand's expected future growth at maximum *mai* (Figure 5.4 illustrates this penalty for waiting until period 4 of the planning horizon.).

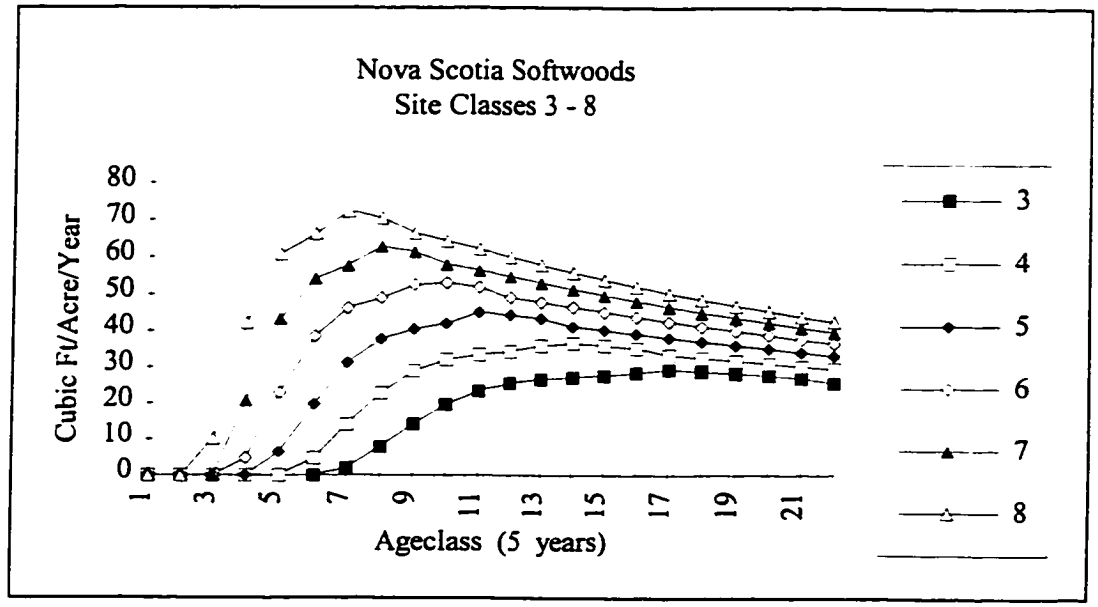


Figure 5.2. Mean Annual Increments

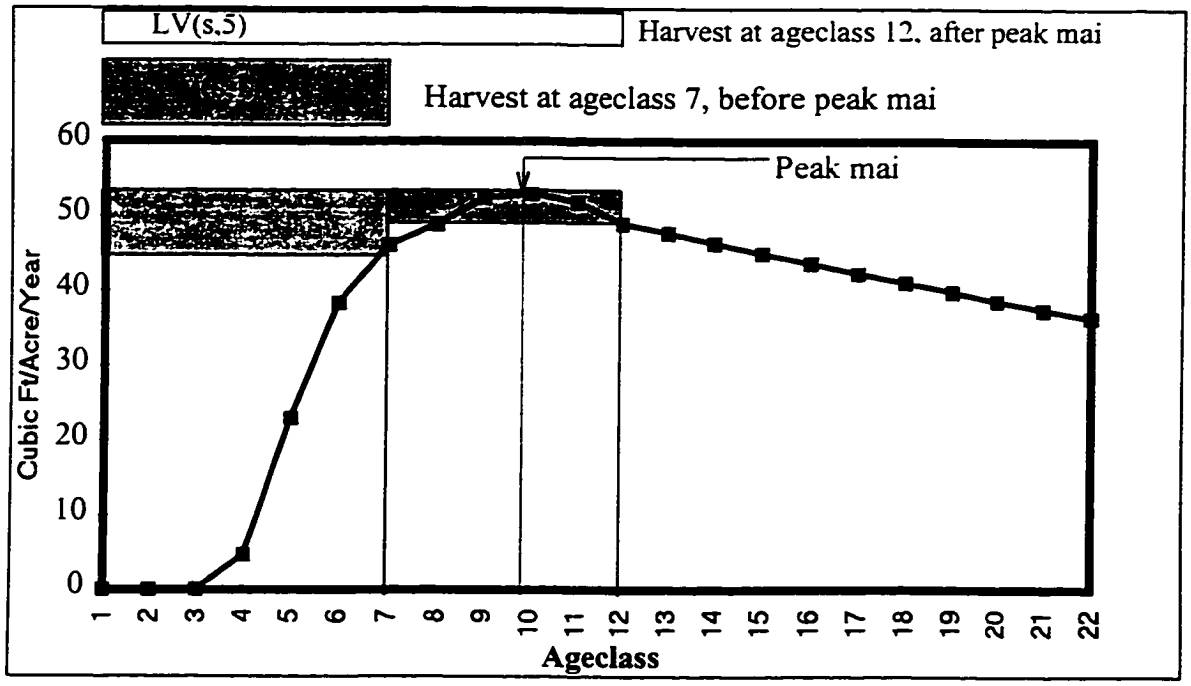


Figure 5.3. Lost Volume Function, Growing Stands

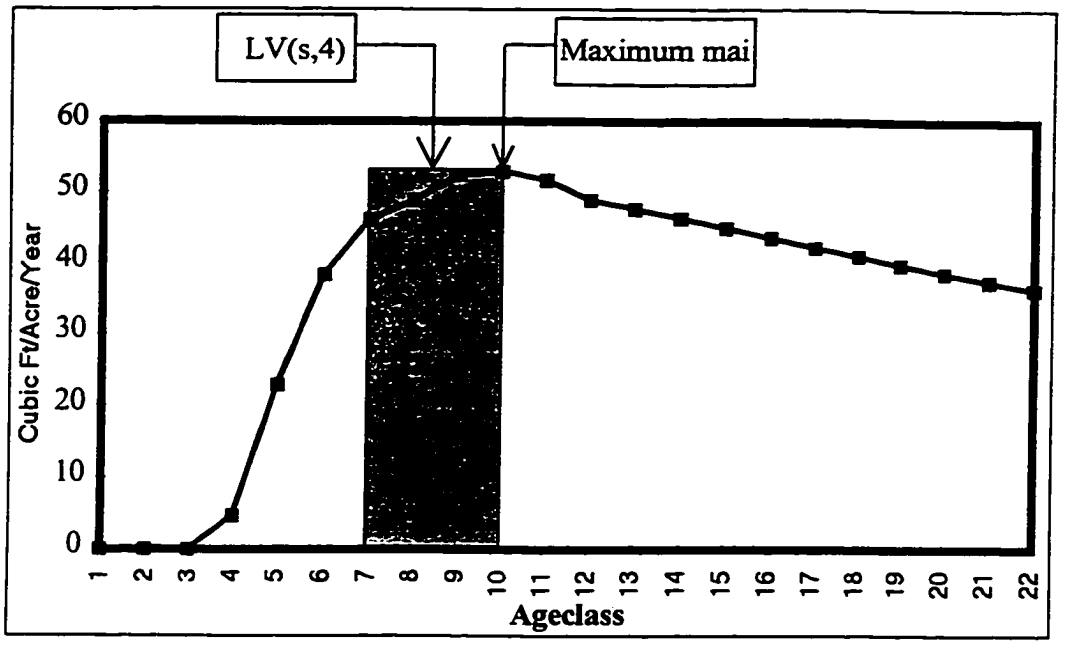


Figure 5.4. Lost Volume Function, Dead Stands

5.4. Harvest Volume Restrictions

Target harvest volumes for each period and for the overall harvest are derived from a strategic planning process. For the tactical model, periodic volumes and total volume are allowed to deviate from target values by a percentage of the target. A larger percentage deviation is allowed on periodic harvests than on total.

Unlike many other tactical harvest scheduling models, this model does not attempt to maximize harvest volumes or net present value of timber. The premise is that the harvest targets have been derived from a strategic model, where maximization of timber product value is done under sustainability constraints over long planning horizons. Actual harvest targets (often called annual allowable cut) produced by a strategic optimization model over this longer horizon with a non-declining yield constraint, will be attained by "harvesting" stands at ages near their peak biological productivity in most cases. Thus, this tactical scheduling model will maintain consistency with the strategic plan by also scheduling the stands at the "best" times where possible. Re-optimizing for

volume in the tactical planning phase is not useful in this hierarchical framework, and may tend to favour schedules which are inconsistent with the upper level strategic planning model assumptions. Thus, within the tactical horizon, the goal is to implement the strategic plan while minimizing costs and meeting spatial requirements.

Define parameters:

V_{sj} *volume from harvesting stand s in period j* (ft^3)

TV *Total volume target* (ft^3)

dTV *Percentage Deviation allowed from Total volume target*

PV_j *Periodic Volume Target, period j* (ft^3)

dPV *Percentage Deviation allowed from Periodic harvest target*

and indicator variables

$$x_{sj} = \begin{cases} 1 & \text{if stand s is scheduled for harvest in period j} \\ 0 & \text{otherwise} \end{cases}$$

Then, the harvest constraints are:

$$TV(1-dTV) \le \sum_j \sum_s V_{sj} x_{sj} \le TV(1+dTV) \qquad \text{Total Target} \qquad (4)$$

$$PV_j(1-dPV) \le \sum_s V_{sj} x_{sj} \le PV_j(1+dPV) \qquad j = 1,\ldots,J \qquad \text{Periodic Targets}$$

$$\sum_j x_{sj} \le 1 \qquad s = 1,\ldots,S \qquad \text{One harvest/ stand}$$

The model is then summarized:

$$\min \sum_{j=1}^{J+1} \sum_{s=1}^{S} LV(s,j) x_{sj} + \rho\, RC\,(x)$$

Subject to:

Spatial Constraints (1)

Harvest Constraints (4)

and operational feasibility for the road network.

RC(x) is the cost of constructing road links so that all stands are accessed. These are determined by solving ***RNP(x)***, the road building problem which is induced by a

harvest schedule x. The parameter ρ is increased (,respectively decreased) to drive the search algorithm to produce solutions with lower (, respectivly higher) roading costs. The road network problem and the heuristic procedure for solving ***RNP(x)*** are fully described in Chapter 6.

CHAPTER 6

ROADING NETWORKS

In the previous chapter, the harvest scheduling component of HSRBP was defined. This chapter deals with the road building optimization problem. Each harvest schedule x induces a road network design problem ***RNP(x)***. This problem is to select from a pre-specified set of road links a minimal cost set which is operationally feasible for x. Multiple access points and cycles in the network are allowed, and in this sense this model deals with more general road networks than those which have been treated to date in the literature.

In this chapter, a graph structure and an integer programming formulation for ***RNP(x)*** are first developed. A solution to the discounted, multi-period road building problem is a directed spanning graph of the road network. It is shown that ***RNP(x)*** is NP-complete by transforming the single-period, undiscounted road design problem to a *Steiner* problem on graphs. A heuristic solution procedure, the *Path Heuristic*, *PH*, is developed, and is shown to produce near-optimal solutions to ***RNP(x)*** with optimal solutions in many cases. In addition, *PH* is especially suitable for use in the tabu search algorithms described in the succeeding chapter. This is because the initial solution to the roading problem, a set of shortest directed paths, is easily used to compute incremental costs of road building when moves are implemented in the tabu search algorithm.

6.1. Creating the Proposed Road Network

A roading system is required to analyze the cost of gaining access to stands

assigned to be harvested in any schedule. If no road network, or only a partial network, exists for the area under study, a proposed system must be created. Its development occurs in two phases. They are the spatial definition of suitable road links and the mathematical definition of the graph representing the road network and the stand/road requirements.

The essential requirement for the proposed roading system is that it defines a connection from every stand in the area to a main road. That is, the network model of the roads must contain at least one path from each stand to one of the existing main roads. Apart from conforming to this connectivity requirement, the network must be designed with sufficient care that it provide a fair representation of the problem at hand. The role of the road model is to approximate the real costs of road building which would be incurred in accessing stands in the forest interior. Thus, the design requirements are that the network be connected, that it make topological sense, and that there be links defined within a minimum distance of each stand .

The proposed links are sketched on a map of the forested area, using the major topological features (e.g., rivers, streams, existing main roads) to determine link placement. If a GIS system and mapped coverage of the area is available, the road design process is considerably enhanced by utilizing the system's spatial analysis capabilities to calculate link lengths, verify connectivity and coverage of the area and assign link identifiers. The effort expended in adding the road network to the GIS will be returned "with interest" when proposed solutions are represented graphically. Once all road links have been created, the stand to road link relationships are defined by assigning the nearest link to each stand. (Stands which are already accessible by main road are assigned a null link value.) Again, this process is less awkward when a GIS system is available The example network in Figure 6.1 has three existing main roads and sixteen

proposed links.

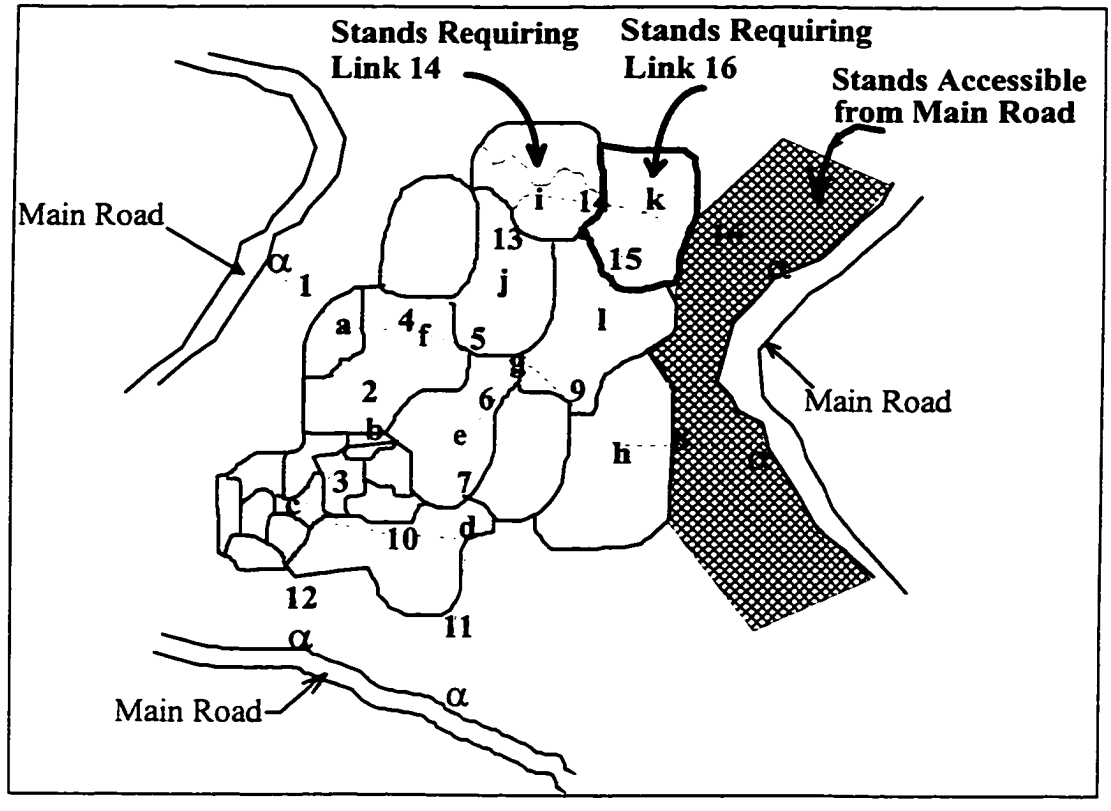


Figure 6.1. Stands and Roading Network

6.2. Graph Representation of the Roading Network

The network is represented as a weighted graph $RG = (V,R,W)$, where the edges R are road links and each weight w_r is the cost to build link r. The cost, w_r, may be the length of link r, although other factors such as the nature of the terrain, road elevation and proximity to water buffers may be included in determining the link construction cost. The graph RG may be non-euclidean when factors other than length are chosen.

The vertices V are end nodes of the links, which are indexed in any unique fashion, with the proviso that only one node index is used to indicate that a link accesses a main road. That is, all existing main roads are "collapsed" into one node α. The network in figure 6.1 has five links which are connected to access roads (1,8,11,12,16).

Its graph is $V=\{\alpha,a,b,c,d,e,f,g,h,i,j,k,l\}$, $R=\{(\alpha,a), (a,b), (b,c), (a,f), (f,g), (g,e), (e,d), (h,\alpha), (g, h), (c,d), (d,\alpha), (c,\alpha), (j,i), (i,k), (k,l), (i,\alpha)\}$, as shown in figure 6.2.

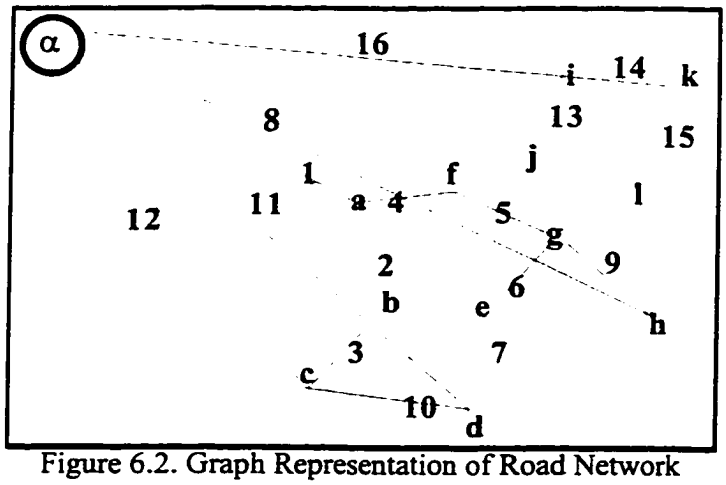


Figure 6.2. Graph Representation of Road Network

Some comments on the nature of these graphs are in order. First, several links may be constructed beginning at a main road, (depending on the length of the road which is incident to the forest area), and the node α may represent more than one of these roads. Thus, the degree of α is expected to be large compared to that of other nodes in the graph. For nodes other than α, the graph is likely to be relatively sparse. To illustrate this, consider the design which is an N by N gridding of the forest area, shown in figure 6.3. Each interior node has degree 4, the number of nodes is $(N-1)^2+4(N-1)$, the number of edges is $(N-1)N+2(N-1)$, and thus the average node degree is $\left\{\frac{(N-1)N+2(N-1)}{(N-1)^2+4(N-1)}=\frac{N+2}{N+3}\right\}$. This is arguably the most dense pattern of potential road links that would be designed, and thus the highest vertex degree we would expect to find in RG (for nodes other than α) is 4.

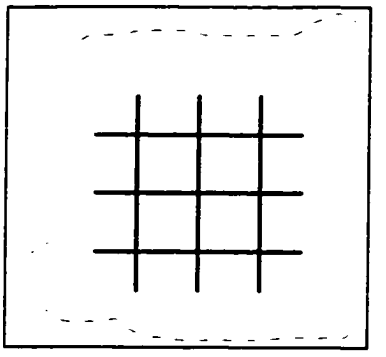


Figure 6.3. Gridded Road Design

6.3. Integer Programming Formulation for *RNP(x)*

Denote by ***RNP(x)*** the problem of finding a minimum cost road plan for a given harvest schedule x. To specify ***RNP(x)*** as an integer program, some parameters, sets and variables are required. As well, for each link in RG which is a member of a cycle, paths from that link to the main roads must be enumerated. This enumeration is practicable on graphs which are sparse as described above, since only a few possibilities exist for each link, and not all links will be in a cycle. This is not a generally applicable method, since too many cycles or a denser graph would render the enumeration unworkable. See Magnanti and Wolsey [1995] for a description of network design models. Nevertheless, this enumeration was done for this problem to produce an integer program which was then used to generate optimal solutions for the road building problem. This section describes the *IP* formulation for ***RNP(x)***.

Parameters

w_{rt} *discounted cost to build link r in period t*

S *Set of stands*

J *number of planning periods*

R *Set of road links*

Sets

$CC = \{s \in S | x(s) = 0\}$ *Existing Clearcuts*

$\delta(r) = \{l \in R \backslash \{r\} | l \text{ is connected to } r\}$ *The cutset of r.*

$D(r) = \{l \in \delta(r) | l \text{ is connected to } t \text{ in } RG(R - (r))\}$

$S_r = \{s \in S \backslash CC | \text{harvest of stand } s \text{ requires link } r\}$

$P_r = \{\text{Paths which connect link } r \text{ to } \alpha\}$ *Paths from r to*

$= \{P_r\}$ *All Paths*

Decision Variables

$$z_{rj} = \begin{cases} 1 & \text{if link } r \text{ is built in period } j \\ 0 & \text{otherwise} \end{cases}$$

Indicator Variables

$$Y_{pk} = \begin{cases} 1 & \text{if path } p \text{ is built in or before period } k \\ 0 & \text{otherwise} \end{cases}$$

Timing and connectivity constraints for this problem must be included to ensure that, for each link r which is built in period j, some path which links r to α is also built in period j (or earlier). For links which are members of a sub-tree of RG containing α, the timing and connectivity requirements are specified by examining the cutset of r, $\delta(r)$ and constructing the set $D(r)$. For these links, at least one of the links in $D(r)$ must be built in the same period or in a prior period.

$$z_{rj} \leq \sum_{\substack{k=1 \\ l \in D(r)}}^{j} z_{lk} \tag{6.1}$$

For links which are members of cycles in RG, indicator variables Y_{pk} and an enumeration of all paths to α are required. For each link r which lies in a cycle of RG containing α, the paths P_r are enumerated and indicator variables Ypk used to form constraints (6.2).

$$|p_l| Y_{lk} \le \sum_{j=1}^{k} \sum_{r \in p_l} z_{rj} \tag{6.2}$$

$$z_{lk} \le \sum_{j=1}^{k} \sum_{p_l \in P_r} Y_{lj}, \tag{6.3}$$

where $|p_l|$ is the cardinality (number of edges) of the path p_l. Equations 6.1, 6.2 and 6.3 then ensure connectivity of the road network.

For any harvest solution $\boldsymbol{x}$, the elements of $\boldsymbol{x}$ which are member of S_r provide a bound on the period at which link r must be built. Define

$$jmin_r(x) = \left\{ \min_{s \in S_r} \{x_s\} \right\} \bmod(J+1).$$

Then the constraints

$$\sum_{j=1}^{jmin_r} z_{rj} \ge 1 \ , r = 1, |R| \tag{6.4}$$

ensure that the required link is built prior to harvest.

The optimization problem ***RNP(x)*** can be expressed as the following (binary) integer programming problem:

RNP1: $\min \sum_{j=1}^{J} \sum_{r=1}^{R} w_{rj} z_{rj}$

Subject to constraints 6.1, 6.2, 6.3, 6.4 and

$\sum_{j=1}^{J} z_{rj} \le 1, \mathrm{r} = 1, |\mathrm{R}|$ *Construct each link at most once*

$z_{rj} \in \{0,1\}$ *Binaryvariables*

6.4. Equivalency to Steiner Tree Problem

The set of links which are required to be built during the planning horizon, *RL*, is the set $\{r | jmin_r(x) > 0\}$ A feasible solution to ***RNP(x)*** is a directed connected subgraph $S(V', R')$ of *RG* such that, for each r in *RL*, there is a directed path in *S*, $P_r = \{r, r_{n_1}, r_{n_2}, ..., r_{n_k}\}$ from the required link r in *RL* to α. That is, the ending link in this

path, r_{n_k}, has one node equal to α. Each link in each path is assigned a construction period, a mapping $\Omega : R' \rightarrow \left[1, J+1 \middle| \Omega(r_{n_k}) \leq \Omega(r_{n_{k-1}}) \leq ..\Omega(r_{n_1}) \leq \Omega(r)\right]$. An optimal solution is one of minimum weight, i.e. one that minimizes the discounted costs of road building $\sum_{r\,\Omega(r)\leq J} \frac{w_r}{(1+d)^{\Omega(r)}}$ (d is the discount rate).

This network design problem has two special features: the requirement for timing the road link construction and the existence of required links. The second observation leads to a comparison of ***RNP(x)*** with the classic Steiner Tree problem.

If timing of road construction is dropped from the problem, (i.e., let J=1), ***RNP(x)*** is reminiscent of the Steiner tree problem on graphs.

6.4.1. The Steiner Tree Problem on Graphs

The Steiner tree problem (STP) on a weighted undirected graph $G=(V,E)$ is to find a minimum cost connected subgraph of G which contains some subset T of V. The nodes T are called "Terminal" or "Special" nodes. The optimal solution to STP is always a tree of G (a connected subgraph of G with no cycles), which contains all of the terminal nodes T and possibly some other nodes in $V \backslash T$. These "extra" nodes are called *Steiner nodes*. If T is equal to V, the problem reduces to the minimum spanning tree problem and is solved in polynomial time using Dijkstra's labeling algorithm, or some variant such as Prim's or Kruskal's algorithm. Other special cases are also solvable in polynomial time, but in general the Steiner tree problem is NP-complete.[Garey and Johnson 1979]

STP arises in many network design problems. For example, suppose that the problem at hand is to install a minimum cost fibre optic network that connects a set of customers (nodes). Any optimal solution must be a minimum spanning tree on the graph of customers (nodes) and possible connections (edges). If, however, not all customers

must be connected, and other nodes can be used to complete the network, the problem becomes a Steiner tree problem, where the terminal nodes T are the "essential" customers. In VLSI design, components (chips) must be connected along horizontal and vertical channels using the least amount of wire. Terminal nodes are those locating the chips, and intermediate nodes are the intersections of the horizontal and vertical channels. This problem is referred to as the rectilinear Steiner tree problem since edge costs are measured using the rectilinear norm. [Magnanti and Wolsey 1995, Hwang and Richards 1992].

6.4.2. *RNP(x)* as a Steiner Tree Problem

Denote by ***SRNP(x)*** the single period road design problem induced by the harvest schedule x. In this road network design problem, instead of a subset of required *nodes*, a set of *links* are required. Also, node α must be in the solution. In contrast to solutions to STP which are always trees, the solution to this network problem may contain cycles. An obvious example is where a set of required links forms a cycle. (In figure 6.2, if a given harvest requires links 1, 2, 3 and 12, this cycle will be in the solution.) Closer investigation of ***SRNP(x)*** reveals that it is in fact equivalent to the following STP, and therefore also NP complete.

Given $RG = (V, R, W)$, the road graph, with $RL \subseteq R$, the set of required links
Define the Steiner Road Graph SRG(SV, SL, W) as follows:
Set RLV (Required Link Vertices) = $\{\alpha\}$
For each edge (v, w) in RL
    Replace (v, w) with a vertex vw. Set RLV = RLV $\cup \{vw\}$.
    If either v or w is α, add a zero - length edge between vw and α
    Re - label all edges in the cutset of (v, w): (u, v) = (u, vw) and (u, w) = (u, vw)
    Set V = V - $\{\{v\}, \{w\}\}$
End processing RL
SV = V $\cup$ RLV
and SL = R - RL

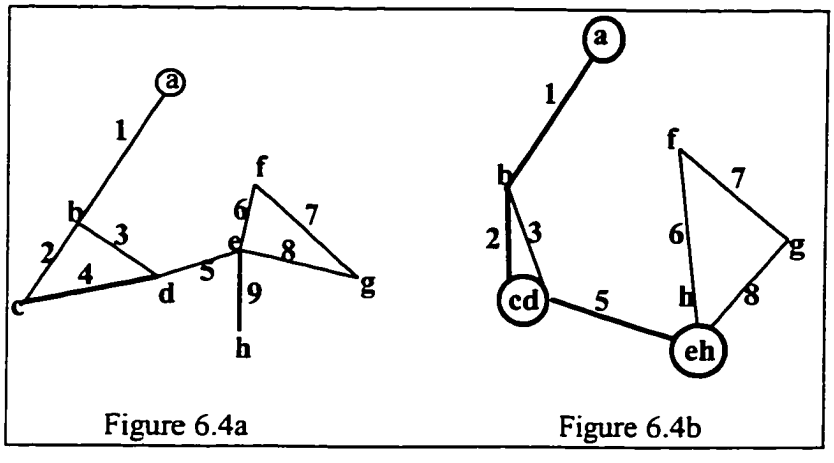
Then, ***SRNP(x)*** is equivalent to the Steiner Tree Problem on *SRG* with Terminal nodes *RLV*. The cost of the solution is the total cost of building the required links, plus the cost of the additional links required to connect all Terminal nodes in *SRG* to α.

As an example, consider the network shown in Figure 6.4a. Links 4 and 9 are required. The transformed graph is shown in Figure 6.4b, where the Terminal nodes are *cd* and *eh*. Edge 2 is now (*b,cd*), edge 3 (*b,cd*), edge 6 is (*f,eh*) and so on. Note that in this case the "Terminal Link" (*c,d*) originally formed a cycle with edges 2 and 3, with only one possibility (link 1) to complete the tree. Thus, the minimum cost Steiner tree will include the shortest of links 2 and 3. This path is shown in boldface in Figure 6.4b in the case that link 2 is of lesser cost than link 3. Figure 6.4c shows the actual road path on the original graph.

6.4.3. Solving Steiner Tree Problems

A number of exponential time exact algorithms have been proposed to solve STP. Aneja [1980] formulated the STP as a set covering problem in a 0-1 integer program, and uses a row generation procedure in the solution. Beasley [1989] and Balakrishnan and Patel [1987] identified reduction schemes which exploit the special structure of Steiner

trees and improve the basic integer formulation. Beasley's algorithm is a branch and bound scheme which uses Lagrangean relaxation techniques to sharpen bounds; Balakrishnan and Patel generate a series of spanning trees of increasing weight. Although these efforts have provided encouraging improvements in solution time (see Beasley 1989 where graphs of thousands of vertices are solved), there is of course still the possibility that that, in solving any instance of *STP*, the solution time will be exponential in the number of variables.



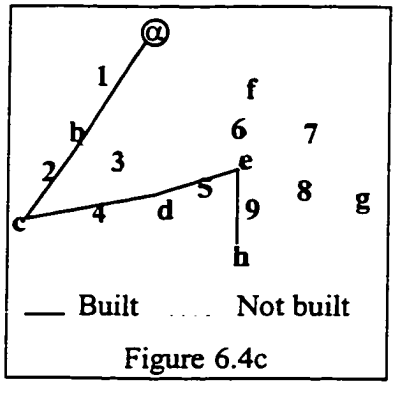


Figure 6.4. Equivalent Steiner Network

A class of heuristic algorithms for *STP* based on shortest path graphs has been shown to provide solutions close to optimal with reasonable computational times. [Wu et al 1986, Widmayer 1986 and Melhorn 1988, Takahashi and Matsuyam 1980, Kou 1990,

Kou and Maki 1987]. The most computationally efficient of these is Melhorn's algorithm [Melhorn 1988], which is of order $(E + V \log V)$, where E is the number of edges and V the number of vertices) in G. Other heuristics for Steiner tree problems and their variants include simulated annealing methods, edge insertion methods and tabu search methods. For a comprehensive discussion of the Steiner tree problem, see Hwang and Richards [1992].

6.4.4. Differences between *SRNP(x)* and *RNP(x)*

Consider ***RNP(x)***, the multi-period problem, which is NP-complete since ***SRNP(x)*** is NP-complete. An optimal solution to ***SRNP(x)*** is not necessarily optimal for ***RNP(x)***. To illustrate this, consider the problem in figure 6.5. Links *l* and *RL* are required, *z* is the length of the shortest path from *a* to *RL* and *x* is the length of the shortest path from α to *RL*. If *x* is greater than *z*, then the optimal solution for the undiscounted (single - period) problem is to build path *P1* and link *l*, with cost equal to *(y+z)*. For the multiple-period problem, suppose that *RL* is required in period 1 and *l* is required in period $p > 1$. Then, if $x + \frac{y}{(1+d)^{p-1}} < y + z$, the minimum cost solution is to build link *l* and path *P2*. For example, if $p = 2$ and the discount rate is .10, the longer path *P2* will be optimal whenever *x* is less than *(z + .0909y)*. Note also that, as the discount rate is increased, the likelihood of finding a cheaper but longer path is increased.

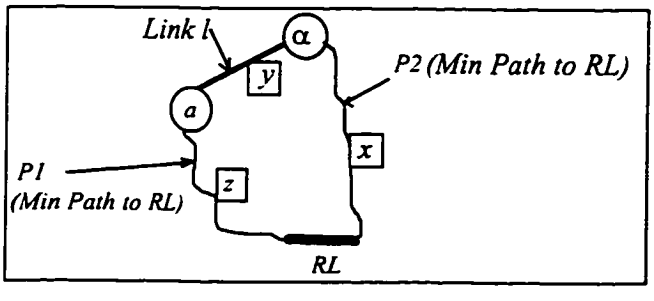


Figure 6.5. Multi-Period vs Single-Period Solution

6.5. Solving *RNP(x)*

An optimal solution to ***RNP(x)*** can be obtained by formulating and solving the integer program RNP1. Developing RNP1 requires a considerable effort in enumeration of connectivity constraints, and may result in a large number of indicator variables and connectivity constraints. The solution of the integer program is computationally prohibitive (Solution times for the Shulkell problem exceeded 30 minutes). Since ***RNP(x)*** must be solved a great many times in the tabu search algorithm, an effective heuristic to solve ***RNP(x)*** was developed.

The path heuristic (*PH*) is based on the well-known class of "label-correcting" algorithms which include Dijkstra's algorithm for shortest paths, Prim's algorithm for minimum spanning tree and others [Ahuja et al 1993]. For convenience, Prim's algorithm [Tarjan 1983, Ahuja et al1993] for constructing the shortest path spanning tree of a graph is outlined in figure 6.6.

Prim's Algorithm
1. Assign weight $W(v)=\infty$ for all vertices v.
2. Begin with an arbitrary vertex k. Set $V=V\backslash\{k\}$. Set $dad(k)=0$.
3. Process all nodes t which are adjacent to k
   For each t;
   if $W(t)>(W(k)$ + length of $(t,k))$
      Assign $W(t) = W(k)$ + length of (t,k)
      Assign $dad(t) = k$
4. If V is not empty, choose the vertex k in V with smallest weight $W(k)$, set $V=V\backslash k$ and go to step 3.

Figure 6.6 Prim's Algorithm for Shortest Path Network

The weight W(t) is a tentative distance label for vertex t. This label is updated whenever a better (i.e., shorter) path is found between t and k. The algorithm begins with a "singleton" tree, and builds on that tree by examining adjacent nodes in a breadth first search. When complete, a directed spanning tree rooted at k is created, in which each

node is contained in a shortest path to the root. The directed tree is stored using the "dad" structure, in which each node is assigned a predecessor ("father") node in the tree.

6.5.1. Path Heuristic

If the first vertex chosen is the main road vertex α, Prim's algorithm will produce a shortest path spanning tree between all nodes in *RG* and α. The difficulty is that these paths will not necessarily include all of (or even any of) the links which are required for the harvest schedule x. This motivates changing Prim's algorithm in the following way: attempt to include the required links by reducing the weighting of paths which contain any element of *RL*. The Path Heuristic (*PH*) is as follows:

Path Heuristic

1. Assign weight $W(v)=\infty$ for all vertices v in V.
2. Begin with α. Set $V=V\backslash\alpha$. Label $k=\alpha$
3. Process all nodes t in V that are adjacent to k
   For each t;
   If(k,t) is a required link,
   assign $W(t)=0$
   Otherwise,
   if $W(t)>(W(k)+$length of $(t,k))$
   assign $W(t)=W(k)+$length of (t,k)
   assign dad$(t)=k$
   End processing edges (k,t)
4. If V is not empty, choose the vertex k in V with smallest weight $W(k)$, set $V=V\backslash k$, and go to step 3.
5. If any required links is not a member of some path, it must form a cycle with two paths. Assign the link to the shortest of these.
6. For each path, assign the earliest required period to each link, and calculate the cost of the road project.

Figure 6.7. Path Heuristic

Clearly, the search begins with node α,since the object is to build paths to the main road access. The difference between *PH* and Prim's algorithm is that, when a required link adjacent to t is encountered in step 2, a weight of 0 (highest priority) is assigned to t. This forces required links into the solution. After completion of steps 1-3, a tree has

been created which connects each node in RG to α.If any required links are missing from this tree, they must then form a cycle with two paths in the tree. Step 4 then adds these links to the shortest of the paths in which the cycle occurs. Finally, step 5 assigns the earliest required harvest period to each link in each path.

One might observe that this heuristic in fact calculates more paths than are necessary to solve ***RNP(x)***. This is true, since it is only strictly necessary to calculate paths until all required links have been included. The extra iterations of Step 3 could be removed by stopping the algorithm when V contains no more vertices incident to required links. The complete set of paths produced by *PH* will be used to quickly calculate the (approximate) incremental roading costs for moves in the tabu search algorithm. So, the algorithm will be used in this form.

6.5.2. Computational Complexity

The running time of Prim's algorithm is $O(|V||R|)$. When implemented with a priority queue effected by a binary heap data structure, this complexity is reduced to $O(|V|+|R|\log|V|)$ [Ahuja et al 1993, Tarjan 1983, Sedgewick 1983]. In the Path Heuristic, some extra computational cost is incurred by adding any missing required links (Step 4) and re-timing the links in each path (Step 5). Step 4 computation effort is $O(|RL|)$, *typically* $<< O(|R|)$, since only those required links which form a cycle in the graph will be left missing from the path network. Step 5 computations require at most $O(|R|)$ comparisons to set the timing of the links. This is easily seen by examining the search method used to assign the timing of the links. (Figure 6.8). The re-timing algorithm makes use of two variables: *period(r)* and *c_period(r)*. *Period(r)* is the period $jmin_r(x)$ determined by the stand assignments and *c_period(r)* is the period assigned for construction of link r.

```
Set period(r)= jmin_r(x), c_period(r)=(J+1) for r = 1,R.
For each link r :
   If r is a leaf (i.e. it has no successors):
        Set c_period(r) = period(r)
        do while {(dad(r)<> 0) and c_period(dad(r))>c_period(r) )}
              c_period(dad(r))=c_period(r)
              r=dad(r)
        end do
   End if
```

Figure 6.8. Link Re-Timing Procedure

The re-timing loop is executed once for each r which is a leaf in the shortest path spanning tree. The first time a path is encountered in this procedure, it is processed entirely (since *c_period* is set to *(J+1)* initially). If the leaves are processed in an unordered way, path segments would be re-processed each time a new leaf incident to that path is encountered. This inefficiency is avoided by first sorting the leaves in increasing order of period. The timing of all road links requires *2R* steps to set initial values, L steps to begin processing each path (L is the number of leaves), R steps to make the assignments and *O(LlogL)* steps to sort the leaves (for example, using a binary heap sorting algorithm [Sedgewick 1983]). Since the number of leaves is dominated by the number of vertices, the running time of *PH* is $O(|V| + |R|(1 + \log|V|))$.

6.5.3. Numerical Results

A sample of 300 harvest solutions x was generated to evaluate the performance of the Path Heuristic on the Shulkell study area. These solutions were generated by randomly assigning each stand a harvest period in [1,20]. The first four periods were used for the tactical planning horizon, with the remaining stands categorized as unassigned. Optimal solutions to ***SRNP(x)*** were obtained by implementing the integer formulation RNP1 in LINDO™[Schrage 1988]. 41.41% of the *PH* solutions were

optimal, the worst case deviation from optimal was 2.81% and the average deviation was 0.43%. (Figure 6.9)

Figure 6.10 compares *PH* results to optimal solutions for samples (size 100) which vary the number of required road links. For smaller numbers of required links, more heuristic solutions are optimal, but the maximum percentage deviation from optimal on the sample tends to be higher. Nevertheless, the *PH* performance is again very good, with average deviation from optimal of less than 1.5% in all cases. These experiments show that the path heuristic performed very well on the single-period problem.

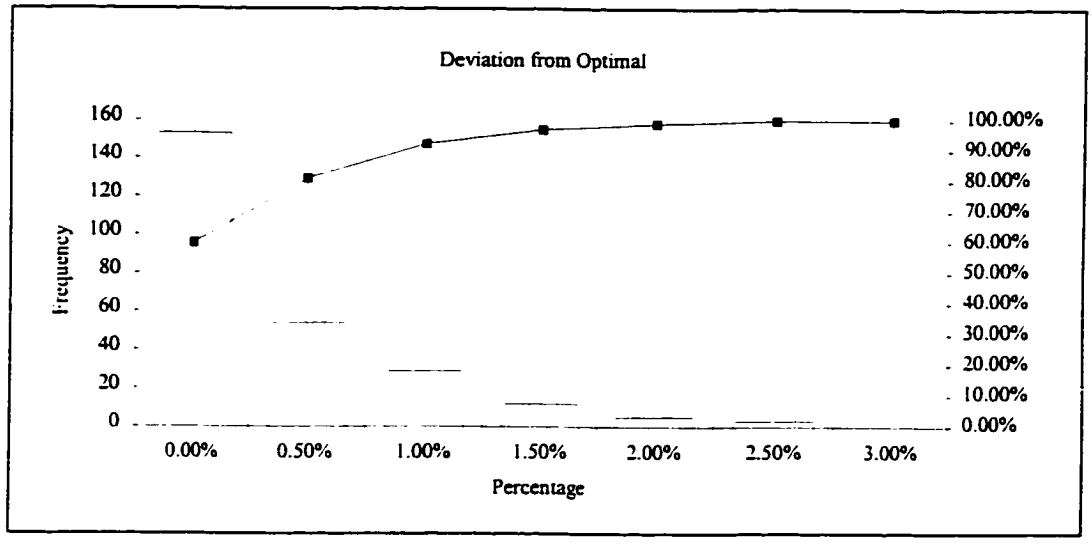


Figure 6.9. PH Performance for Single-Period Problem, Randomly Generated Stands

# Required Links	Maximum Deviation	Average Deviation	% Optimal
10	11.94%	1.26%	79%
20	14.69%	0.99%	82%
30	9.64%	1.40%	56%
40	6.66%	1.02%	54%
50	5.19%	0.63%	67%

Figure 6.10. SRNP(x) Deviation from Optimal by Number of Required Links

Sixty-four instances of the multiperiod problem (with discount rate 10%) were solved to optimality using LINDO™. The left half column in Figure 6.11 compares path heuristic results with the optimal solution. In seven of the sixty-four runs, the Path Heuristic found an optimal solution. The worst case deviation from optimal was 10.48 %, with average deviation of 1.95%. Thus, the heuristic performed very well for the multi-period problem, at this discount rate. The right hand side of Figure 6.11 documents the differences between the discounted multi-period solution and its optimal single-period solution. In twenty-five percent of the cases (16), the optimal single-period solution and the optimal multi-period solution were identical. There was a maximum observed increase in the total length of road links of 3.21%, and an average difference of 0.61%.

Percentage Deviation from Optimal		**Length Increase over Single Period**	
Mean	1.95%	Mean	0.61%
Minimum	0.00%	Minimum	0.00%
Maximum	10.48%	Maximum	3.21%
Sample Size	64	Sample Size	64
# OPTIMAL Solutions	7	Multi=Single	16

Figure 6.11. Path Heuristic Multi-Period Results

CHAPTER 7
TABU SEARCH ALGORITHMS FOR HSRBP

In chapter 4, the tabu search method and some of its important variants was described. It was shown that there is a wide range of sophistication in TS algorithms, and that researchers have spent considerable effort in choosing appropriate TS structures that work well on given problems. The problem here is to choose a solution methodology for the harvest scheduling and road building problem *HSRBP*.

First, a heuristic search method is evidently required. *HSRBP* has a constraint structure that is complex, its decision variables are integer and practical problem instances have a large number of variables. Moreover, exact formulations of the adjacency constraints are not possible. The neighbourhood structure for this problem can be designed so that moves are easily evaluated; thus a search algorithm is appropriate. Amongst the well known metaheuristic search strategies, TS was chosen because of its considerable record of success in solving hard optimization problems.

A number of TS methods were tested, which varied in complexity from the simple fixed tabu search to algorithms with complicated dynamic search strategies. Given the difficult nature of the problem, it is not surprising that straightforward implementations of fixed tabu search were found to be ineffective in consistently obtaining good solutions to *HSRBP*. The best results were obtained from using an algorithm which combines reactive tabu search self-tuning principles, a strategic oscillation through constraint barriers effected by means of a modified objective function, and stochastic diversification moves.

This chapter describes the details of the TS algorithms that were designed to solve

HSRBP. The following chapter documents the empirical studies which were done to compare the algorithm variants.

7.1. Search Algorithm Structure

Figure 7.1 is top-level flowchart of the search algorithm structure. Each TS algorithm implements the same neighbourhood search and move. The main differences lie in the methods employed to determine tabu tenure, the inclusion/exclusion and choice of stochastic diversification strategies and the inclusion or exclusion of infeasible moves. Inputs to the model are the discount rate, harvest targets, allowed deviations, the maximum opening size and adjacency delay time, the planning periods to be considered and the stand and road data. The road data consists of an adjacency list (nodes) and a cost for each link in the proposed road network. Stand characteristics are the cover type, site capability, current age, stocking, a list of adjacent stands, and the road link required to access the stand.

The first phase is pre-processing of the input data. Mean annual increments for the planning periods are determined (using the Nova Scotia Growth and Yield model) and projected harvest volumes for the planning periods are calculated. For each stand, the lost volume penalties accruing from each possible harvest assignment are calculated and stored in the stand data structure. A linked list of stands which require each road link is calculated and stored. Finally, the openings (graphs) of period 1 are constructed for all stands which have been clearcut in the period immediately preceding the first planning period.

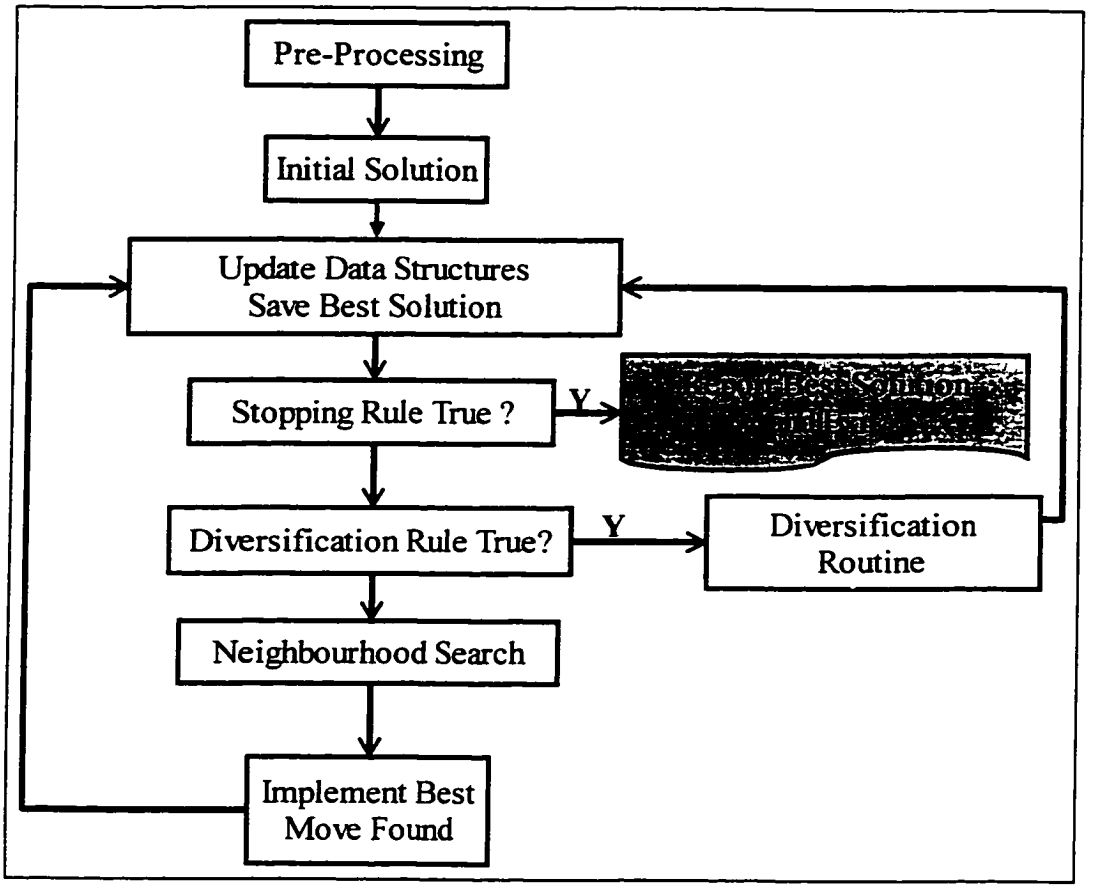


Figure 7.1. Search Algorithm Structure

The second stage of the algorithm is to generate a starting solution. This is done using a Monte Carlo procedure. Stands which border on a main road are randomly selected and assigned to each period in turn until the periodic harvest target is achieved. For algorithms which do not allow infeasible solutions (FTS, RTS), assignments which violate opening size constraints are rejected, and the solution is also required to be feasible with respect to total harvest target. The result of the process is an initial solution which requires no roading. If it is not possible to meet total harvest without building roads, the initial solution either may be made feasible by constructing some small set of roads, or an infeasible starting solution may be accepted. The algorithm A road network is then constructed, using the Path Heuristic. This initial network is in fact a shortest path network on the nodes of the road graph. At this stage, the solution incurs a large

lost volume penalty and no roading costs. See Appendix A, Figure A.1.

The third stage is the tabu search algorithm. Moves, which perturb the current solution, change the harvest assignment of one stand. The evaluation function for neighbourhood search is the sum of lost volume and roading costs. This function is augmented with terms which penalize infeasibilities with respect to each constraint set for the oscillating search algorithms (OTS, ORTS). In all cases, the full neighbourhood of the current solution is searched, and the best move is chosen.

This best move is implemented by making the stand assignment, updating the opening graph structure and updating the roading network if necessary. If the move improves on the best solution to date, the solution (i.e. all stand assignments and the roading network assignments) is saved. The tabu status of the stand chosen is set by storing the current move count in the stand data.

Once the move has been implemented, search status counters are updated. These include counters for the number of moves taken (*move_count)* and the number of moves since improvement *(moves_since_improve)* in the objective function. A diversification strategy may be invoked if *moves_since_improve* exceeds a pre-set limit. In RTS and ORTS, data structures which store the hashed value of the current solution are updated, and search status counters which measure cycling to previous solutions are updated. Based on these counters, tabu tenure may be increased or decreased, and a chaotic cycling indicator may be set to true, which then will cause a diversification routine to be executed.

Finally, the stopping rule is tested. The algorithm is terminated when the number of moves taken is greater than a specified maximum (*maxiters*) and no feasible improving move has been found for a specified number of iterations (*max_non_improving*). This second condition ensures that the neighbourhood of the last

improving move is thoroughly investigated.

7.2. Moves and Neighbourhood Search

Recall that a harvest solution x is an S-vector whose elements are the harvest period assigned to each stand, where harvest periods are integers in the range $[0,J+1]$. Assignment of $(J+1)$ indicates that the stand is not scheduled to be harvested, and stands which have been clearcut previously are assigned period 0. Neighbourhood search details are shown in figure A.2.

7.2.1. Move Types

Given a solution x, the moves which lead to a new solution are a re-assignment of any component of x. That is, moves change the harvest assignment of *one* stand. These moves can be classified as add, swap and delete moves, in that the stand is added to the harvest schedule, has its harvest period swapped from one period to another in $[1,J]$, or is removed from the harvest schedule. Note that existing clearcuts are of course not candidates for any move.

Definition 7.1 The moves $m=(s,k)$ which define the neighborhood $N(x)$ of a solution are $x_s : j \rightarrow k,\ k \in [1, J+1],\ k \neq j,\ s \in [1, S], x_s \neq 0$.

Move Type	Condition
Add	$j = J+1$
Delete	$k = J+1$
Swap	$j,k \leq J$

Figure 7.2. Move Types

All algorithms employ a full neighbourhood search. For larger datasets (more stands), implementation of a candidate list strategy (see section 4.2) would be appropriate.

7.2.2. Tabu Status and Aspiration Criteria

Once a move $x_s: j \rightarrow k$ is taken, the stand s is made *tabu* for *tabu_tenure* moves. This is effected by storing the current move counter in the stand's data. Checking tabu status is done by comparing the current move counter to this value and *tabu_tenure*. The duration of *tabu_tenure* is fixed throughout the algorithm in the FTS and OTS methods, and is dynamically varying in RTS and ORTS. Note that the tabu status forbids all non-aspirated moves involving stand s. It is a strong condition that may exclude a total of J moves.

Only one aspiration criterion, *aspiration by objective*, was used. The tabu status of a move is disregarded if executing the move would result in a feasible solution which is better than any solution encountered thus far in the search .

7.2.3. Calculating Change in Objective Function

In neighbourhood search, each potential move is evaluated by calculating the change in objective function which would result from implementing the move. The evaluation function for these algorithms is

$$z'(x) = LV + \rho\ RNP(x) + \alpha\ Dev\_total + \beta\ Dev\_per + \gamma\ Dev\_maxopen$$

This function consists of two cost factors, LV and RC, and three penalty terms *Dev_total*, *Dev_per* and *Dev_maxopen*, which measure the amount of deviation of the solution from the feasible region for each corresponding constraint boundary. (Parameters α, β and γ are used in the oscillating search method to guide the solution into and out of feasible regions, while ρ is used to examine the tradeoff between road cost and lost volume.) Using indicator variables x_{sj} and z_{rj} which are 1 (true) if stand s is to be harvested (respectively, link r to be built) in period j, each term is defined as follows:

Term	Description	Definition
LV(x)	Lost Volume	$\sum_{j=1}^{J+1}\sum_{s=1}^{S} LV(s,j)x_{sj}$
RC(x)	Road Cost	$\sum_{j=1}^{J}\sum_{r=1}^{R} w_{rj}z_{rj}$
Dev_total(x)	Deviation from total harvest target	$\left[\left\lvert\sum_{j}\sum_{s} V_{sj}x_{sj} - TV\right\rvert - dTV \times TV\right]^{+}$
Dev_periodic(x)	Sum of deviations from periodic harvest targets	$\sum_{j=1}^{J}\left[\left\lvert\sum_{s} V_{sj}x_{sj} - PV_{j}\right\rvert - dPV \times PV_{j}\right]^{+}$
Dev_maxopen(x)	Sum of opening size deviations from maxopen.	$\sum_{p=1}^{J}\sum_{k}\left[\left(\sum_{s\in O_k^p} a_s\right) - \text{maxopen}\right]^{+}$

Figure 7.3. Definition of Objective Function Terms

In full neighbourhood search, all possible moves m are evaluated by calculating $z(x \oplus m)$. In the following sub-sections, the calculations required for each term in z' are detailed.

7.2.3.1. Loss Penalty

The incremental change in lost volume from a move *(s,k)* is the lost volume induced by the proposed assignment less the lost volume from the current stand assignment. Thus, the new loss penalty is easily computed

$$LV(x \oplus m) = LV(x) + LV(s,k) - LV(s,j)$$

7.2.3.2. Roading Cost

Recall that, in the generation of the initial solution, the roading network is calculated by the Path Heuristic, resulting in a directed shortest path network on the nodes of the road network, with each link in the network assigned a period $r_l \in [1, J+1]$. Initially, the network consists of a minimum cost directed spanning tree with all links assigned to $(J+1)$. As stands are added to the harvest solution, the roading network is

made feasible by re-timing (i.e. assigning an earlier construction period to) each link that is required to access the stands (See Figure 7.4). If the stand to be added requires a link which is not in the current path network, the incremental cost to add this link is estimated by calculating the cost to insert that link into the shortest adjacent path.

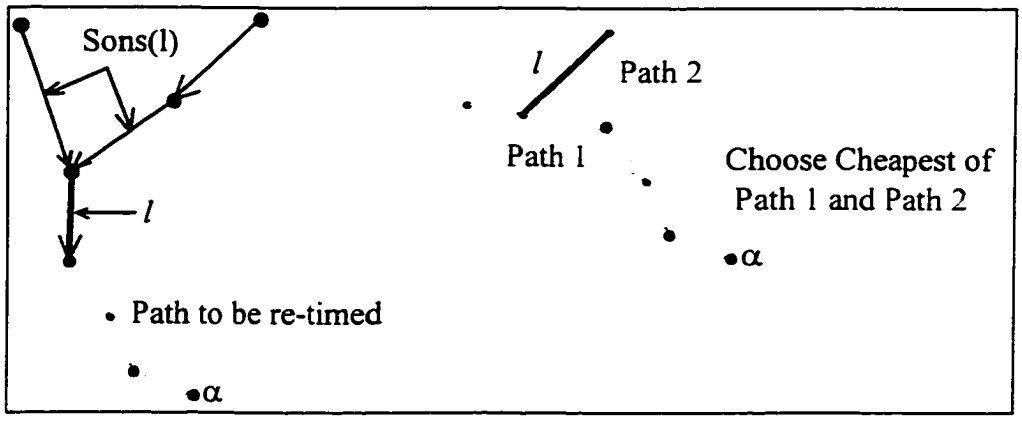


Figure 7.4. Re-Timing Links in a Path

Each stand s is either assigned a link (*link(s)*) in the road network (if road building is required to access that stand), or is assigned a "dummy" link 0 if the stand is accessible by main road. For each road link l, the set S_l is the set of stands requiring link l. Figure 7.5 shows the calculations which determine the incremental roading cost for a move. Note that in the case that a link is re-assigned to a later period, the incremental costs will be negative, thus decreasing the total roading cost *RC(x)*.

Calculation:

1. If *link(s)*=0,
   road cost change is 0. END
   Otherwise, set l = *link(s)*
2. If l is not included in a path, add l to the cheapest of the two possible paths.
3. Set $x_s = k$
   Calculate smin = $\min_{m \in S_l}(x_m)$, the earliest period required by all stands, and
   rmin = $\min_{m \in Sons(l)}(r_m)$, the earliest period required by preceding links. Then
   $p = min(smin, rmin)$ is the period required for this link.
   If $r_l = p$, road cost change is 0.0 END
4. Otherwise, calculate the re-timing cost
5. Cost = $w_{lp} - w_{l,r_l}$!cost of re-timing the link
6. Do until $l = 0$
   l = father(l) !next link in path
   $p = min(r_l, p)$!new assignment
   Cost=cost+$w_{lp} - w_{l,r_l}$!cost to re-time
   End do
7. Re-set $x_s = j$

END of Calculation

Figure 7.5. Calculating Incremental Road Cost

7.2.3.3. Deviation from Maximum Opening Size

For simplicity in describing these calculations, assume an adjacency delay time of two planning periods. Thus, each stand may belong to at most two openings. Further notation for these calculations is as follows:

a_s	*size in acres of stand s*
$Osize_k$	*Size of opening k*
$open\_dev_k$	$[Osize_k - maxopen]^+$
move_dev_open	*change in Dev_maxopen if the move is implemented*

7.2.3.4. Add Move.

In this case the stand may add to the acreage of existing openings if there are any adjacent to the stand. More specifically, the stand adds to any adjacent openings which are of opening period k or $(k+1)$, since *ADT* is two periods. If the stand is adjacent to

more than one opening, the move results in a merging of those openings. Thus, to calculate *Dev_maxopen*, the adjacency list of stand *s* is searched for adjacent openings. If there are no adjacent openings of period *k* or *(k+1)*, then the move incurs no additional *maxopen* penalty. Otherwise, the size of the merged openings is calculated, compared with *maxopen*, and any additional penalty incurred by the move is calculated. Figure 7.6 shows these calculations.

Let $\Omega = \{o_1^p, o_2^p, ..., o_n^p\}, p = k, k+1$ be the set of n adjacent openings for each opening period. If Ω is empty, the penalty is 0.0. Otherwise,

1. Set $move\_dev\_open = 0.0$
2. For each opening O_j^p in Ω, subtract the existing deviation, if any.
   $move\_dev\_open = move\_dev\_open - open\_dev_{o_j^p}$
3. For each opening period p,

$$Osize_p = a_s + \sum_{j=1}^{n} Osize_{o_j^p} \qquad \text{size of merged open for period } p$$

$$Move\_dev\_open = Move\_dev\_open + [Osize_p - maxopen]^+$$

Figure 7.6. Calculating Maxopen Penalty from Add Move

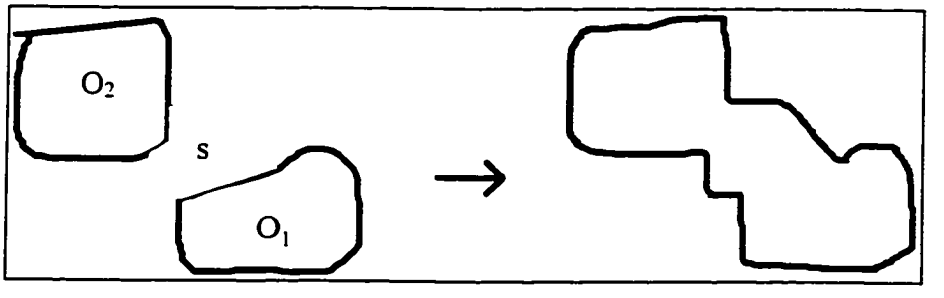


Figure 7.7. Merging Adjacent Openings

7.2.3.5. Delete Move.

If the openings in which the stand is a member are smaller than *maxopen*, deleting the stand induces no change in *Dev_maxopen*. Otherwise, the delete move will either reduce the current deviation penalty accruing from these openings, or remove it entirely. To determine the size of affected openings, we observe that removing stand *s* will

disconnect the opening graph if s is an *articulation point* of the graph [Sedgewick 1983]. Thus, the effect of deleting stand s is calculated as shown in figure 7.8.

Set move_dev_open = 0.0
For each opening o in which s is a member:
1. If $Osize_o - a_s \leq maxopen$, then
$move\_dev\_open = move\_dev\_open - Open\_dev_o$
2. Otherwise, if s is an articulation point of the opening, (Figure 7.8)
Using depth first search, find the set V of connected subgraphs of $O'_o = O_o \setminus s$. For each v in V, calculate the deviation penalty. Then,
$move\_dev\_open = \sum_{v \in V} Open\_dev_v - Open\_dev_o$
3. If s is not an articulation point of the opening o, (Figure 7.6)
$move\_dev\_open = [osize_o - a_s - maxopen]^- - Open\_dev_o$

Figure 7.8. Calculating Maxopen Penalty from Delete Move

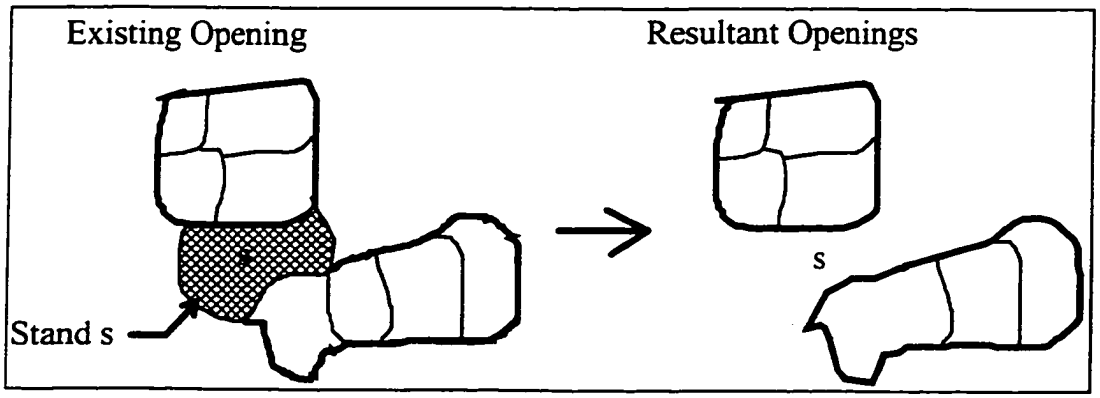


Figure 7.9. Splitting an Opening

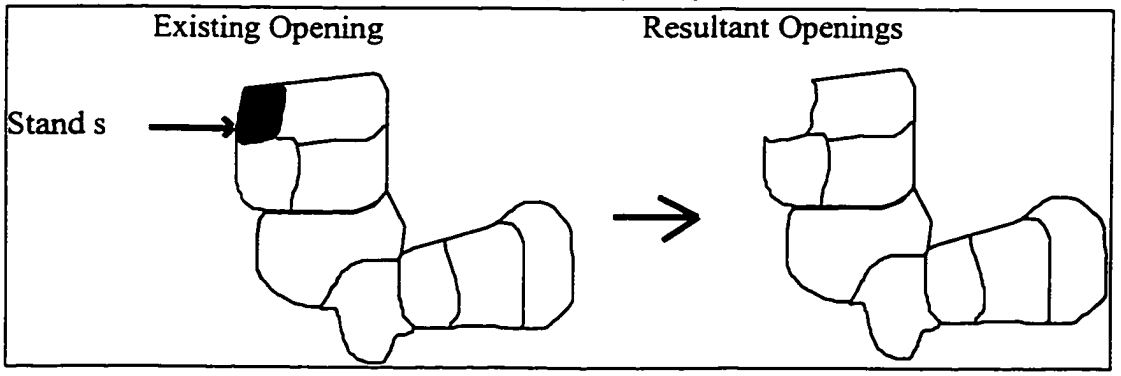


Figure 7.10. Reducing an Opening

7.2.3.6. Swap Move.

In this case, the total change in deviation from maxopen is the change incurred by deleting the stand from period j and that of adding it to period k. In the case where the move is to shift the stand assignment by one period, some efficiency can be gained by not calculating openings that do not change. For example, if a stand is to be moved from period 1 to period 2, it will be removed from openings of period 1 and added to openings of period 3.

7.2.3.7. Harvest Target Deviations

Deviations from periodic and total harvest targets are determined from the current harvest and the volume which would be added or deleted to or from each period by the move. Denote by $H(j)$ the total volume harvested in period j, and by TH the total harvest for the current solution. Then, for the move which changes the assignment of stand s from period j to period k,

$$\begin{aligned} H(j) &= H(j) - V_{sj} && j \in [1, J] \\ H(k) &= H(k) + V_{sk} && k \in [1, J] \\ TH &= TH - V_{sj} + V_{sk} && j, k \in [1, J] \end{aligned}$$

and the resulting deviations are

$$dev\_total = \left[|TH - TV| - dTV \times TV \right]^{+}$$

$$dev\_periodic = \sum_{j=1}^{J} \left[\left| H(j) - PV_j \right| - dPV \times PV(j) \right]^{+}$$

7.3. Special Diversifying Moves

In the RTS and ORTS algorithms, a set of special diversifying moves (called ESCAPES) is invoked when the search history indicates that the trajectory is cycling "chaotically " [Battiti and Tecchiolli 1995]. These "escapes" are also used to diversify the search when no improvement has been observed for a sufficiently long time.

These diversification schemes serve two purposes. First, they increase the flexibility of the algorithm in "escaping" from a local optimum or in "jumping" to a new area of the solution space. Secondly, the stochastic nature of the moves increases the robustness of the algorithm. This effect was indicated in empirical tests by a reduced variance in samples from algorithms which included ESCAPES. (See Chapter 8).

Two types of diversification moves were tested. The first, *ESCAPE1*, selects a random sample of stands and either deletes them from or adds them to the harvest, according to whether or not a stand is currently in or not in the harvest solution (figure A.3). As in the *R-Tabu* [Battiti and Tecchiolli 1995] algorithm, the size of the sample is chosen to be proportional to the moving average of detected cycle length: (For OTS and FTS, a constant number of random moves, proportional to the number of stands, was chosen.)

$$\{\{sample\_size = \lceil r \times moving\_average \rceil, r \in U[0,1]\}\}.$$

The second strategy, *ESCAPE2*, is to randomly select a road link in the solution and remove it, and every preceding link in its path, from the solution. This is done by executing delete moves for each stand that are in the current solution and which require any element of the path. The road network is then re-calculated using *PH*. In the example in Figure 7.11, if link *i* is selected, stands which require links *i,j,k,l* and *m* must all be deleted.

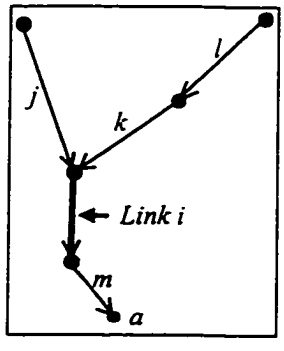


Figure 7.11. ESCAPE2 Link Selection

The motivation for this type of escape routine comes from considering the relationship between stands and road links. One road link may serve many stands, but one stand requires at most one link. Thus, evaluation of single stand moves is not effective in directing the search towards solutions that have different roading structure. Add moves favour adding road links when the loss penalty would be reduced by more than the road cost incurred. Once a link is in the solution, subsequent add moves incur no further roading costs. Thus, it is unlikely that a sequence of moves that would cause a link to be deleted (assigned to period $J+1$) or re-timed (moved from current assignment to a later one) will be chosen. This is because there is no direct mechanism in the stand-based move evaluation to predict the objective function change would occur by removing or re-timing road links. For this reason, the diversifying escape moves are based on choosing a link and removing it, and all stands requiring it, from the solution. As in *ESCAPE1*, the tabu status of each stand is set after it is deleted. *ESCAPE2* is outlined in figure A.4.

This type of diversification was not used in algorithms *FTS* and *OTS* since it is difficult to choose link deletion moves that maintain feasibility. For *ORTS* and *RTS*, the *ESCAPE2* strategy worked less well than expected. Further investigation of the algorithm performance led to changing the method. Instead of selecting any link in the road network, the procedure was changed to select the link that is a leaf of the road network graph, and which contributes the greatest reduction in roading costs if it is re-timed. This leaf link was then re-timed one period forward from k to period $(k+1)$. That is, for each stand associated with the link, its harvest assignment was set to the larger of its current assignment and $(k+1)$. This diversification produced better results on the datasets which were tested.

The final diversification strategy, *ESCAPE3*, is a combination of *ESCAPE1* and

ESCAPE2. If the number of links in the current road network is less than 10% of total, the stand escape routine *ESCAPE1* is chosen, otherwise *ESCAPE2* is chosen. See figure A.5.

7.4. Fixed Tabu Search Algorithm (FTS)

As described in Chapter 3, the fixed tabu search method has a fixed tabu tenure *tabu_tenure*, and moves are restricted to those which produce feasible outcomes. The objective function is the sum of the lost volume penalty and the roading cost, $z = LV+RC$. This method was tested for various settings of *tabu_tenure*. The trend was that larger values of *tabu_tenure* gave better results, but of course as *tabu_tenure* grows, the system eventually runs out of feasible moves. Although FTS was not expected to perform well here due to the complex nature of the maxopen constraints, and the restrictive nature of the harvest target constraints, experimentation with this relatively straightforward TS method was included to provide a baseline against which to compare the more sophisticated algorithms [Barr et al 1995].

7.5. Oscillating Tabu Search Algorithm (OTS)

This is an implementation of the principle of strategic oscillation [Glover 1990a, Kelly, Golden and Assad 1992]. The method of dynamic penalty parameters, as reported by Gendreau et al [1991] for the vehicle routing problem, was used to control the search trajectory.

Recall that the objective function with penalty terms is

$$z'(x) = LV + \rho\ RC(x) + \alpha\ Dev\_total + \beta\ Dev\_per + \gamma\ Dev\_maxopen$$

The best move chosen in neighbourhood search is that with the lowest value of z'. For feasible solutions *xfeas*, $z'(xfeas) \equiv z(xfeas)$, while for infeasible solutions, one or more of the penalty terms is positive. Initially, α,β and γ are set to a large value,

upper_bound. After each move *m*, a counter is incremented for each penalty term that is zero in $z'(x \oplus m)$. After *check_interval* steps have been taken, each penalty parameter is increased (doubled) if its counter is equal *check_interval*, or decreased (halved) if its counter is zero. This has the effect of increasing the weighting on constraints which have not been satisfied for the last *check_interval* iterations and decreasing the weighting on constraints which have been violated for all steps. Thus, the penalty parameters pull the solution in and out of the feasible region systematically.

The interaction between the special diversification moves and the best setting for the penalty parameters was studied, and it was determined empirically that best results were achieved when α,β, and γ were set to 1.0 after a diversification required by chaotic cycling, and set to maximum value after a diversification implemented due to no improvement. This is an experimental result only; however it is logical. Setting penalty parameters to 1.0 gently pulls the solution back to the feasible region. Setting parameters to *upper_bound* radically (more quickly) yanks the solution back to the feasible region.

7.6. Reactive Tabu Search Algorithms (RTS)

The flowchart in figure 7.12 outlines the methodology used to track cycling to previously found solutions, and to use this search history information to dynamically set *tabu_tenure*. This procedure is the same basic method as in Battiti and Tecchiolli [1995], except that it was extended to use the solution value ($z = LV + RC$) to detect collisions, and use linear probing to resolve the hashing address in the case of collisions.

7.6.1. RTS Data Structures and Cycle Detection

The *RTS* structures are a hashing table of fixed size *table_size*, a configuration table with entries $z = LV + RC$; the solution value, *num_reps;* the number of times that solution has been repeated and *time_last_found;* the time of the last repetition. At each

iteration of the algorithm, a hash address for the solution x is calculated. If this address has been used previously, the current solution $z(x)$ is compared with the solution value stored for that hash address. If they are equal, then this is assumed to be a repeated solution, and the cycle length is calculated. Cycle length is the number of steps in the solution trajectory since the solution was last encountered. If this cycle length is less than the parameter *cycle_max*, the moving average of cycle length is updated, and tabu tenure is increased by a factor of 1.1. The effect of the exponential increase in *tabu_tenure* is to "break" the cycling to previous solutions, thus promoting search diversification.

When a new solution is found, its hashing table entry is updated (with a pointer) and the solution value and *move_count* stored If the number of iterations since *tabu_tenure* has been changed (counted in variable *steps_since_size_change*) is greater than the moving average of cycle length, the tabu tenure is decreased by a constant factor. Thus, the search trajectory is less constrained when a suitable number of steps have been taken without returning to a previous solution, and thus may be intensified in the new search region.

If the neighbourhood search finds no non-tabu moves, tabu tenure is decreased. Thus, the RTS algorithms do not terminate on finding that all moves are tabu.

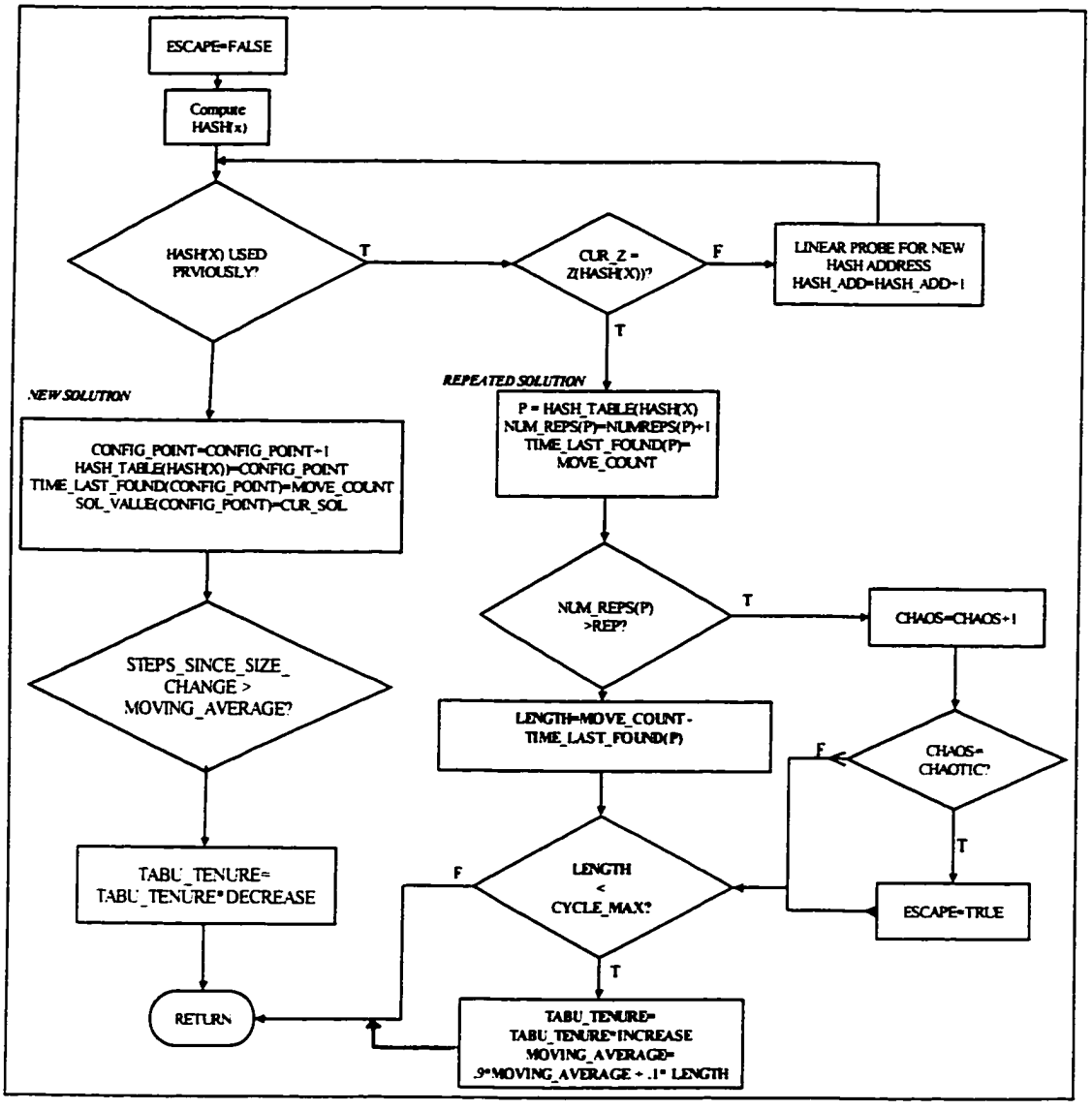


Figure 7.12. Update RTS Structures

7.6.2. Hashing Address Computation

The hashing function is a mapping from a solution x to an integer in the range [0,*table_size*]. It is determined by the following computation:

Denote by ls(I) a left cyclic bit shift of the integer I

$H_1 = x_1$

$H_n = ls(H_{n-1}) \times x_n; \quad n = 2,S$

$H(x) = H_S \ mod \ table\_size$

That is, the hash function iteratively computes the product modulo w of each x_i, first left shifting the previous product. (w is the word size of the integer H) Then, the hash address is the result of these products taken modulo *table_size*. This is a recommended method for dealing with hashing of vectors with multiple identical entries [Knuth 1973]. In this problem, the solution vector $\boldsymbol{x}$ will have entries in the range $[0,J+1]$, thus only $J+2$ possibilities. There are likely to be a preponderance of entries equal to $(J+1)$. Thus, the hashing table size was chosen so that it is a prime number which does not divide $(J+2)^k \pm a$ for small values of k and a. That is, *table_size* is chosen to be prime so that $(J+2)^k$ is not congruent to a modulo *table_size*. For the Shulkell study area, *table_size* was chosen to be 50027. A small study was done to estimate the number of collisions (cases where the hashed address for a new solution is equal to that of a previously encountered solution) that would be expected with this size of table. 5000 randomly generated solutions yielded 234 collisions. Although this number is small (approx. 4.68%), it was decided to include collision resolution by linear probing. The key used for collision resolution is the solution value. Thus, if $H(x)$ is already used, and its associated z does not match that of the solution x, the table $H(x)$ is linearly searched for unused slots. The expected cost of collision resolution is small (See Knuth 1973 for a comprehensive description of hashing.).

7.7. Oscillating Reactive Tabu Search Algorithm (ORTS)

This algorithm combines the feedback parameter tuning of RTS and strategic oscillation through boundaries of the feasible region of OTS. The ORTS method

produced solutions that were better or comparable to OTS, but with a reduced variance in solution quality in samples obtained from a set of random initial solutions. Moreover, no experimentation is required to determine an appropriate duration for tabu tenure. Thus, this is the recommended algorithm and the one which was used to produce tradeoff curves for the datasets. The ORTS algorithm in its final form is outlined in figure 7.13.

This algorithm uses the *ESCAPE3* diversification strategy in two places. The first when either the *chaotic* variable indicates that the solution trajectory has returned too many times to the same solutions. When the diversification moves have been taken, the penalty parameters are each set to 1.0. This causes the search trajectory to be drawn smoothly to the feasible region. The second instance where diversification is invoked is when no improvement in the solution has been found for 300 moves. After effecting the diversification, penalty parameters are set to their maximum value *upper_bound.*

1. Preprocessing and Initial Solution
2. Initialize Data Structures
3. Repeat *RTS* for *check_interval* iterations

RTS:

3.1 Implement move and update best solution found.

3.2 Compute Hashing address *H(x)* for current solution.

3.2.1 If *H(x)* is used, then this is a repeated solution.

Update number of repetitions for this move, and calculate the cycle length.

If the cycle length is less than cycle max:

Calculate the moving average of cycle length.

Increase tabu tenure.

If the number of repetitions for this solution has reached 3, add one to the chaotic counter.

If the chaotic counter has reached 3, return *escape = .true.*

3.2.2 Otherwise, this is a new solution:

Store new solution *H(x)* and *z* in *hash_table.*

If the number of moves since tabu tenure has been changed is greater than *moving_average:* decrease *tabu_tenure*

Return *escape=.false.*

3.3 If escape is true:

Call Diversification Routine

Set penalty parameters to 1.0

3.4 Neighbourhood Search.

3.5 If no move is found:

Decrease tabu tenure

Goto Neighbourhood Search

END RTS

4. Update penalty coefficients.
5. If diversification is required

Call diversification routine

Set penalty parameters to *upper_bound.*

6. If Stopping rule is true

Report solution and Stop

7. Go to Step 3.

Figure 7.13. ORTS Algorithm

CHAPTER 8

EMPIRICAL RESULTS: SHULKELL STUDY REGION

This chapter documents numerical results of several experiments which were carried out to compare the tabu search algorithms that were described in Chapter 7. The data for these tests is based on the GIS coverage of a region of Cumberland County in Nova Scotia, Canada. This data was then manipulated to produce five additional datasets. Baselines were produced using FTS, OTS and RTS algorithms. The ORTS method, which combines the dynamic penalty parameter evaluation function of OTS and the reactive search methods of RTS, was then compared to the baseline results. With ORTS, the best form of the starting solution and the best diversification strategy was determined. This algorithm was then used to produce tradeoff curves for all datasets.

This chapter is organized as follows. First, the study region characteristics and datasets used to validate the algorithms are described. Then, a comparison of different algorithms based on solution quality and range of solutions is given. The ORTS algorithm variants are described and the results of comparative analysis presented. Tradeoff curves for each dataset are then shown, and discussed.

8.1. Study Region and Model

A section of the Chignecto Management Unit, in Cumberland County, Nova Scotia, consisting of crown lands on map sheets D21H10T2 and D21H10T4, was chosen to test the algorithms. (Figure 8.1) The Shulie and Kelly rivers are the major waterways in the area, and hence the name SHULKELL was coined for this portion of the

management unit. There are several main roads (the Aub Brown, Bucktogen, Goodwin, Tipping and Meadow Brook roads) which crisscross an area of 5239 hectares. 4493 hectares are in 1039 forested stands, the remainder being barren, swamp or bog (Table 8.1).

Figure 8.1 Image of the Shulkell Study Area

8.1.1. Characteristics of the Forested Stands

Nearly half of the SHULKELL area is in stands of age 41-60 years, accounting for 65% of the merchantable volume (Table 8.2). Stands of age 61-80 years represent 9.6% of the area and contribute 23.5% of the merchantable volume, while only three stands are of age greater than 80 years.

61% of the area is in softwood stands, 36.5% in hardwood stands and 2.5% in

mixedwood stands (Table 8.3). The majority of the area (59.4%) is comprised of natural, untreated and unmanaged stands. 4% of the area has been recently clearcut and 4% is in managed plantations. The remaining 32% is classified as "dead", meaning that evidence of dead material (standing or fallen) was found. Sub-classifications dead, dead-1 and dead-2 further categorize dead stands as to the amount of live residual material on the stand (less than 25%, 26-50% and 51-75% of crown closure respectively) [Province of Nova Scotia 1992]. These dead stands are the shaded areas in figure 8.1.

Table 8.1. Shulkell Region Land Types

Non-Forested		**Forested**	
Land Type	***Hectares***	***Land Type***	***Hectares***
Bog	341.38	Natural	2,669.52
Brush	111.81	Dead	1,466.46
Barren	70.77	Plantation	182.00
Alders	199.51	Clearcut	175.28
Marsh/Swamps	20.37		
Miscellaneous	2.00		
Total Non-Forested	***745.84***	***Total Forested***	***4,493.25***

Table 8.2. Distribution of Forested Stands by Age and Merchentable Volume

Age Range	**Stand Count**	**Area (Hectares)**	**% of Total Area**	**Merch. Vol. (Cubic Metres)**	**% of Total Merch. Vol**
0-20	162	1,138.0	25.33%	104.3	0.03%
21-40	198	749.8	16.69%	22,471.6	7.28%
41-60	540	2,044.9	45.51%	201,248.8	65.20%
61-80	103	429.6	9.56%	72,396.4	23.46%
81-100	3	18.5	0.41%	2,411.4	0.78%
All Aged	33	112.5	2.50%	10,020.1	3.25%

Table 8.3. Stands by Cover Type

Covertype	Merch. Vol. (m^3)	Merch Vol. (% of Total)	Area (Hectares)	Area (% of Total)	Stand Count
Unclassified	0	0.00	764	17.00	94
Softwood	188,411	61.00	2,546	56.70	651
Mixedwood	7,629	2.50	144	3.20	38
Hardwood	112,312	36.50	1,039	23.10	256

Table 8.4. Shulkell Stands by Stand Type

Stand Class	Merch. Vol. (m^3)	% of Total Merch. Vol.	Hectares	% of Total Hectares	Number of Stands
Natural	256,429	83.1%	2,670	59.4%	722
Dead	79	0.0%	594	13.2%	73
Dead-1	31,764	10.3%	716	15.9%	153
Dead-2	20,380	6.6%	157	3.5%	44
Plantation	0	0.0%	182	4.1%	23
Clearcut	0	0.0%	175	3.9%	24
Totals	308,653	100.0%	4,493	100.0%	1,039

8.1.2. Alternate Datasets

Alternate datasets were generated from the Shulkell data to test robustness of the algorithms. The datasets were produced by manipulating the age of all stands except those classified as dead or clearcut. To maintain the distribution of stands across age-classes, a discrete probability distribution for ageclass was created from the Shulkell dataset. Then, the new ages were generated by drawing a random sample of ages from the empirically determined distribution. Five new datasets were generated Images of all datasets are in Appendix B, Figures B.1 to B.6. Figures B.7 and B.8 show the relative distribution of stands by ageclass in these alternate datasets.

8.1.3. Roading Network

Existing main roads and the proposed road network are shown in Figure 8.2. The proposed road network has 135 links (edges) and 125 nodes representing a total of 68.7 kilometres of potential road building. The roading network was developed with some assistance from Nova Scotia Dept. Lands and Forests personnel. This was then mapped onto the GIS coverage of the forest area using ARCVIEW™. Each stand which extended further than .5 km from a main road was assigned the road link which was nearest. This stand to road link assignment was performed manually, with the assistance of the ARCVIEW™ software. 274 of the stands are accessible by main road. The remainder (765 stands) require the construction of at least one road link if they are to be harvested.

Figure 8.2. Shulkell Area Road Network

8.1.4. Model Parameters

The planning horizon is a total of 20 years in four 5-year periods. Adjacency delay and maximum opening sizes were determined from the Province of Nova Scotia [1990] Forest/Wildlife Guidelines and Standards. The maximum opening size is 50 hectares, except for openings which include dead stands. In this case, the acreage contributed by a dead stand is weighted by a factor of 0.5. This is to represent the decreased insistence on a maximum opening size in the spirit of the guidelines [Province of Nova Scotia 1990]. The total harvest volume target of two million (solid) cubic feet was determined by using the SAWS simulation and optimization program [Gunn 1994b]. Model parameters are shown in Table 8.5.

Table 8.5. Model Parameters

Planning Period Length	5 years
Planning Horizon	4 periods
Total Volume Target	2,000,000 cubic feet
Periodic Volume Target	500,000 cubic feet
Percentage Deviation from Total	2%
Percentage Deviation from Periodic	4%
Adjacency Delay Time	2 periods
Maximum Opening Size	50 hectares
Maxopen factor on Dead stands	50%
Cost/Km of Road Construction	$5,000
Annual Discount Rate	10%

The Revised Growth and yield tables for Nova Scotia Softwoods [Province of Nova Scotia 1993] were used to provide the mai curves for the datasets. For this study, the softwood covertype was arbitrarily assigned to all stands, and the second-rotation, natural stand growth model was used. Thus, the dataset represents the area in the spatial configuration of stands, but growth and volume data are not necessarily true values.

8.2. The Algorithms

Fixed Tabu Search, Reactive Tabu Search with and without random diversification, Oscillating Tabu Search and Oscillating Reactive Tabu search algorithms were tested. All results reported in this section are based on an equal weighting of road cost and lost volume factors in the objective function, and were produced using the SHULKELL dataset.

8.2.1. Fixed Tabu Search

The Fixed Tabu Search (FTS) algorithm (as described in the previous chapter) allows only feasible moves, and its only free parameter is *tabu_tenure*. Samples (size 30) of solutions were generated for nine settings of *tabu_tenure*. The search was terminated after 5000 iterations (neighbourhood searches) or if no feasible non-tabu move was found. Table 8.6 shows the sample mean, best (minimum) solution, standard deviation, average number of steps taken (Mean T), number of steps to reach the best solution and exit status for the run which achieved the best solution.

First, observe that as tenure is increased to 360 and 410, the program exits with no feasible moves found. Secondly, as tabu tenure is increased, a general decrease in standard deviation occurs, until tenure reaches 310. The search appears to be inefficient for larger values of tabu tenure, since the best move is found very early in the search. This indicates either an over-constrained search trajectory or a lack of diversification in the search, with the trajectory being "stuck" at the local optimum found. By observation, the quality of the solution obtained and the standard deviation of the sample varies significantly with the value of *tabu_tenure* which is chosen. (See table 8.6) The best observed solution for this instance is 494,293; it is found for *tabu_tenure* equal to 310.

Table 8.6. FTS Solutions

Tenure	Mean Z	Best Z	Std. Dev.	Mean T	Time of Best	Exit Status
10	589,963	562,467	17,212	1,345	4107	Max iterations reached
60	571,098	542,240	17,017	2,862	2102	Max iterations reached
110	561,668	538,072	14,305	2,046	1109	Max iterations reached
160	556,369	536,441	13,286	1,921	1010	Max iterations reached
210	544,288	519,543	13,257	1,587	1429	Max iterations reached
260	533,619	512,293	12,907	1,553	1042	Max iterations reached
310	530,876	494,293	16,006	1,015	1179	Max iterations reached
360	536,122	509,467	16,461	646	932	No Move Found
410	539,866	524,106	12,572	530	521	No Move Found

8.2.2. Fixed Tabu Search with Random Diversification Moves (FTSESC)

Next, the FTS algorithm was augmented with random diversification moves. As described in chapter 7, these moves are a random selection of stands which are then added or deleted from the harvest. All moves, including the diversification moves, must be feasible. These random moves were invoked whenever the search had executed 200 iterations without finding an improved best solution. The search was terminated when 5000 iterations were completed and at least 500 iterations since the last execution of diversification moves had been taken. This enhancement was tested on the same thirty initial solutions as was done for FTS (Table 8.7).

To compare FTSESC and FTS, percentage difference in solution value found and standard deviation for each tabu tenure were calculated (Table 8.8). Average solution value was better or nearly the same for all selections of tabu tenure. The standard deviation for FTSESC was significantly lower for some cases (tenure = 10, 60, 160, 260, 310) The best solution obtained by FTSESC was less than that of FTS in all but the case where tabu tenure = 310, yet the percentage difference was at most 5.14%. Thus, although these diversification moves improved the algorithm in some cases, the

dependency on *tabu_tenure* still affects results.

Table 8.7. FTSESC Solutions

Tenure	Mean z	Best z	Standard Deviation
10	573927.3	533580.4	15797.32
60	562187.8	541226.3	13891.18
110	552213.8	525635.7	15053.7
160	547635.6	527543.6	10042.51
210	540197	513337.4	2542.267
260	535001.5	511371.9	9270.136
310	534384.3	502723.8	14480.9

Table 8.8. Percentage difference in FTS over FTSESC

Tenure	**Mean**	**Best**	**Standard Deviation**
10	2.79%	5.41%	8.96%
60	1.58%	0.19%	22.50%
110	1.71%	2.37%	-4.97%
160	1.59%	1.69%	32.30%
210	0.76%	1.21%	4.28%
260	-0.26%	0.18%	39.23%
310	-0.66%	-1.68%	10.53%

8.2.3. Reactive Tabu Search (RTS)

This algorithm is a straightforward implementation of *R-Tabu* [Battiti and Tecchiolli 1995]. The search is confined to the feasible region, and *tabu_tenure* is varied as cycles are detected. The hashing function *H(x)* is as described in section 7.6.2 with linear probing to resolve collisions. Cycles of length less than or equal to fifty moves are used in calculating the moving average of cycle length, and tabu tenure is increased upon detection of a repeated solution. Tabu tenure is decreased by a factor of 0.9 after a number of moves (equal to *moving_average*) have been executed without repeating a solution. If three solutions have been repeated three times, the system is assumed to be

chaotically cycling and the *ESCAPE1* diversification sequence is executed.

Two versions of RTS were tested. The first, RTS1, follows the R-Tabu algorithm as described above. The second, RTS2, is augmented by diversification moves (as in FIXEDESC) when a large number of steps have been taken without improvement in the best solution. RTS2 produced slightly better results than RTS1, and standard deviation of the sample for RTS2 was significantly lower (15.96%). Surprisingly, RTS did not find better solutions than FTS. The reasons for this were not made apparent by the experiments.

	RTS1	RTS2	100(RTS2-RTS1) /RTS1
Mean	586,292	582,893	-0.58%
Best	552,214	551,724	-0.09%
Worst	618,664	614,001	-0.75%
Std. Dev.	18,062	15,182	-15.95%

Table 8.9. Reactive Tabu Search Results

8.2.4. Oscillating Tabu Search (OTS)

Oscillating tabu search, as described in Chapter 7, guides the search trajectory in and out of the feasible region. There are three constraint sets, (restrictions on total and periodic harvests and maximum opening size constraints) for which penalty parameters α, β and γ are defined. Thus, (recall that ρ is used only to examine tradeoffs), the objective function $z'(x) = LV(x) + \rho\, RC(x)$ is replaced with

$$z'(x) = LV + \rho\, RC(x) + \alpha\, Dev\_total + \beta\, Dev\_per + \gamma\, Dev\_maxopen$$

Parameters α, β and γ are initially set to their upper bound, and are increased (doubled) or decreased (halved) according to the feasibility of the previous set of ten solutions with respect to each penalty term. *Tabu_tenure* is the only free parameter. The

stopping rule terminates the algorithm at a maximum number of iterations (*maxiters)* with no improvement in the last 300 iterations. Figure 8.3 shows a sample OTS solution trajectory.

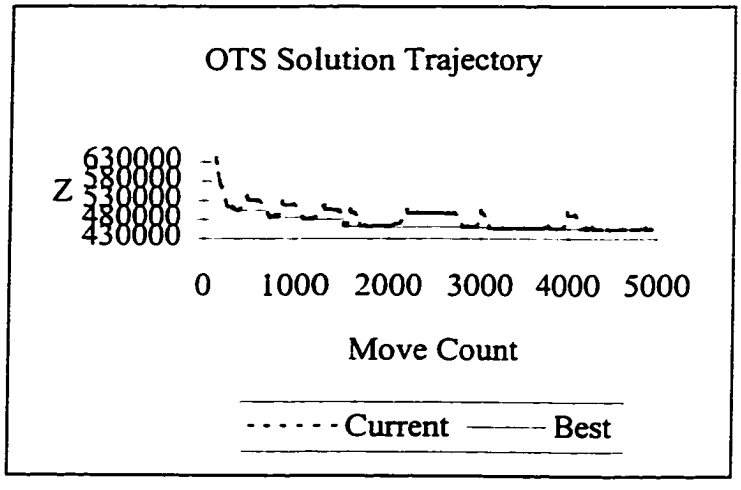


Figure 8.3. OTS Solution Trajectory

The OTS algorithm out-performs FTS, FTSESC, RTS1 and RTS2 with consistently better average and best solutions (See table 8.10). As for determining a value of tabu tenure that is "best", these results are somewhat inconclusive. The best solution was found with *tabu_tenure* at 40, the lowest sample average solution was for *tabu_tenure* equal to 70, and the tightest range of solutions was found with tenure equal to 50.

8.2.5. Oscillating Reactive Tabu Search

Oscillating Reactive Tabu Search (ORTS) is a hybrid of the reactive tabu search and strategic oscillation methods. ORTS includes the expanded neighbourhood of OTS, and eliminates the need to pre-set *tabu_tenure* by implementing the *R-Tabu* feedback mechanisms.

Several variant algorithms were examined. Some minor algorithm design issues are setting RTS parameters for *cycle_max, increase, decrease*, and determining the best

method for modifying penalty coefficients α, β, and γ. No significant differences were found by modifying the factors *increase, decrease and cycle_max*. Thus these parameters were set to 1.1, 0.9 and 50 respectively.

Table 8.10. OTS Statistics

Tenure	Maxiter	Mean	Best	Worst	Std. Dev.
10	5000	466,461	426,962	494,487	18,093
10	8000	461,499	426,962	494,487	19,075
20	5000	457,806	424,731	492,361	14,895
20	8000	449,631	415,225	478,257	16,402
30	5000	450,222	423,815	474,724	13,367
30	8000	444,960	416,515	474,274	14,707
40	5000	449,042	415,347	486,525	15,843
40	8000	439,590	**407,128**	476,982	16,704
50	5000	440,029	413,195	472,798	15,220
50	8000	430,477	413,195	455,075	**10,692**
60	5000	444,664	414,692	494,833	18,431
60	8000	436,171	414,019	482,642	15,858
70	5000	436,507	413,103	468,319	15,951
70	8000	**428,906**	410,887	467,525	12,588
80	5000	437,960	414,460	475,529	17,258
80	8000	432,034	410,721	475,529	17,409
90	5000	438,284	411,317	484,410	17,296
90	8000	429,619	411,317	**453,426**	10,945
100	5000	435,571	416,943	481,530	15,569
100	8000	431,492	412,454	480,716	14,531

The major design issues are to produce an effective diversification strategy and to integrate this strategy with strategic oscillation. Amongst diversification strategies, the *ESCAPE3* method, which uses a combined stand and link based strategy (section 7.3) was found to be the best. This section documents results from comparisons of five ORTS algorithms (Table 8.11). It was found that, for this problem, it was important to start with a feasible solution, and that the ESCAPE3 diversification mechanism was the most effective. Table 8.12 contains statistics from a sample of thirty different starting

solutions on the SHULKELL dataset. ORTS outperformed the other schemes with the best solution and lowest sample average. The sample standard deviation was higher than ORTSB1 and ORTSB2, but not significantly so. Thus it was concluded that this ORTS algorithm was the best found so far. It remained to determine robustness of the algorithm across different datasets and the differing cost coefficients which occur when ρ is varied.

Evidence that ORTS is a robust algorithm is presented in Table 8.13. ORTS was run on each dataset for values of ρ ranging from 0.1 to 20. Thus, it was tested on 114 problem instances. Tables D.1 to D.6 contain sample statistics for each dataset and each value of ρ. Each instance was repeated for thirty different starting solutions. Table 8.13 shows the coefficient of variation for each sample. The worst case is on SHULKELL for ρ equal to 0.1 and 0.2 where standard deviation is less than five percent of the mean.

Table 8.11. ORTS Algorithm Features

ORTSA1	Starting Solution may *not* be feasible to maxopen. ESCAPE1 diversification.
ORTSB1	Starting Solution may *not* be feasible to maxopen. ESCAPE2 diversification
ORTSA2	Starting Solution *feasible* to maxopen. ESCAPE1 diversification
ORTSB2	Starting Solution *feasible* to maxopen. ESCAPE2 diversification
ORTS	Starting Solution *feasible* to maxopen. ESCAPE3 diversification

Table 8.12. ORTS Sample Results

COMPARISON OF ORTS VARIANTS ON SHULKELL DATASET					
	ORTSA1	ORTSB1	ORTSA2	ORTSB2	ORTS
Mean	427,647	427,031	425,306	425,011	416,191
Standard Deviation	5,277	4,627	5,429	4,195	4,907
Variance	27,849,815	21,406,897	29,469,198	17,602,096	24,078,967
Range	18,776	16,610	22,067	18,161	16,656
Minimum	419,463	419,050	415,831	414,865	406,966
Maximum	438,239	435,661	437,898	433,026	423,622

Table 8.13. Coefficient of Variation

ρ	SHULKELL	SET 1	SET 2	SET 3	SET 4	SET 5
0.10	4.94%	2.88%	2.39%	2.41%	1.68%	1.62%
0.20	4.61%	3.65%	2.35%	3.00%	2.32%	2.53%
0.30	2.45%	2.46%	2.13%	2.32%	2.12%	1.61%
0.40	2.51%	3.23%	2.95%	2.96%	1.77%	2.20%
0.50	1.70%	2.30%	1.97%	1.90%	1.35%	1.48%
0.60	1.92%	2.45%	2.98%	1.85%	1.57%	2.24%
0.70	2.22%	2.04%	1.97%	1.48%	1.21%	1.32%
0.80	1.48%	2.20%	1.49%	2.06%	1.08%	1.42%
0.90	2.39%	1.71%	1.73%	2.12%	0.83%	1.51%
1.00	1.17%	3.00%	3.08%	2.57%	1.08%	1.19%
2.00	0.92%	1.80%	1.91%	1.09%	1.02%	1.13%
3.00	0.78%	0.93%	1.17%	1.11%	0.97%	0.98%
4.00	1.25%	1.03%	1.48%	0.96%	0.55%	1.65%
5.00	1.13%	1.29%	0.64%	1.26%	0.51%	1.51%
6.00	1.20%	1.98%	1.12%	1.27%	0.78%	1.34%
7.00	0.86%	1.13%	0.98%	0.81%	0.66%	0.99%
8.00	1.14%	0.94%	0.87%	0.41%	0.75%	0.84%
9.00	1.31%	0.97%	1.09%	0.48%	1.82%	2.32%
10.00	2.21%	0.87%	2.09%	1.94%	1.78%	1.74%
11.00	3.36%	3.52%	2.07%	2.57%	1.99%	2.52%
12.00	2.78%	2.69%	1.87%	2.80%	1.97%	2.62%
13.00	2.44%	3.07%	1.82%	2.73%	1.58%	2.17%
14.00	2.53%	3.09%	1.78%	2.66%	1.60%	2.00%
15.00	2.17%	2.93%	1.75%	1.96%	1.62%	1.84%
16.00	1.77%	2.75%	2.02%	1.60%	1.75%	1.87%
17.00	1.45%	2.11%	1.49%	2.17%	1.99%	1.66%
18.00	1.00%	1.93%	1.89%	1.73%	2.07%	1.75%
19.00	1.25%	1.53%	1.56%	1.89%	1.96%	1.67%
20.00	1.25%	1.29%	1.62%	1.36%	1.67%	1.67%

8.3. Tradeoff Analysis

Recall the objective function

$$z'(x) = LV + \rho\ RC(x) + \alpha\ Dev\_total + \beta\ Dev\_per + \gamma\ Dev\_maxopen$$

The coefficient of road cost, ρ, is a weighting factor. The unweighted roading costs are in thousands of dollars, and are discounted at 10% per year. When ρ is increased, solutions with lower roading costs are favoured by the algorithm. Similarly, decreasing ρ leads to solutions which allow more road building costs so as to reduce the lost volume penalty. The tradeoff curve is the efficient frontier for the two attributes, minimum road cost and minimum lost productivity.

Tradeoff curves were produced by varying ρ from 0.1 to 20, and running ORTS for 30 different starting solutions. Figures D.1 - D.6 are charts of these solutions. The tradeoff curve for the Shulkell dataset is in Figure 8.4. At the extremes, it "costs" 950,000 cubic feet of lost volume to spend nothing on road building. At the other extreme, spending $175,000 on road building (at $5000 per km) drives the lost volume to approx. 300,000. More importantly, increasing investment in road building to $40,000 can reduce the lost volume to approximately 425,000 ft^3, a reduction of nearly 55%. Furthermore, the curve shows that there is very little point in increasing road spending to more than $80,000 since the returns on reducing lost volume are small.

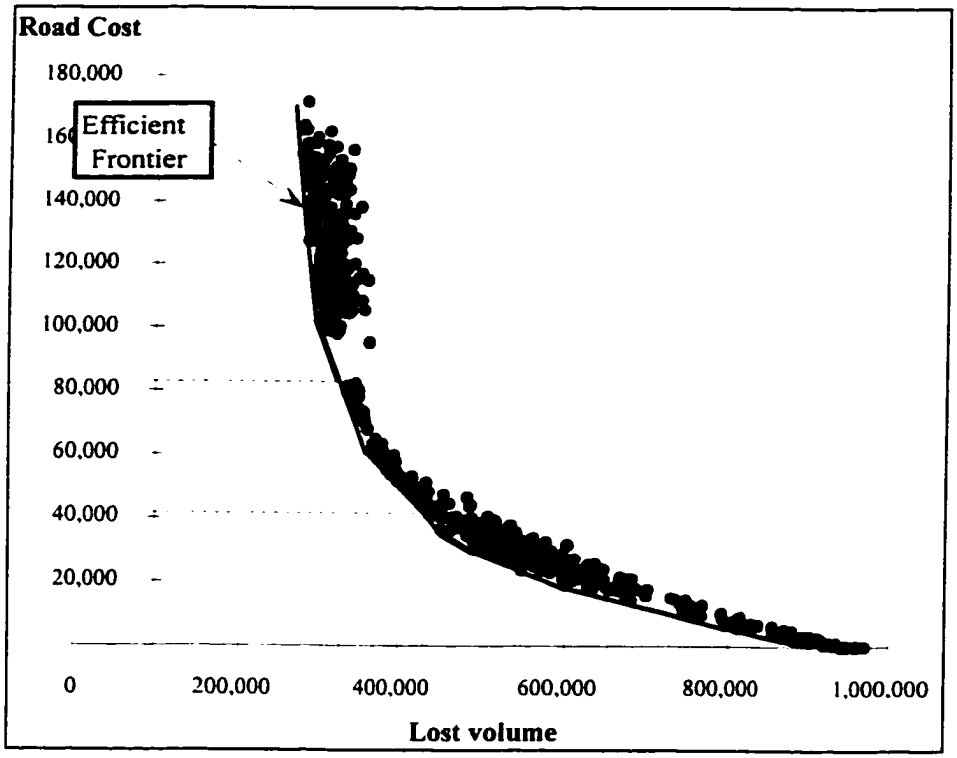


Figure 8.4. Efficient frontier for Shulkell Dataset.

Figures D.7 to D.11 show several harvest schedules, with road building costs ranging from no cost to those which incur $105,419 in road construction costs. Figures D.12 and D.13 show opening configurations for one of these solutions.

CHAPTER 9

DISCUSSION

9.1. Summary

This model and tabu search solution methodology provide a flexible framework for posing and solving forest planning problems. The model is the first to successfully deal with defining adjacency constraints on stands, with no restrictions on the number of planning periods in the adjacency delay time. The model also allows for general roading networks with multiple access points and cycles. The objective function lost volume penalty function is a very different concept from any in the forest management literature. This work has shown that it is possible to design and solve mathematical models to support the analysis of tradeoffs between competing factors such as lost production and capital cost of road building. This capability adds significantly to the decision making process -- no assumptions are made regarding the manager's tolerance for lost productivity nor his/her roading budget. Thus, the information can be used to freely analyze the substitution effects without bias.

It has been shown that tabu search methods can be used to solve this problem. The most important feature of the TS algorithm is the strategic oscillation through the feasible region boundaries. This feature is essential in obtaining good solutions -- without it all methods failed. The algorithm is enhanced with a reactive feedback mechanism to automatically set tabu tenure. This eliminates the need for a pre-solution

experiment to determine a good value of tabu tenure. It was also shown that diversification with stochastic elements is useful to narrow the range of solutions produced, and to improve overall solutions. This problem has two very clear sub-structures. The harvest scheduling portion is like a bin-packing problem, and the roading network is like a fixed-charge problem. These make for a complicated solution space and difficulties in designing a suitable move evaluation function. These barriers were addressed in the diversification strategies, by choosing moves which diversify while selectively increasing or decreasing the road network.

Successful tabu search algorithms require efficient methods to evaluate moves. This problem, which has a complex constraint structure, was successfully attacked by using some basic graph methods to deal with openings and an efficient heuristic method for calculating near-optimal road networks. The algorithm was implemented in FORTRAN, and no claims are made as to the efficiency of the coding. In fact, the program is not especially fast. It requires approximately one minute of CPU time per thousand neighbourhood searches (using an IBM R6000 Model 43P-132 computer). It is workable, however, and the importance of the information produced offsets the magnitude of computing costs.

A major design objective for the model and algorithm is portability to different problem instances. Hence, the emphasis on self-tuning for penalty parameters, tabu tenure and history-based detection of the need for search diversification. This algorithm is a framework which can be adapted to other problems.

9.2. Directions for Further Research

Some areas where further research is indicated are integer programming formulations, managing GIS systems and stand characteristics, the form of productivity

loss functions and the incorporation of different goals and objectives into the model. Extensions of the model to allow for more intervention types and for an expanded definition of stand access could prove to be useful.

9.2.1. Integer Programming Formulations

In Integer Programming formulations of adjacency, the clique constraints are the most important inequalities. For small problems, it has been shown (Chapter 3) that it is feasible to produce all of the maximal clique constraints and significantly reduce the running time of the branch and bound solution method. The number of variables in a problem formulation increases with the number of polygons, the number of intervention types and the number of periods. As problem size increases, generating all the maximal clique constraints becomes unworkable. In addition, it can be shown that there are a large number of lifted odd hole inequalities for these problems, yet experience has been that few of them are violated in LP solutions [Weintraub, Barahona and Epstein 1994]. Thus, a cutting planes algorithm, in which violated inequalities are identified and added systematically to the simplex tableau, is needed. Significant work has already been done in this area, but it has not been applied, in any great extent, to forest planning problems. Nemhauser and Sigismondi [1992] have developed a modular LP/branch-and-bound system for the node packing problem. They augment the inequality system by identifying violated maximal clique and lifted odd hole inequalities. Weintraub, Barahona and Epstein [1994] used a similar strategy in solving the *node packing* sub-problem to generate columns for the master problem in their algorithm. (They also used some other facet-defining inequalities of the *node packing* problem.)

The node packing problem is only one component of the harvest and road construction scheduling problem, however. What is not known is what other strong

inequalities, which relate the road network to adjacency constraints, are appropriate to further sharpen the LP relaxation of these models.

Thus it is suggested that sharpening the LP formulations for forest planning problems be approached from the existing foundations in cutting planes algorithms.

9.2.2. Stand types and GIS Management

This thesis proposes the use of the forest stand for the basic spatial decision unit. The reasoning is that the stand is the smallest unit which is uniform in age and future growth, and therefore must be the best choice from a biological productivity perspective. There are some problems with this choice, and some thought as to other implications of the spatial unit choice would be helpful. The first problem which was observed through the course of this work is the adjacency definitions. The practice in New Brunswick and Nova Scotia has been to define stands to be adjacent when they share a common boundary, which in the GIS is a shared arc. The GIS coverage data has, in both provinces, been "buffered". This has resulted in stands being split by road buffers, creating artificial boundaries between stands which are, in reality, adjacent or the same stand. Thus, using the GIS data in this way to define adjacency is somewhat suspect. An obvious and simple solution to this difficulty is to use a distance criterion to determine adjacency. The second problem with stands is that they are often too large, and sometimes are too small to be meaningful management choices for harvest or treatment. For example, one stand may be larger than the maximum opening size. This size difficulty can be alleviated by pre-processing the GIS data, splitting any large stands, and aggregating small and artificially fragmented stands. The third problem with stands is their shape. Areas of very irregular perimeter may be unsuitable for operational planning. (For examples of some extremely irregular shapes, see the solutions shown in

Appendix D for the Shulkell area.) This suggests that the area should be "gridded", producing regular shapes that are of a reasonable area and which are, within a tolerance level, uniform in coverage and growth. The drawback is that gridding could create more decision units (although it might in some cases reduce the set).

One point which should be noted is that this model ignores any effects on wood flow and openings resulting from road building. A possible enhancement to the model is to treat road links as special stands, which contribute volume to harvests and which also contribute to openings. This would imply that road links be analyzed, using the GIS, for forest cover and for acreage in order to calculate the wood flows from clearing a road link.

All of these considerations are issues that can be solved with appropriate management of GIS systems and appropriate attention to the impact of spatial unit choices on models, their solution, and the quality of the information they can produce.

9.2.3. Productivity Loss Functions

In this work, a lost volume penalty function has been proposed. The form of this function merits some study. For example, the function should reflect the desire of the decision-maker to access different areas in the forest, as well as deal with lost potential productivity. Thus, different forms of the lost volume function for dead stands may be designed to reflect lower or higher priority in accessing these stands.

The function proposed in this thesis uses an unweighted estimate of total lost volume to penalized less than optimal harvest scheduling. Forms which are differently weighted, or which are non-linear may be appropriate.

9.2.4. Incorporating Different Goals or Constraints.

The model framework, where all constraints are dealt with as penalty terms, is

amenable to modification to include other goals or restrictions. For example, if an end period age-class distribution for the planning area is required, this could be incorporated as another penalty term in the objective. The effect of adding more penalty terms is to increase the complexity of the oscillation procedure; although it appears that this is easily incorporated, the solution algorithm may need to be modified to effect appropriate parameter changes and to include appropriate memory structures to detect the need for diversification.

9.2.5 Other Types Of Intervention and Road Network Extensions

The model considers only one type of intervention in the forest, the clearcut. A useful extension would be to include other types of harvests, such as selective cutting or shelterwood cutting and silvicultural treatments, such as thinnings. These activities generate the same sort of requirements for roading access. No stand would be eligible for both thinning and harvesting within the tactical planning horizon, and thus only one decision variable per stand need be considered The model would need to be adjusted to deal with differences in contributions to volume and conditions for evaluating eligibility of a stand for thinning.

Contributions to volume from thinnings and selection cuttings can be estimated in the same manner that is done in the aspatial simulation [Gunn1994b]. It can be expected that the strategic plan specify a desired (aspatial) level of silvicultural activity. Also, suitability of a stand for a thinning activity could be measured with a penalty function. The objective function of this extended model would then have another penalty term, and there would be additional constraints (or penalty terms) to ensure feasibility with respect to the silviculture level targets.

Road maintenance costs could be added to this model. Each road link that is

constructed on one period and required in later periods would require maintenance. These costs would be added to the roading cost portion of the objective function, and they could be calculated in much the same way that the link timing is done in this model.

The road network model is quite general in that it allows for multiple main road access points and for cycles in the graph representing the proposed set of links. It does not allow the condition that one stand may be equally well accessed by more than one road link. This limitation should be addressed in future work.

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APPENDIX A

FLOWCHARTS

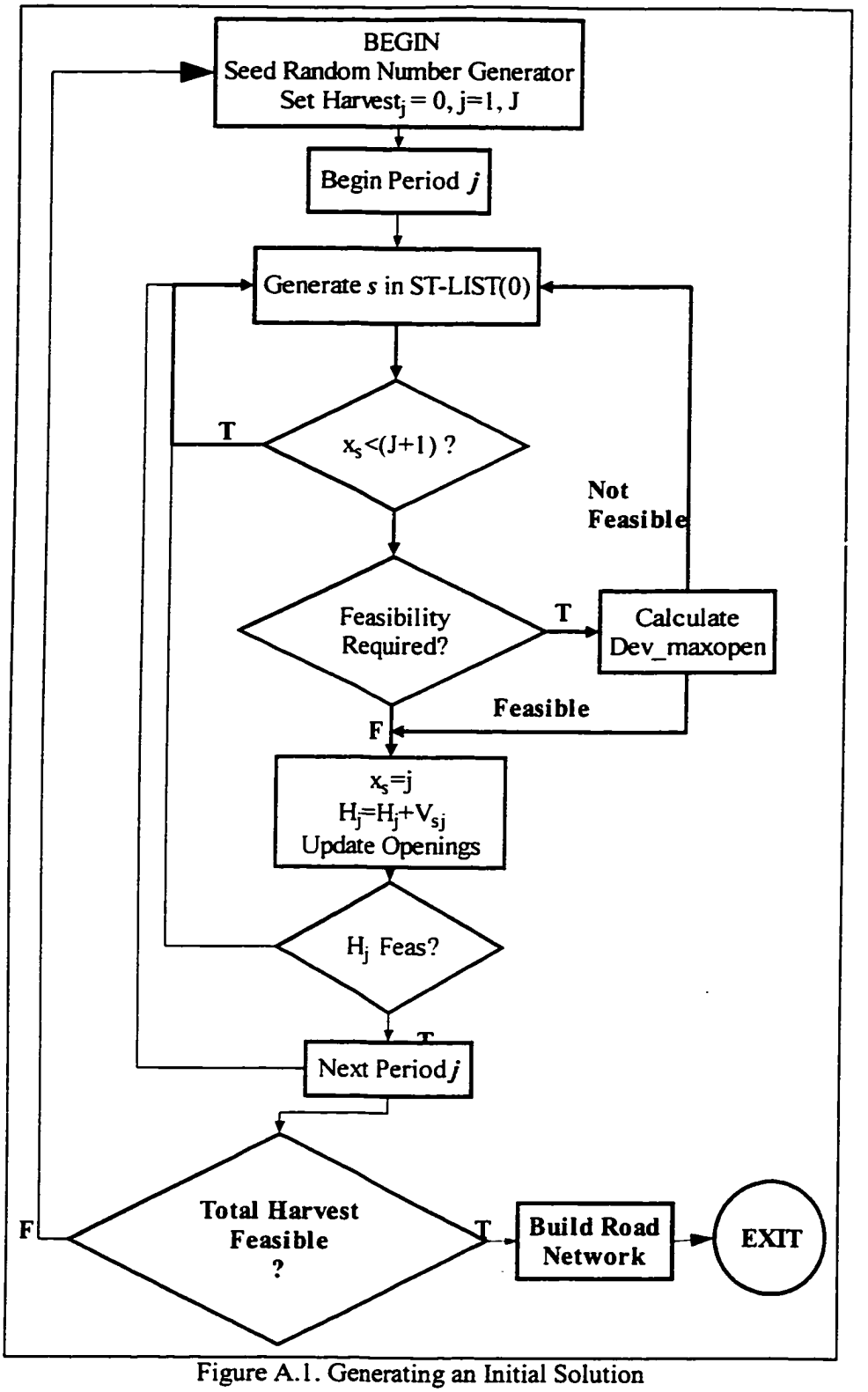


Figure A.1. Generating an Initial Solution

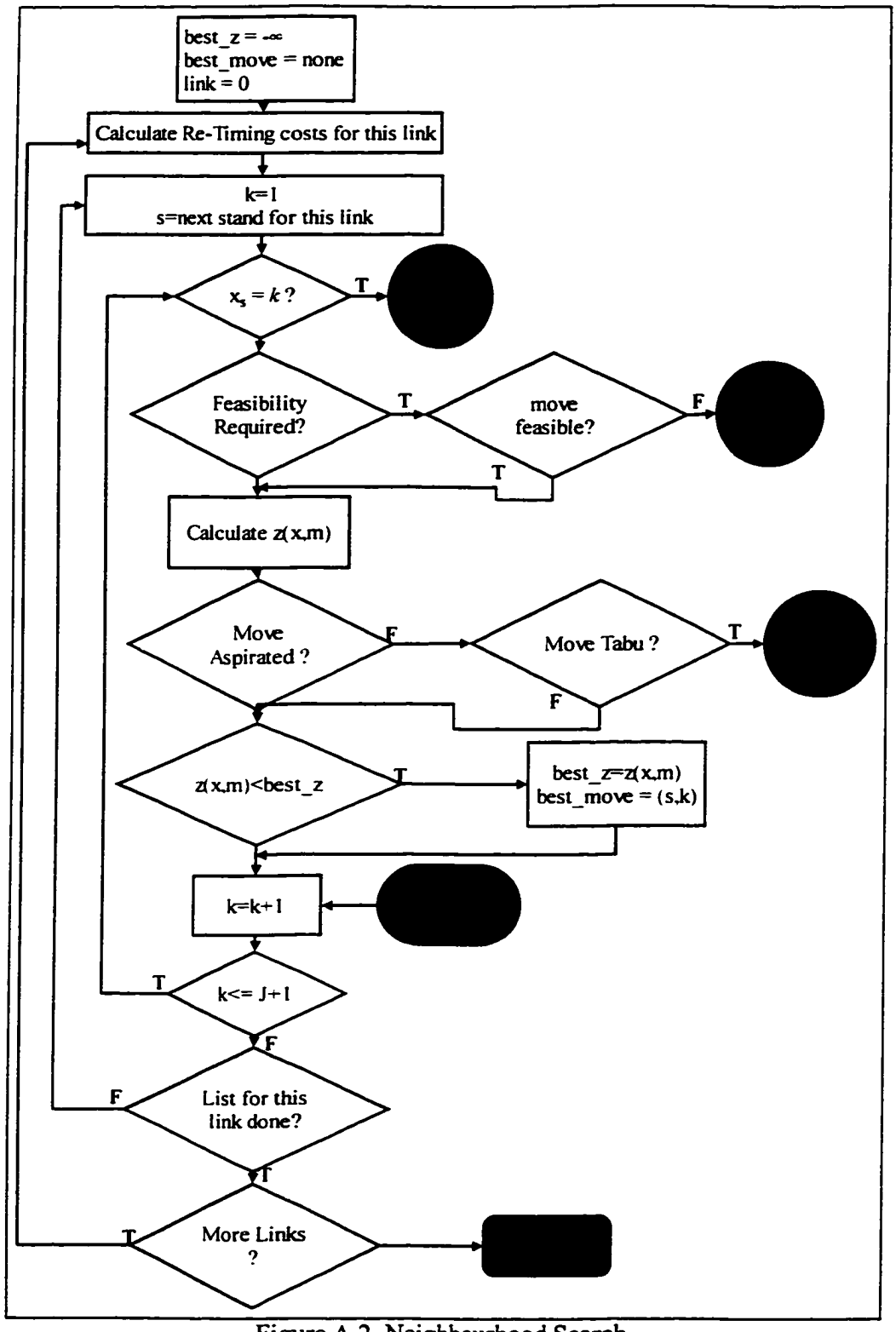


Figure A.2. Neighbourhood Search

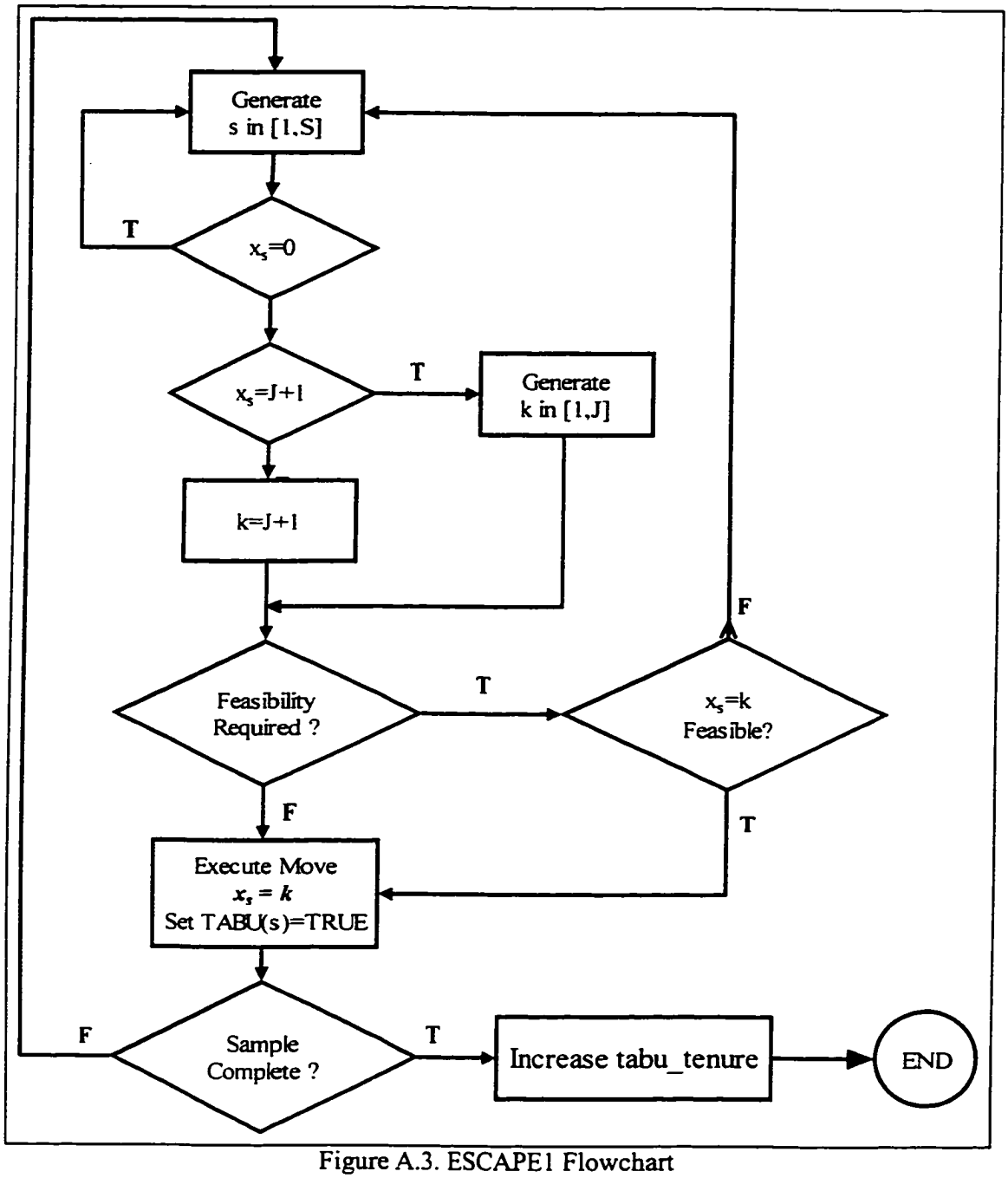


Figure A.3. ESCAPE1 Flowchart

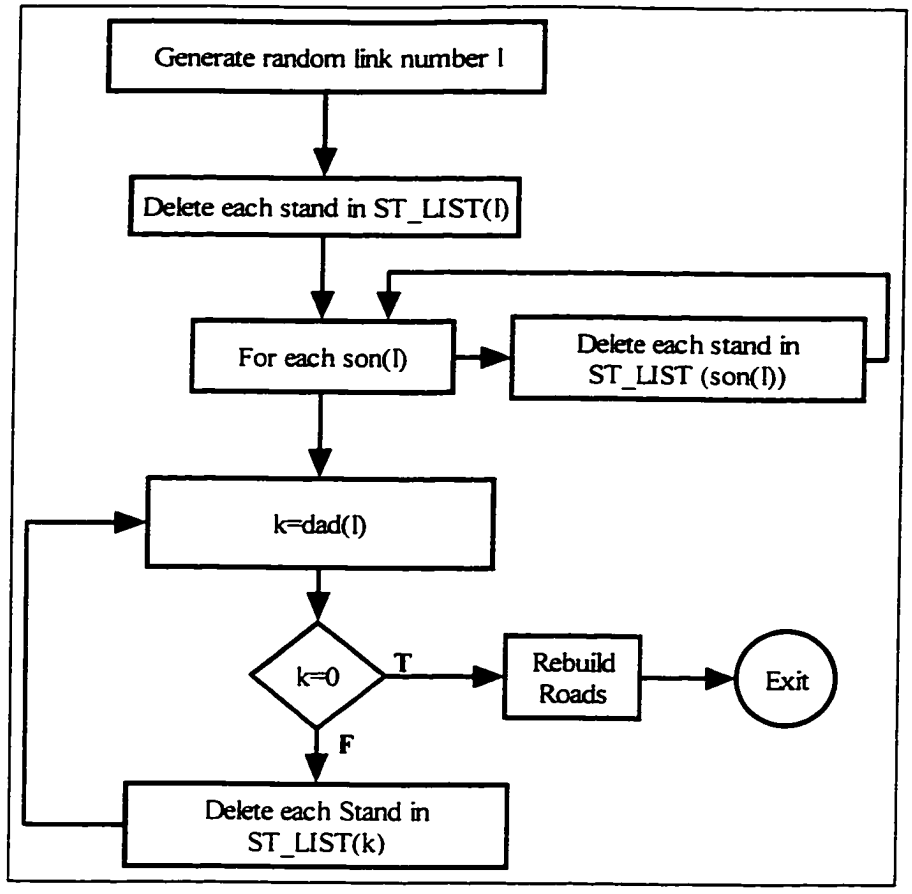


Figure A.4. ESCAPE2 Flowchart

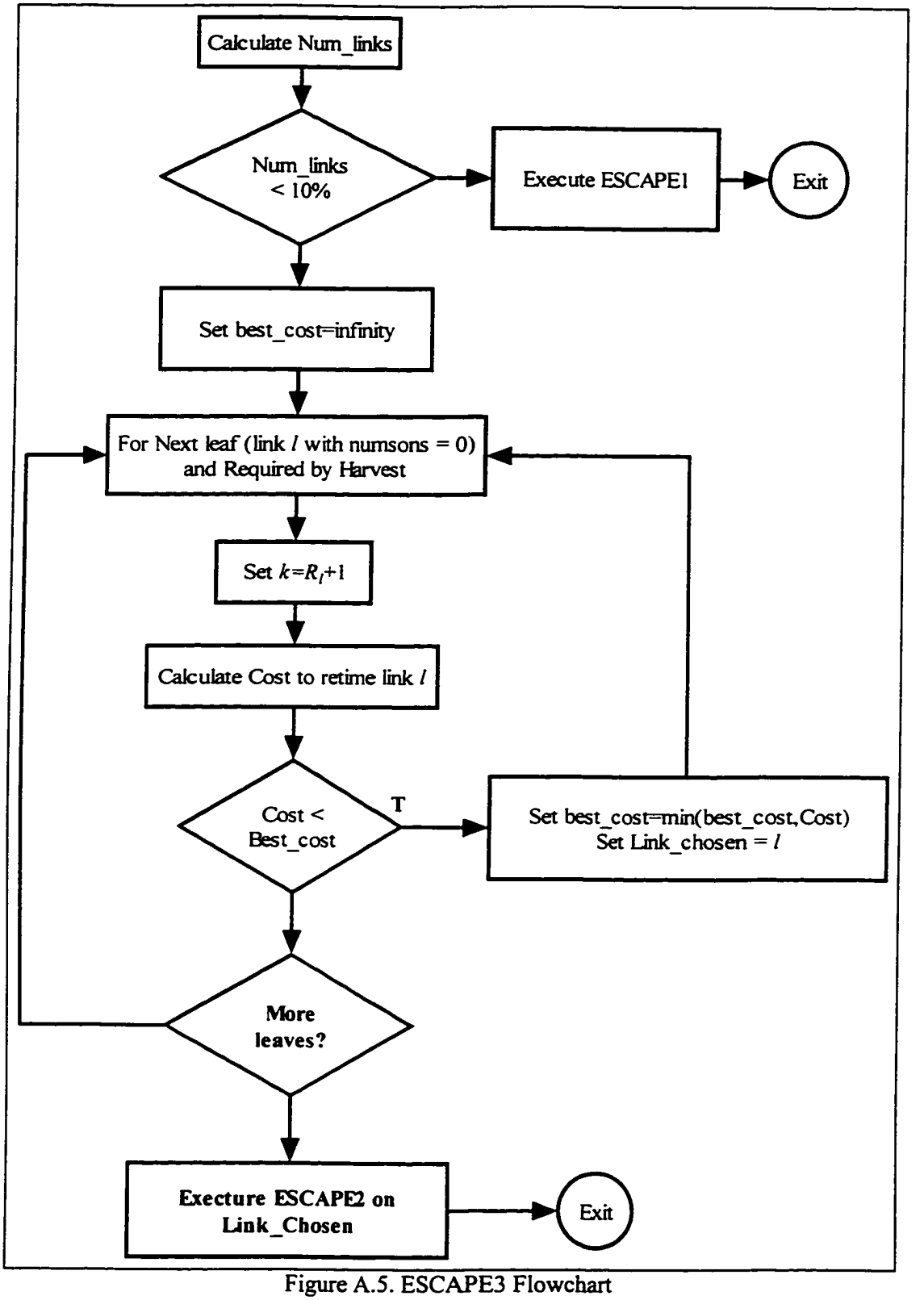


Figure A.5. ESCAPE3 Flowchart

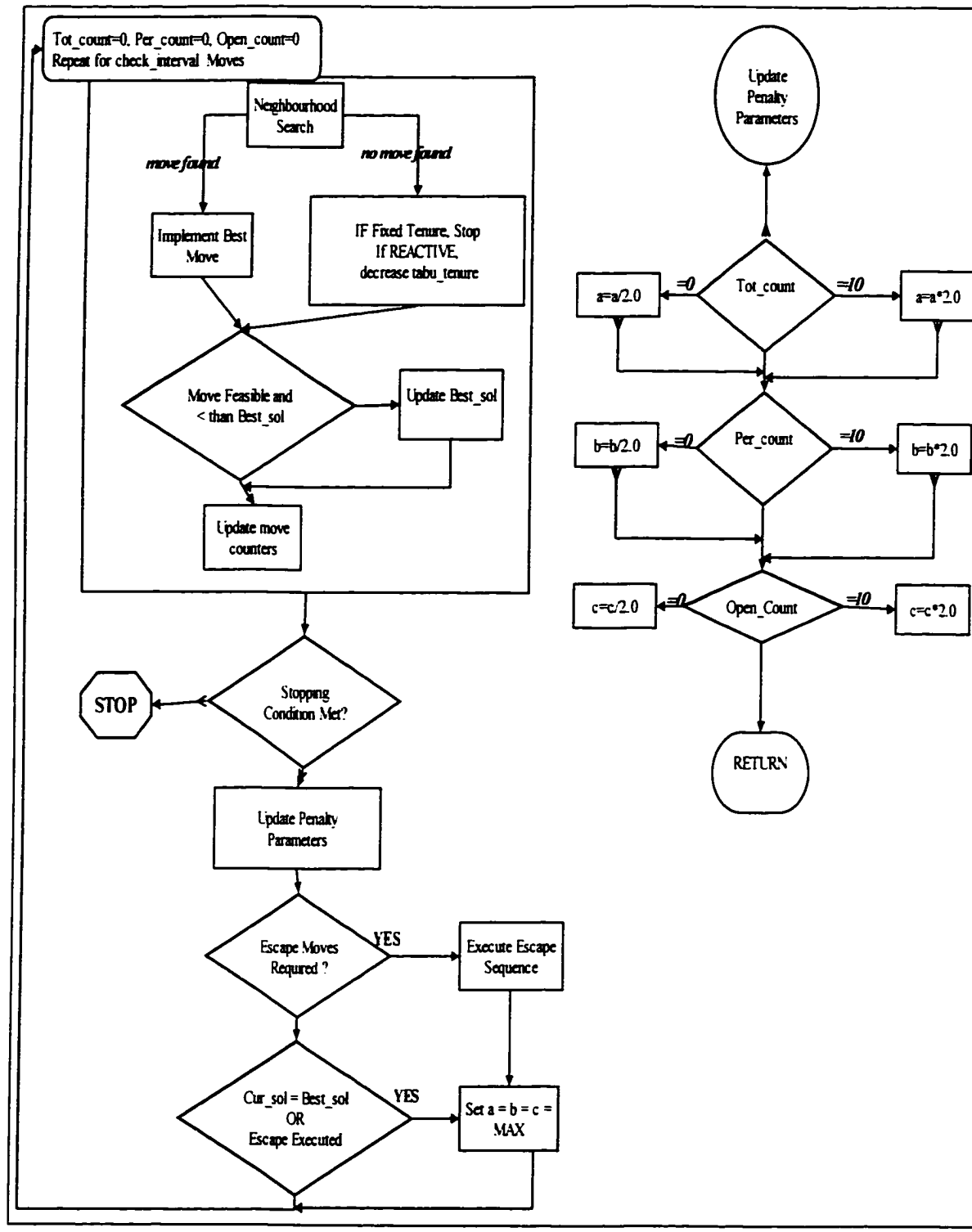


Figure A.6 OTS Algorithm

APPENDIX B

DATASETS

Dataset 1

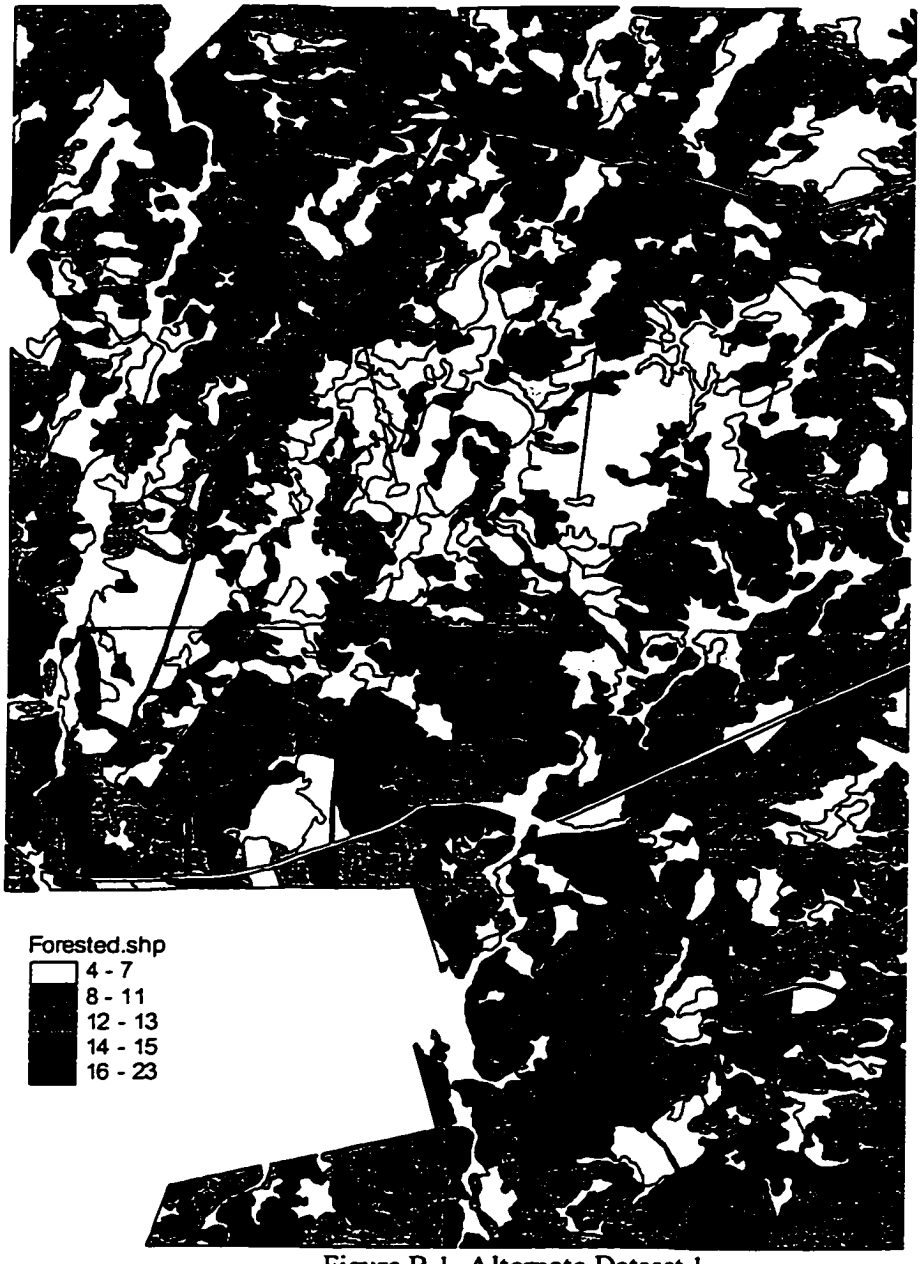


Figure B.1. Alternate Dataset 1

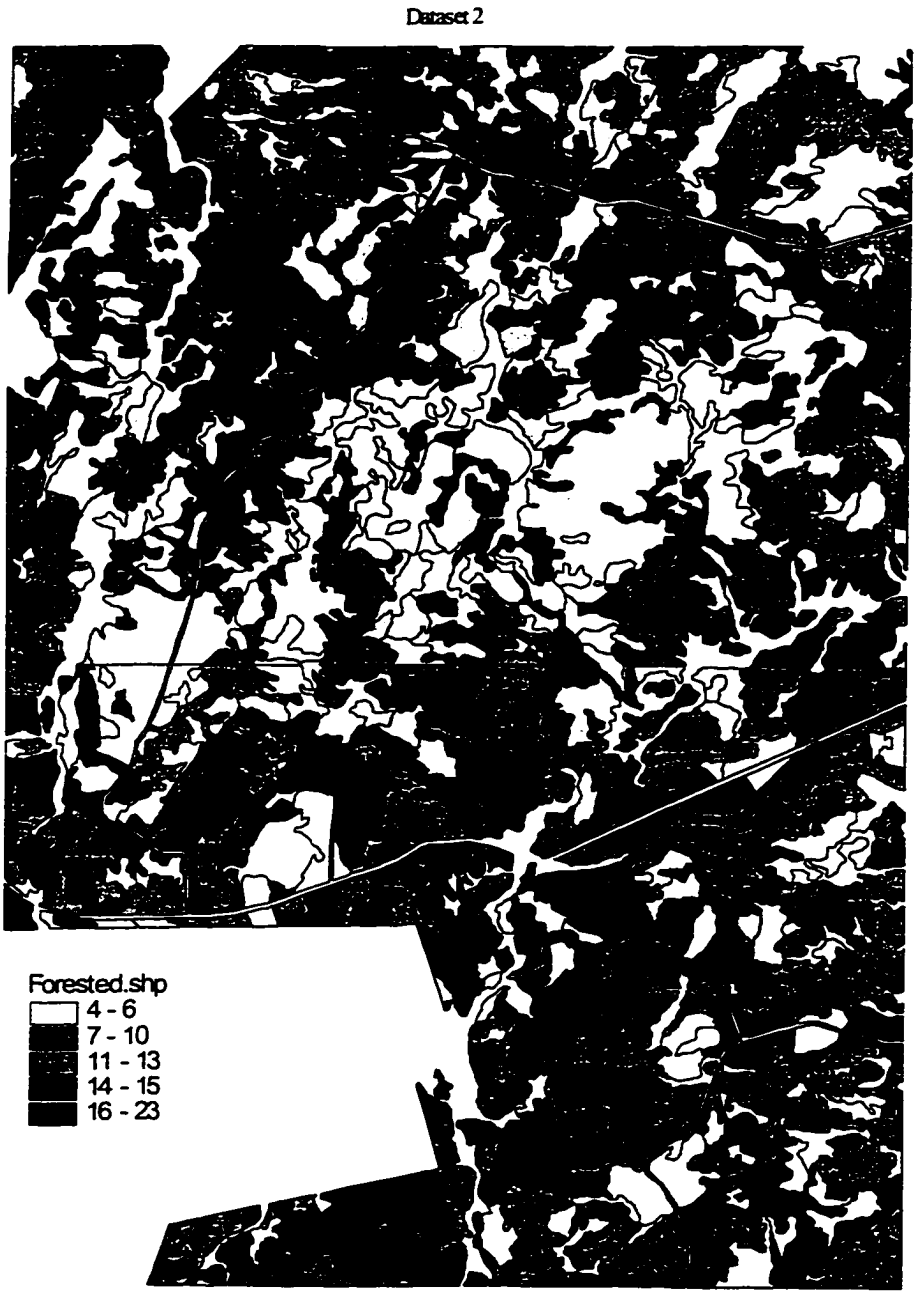


Figure B.2. Alternate Dataset 2

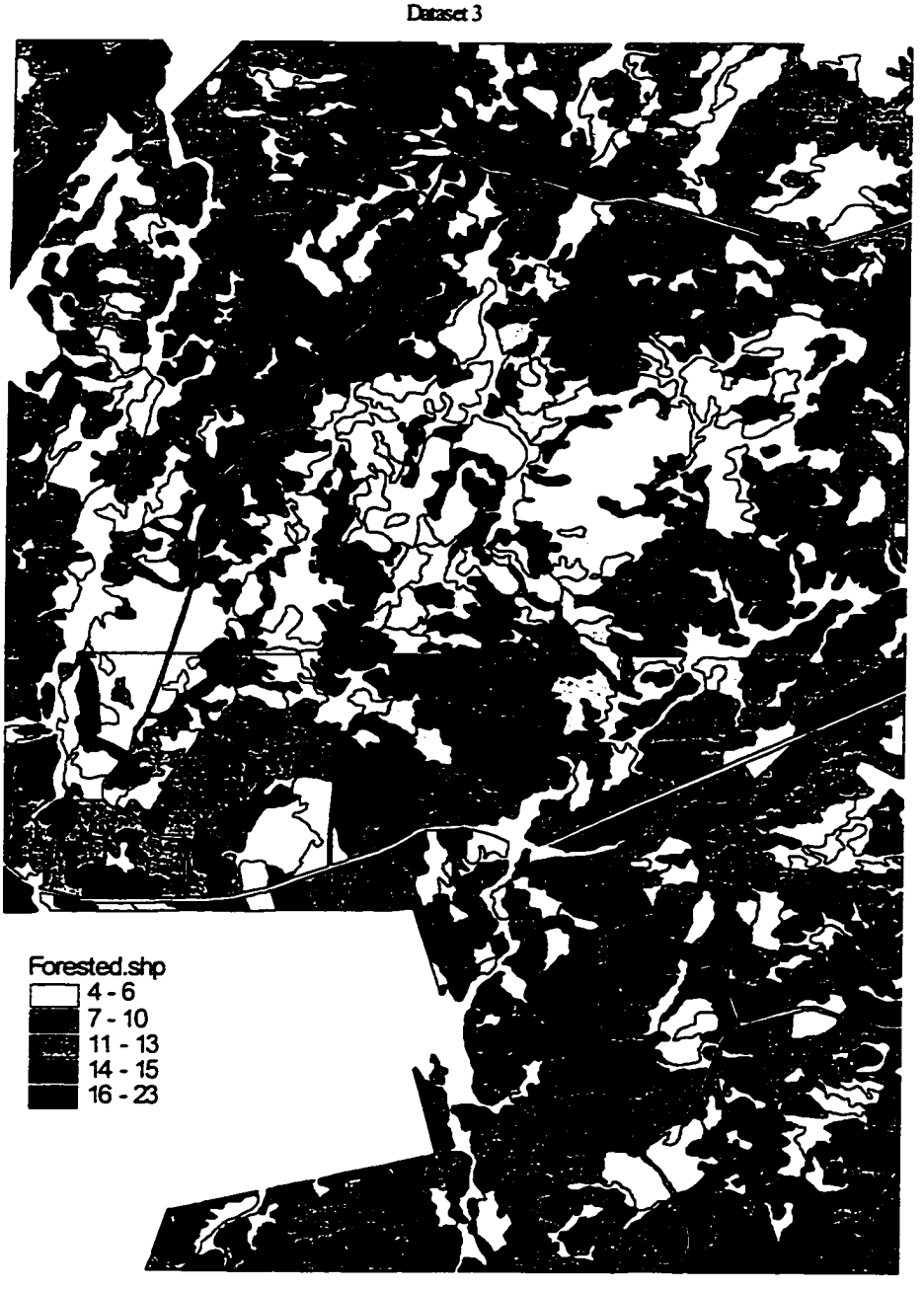


Figure B.3. Alternate Dataset 3

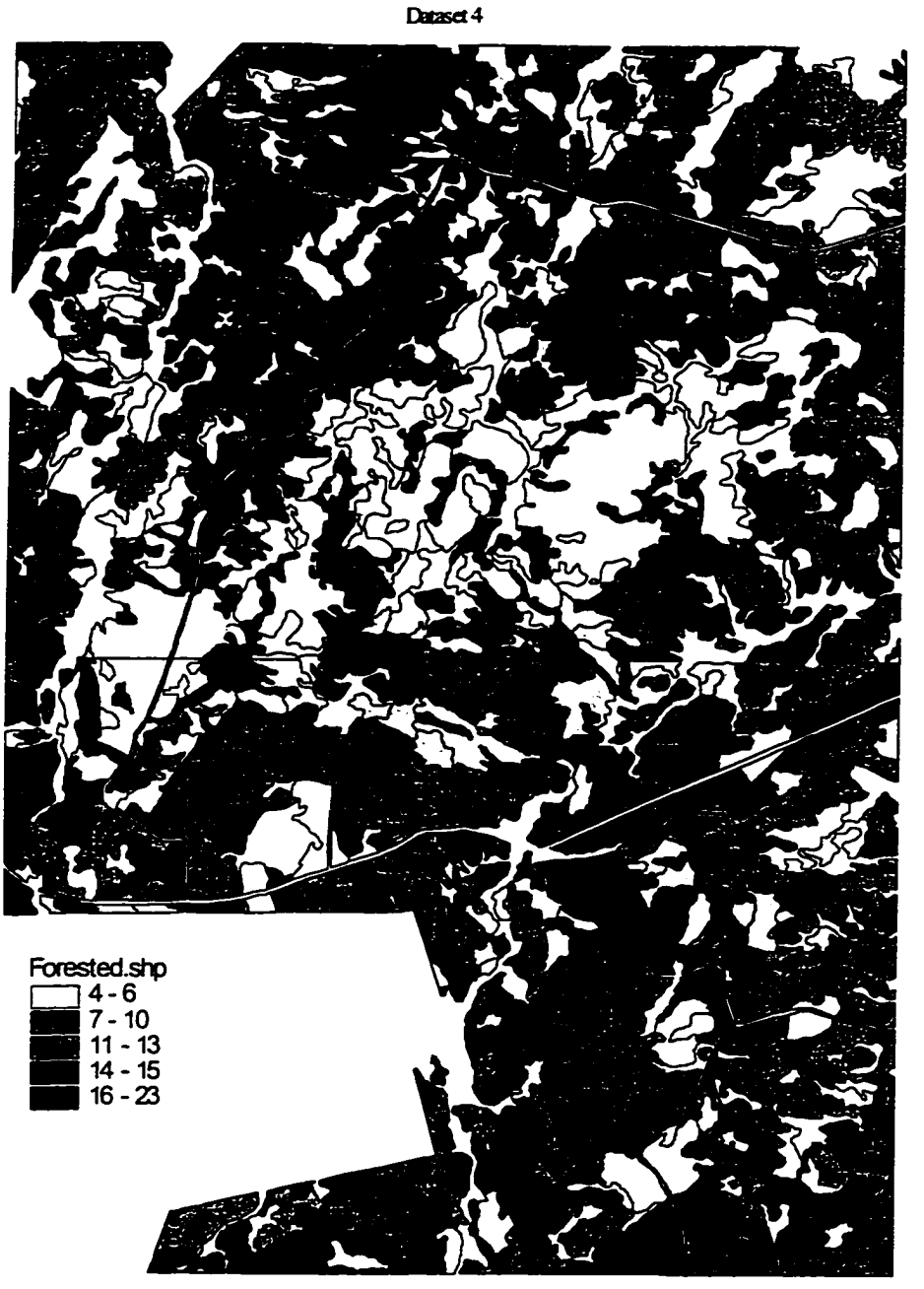


Figure B.4. Alternate Dataset 4

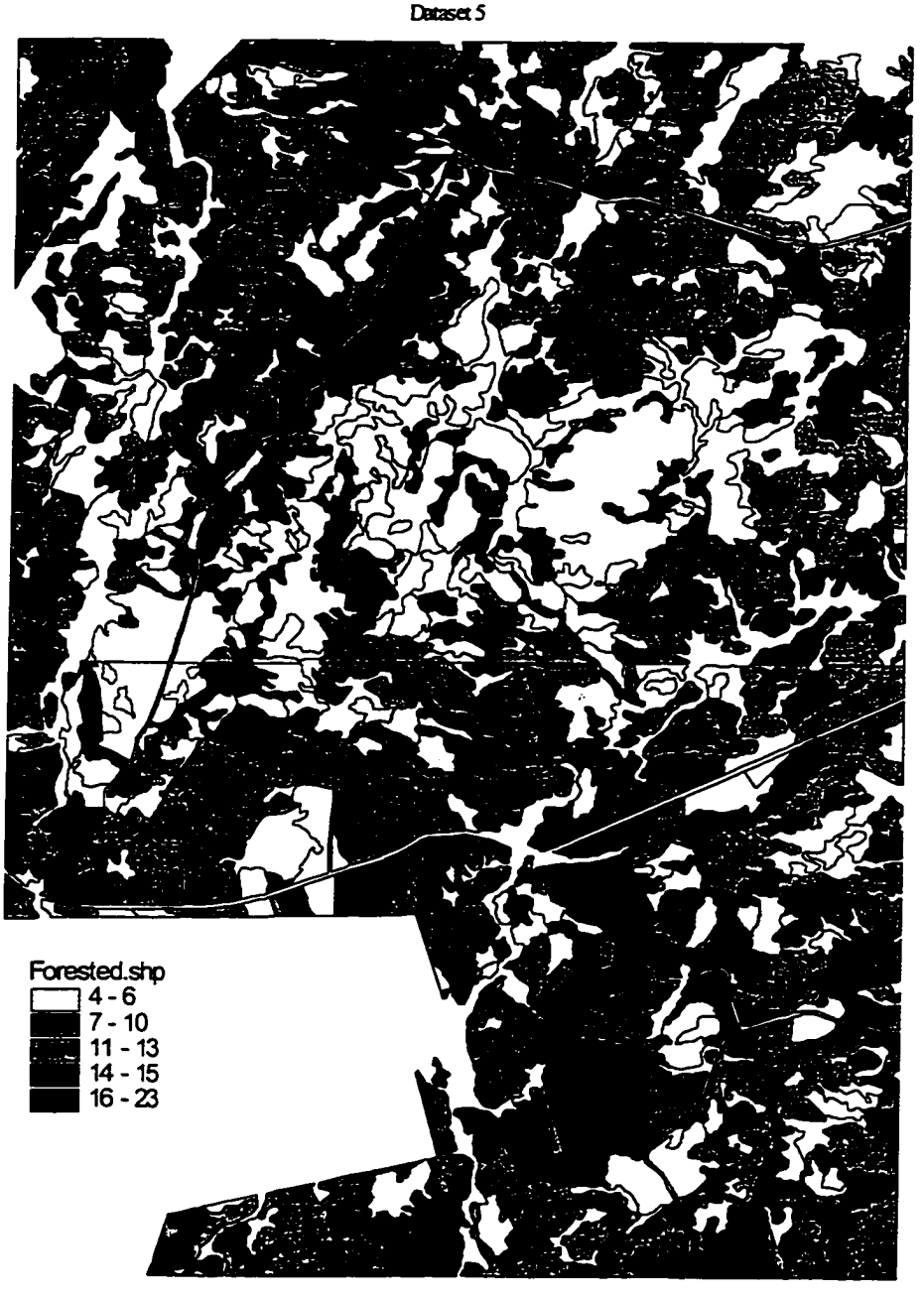


Figure B.5. Alternate Dataset 5

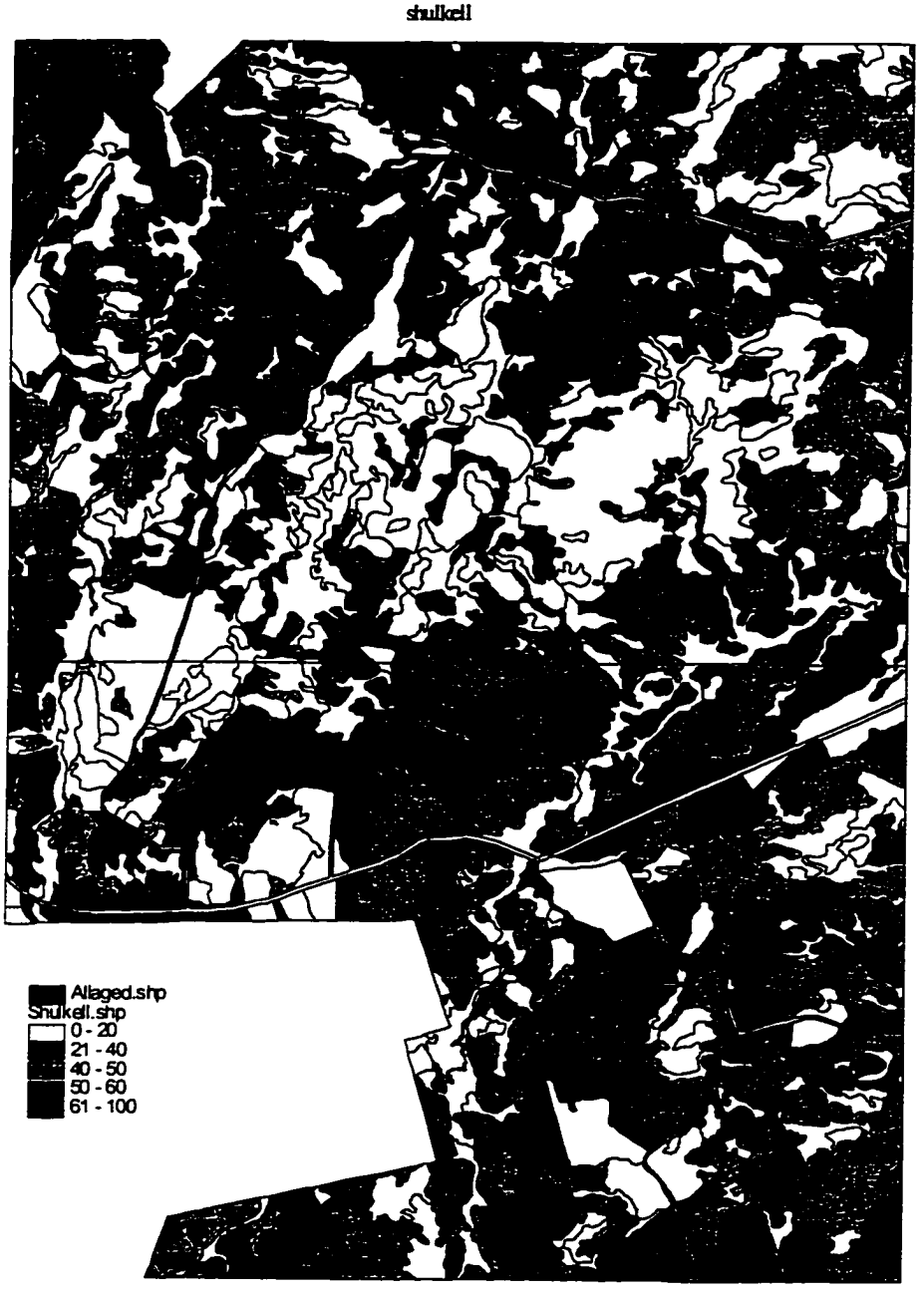


Figure B.6. Shulkell Dataset

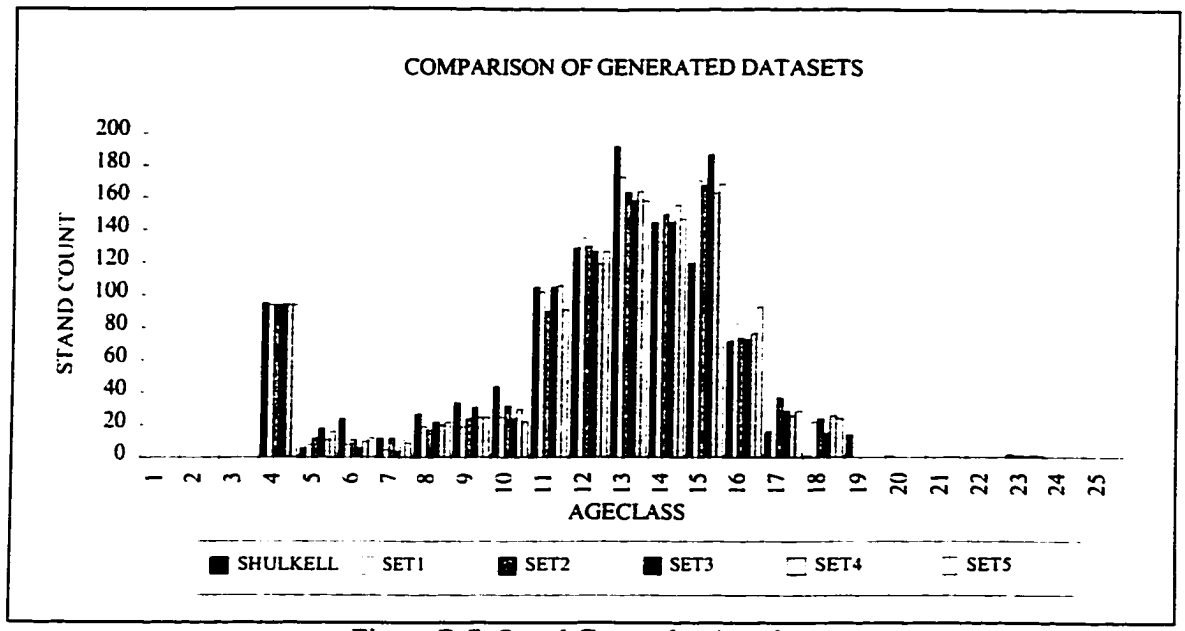


Figure B.7. Stand Counts by Ageclass

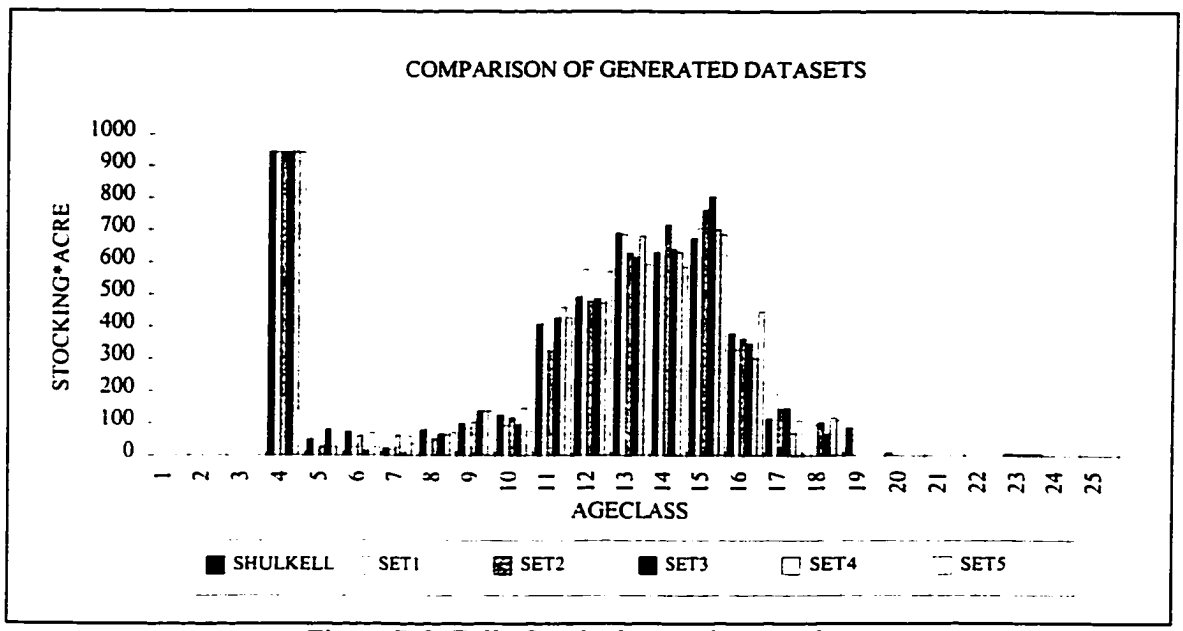


Figure B.8. Fully Stocked Acres by Ageclass

APPENDIX C

FORTRAN CODE

common blocks

Parameters and Constants

```
      integer*4 numstands,numperiods,numnodes,numroads,ifuture
      integer*4 num_opens,maxadj,maxvert
      parameter (numstands=1039)
      PARAMETER (numperiods=4)
      parameter(num_opens=1039,maxvert=440,maxadj=600)
      real*4 rmaxopen
      PARAMETER(RMAXOPEN=126.5)
      parameter(numroads=135)
      parameter(numnodes=124)
      parameter(ifuture = numperiods+1)
      real*8 gamma_upper,lower_bound,upper_bound
      parameter(upper_bound=32767.0)
      parameter(lower_bound=.0001)

      common/sol_param/htarget,ptarget,periodic_all,total_all,cur_alpha,
     >cur_beta,cur_gamma,d_factor,r_factor
      real*8 htarget,ptarget,periodic_all, total_all,cur_alpha,cur_beta,cur_gamma,d_factor(ifuture)
      real*8 r_factor
```

best_move

```
      common/best_move/best_r_cost,
     > least_objective,
     > m_best_loss_penalty,
     > m_best_dev_fr_total,
     > m_best_dev_fr_periodic,
     > m_best_dev_fr_maxopen,
     > m_best_harvest,
     > best_move_asp,
     > best_stand,best_period,best_type,
     > best_link_period,
     > best_link_period_stands
      real*8 best_r_cost,least_objective,
```

```
     > m_best_loss_penalty,
     > m_best_dev_fr_total,
     > m_best_dev_fr_periodic(numperiods),
     > m_best_harvest,
     > m_best_dev_fr_maxopen
       integer*2 best_stand,
     > best_period,
     > best_type,
     > best_link_period,
     > best_link_period_stands
       logical best_move_asp
```

best_sol

```
      common/best_sol/x_save,road_save
      integer*2 x_save(numstands)
      integer*2 road_save(numroads)
```

stand_information

```
     common/data/stand_info,numread
     structure /stands/
      real*4 unass_penalty
      real*4 ass_penalty(numperiods)
      real*4 volume(numperiods)
      real*4 acres
      real*4 stocking
      real*4 ivol
      integer*2 adj(maxvert)
      integer*2 link_req
      integer*2 opening(2)
      integer*2 stand_no
      integer*2 dead
      integer*2 for_non
      integer*2 ageclass
      integer*2 site
      integer*2 cover_type
      integer*2 numadj
     end structure
     record/stands/stand_info(numstands)
     integer*2 numread
```

mai curves

```
     common/growth/mai,mai_max_age
     integer*2 mai_max_age(6)
     real*4 mai(6,22)
```

Hashing Table

```
common/hash/config_info,hash_table,config_point
parameter(itable_size=50021)
integer*2 hash_table(0:itable_size)
integer*2 config_point
structure /sol_stats/
real*8 sol_value
integer*2 num_rep
integer*2 time_last_found
end structure
record/sol_stats/config_info(0:10000)
```

Move Data

```
 common/move/ move_harvest, move_loss_penalty, move_road_cost,
>move_dev_fr_periodic, move_dev_fr_total, move_dev_fr_maxopen,
>move_infeasible, r_cost, move_feas, move_asp, move_stand,move_period,move_type,
>link_period, link_period_stands
 integer*2 move_type,move_stand,move_period,link_period,link_period_stands
 real*8 move_harvest
 real*8 move_loss_penalty, move_dev_fr_periodic(numperiods),
>move_dev_fr_total, move_infeasible, move_road_cost,
>r_cost(ifuture),move_dev_fr_maxopen
 logical move_feas,move_asp
```

Opening Data

```
common/openings/opens
common/open_pt/o_avail,o_last,av_list ,o_top
structure/op_info/
    real*4 acres
    integer*2 operiod
    integer*2 numvert
    integer*2 numedges
    integer*2 v(maxvert)        !store stand list
    integer*2 epointer(maxvert) !used to point to adjacent stands
    integer*2 e(maxadj)         !adjacency list
    integer*2 pointer_fwd       ! points to next available opening num
    integer*2 pointer_back      !points to the previous opening
end structure
record/op_info/opens(0:num_opens)
integer*2 av_list(num_opens)  !availability list for openings
integer*2 o_avail        !points to top of availability list
integer*2 o_last                !points to last opening added
integer*2 o_top                 !points to the top of the opening list
```

RTS Data

```
common/reactive/moving_average,increase,decrease,rep,chaotic,chaos,cycle_max
```

```
      integer*2 chaotic,chaos,cycle_max
      integer*2 rep
      real increase,decrease,moving_average
```

Tabu List

```
      common/tabu/tabu_tenure,tabu_list,steps_since_size_change,link_tenure
      integer itabu_len
      parameter (itabu_len=numstands)
      integer*2 tabu_list(itabu_len)
      real tabu_tenure,link_tenure
      integer*2 steps_since_size_change
```

Road Network

```
common/roads/priority,val,roads,road_heap,heap_size,adj_point,inv,adj,st_list,st_point,link,dad
      structure/road_net/
      real*4 lgth
      integer*2 x
      integer*2 y
      integer*2 period
      integer*2 period_assigned
      integer*2 nhops
      integer*2 dad_link
      integer*2 numsons
      integer*2 sons(5)
      integer*2 time                !move when link is last selected for diversify
      logical*1 required_by_harvest
      logical*1 required_by_connect
      end structure
      record/road_net/roads(0:numroads)
c  heap data structure NOTE ARRAY LOWER BOUND OF 0 IS REQUIRED
      integer*2 road_heap(0:numnodes+1),heap_size
      integer*2 inv(0:numnodes+1)
      integer*2 adj_point(numnodes+2),adj(3*numnodes,2)
      real*4 priority(0:numnodes+1),val(0:numnodes+1)
c list of stands that are accessed by each road
      integer*2 st_list(numstands),st_point(0:numroads+1)
      integer*2 link(0:numnodes+1)
      integer*2 dad(0:numnodes+1)
      integer*2 st_list_all(numstands*3),st_all_point(numroads)
```

Current Solution

```
      common/solution/min_loss_penalty, hvol, best_sol, cur_sol,cur_loss_penalty,
     > best_loss_penalty, cur_dev_fr_periodic,cur_dev_fr_total, cur_dev_fr_maxopen,
     > cur_infeasible, best_infeasible,cur_road_cost, best_road_cost,
     > cur_feasible, best_feasible, hash_add, x
      integer*2 x(numstands)
```

```
      real*8 hvol(numperiods),best_sol,cur_sol,cur_loss_penalty,best_loss_penalty,
     >cur_dev_fr_periodic(numperiods),cur_dev_fr_total,cur_dev_fr_maxopen
      real*8
cur_infeasible,best_infeasible,cur_road_cost,best_road_cost,cur_feasible,best_feasible
      real*8 min_loss_penalty
      integer*4 hash_add
```

Initial Solution

```
      common/init_sol/i_sol
      integer*2 i_sol(numstands)
```

Search Status

```
      common/search_status/ message,reset_value, at_end, num_esc_steps, total_time,
     > s_time, etime_struct, maxiters, move_count, moves_since_improve, imp_time,
     > feas_count_total, feas_count_per, feas_count_open, infeas_count_total,infeas_count_per,
     > infeas_count_open, check_interval,escape_time, no_improve_tol,after_escape_moves
      logical at_end
      integer*2 maxiters,move_count,moves_since_improve
      integer num_esc_steps
      integer*2 no_improve_tol,after_escape_moves,feas_count_total,feas_count_per
      integer*2 infeas_count_total,infeas_count_per,infeas_count_open,feas_count_open
      real total_time,s_time,reset_value
      integer*2 imp_time,escape_time,check_interval
      TYPE TB_TYPE
            SEQUENCE
            REAL*4 USRTIME
            REAL*4 SYSTIME
      END TYPE
      TYPE (TB_TYPE) ETIME_STRUCT
      character*32 message
```

Orts Main Program

```
      include  'params.f'
      include 'sol_param2.f
      include  'com_open.f'
      include  'com_data.f'
      include  'road_com_sol.f'
      include  'com_tabu2.f'
      include  'com_move.f'
      include  'search_status.f'
      include 'road_com.f'
      include 'best_move.f'
      include 'com_reactive.f'
      character*8 mapin
      real etime
      logical escape
      integer icount,istart,numruns
```

```
      character*12 ofile
      character*12 dataset
      real seedval
 c init
 c  get data file and operating parameters
      write(*,*) 'Reactive tabu search'
      write(*,*) 'Dynamic penalty Coeff'
      mapin = 'shulkell'
      write(*,*) 'Enter Dataset name'
      read(*,'(a12)') dataset
 40   format(a8)
 c setup data
      call read_growth                    !read the mai values
      call init_x                         !set all x(i)=future
      call init_stands                    !initialize stand structure
      call init_opens                     !init opening structure
      call init_roads                     !init road structures
      call get_data(dataset)              !read road,stand and adj data
      call calc_base_loss                 !get min loss penalty
 c set up parameters
      call init_reactive                  !init reactive search parameters
      call init_search_params             !maxiters etc
      call calc_parameters                !alpha,beta,bounds for deviations etc
      call make_opens2                    !openings for clearcuts
 c begin the search
      write(*,*) 'Enter start stream,end stream'
      read(*,*) istart,numruns
      write(*,*) 'Enter max iters'
      read(*,*) maxiters
      write(*,*) 'enter increase,decrease,cyclemax'
      read(*,*) increase,decrease,cycle_max
      write(*,*) 'output file '
      read(*,'(a12)') ofile
      write(*,*) 'first factor'
      read(*,*),ifirst
      write(*,*) 'last factor '
      read(*,*) ilast
      write(*,*) 'interval'
      read(*,*) interval
      write(*,*) 'enter value to reset parameters to after escape'
      read(*,*) reset_value
      write(*,*) 'No improve tolerance,after escape_moves'
      read(*,*) no_improve_tol,after_escape_moves
      link_tenure = 5.0*float(after_escape_moves)
 c  open files
      open (unit=11,status='NEW',file=ofile)
      open (unit=21,file=ofile//'.tr')
      write(11,*) dataset
      call write_heading_rts
      do icount=istart,numruns                    !number of runs
```

```
 write(*,*) 'random stream',icount
 call mcarlo_rand_feas(icount)                !get an initial solution
 call save_init_sol                           !and save it
 do k=ifirst,ilast,interval                   !for the range of r_factor
 seedval = icount
 call srand(seedval)                          !do this so the solution can be repeated
 r_factor = 0.1*float(k)                      !convert to real
 call init_move_counters2                     !move_count=0 etc
 call init_best_values                        !set best to big numbers
 call init_hash_table                         !initialize the hashtable
 call init_opens                              !init the opening list
 call make_opens2                             !make the opening graphs
 call build_roads                             !build the path network
 call calc_objective                          !calculate the current solution
 call time_stats(s_time)                      !get start time
 call update_best                             !saves the best values
 call save_sol                                !save initial solution
 call init_tabu_rts                           !init tabu list and tenure
 at_end = .false.                             !loop control
 do while(.not.at_end)                        !Next solution
 do icheck=1,check_interval                   !Do a small number of moves
  steps_since_size_change=steps_since_size_change+1 !bump counter
  call check_for_reps(escape)                         !RTS structures for the current solution
  if(.not.escape)then                         !if not chaotic cycling
   call calc_full_nbhood6                     !search the neighborhodd for best move
   if (best_type.ne.0)then                    !found a move
    call implement_best_move2                 !implement it
    call update_best                          !update best values and save if necessary
    call update_move_counters2                !bump the move counters
   else                                       !no move found
       tabu_tenure = max(1.0,int(tabu_tenure*decrease))! decrease tabu tenure
   endif
  else                                        !escape required due to chaotic cycling
   escape_time=move_count                     !set the counter
    call rts_escape_routine2                  !implement ESCAPE3 strategy
       call clean_hash_table                  !
       moving_average = 0.0
      exit
 endif
 end do                                       !next icheck
 if((move_count.gt.maxiters).and.
> (moves_since_improve.ge.no_improve_tol))then     !check stop condition
  at_end=.true.
  message = 'Max iterations reached'
  exit
 endif
 if(.not.escape)then
  call update_obj_coeff2                      !update alpha, beta, gamma
 else
  cur_alpha = reset_value                     !escape was done, set them to 1.0
```

```
 cur_beta = reset_value
 cur_gamma = reset_value
endif
if((moves_since_improve.ge.no_improve_tol).and.     ! long time since improve
> (move_count-escape_time.ge.after_escape_moves))then    !and intensification phase over
 escape_time=move_count
 call rts_escape_routine2                           !do a diversifying strategy
 cur_alpha = upper_bound                            ! and max out coefficients
 cur_beta = upper_bound
 cur_gamma = upper_bound
 moving_average = 0.0
endif
end do
call time_stats(etime)                              !get end time
total_time = etime-s_time                           !and calculate run time
 call write_data_rts(icount)                        !stats for runs
 call get_init_sol                                  ! go back to the starting solution
 end do                                             !and do the next r_factor
 call clear_solution                                !clear solution for next run
 call init_roads                                    !clear roads
 call init_opens                                    !clear the openings
 call make_opens2                                   !openings for clearcuts
end do                                              !next initial solution
close(unit=11)                                      !close files
close(unit=21)

stop
end
```

Initial Solution

```
      subroutine mcarlo_rand_feas(icount)
      include 'params.f'
      include 'sol_param2.f'
      include 'search_status.f'
      include 'com_data.f'
      include  'road_com_sol.f'
      include 'com_open.f'
      include 'com_move.f'
      include 'com_growth.f'
      include 'road_com.f'
      real*4 open_size
      integer icount
      integer isize
      real seedval
      seedval = icount
      call srand(seedval)
      isize = st_point(1)-1
      move_type = 1 !used to update solution
c make up an initial solution by randomly assigning
c stands that require no roads initially
      move_type = 1
      do move_period = 1,numperiods
      hvol(move_period)=0.0
      do while ( hvol(move_period).lt.(ptarget-periodic_all))
      move_stand = st_list(int(rand()*isize)+1)
      if(x(move_stand).eq.ifuture)then                !not in
       if(stand_info(move_stand).volume(move_period).ne.0)then
        call calc_feas_for_maxopen(move_stand,move_period,move_type)
            if (dtrunc(move_dev_fr_maxopen).eq.0.0) then              !feasible
            if(hvol(move_period)+stand_info(move_stand).volume(move_period)
     >      .le.(ptarget+periodic_all))then
            if(stand_info(move_stand).link_req.ne.0)then
             roads(stand_info(move_stand).link_req).period =
     >        min0(move_period,roads(stand_info(move_stand).link_req).period)
             roads(stand_info(move_stand).link_req).required_by_harvest=
     >        .true.
        endif
            call add_stand2(move_stand,move_period)
            x(move_stand)=move_period
            hvol(move_period)=hvol(move_period)+
     >      stand_info(move_stand).volume(move_period)
       endif
       endif
       endif
       endif
      end do
```

```
      end do                !next period
      return
      end
```

subroutine mcarlo_rand7(icount)

```
c  This routine generates an initial solution which may be infeasible
      include 'params.f'
      include 'sol_param2.f'
      include 'search_status.f'
      include 'com_data.f'
      include  'road_com_sol.f'
      include 'com_open.f'
      include 'com_move.f'
      include 'com_growth.f'
      include 'road_com.f'
      real*4 open_size
      integer icount
      integer isize
c     call srand(s_time)              !use start time for the seed
      real seedval
      seedval = icount
      call srand(seedval)
      isize = st_point(1)-1
c     write(*,*) 'isize is ',isize
      move_type = 1 !used to update solution
c make up an initial solution by randomly assigning
c stands that require no roads initially
      do move_period = 1,numperiods
      hvol(move_period)=0.0
      do while ( hvol(move_period).lt.ptarget)
      move_stand = st_list(int(rand()*isize)+1)
      if(x(move_stand).eq.ifuture)then                !not in
       if(stand_info(move_stand).volume(move_period).ne.0)then
           if(stand_info(move_stand).link_req.ne.0)then
            roads(stand_info(move_stand).link_req).period =
     >       min0(move_period,roads(stand_info(move_stand).link_req).period)
            roads(stand_info(move_stand).link_req).required_by_harvest=
     >       .true.
       endif
           x(move_stand)=move_period
           hvol(move_period)=hvol(move_period)+
     >     stand_info(move_stand).volume(move_period)
       endif
       endif
       end do
      end do                  !next period
      return
      end
```

Hashing Subroutines

subroutine hashfn(numread)

```
include 'params.f'
include 'sol_param2.f'
include 'road_com_sol.f'
include 'com_hash.f'
include 'search_status.f'
integer*2 numread
integer*4 temp
hash_add=x(1)
do i=2, numread
 temp=x(i)
 hash_add=xor(ishftc(hash_add,1,32),temp)
end do
if (hash_add .lt.0) then
 hash_add=-1*hash_add
endif
hash_add = mod(hash_add,itable_size)
return
end
```

subroutine clean_hash_table

```
include 'com_hash.f'
include 'search_status.f'
do i=0,config_point
     config_info(i).num_rep=0
end do
return
end
```

subroutine init_hash_table

```
include 'params.f'
include 'com_hash.f'
config_point = 0
do i=0,itable_size
 hash_table(i)=-1
end do
do i=0,10000
    config_info(i).num_rep=0
```

```
        config_info(i).time_last_found=-32766
        config_info(i).sol_value = -1.0
      end do
      return
      end
```

Openings and Graphs

subroutine del_one_open(op_no)

```
c This routine deletes the opening op_no
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      integer*2 op_no,period
      integer*2 iprev,inext
c get data
      period = opens(op_no).operiod
c get pointers
      iprev = opens(op_no).pointer_back
      inext = opens(op_no).pointer_fwd
c update stand info
           do  k=1,opens(op_no).numvert
            do j=1,2
            if(stand_info(opens(op_no).v(k)).opening(j).eq.op_no)then
            stand_info(opens(op_no).v(k)).opening(j) = 0
            endif
            end do
           end do
c update pointers
      if ((op_no).eq.o_top)then
           o_top = (inext)
       endif
      if (iprev.ne.0) then
           opens(iprev).pointer_fwd = inext
      endif
      if (inext.ne.0) then
          opens(inext).pointer_back = iprev
      endif
c zero opening data
      opens(op_no).operiod=0
      opens(op_no).acres=0.0
      opens(op_no).numvert=0
      opens(op_no).numedges=0
      do ii=1,maxvert
          opens(op_no).v(ii)=0
          opens(op_no).epointer(ii)=0
```

```
      end do
      do ii=1,maxvert
          opens(op_no).e(ii)=0
      end do
      opens(op_no).pointer_fwd=0
      opens(op_no).pointer_back=0
c update o_avail
      av_list(op_no)=o_avail
      o_avail = op_no
          if (op_no.eq.o_last) then
           o_last = iprev
          endif
          return
          end
```

subroutine make_opens2

```
c this routine makes up all openings from the current settings of x
      include 'params.f'
      include 'search_status.f'
      include  'com_data.f'
      include  'com_open.f'
      include  'road_com_sol.f'
      integer*2 o_period
      integer*2 numon
      integer*2 vert(maxvert)
c given a solution in X(i,j), build all the openings
c do for each opening type
c type 1  = harvest 0,1
c type 2  = harvest 1,2
c type 3  = harvest 2,3
c type 4  = harvest 3,4
    do o_period = 1,numperiods
c init vertex list
     do  i=1,maxvert
      vert(i)=0
     end do
     numon=0
     do  i=1,numread
      if ((x(i).eq.o_period).or.(x(i).eq.o_period-1)) then !add the stand to the list
           numon=numon+1
           vert(numon)=i
      endif
     end do
c  now, build the  openings for this list of stands
      if(numon.gt.0)then
       call dfs_build2 (vert,numon,o_period)
      endif
c next opening period
```

```
      end do
      return
      end
```

subroutine del_stand2(stand)

```
c  This routine removes stand from harvest
      include 'params.f'
      include 'com_data.f'
      include 'com_open.f'
      include 'road_com_sol.f'
      integer*2 stand,period,open_no,o_period
      integer*2 vert(maxvert),numon
c check the openings
      do ipos = 1,2
      open_no = stand_info(stand).opening(ipos)
      o_period=opens(open_no).operiod
      stand_info(stand).opening(ipos)=0
      if(open_no.ne.0)then
      if(opens(open_no).numvert .eq. 1) then
       call del_one_open(open_no)
       else
c build the vertex list
       numon = 0
       do i=1,opens(open_no).numvert
       if(opens(open_no).v(i).ne.stand)then
           numon=numon+1
           vert(numon)=opens(open_no).v(i)
       endif
       end do
       call del_one_open(open_no)
       call dfs_build2(vert,numon,o_period)
      endif
      endif
c do the next opening period
     end do
     return
     end
```

subroutine dfs_build2(vert,numon,o_period)

```
c This is a depth first search routine to build all connected components of VERT
     include 'params.f'
     include  'com_data.f'
     include  'com_open.f'
     include  'road_com_sol.f'
     include 'search_status.f'
     integer*2 numon,now,vlook,o_period
```

```
      integer*2 vert(maxvert),val(maxvert),o_adj(maxvert,maxadj)
      integer*2 numadj(maxvert)
      integer*2 adj_point (maxvert)
      logical endchain
      integer*2 vlist(maxvert),vadj,epoint,jj,i,j,k
      integer*2 rstack(maxvert)                    !stack to make the recursion work
      integer stack_end
c now, the appropriate stands are in array VERT and the adjacencies in o_adj
c make up an OPENING adjacency list for each vertex by intersecting
c VERT with the stand adjacencies.
c Delete the original
c and rebuild
c init vlist, val
      do ii =1,numon
      val(ii)=0
      end do
c init ajacency pointers
      do ii=1,numon
      adj_point(ii) = 1
      numadj(ii)=0
      end do
c build adjacency lists
      do i=1,numon
      numa=stand_info(vert(i)).numadj
      do j=1,numa
      do k=1,numon
       if(stand_info(vert(i)).adj(j).eq.vert(k))then
        numadj(i)=numadj(i)+1
          o_adj(i,numadj(i))=k
          exit
       endif
      end do
      end do
      end do
      endchain = .FALSE.
c start filling up openings, first available is o_avail
      do  i=1,numon      !numon is the number of Xij=1
       now=0          !visit pointer
       do ii=1,numon
          vlist(ii)=0          ! now used to store pointers to found nodes
       end do
       stack_end = 0
       if (val(i).eq.0) then ! node not visited
          now=now+1          !increment visit pointer
          val(i)=now         !store visit number
          vlist(now)=i       !store node pointer
          vlook = i
           stack_end=stack_end+1
        rstack(stack_end)=i   !add node to recursion stack
99     call findadj(vlook,o_adj,vadj,val,
```

```
     >    adj_point(vlook),numadj(vlook),endchain) !find a node adjacent to vlook
           if (.not.endchain) then !found one
            now=now+1            !update visit pointer
            val(vadj)=now        !store visit number
            vlist(now)= vadj !store found node
            vlook = vadj   !next vertex to search in chain
          if (adj_point(vadj).le.numadj(vadj)) then
              stack_end=stack_end+1
              rstack (stack_end)=vadj !update stack
          endif
              goto 99
             else
 c end of downward chain
 c take last entry off stack
             vlook=-1
             do jj = stack_end,1,-1
              if(adj_point(rstack(jj)).le.numadj(rstack(jj)))then
               vlook = rstack(jj)
               exit
              endif
             end do
             if(vlook.ne.-1)then
              goto 99
             else !r_pointer = 0 thus, done for this connected component
 c create the new the opening structure
            opens(o_avail).operiod=o_period
            opens(o_avail).numvert=now
            opens(o_avail).pointer_fwd = 0  !forward pointer
            opens(o_avail).pointer_back = o_last    !backward pointer
            if (o_last.ne.0) then
             opens(o_last).pointer_fwd=o_avail    !forward pointer,previous opening
            endif
            do  kk=1,now    !add the vertex information
             opens(o_avail).v(kk)=vert(vlist(kk))
             if(x(vert(vlist(kk))).eq.o_period)then
             stand_info(vert(vlist(kk))).opening(1)=o_avail
             else
             stand_info(vert(vlist(kk))).opening(2)=o_avail
             endif
            opens(o_avail).acres=opens(o_avail).acres +
     >   (1.0 - 0.5*stand_info(vert(vlist(kk))).dead)*
     >      stand_info(vert(vlist(kk))).acres
            if(x(vert(vlist(kk))).eq.o_period)then
            stand_info(vert(vlist(kk))).opening(1)=o_avail
            else
            stand_info(vert(vlist(kk))).opening(2)=o_avail
            endif
           end do
 c now, add the edge lists
           epoint=0
```

```
          do  kk=1,now
           do  jj=1,numadj(vlist(kk))
            opens(o_avail).e(epoint+jj)=
     >       (vert( o_adj(vlist(kk),jj) ))
           end do
           opens(o_avail).epointer(kk) = epoint+1
           epoint=epoint+numadj(vlist(kk))
          end do
 c add another epointer so that other procedures can find the end of the list
          opens (o_avail).epointer(now+1) =
     >   opens(o_avail).epointer(now)+numadj(vlist(now))
          opens(o_avail).numedges = opens(o_avail).epointer(now+1)
          o_last=o_avail                !save last spot
          o_avail = av_list(o_avail)     !next available spot
 c end updating structures
       endif
       endif
       endif
       end do
      return
      end
```

subroutine merge_opens2(open_list,a_count,stand,o_period)

```
c  This routine merges the openings in open_list
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      integer*2 stand,o_period
      integer*2 open_list(maxvert),a_count
      integer*2 vert(maxvert),numon
c build the vertex list
      numon = 0
      do i=1,a_count
       do j = 1, opens(open_list(i)).numvert
        numon=numon+1
        vert(numon)=opens(open_list(i)).v(j)
       end do
      end do
      numon = numon+1
      vert(numon)=stand
      do i=1,a_count
      call del_one_open(open_list(i))
      end do
      call dfs_build2(vert,numon,o_period)
      return
      end
```

subroutine make_new_open2(stand,period,o_period)

```
c make new opening for this stand
      include 'params.f'
      include 'search_status.f'
      include 'com_open.f'
      include 'com_data.f'
      integer*2 stand,period,o_period
      if(period.eq.o_period)then
       stand_info(stand).opening(1)=o_avail
       else
       stand_info(stand).opening(2) = o_avail !second position
      endif
       opens(o_avail).v(1)=stand
       opens(o_avail).operiod=o_period
       opens(o_avail).numvert=1
       opens(o_avail).numedges = 0
       opens(o_avail).epointer(1)=0
       opens(o_avail).pointer_fwd = 0   !forward pointer
       opens(o_avail).pointer_back = o_last     !backward pointer
       if (o_last.ne.0) then
           opens(o_last).pointer_fwd=o_avail        !forward pointer,previous opening
       endif
       opens(o_avail).acres=(1.0 - 0.5*stand_info(stand).dead)*
     >      stand_info(stand).acres
       o_last=o_avail                !save last spot
           o_avail = av_list(o_avail)      !next available spot
      return
      end
```

subroutine add_stand2(stand,period)

```
c This routine adds stand in period/
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      integer*2 stand,period,a_count,open_list(maxvert),o_period
      integer*2 istart_period,iend_period
      logical found
c find adjacent openings
      if(period.eq.0)then
       istart_period=1
       iend_period=1
      else if(period.eq.numperiods)then
       istart_period=period
       iend_period=period
      else
       istart_period=period
```

```
      iend_period=period+1
     endif
     do o_period=istart_period,iend_period  !one or two possibilities
      a_count=0
      do i=1,stand_info(stand).numadj
       ilook = stand_info(stand).adj(i)
       if(x(ilook).eq.o_period) then !in first
        j=1
       else   !in second
        j=2
       endif
       if(opens(stand_info(ilook).opening(j)).operiod.eq.o_period) then
        found = .false.
            do  kk=1,a_count
             if(stand_info(ilook).opening(j).eq.open_list(kk)) then
               found = .true.       !already found
             endif
            end do
        if (.not.found) then
            a_count=a_count+1
            open_list(a_count)=stand_info(ilook).opening(j)
           endif
       endif
      end do
      if(a_count.gt.0) then
       call merge_opens2(open_list,a_count,stand,o_period)
      else
       call make_new_open2(stand,period,o_period)
      endif
     end do
     return
     end
```

subroutine findadj(vlook,o_adj,vadj,val,

```
    >    adj_point,numadj,endchain) !find a node adjacent to vlook
     include 'params.f'
     integer*2 vlook,vadj,val(maxvert),o_adj(maxvert,maxadj)
     integer*2 adj_point ,numadj,k
     logical endchain
     logical done
      if (adj_point.gt.numadj) then
           endchain = .true.
           return
     endif
     done = .false.
c adj_point points to the next adjacency point to look at for this vertex
           do  k=adj_point,numadj !search through opening adjacency list for stand ilook
```

```
            vadj=o_adj(vlook,k)
 c add edge (this is a back-edge if val(vadj) .ne.0
            if (val(vadj).eq.0) then !stand not visited before
              done = .true.
              exit
            else !stand visited before, store the back-edge
 c insert store back edge here
            endif
          end do
      endchain = .not. done
      if (done) then
          adj_point=k+1
      else
          adj_point = k
      endif
      return
      end
```

Move Calculations

subroutine calc_full_nbhood6

```
      include 'params.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      include 'com_move.f'
      include 'com_growth.f'
      include 'road_com.f'
      include 'best_move.f'
      logical asp,tabu
      real*4 big_number
      integer*4 tabu_reject_count
c  variables for road links
          integer*2 link_to_change
          integer*2 link_period_prev
          logical update
          update = .false.
          big_number = 2.0E32
       least_objective = 2.0E32
          tabu_rej_count = 0
       best_type = 0
c check the entire neighborhood
c but do it by road link to minimize # calcs required
      do link_to_change = 0,numroads                    !each link
      link_period_stands = ifuture
      link_period_prev = ifuture
      if(link_to_change.ne.0)then
       call get_l_p_prev(link_to_change,link_period_prev)
       call calc_retime_cost(link_to_change)            !calc re-time costs
```

```
      endif
c  process each stand that requires this link
c  i points into the list of stands for this link
      do i=st_point(link_to_change),st_point(link_to_change+1)-1
       move_stand = st_list(i)                                    !stand to consider
c calculate the min stand assignment for other stands
       call get_l_p_stands
       do move_period = 1,x(st_list(i))-1     !all reductions
          if(stand_info(move_stand).volume(move_period).ne.0.)then
           link_period =
     >    min0(move_period,link_period_stands,link_period_prev)
            call calc_obj_change5
            call get_aspiration2(asp)
            if(.not.asp) then                          !if not aspirated
             call check_tabu(tabu)
         else
             tabu=.false.
            endif
         if (.not.tabu) then                           !not tabu, check values
             if (move_infeasible .lt. least_objective)then
              best_move_asp = asp
              best_stand = move_stand
              best_period = move_period
              best_type = move_type
              least_objective = move_infeasible
              best_r_cost = r_cost(link_period)
              best_link_period = link_period
              best_link_period_stands=link_period_stands
              m_best_loss_penalty = move_loss_penalty
              m_best_dev_fr_total = move_dev_fr_total
              do j=1,numperiods
               m_best_dev_fr_periodic(j)=move_dev_fr_periodic(j)
              end do
              m_best_harvest = move_harvest
              m_best_dev_fr_maxopen=move_dev_fr_maxopen
         endif
            else                                !tabu rejection
             tabu_rej_count = tabu_rej_count + 1
            endif
           endif
       end do                                          !end reductions
c begin increases in stand assignment
          do move_period = x(st_list(i))+1,ifuture   !all increases
           link_period = min0(link_period_prev,link_period_stands,
     >     move_period)
            call calc_obj_change5
            call get_aspiration2(asp)
            if(.not.asp) then                          !if not aspirated
             call check_tabu(tabu)           !move tabu?
         else
```

```
        tabu = .false.
           endif
        if (.not.tabu) then            !not tabu, check values
            if (move_infeasible .lt. least_objective)then
             best_move_asp = asp
             best_stand = move_stand
             best_period = move_period
             best_type = move_type
             least_objective = move_infeasible
             best_r_cost = r_cost(link_period)
             best_link_period = link_period
             best_link_period_stands=link_period_stands
             m_best_loss_penalty = move_loss_penalty
             m_best_dev_fr_total = move_dev_fr_total
             do j=1,numperiods
              m_best_dev_fr_periodic(j)=move_dev_fr_periodic(j)
             end do
             m_best_harvest = move_harvest
             m_best_dev_fr_maxopen=move_dev_fr_maxopen
        endif
           else                                !tabu rejection
            tabu_rej_count = tabu_rej_count + 1
           endif
          end do                                                    !next increase
      end do                                                        !next stand in list
     end do                                                         !next link
     return
     end
```

subroutine calc_obj_change5

```
c this routine calculates the objective function change that would
c occur if the move of stand,period was done
c  objective function has four terms
c  penalty due to lost volume due to harvest period
c  penalty due to deviations from periodic harvest target
c  penalty due to deviations from total harvest target
c  cost of road building
c  when this routine is called, the proposed move is in com_move.f
c  existing assignments are in the stand info
      include 'params.f'
      include 'sol_param2.f'
      include 'com_data.f'
      include 'com_move.f'
      include 'road_com_sol.f'
      include 'com_growth.f'
      real*4 volume,ass_penalty
      logical test_move_feas
      move_infeasible = 0.
```

```
      do j=1,numperiods
       move_dev_fr_periodic(j)=cur_dev_fr_periodic(j)
      end do
c calculate volume
      if(move_period .eq.ifuture)then                                    !delete
       move_type = 3
       move_harvest =
     > stand_info(move_stand).volume(x(move_stand))
       move_dev_fr_periodic(x(move_stand))=
     > ddim(dabs(hvol(x(move_stand))
     > -move_harvest-ptarget),
     > periodic_all)
       move_dev_fr_total = ddim(dabs(cur_sol-move_harvest-htarget),
     > total_all)
       move_loss_penalty = stand_info(move_stand).unass_penalty
     > - stand_info(move_stand).ass_penalty(x(move_stand))
      else if (x(move_stand).eq.ifuture)then                          !add
       move_type = 1
       move_harvest = stand_info(move_stand).volume(move_period)
       move_dev_fr_periodic(move_period)=
     > ddim(dabs(hvol(move_period)
     > +move_harvest-ptarget),
     > periodic_all)
       move_dev_fr_total = ddim(dabs(cur_sol+move_harvest-htarget),
     > total_all)
       move_loss_penalty =
     > stand_info(move_stand).ass_penalty(move_period) -
     > stand_info(move_stand).unass_penalty
      else                                                            !swap
       move_type = 2
       move_dev_fr_periodic(x(move_stand))=
     > ddim(dabs(hvol(x(move_stand))
     > -stand_info(move_stand).volume(x(move_stand))-ptarget),
     > periodic_all)
       move_dev_fr_periodic(move_period)=
     > ddim(dabs(hvol(move_period)
     > +stand_info(move_stand).volume(move_period)-ptarget),
     > periodic_all)
       move_harvest =stand_info(move_stand).volume(move_period)-
     > stand_info(move_stand).volume(x(move_stand))
       move_loss_penalty =
     > stand_info(move_stand).ass_penalty(move_period)
     > - stand_info(move_stand).ass_penalty(x(move_stand))
      move_dev_fr_total = ddim(dabs(cur_sol+move_harvest-htarget),
     > total_all)
      endif
       call calc_road_cost
       call calc_dev_fr_maxopen(move_stand,move_period,move_type)
       move_dev_fr_maxopen=move_dev_fr_maxopen+cur_dev_fr_maxopen
c store the total penalty for periodic deviation and total deviation
```

```
      move_loss_penalty = move_loss_penalty + cur_loss_penalty
      move_infeasible=cur_beta*move_dev_fr_total+
     > cur_gamma*move_dev_fr_maxopen
      do j=1,numperiods
      move_infeasible=move_infeasible+move_dev_fr_periodic(j)*cur_alpha
      end do
      move_infeasible =  move_infeasible +
     >  move_loss_penalty + move_road_cost
      move_feas=test_move_feas()
      return
      end
```

subroutine calc_ass_penalty(stand,period,ass_penalty)

```
c this routine calculates the objective function change that would
c occur if the move of stand,period was done
      include 'params.f'
      include 'sol_param2.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      include 'com_growth.f'
      integer*2 stand,period
      integer*2 site
      real*4 ass_penalty
      integer*2 cur_ageclass
      real*4 cur_mai,max_mai,stock
c get the stand parameters
      site = stand_info(stand).site - 2   !have to offset by 2 for the index
      cur_ageclass=min0(22,stand_info(stand).ageclass+period-1)
      stock = stand_info(stand).stocking
      cur_mai = mai(site,cur_ageclass)
      max_mai = mai(site,
     > mai_max_age(site))
c calculate penalty to assign stand to harvest in this period
      if(stand_info(stand).dead.eq.0) then   !not dead
       ass_penalty = abs(5.0*                    !width is 5
     >  float(cur_ageclass)*                  !current age
     > (max_mai - cur_mai)*                        !diff in mai
     > stand_info(stand).acres)*stock        !stand area*stock
      else                                  !stand is dead
       ass_penalty = 5.0*(float(period-1))*        !# periods to wait
     > stand_info(stand).acres                     !stand area
     > *max_mai*stock                              !max loss
       endif
      return
      end
```

subroutine calc_unass_penalty(unass_penalty)

```
      include 'params.f'
```

```
      include 'sol_param2.f'
      include 'com_data.f'
      include 'com_move.f'
      include 'road_com_sol.f'
      include 'com_growth.f'
      real*4 volume
      integer*2 site
      real*4 ass_penalty,unass_penalty
      integer*2 cur_ageclass,age_at_end,age_before
      real*4 cur_mai,max_mai,stock
c get the stand parameters
      site = stand_info(move_stand).site - 2   !have to offset by 2 for the index
       cur_ageclass=min0(22,stand_info(move_stand).ageclass)
      stock = stand_info(move_stand).stocking
      cur_mai = mai(site,cur_ageclass)
      age_at_end = min0
     > ((stand_info(move_stand).ageclass+numperiods-1),22)
      max_mai = mai(site,
     > mai_max_age(site))
      age_before = stand_info(move_stand).ageclass -1
       if(stand_info(move_stand).dead.eq.0)then    !not dead
        if(mai_max_age(site).le.age_at_end) then !max in period or before
         unass_penalty = 5.0*
     >   max(age_before,mai_max_age(site))*
     >   abs(max_mai - mai(site,age_before))*       !diff in mai
     >   stock*stand_info(move_stand).acres                    !stock * area
        else
         unass_penalty = 0.0
        endif
       else   !stand is dead
        unass_penalty = 5.0*max_mai*stand_info(move_stand).acres*numperiods*stock
       endif
      return
      end
```

subroutine calc_volume(stand,period,volume)

```
      include 'params.f'
      include 'com_data.f'
      include 'com_growth.f'
      include 'road_com_sol.f'
      integer*2 stand,period
      real*4 volume
      integer*2 ageclass
      real*4 acres,cur_mai
      if(stand_info(stand).for_non.eq.9960) then !existing clearcut
           volume = 0.
      else if (stand_info(stand).dead.eq.1) then
          volume = stand_info(stand).ivol*stand_info(stand).acres
```

```
      else
       ageclass = min0(22,(stand_info(stand).ageclass+period-1))
          cur_mai=mai(stand_info(stand).site-2,ageclass)
          acres = stand_info(stand).acres
          volume = 5.0*float(ageclass)*
     >    cur_mai*acres*stand_info(stand).stocking/1000.
       endif
       return
       end
```

subroutine calc_objective

```
      include 'params.f'
      include 'sol_param2.f'
      include 'com_data.f'
      include 'road_com.f'
      include 'com_open.f'
      include 'road_com_sol.f
      integer*2 i
c init to zero
      cur_loss_penalty = 0.0
      cur_sol = 0.0
      do j=1,numperiods
       cur_dev_fr_periodic(j)=0.0
       hvol(j) = 0.0
      end do
      cur_dev_fr_maxopen = 0.0
      cur_dev_fr_total = 0.0
c calculate volumes and loss penalty for this solution
      do i=1,numread
      if(x(i).gt.0)then
      if(x(i).eq.ifuture)then
       cur_loss_penalty = cur_loss_penalty + stand_info(i).unass_penalty
      else
       cur_loss_penalty=cur_loss_penalty+stand_info(i).ass_penalty(x(i))
       hvol(x(i))=hvol(x(i))+stand_info(i).volume(x(i))
      endif
      endif
      end do
c subtract the unavoidable loss
      cur_loss_penalty = (cur_loss_penalty - min_loss_penalty)
c add up the volumes
      do i=1,numperiods
       cur_sol=cur_sol+hvol(i)
      end do
c calculate dev from maxopen
      i = o_top
      do while (i.ne.0)
      cur_dev_fr_maxopen=cur_dev_fr_maxopen+
```

```
     > dim(opens(i).acres,rmaxopen)
      i=opens(i).pointer_fwd
      end do
 c calculate deviations from total and periodic
      do i=1,numperiods
       cur_dev_fr_periodic(i)= ddim(dabs(hvol(i)-ptarget),periodic_all)
      end do
      cur_dev_fr_total= ddim(dabs(cur_sol-htarget),total_all)
      cur_infeasible = cur_loss_penalty+
     > cur_road_cost+
     > cur_dev_fr_total+
     > cur_dev_fr_maxopen
      do i=1,numperiods
       cur_infeasible=cur_infeasible+cur_dev_fr_periodic(i)
      end do
      cur_feasible=cur_loss_penalty+cur_road_cost
      return
      end
```

subroutine calc_base_loss

```
      include 'params.f'
      include 'sol_param2.f'
      include 'com_growth.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      integer*2 stand,ageclass,site,max_age,period
      real*4 ass_penalty
      min_loss_penalty = 0.0
      do stand=1,numread                                  !for each stand
      if(x(stand).gt.0)then
       site = stand_info(stand).site - 2
       max_age = mai_max_age(site)
       if(max_age.lt.stand_info(stand).ageclass) then     !before, put in period 1
           period = 1
           min_loss_penalty = min_loss_penalty +
     >     stand_info(stand).ass_penalty(period)
       endif
      endif
      end do
      return
      end
```

subroutine calc_dev_fr_maxopen(stand,period,type)

```
c Calculate deviation from maxopen if move is done
      include 'params.f'
```

```
      include 'com_open.f'
      include 'com_data.f'
      include 'com_move.f'
      include 'search_status.f'
      include 'road_com_sol.f'
      integer*2 stand,period,type
      real*4 open_size
      integer*2 open_list(20),start_period,j,l
      logical found
      integer numfound
      real*4 dev_penalty
      integer*2 next_period
c calculate the penalty for of openings that would be created by adding this
c stand in this period
c  this is an incremental penalty, for this move only
c set penalty to zero
      next_period = period + 1
      move_dev_fr_maxopen = 0.0
      if (type.eq.3) then
       call calc_rem_stand
     > (stand,stand_info(stand).opening(1),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_rem_stand
     >  (stand,stand_info(stand).opening(2),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
      else if (type.eq.2) then                !swap move
       idir = period - x(stand)
       if(idir .eq.1) then              !increase by one
        call calc_rem_stand
     >   (stand,stand_info(stand).opening(1),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_add_stand(stand,next_period,dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
      else if (idir.eq.-1) then
       call calc_rem_stand
     >   (stand,stand_info(stand).opening(2),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_add_stand(stand,period,dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
      else !non-consecutive moves
       call calc_rem_stand
     >   (stand,stand_info(stand).opening(1),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_rem_stand
     >   (stand,stand_info(stand).opening(2),dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_add_stand(stand,period,dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
       call calc_add_stand(stand,next_period,dev_penalty)
       move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
```

```
 endif                                              !swap move finished
 else if (type .eq.1)then                                        !add move
  call calc_add_stand(stand,period,dev_penalty)
  move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
  call calc_add_stand(stand,next_period,dev_penalty)
  move_dev_fr_maxopen=move_dev_fr_maxopen+dev_penalty
 else                                                    !bad move
 stop
 endif
 move_dev_fr_maxopen=(move_dev_fr_maxopen)
 return
 end
```

subroutine calc_add_stand(stand,period,dev_penalty)

```
 include 'params.f'
 include 'com_data.f'
 include 'com_open.f'
 include 'com_move.f'
 include 'search_status.f'
 integer*2 stand,period
 real*4 dev_penalty,open_size
 real*4 dev_now
 integer*2 open_list(20)
 integer*2 open_no
 logical found
 numfound=0
 dev_penalty=0.0
 dev_now = 0.0
 if(period .gt.numperiods)return
 open_size = (1.0 - 0.5*stand_info(stand).dead)*
>     stand_info(stand).acres
 do k=1,stand_info(stand).numadj  !for each adjacent stand
  ilook=stand_info(stand).adj(k)
  do l=1,2
      open_no=stand_info(ilook).opening(l)
      if(open_no.ne.0)then
   if (opens(open_no).operiod.eq.period)then
    found = .false.
    do m=1,numfound
     if(open_list(m).eq.open_no)then
         found=.true.
         exit
        endif
    end do
    if(.not.found)then
     numfound=numfound+1
     open_list(numfound)=open_no
        open_size = open_size+opens(open_no).acres
```

```
            dev_now = dev_now + dim(opens(open_no).acres,rmaxopen)
          exit                          !only one to find
         endif
        endif
       endif
      end do                !next opening number (l)
     end do                 !next adjacency
     dev_penalty = dim(open_size,rmaxopen)-dev_now
     return
     end
```

subroutine calc_new_open(stand,open_no,dev_value)

```
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      integer*2 stand,open_no
      real*4 dev_value,opensize
     integer*2 numon,now,vlook,o_period,opening
     integer*2 vert(maxvert),val(maxvert),o_adj(maxvert,maxadj)
     integer*2 numadj(maxvert)
     integer*2 adj_point (maxvert)
     logical endchain
     integer*2 vlist(maxvert),vadj,epoint,jj,i,j,k
     integer*2 rstack(maxvert),stack_end !stack to make the recursion work
c this routine determines whether or not deletion of stand ould split the
c opening and the resultant opening sizes
c returns value = 0.0 if resultant openings less than rmaxopen
c otherwise returns dev_value = rmaxopen - opening size - stand acres
c o_period points to the opening in stand_inf that is being considered
c  The opening is currently larger than rmaxopen
      dev_value = 0.0
c build the vertex list
      numon = 0
      do i=1,opens(open_no).numvert
      if(opens(open_no).v(i).ne.stand)then
          numon=numon+1
          vert(numon)=opens(open_no).v(i)
      endif
      end do
c now, the appropriate stands are in array VERT
c make up an OPENING adjacency list for each vertex by intersecting
c VERT with the stand adjacencies.
c init vlist, val
     do ii =1,numon
     val(ii)=0
     end do
c init ajacency pointers
     do ii=1,numon
```

```
      adj_point(ii) = 1
      numadj(ii)=0
      end do
 c build adjacency lists
      do i=1,numon
      numfound=0
      numa=stand_info(vert(i)).numadj
      do j=1,numa
      do k=1,numon
       if(stand_info(vert(i)).adj(j).eq.vert(k))then
        numadj(i)=numadj(i)+1
            o_adj(i,numadj(i))=k
            exit
       endif
      end do
      end do
      end do
      endchain = .FALSE.
 c start filling up openings, first available is o_avail
      do  i=1,numon       !numon is the number of Xij=1
       now=0          !visit pointer
       do ii=1,numon
            vlist(ii)=0          ! now used to store pointers to found nodes
       end do
       stack_end=0     !empty stack to begin
       if (val(i).eq.0) then ! node not visited
            now=now+1          !increment visit pointer
            val(i)=now         !store visit number
            vlist(now)=i       !store node pointer
            vlook = i
            stack_end=stack_end+1
       rstack(stack_end)=i   !add node to recursion stack
 99    call findadj(vlook,o_adj,vadj,val,
     >     adj_point(vlook),numadj(vlook),endchain) !find a node adjacent to vlook
           if (.not.endchain) then !found one
            now=now+1            !update visit pointer
            val(vadj)=now        !store visit number
            vlist(now)= vadj !store found node
            vlook = vadj   !next vertex to search in chain
          if(adj_point(vadj).le.numadj(vadj))then
             stack_end=stack_end+1
             rstack (stack_end)=vadj !update stack
             endif
           goto 99
           else
 c end of downward chain
 c take entry off stack
       vlook = -1
           do jj=stack_end,1,-1
            if(adj_point(rstack(jj)).le.numadj(rstack(jj)))then
```

```
            vlook = rstack(jj)
            exit
          endif
         end do
            if (vlook.ne.-1) then
             goto 99
            else !thus, done for this connected component
c calculate the size of the opening
           opensize = 0.0
           do  kk=1,now    !add the stands
            opensize=opensize+stand_info(vert(vlist(kk))).acres *
     > (1.0-0.5*stand_info(vert(vlist(kk))).dead)
           end do
       dev_value = dev_value + dim(opensize,rmaxopen)
       endif
       endif
       endif
       end do                          !next connected component
       return
       end
```

subroutine calc_rem_stand(stand,opening,dev_penalty)

```
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      integer*2 stand,opening
      real*4 dev_penalty,dev_now,contrib
      dev_penalty=0.0
      if (opening.eq.0)return
      dev_now = opens(opening).acres - rmaxopen
      if(dev_now .le.0.0)return
      contrib=dev_now -
     >  (1.0 - 0.5*stand_info(stand).dead)*
     >stand_info(stand).acres
      if(contrib.le. 0.0) then
       dev_penalty = -1*dev_now                    !simple delete ok, return
      else                                    !check opening structure
       call calc_new_open(stand,opening,contrib)
       dev_penalty=contrib-dev_now
      endif
      return
      end
```

subroutine calc_opens(test_dev_fr_maxopen)

```
      include 'params.f'
      include 'com_open.f'
```

```
      include 'com_data.f'
      include 'road_com_sol.f'
      real*4 test_dev_fr_maxopen
      integer*2 op_no
      test_dev_fr_maxopen = 0.0
      op_no = o_top
      do while(op_no.ne.0)
      test_dev_fr_maxopen=test_dev_fr_maxopen+
     >   dim(opens(op_no).acres,rmaxopen)
      op_no=opens(op_no).pointer_fwd
      end do
      return
      end
```

subroutine calc_feas_for_maxopen(stand,period,type)

```
      include 'params.f'
      include 'com_open.f'
      include 'com_data.f'
      include 'com_move.f'
      include 'search_status.f'
      include 'road_com_sol.f'
      integer*2 stand,period,type
      real*4 open_size
      integer*2 open_list(20),start_period,j,l
      logical found
      integer numfound
      real*4 dev_penalty
      integer*2 next_period
c  This routine is to be used for the feasible moves only; assume all moves
c taken prior to this one are feasible.
c  Calculate the opening size that would be created by adding this stand
c  or swapping the stand
c  If the move is to delete, return
      if (type.eq.3)return
c set variables
      move_dev_fr_maxopen = 0.0
      next_period = period + 1
      if (type.eq.2) then               !swap move
      call calc_add_stand(stand,period,dev_penalty)!check first type
      if(rtrunc(dev_penalty).gt.0.0)then
       move_dev_fr_maxopen = dev_penalty
       return
      endif
       if(period.lt.numperiods)then
           call calc_add_stand(stand,next_period,dev_penalty)!check second type
           move_dev_fr_maxopen=dev_penalty
       endif
```

```
      else if (type .eq.1)then                                    !add move
       call calc_add_stand(stand,period,dev_penalty)!first type
      if(rtrunc(dev_penalty).gt.0.0)then
       move_dev_fr_maxopen = dev_penalty
       return
      endif
       if(period.lt.numperiods)then!second type
       call calc_add_stand(stand,next_period,dev_penalty)
       move_dev_fr_maxopen=dev_penalty
       endif
      endif
      return
      end
```

subroutine calc_r_cost_sngl(ilink,cost,l_period)

```
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'com_move.f'
      real*4 cost
      integer*2 ilink,l_period,imin,p_link,thelink
      logical debug
      imin = l_period
      p_link = -1
      debug=.false.
      thelink=ilink
c  first check sons of the link to change
      do j=1,roads(ilink).numsons
      if(roads(ilink).sons(j).ne.p_link)
     > imin = min(imin,roads(roads(ilink).sons(j)).period_assigned)
      end do
      if(imin.eq.roads(ilink).period_assigned)then
       cost = 0.0
       return
      else
      cost= (roads(ilink).lgth)*
     >      (d_factor(imin)-d_factor(roads(ilink).period_assigned))
      p_link=ilink
      ilink=roads(ilink).dad_link
      do while ((imin.lt.roads(ilink).period).and.(ilink.ne.0))
c  first check sons of the link to change
      do j=1,roads(ilink).numsons
      if(roads(ilink).sons(j).ne.p_link)
     > imin = min(imin,roads(roads(ilink).sons(j)).period_assigned)
      end do        !now imin is min(imin,sons)
      imin=min(imin,roads(ilink).period) !and now min(sons,link)
      cost=cost + roads(ilink).lgth*
     >      (d_factor(imin)-d_factor(roads(ilink).period_assigned))
      p_link = ilink
```

```
      ilink = roads(ilink).dad_link
      end do
      endif
      ilink=thelink
      return
      end
```

subroutine calc_road_cost

```
      include 'params.f'
      include 'sol_param2.f'
      include 'com_move.f'
      include 'road_com.f'
      include 'road_com_sol.f'
      include 'com_data.f'
      integer*2 link_to_change
      if (stand_info(move_stand).link_req.eq.0)then
       move_road_cost = cur_road_cost
      else
       move_road_cost = cur_road_cost +r_cost(link_period)
      endif
      return
      end
```

Move Implementation

subroutine implement_best_move2

```
      include 'params.f'
      include 'search_status.f'
      include 'sol_param2.f'
      include 'best_move.f'
      include 'road_com_sol.f'
      include 'com_data.f'
      include 'com_move.f'
      real*4 volume
      call update_roads
c calc periodic harvests
     if(best_type .eq. 1) then                              !add
      hvol(best_period)=hvol(best_period)+m_best_harvest
     cur_sol = cur_sol + m_best_harvest
     else if (best_type.eq.3) then                          !delete
      hvol(x(best_stand))=
     >  hvol(x(best_stand))-m_best_harvest
     cur_sol = cur_sol - m_best_harvest
     else                                                           !swap move
      cur_sol=cur_sol+m_best_harvest
      hvol(best_period)=hvol(best_period)+
```

```
     > stand_info(best_stand).volume(best_period)
      hvol(x(best_stand))=hvol(x(best_stand))-
     > stand_info(best_stand).volume(x(best_stand))
      endif
 c update_roads does current road cost
      cur_loss_penalty  = m_best_loss_penalty
      cur_dev_fr_total = m_best_dev_fr_total
      cur_infeasible = least_objective
      cur_feasible =cur_loss_penalty + cur_road_cost
      do j = 1, numperiods
       cur_dev_fr_periodic(j)=m_best_dev_fr_periodic(j)
      end do
       cur_dev_fr_maxopen=m_best_dev_fr_maxopen
       x(best_stand)=best_period
      if(best_type.eq.1) then                    !add move
           call add_stand2(best_stand,best_period)
      else if (best_type .eq. 2) then            !swap move
       call del_stand2(best_stand)
       call ADD_STAND2 (best_stand,best_period)
      else if (best_type.eq.3) then         !delete move
       call DEL_STAND2 (best_stand)
      endif
      call tabu_add(best_stand)
      return
      end
```

subroutine implement_stand_move2

```
      include 'params.f'
      include 'search_status.f'
      include 'sol_param2.f'
      include 'road_com_sol.f'
      include 'com_move.f'
      include 'com_data.f'
      real*4 volume
c this routine implements the move
      if(move_type.eq.1)then                                  !add
       hvol(move_period)=hvol(move_period)+move_harvest
      cur_sol = cur_sol + move_harvest
      else if (move_type.eq.3) then                                !delete
       hvol(x(move_stand))=
     > hvol(x(move_stand))-move_harvest
      cur_sol = cur_sol - move_harvest
      else                                                    !swap move
       hvol(move_period)=hvol(move_period)+
     > stand_info(move_stand).volume(move_period)
      cur_sol = cur_sol + stand_info(move_stand).volume(move_period)
       hvol(x(move_stand))=
     >     hvol(x(move_stand))-
```

```
     >    stand_info(x(move_stand)).volume(x(move_stand))
      cur_sol = cur_sol -
     > stand_info(x(move_stand)).volume(x(move_stand))
      endif
c  update the solution variables
      if((move_type.eq.1).or.(move_type.eq.2)) then                !add or swap
       x(move_stand)=move_period
      else if (move_type .eq.3) then                               !delete
       x(move_stand)=ifuture
      endif
      cur_loss_penalty = move_loss_penalty
      cur_dev_fr_total = move_dev_fr_total
      do j= 1, numperiods
      cur_dev_fr_periodic(j)=move_dev_fr_periodic(j)
      end do
      cur_dev_fr_maxopen = move_dev_fr_maxopen
      cur_infeasible = move_infeasible
      cur_feasible = cur_loss_penalty
      if(move_type.eq.1) then                          !add move
           call add_stand2(move_stand,move_period)
      else if (move_type .eq. 2) then                  !swap move
       call del_stand2(move_stand)
       call ADD_STAND2 (move_stand,move_period)
      else if (move_type.eq.3) then                    !delete move
       call DEL_STAND2 (move_stand)
      endif
      return
      end
```

subroutine do_this_move2

```
      include 'params.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      include 'com_move.f'
      include 'com_growth.f'
      include 'road_com.f'
      include 'best_move.f'
c this routine calculates and implements the move in com_move.f
c move_stand,move_period,move_type
      logical asp,tabu
c  variables for road links
      integer*2 link_to_change
      integer*2 link_period_prev
      link_to_change = stand_info(move_stand).link_req
      link_period_stands = ifuture
      link_period_prev = ifuture
      if(link_to_change.ne.0)then
       call get_l_p_prev(link_to_change,link_period_prev)!prev link period
```

```
      call calc_retime_cost(link_to_change)                    !calc re-time costs
 c calculate the min stand assignment for other stands
      call get_l_p_stands
      link_period =
     >    min0(move_period,link_period_stands,link_period_prev)
     endif
      call calc_obj_change5
      best_stand = move_stand
      best_period = move_period
      best_type = move_type
      least_objective = move_infeasible
      best_r_cost = r_cost(link_period)
      best_link_period = link_period
      best_link_period_stands=link_period_stands
      m_best_loss_penalty = move_loss_penalty
      m_best_dev_fr_total = move_dev_fr_total
      do j=1,numperiods
          m_best_dev_fr_periodic(j)=move_dev_fr_periodic(j)
      end do
      m_best_harvest = move_harvest
      m_best_dev_fr_maxopen=move_dev_fr_maxopen
      call implement_best_move2
     return
     end
```

subroutine update_roads

```
c this routine updates roading for best_move.f
c called by implement_best_move
     include 'params.f'
     include 'road_com.f'
     include 'com_data.f'
     include 'road_com_sol.f'
     include 'best_move.f'
     include 'search_status.f'
     include 'sol_param2.f'
     integer*2 link_to_change,old_period
     link_to_change = stand_info(best_stand).link_req
     if (link_to_change.eq.0) return                    !nothing to do
       roads(link_to_change).period=
    >    min(best_link_period_stands,best_period)
     if(best_period.ne.ifuture)then
      roads(link_to_change).required_by_harvest=.true.
     else
      roads(link_to_change).required_by_harvest = .false.
     endif
     call build_roads
     return

          end
```

subroutine re_time

```
c this routine retimes the links in the path as defined by best_mvoe.f
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'road_com_sol.f'
      include 'com_data.f'
      include 'best_move.f'
      integer*2 link_to_change
      integer*2 imin,p_link,prev_path
      link_to_change = stand_info(best_stand).link_req
      if((best_link_period.lt.1).or.(best_link_period.gt.ifuture))then
       write(21,*) 'error in link_period ',best_link_period
       write(21,*) best_stand,best_period,best_type,link_to_change
       write(21,*) 'stand currently assigned to',x(best_stand)
       stop
      endif
      roads(link_to_change).period=
     > min(best_link_period_stands,best_period)
      roads(link_to_change).required_by_harvest = .true.
c if the same, return
      if (best_link_period .eq.
     >  roads(link_to_change).period_assigned)return
       roads(link_to_change).period_assigned = best_link_period
c and retime the path
      imin = best_link_period
c save this link
      p_link = link_to_change
c     get next link
      link_to_change = roads(link_to_change).dad_link
     do while(link_to_change.ne.0)
c if there is another path adjoining at this link,
c find min of other path
      call get_prev_path(link_to_change,p_link,prev_path)
      imin = min(imin,roads(link_to_change).period,prev_path)      !min calculated
      roads(link_to_change).period_assigned = imin                 !make change
      p_link = link_to_change
      link_to_change = roads(link_to_change).dad_link
     end do
     return
     end
```

subroutine get_l_p_stands

```
include 'params.f'
include 'road_com_sol.f'
include 'road_com.f'
include 'com_move.f'
include 'com_data.f'
link_period_stands = ifuture
if (stand_info(move_stand).link_req.eq.0)return
do k = st_point(stand_info(move_stand).link_req),
> st_point(stand_info(move_stand).link_req+1)-1
 if(st_list(k).ne.move_stand) then
  link_period_stands = min0(x(st_list(k)),link_period_stands)
 endif
end do
return
end
```

subroutine get_l_p_prev(link_to_change,link_period_prev)

```
include 'params.f'
include 'road_com.f'
include 'com_move.f'
include 'com_data.f'
include 'road_com_sol.f'
integer*2 link_period_prev
integer*2 link_to_change
link_period_prev = ifuture
if(link_to_change.eq.0) return
do j = 1 , roads(link_to_change).numsons
 link_period_prev = min0(link_period_prev,
> roads(roads(link_to_change).sons(j)).period_assigned)
end do
return
end
```

subroutine get_prev_path(link_to_change,p_link,path_period)

```
include 'params.f'
include 'road_com.f'
include 'com_move.f'
integer*2 p_link,path_period
integer*2 link_to_change
if(link_to_change.eq.0) return
path_period = ifuture
do j = 1 , roads(link_to_change).numsons
 if (roads(link_to_change).sons(j).ne.p_link)then
```

```
        path_period = min0(path_period,
     >  roads(roads(link_to_change).sons(j)).period_assigned)
       endif
      end do
      return
      end
```

subroutine get_all_links(ilink,link_list,link_len)

```
      include 'params.f'
      include 'road_com.f'
      integer*2 ilink,link_list(numroads),link_len
      integer*2 now,k,stack_end,stack(numroads)
c simplified search since only backward links are included in sons
c and the structure is a tree
      now=1
      stack_end=0
      link_list(now)=ilink
10    continue
      do k=1,roads(ilink).numsons
       now=now+1
       link_list(now)=roads(ilink).sons(k)
       stack_end=stack_end+1
       stack(stack_end)=link_list(now)
      end do
      if(stack_end.ne.0)then
       ilink=stack(stack_end)
       stack_end=stack_end-1
       goto 10
      endif
      link_len=now
       return
       end
```

subroutine stand_escape_routine

```
      include 'params.f'
      include 'sol_param2.f'
      include 'search_status.f'
      include 'road_com_sol.f'
      include 'com_data.f'
      include 'com_move.f'
      include 'road_com.f'
      include 'com_reactive.f'
      logical feas
```

```
      num_esc_steps =min(60,int((1+rand())*moving_average))
      do i=1,num_esc_steps
10     move_stand = int(rand()*numstands)+1
       if(x(move_stand).eq.ifuture)then
            move_type = 1
            move_period = int(rand()*numperiods)+1
       else if (x(move_stand).ne.0) then
        move_period = ifuture
        move_type = 3
          else
           goto 10
       endif
      x(move_stand)=move_period
      if(move_type.eq.1) then                          !add move
          call add_stand2(move_stand,move_period)
      else
       call DEL_STAND2 (move_stand)
      endif
      call tabu_add(move_stand)
       end do
       call init_roads
       do i=1,numread
       if ((x(i).ne.0).and.(stand_info(i).link_req.ne.0))then
           roads(stand_info(i).link_req).period=min0(
     >     roads(stand_info(i).link_req).period,x(i))
       endif
       end do
       do i=1,numroads
       if(roads(i).period.lt.ifuture)
     > roads(i).required_by_harvest = .true.
       end do
       call build_roads
       cur_road_cost=cur_road_cost*r_factor
       call calc_objective
       call update_best
       return
       end
```

subroutine update_best

```
      include 'params.f'
      include 'search_status.f'
      include 'com_move.f'
      include 'road_com_sol.f'
      include 'best_sol.f'
      logical test_sol_feas,escape
      escape=.false.
      move_feas=test_sol_feas()
```

```
c update best solutions
     if(.not.move_feas)then                                    !infeasible move
      best_infeasible = dmin1(cur_infeasible,best_infeasible)
      moves_since_improve = moves_since_improve + 1
     else                                                      !feasible move
      if(cur_feasible.lt.best_feasible)then                    !improving
          imp_time =move_count
          best_feasible = cur_feasible
          best_loss_penalty = cur_loss_penalty
          best_road_cost = cur_road_cost
          best_sol = cur_sol
          moves_since_improve = 0
       call save_sol
      else                                                                !feasible,non-improving
          moves_since_improve = moves_since_improve + 1
      endif
     endif
     return
     end
```

subroutine rts_escape_routine2

```
c This is the final routine called ESCAPE3
     include 'params.f'
     include 'sol_param2.f'
     include 'search_status.f'
     include 'road_com_sol.f'
     include 'com_reactive.f'
     include 'com_hash.f'
     include 'com_data.f'
     include 'road_com.f'
     logical done,escape
     escape=.true.
c calc number of links in road system
     num_links = 0
     do k=1,numroads
     if(roads(k).period_assigned.ne.ifuture)num_links=num_links+1
     end do
     if ((float(num_links)/float(numroads)).gt. .10)then
      call new_escape_routine
     else
      call stand_escape_routine
      return
     endif
c  check the final solution and add it to the hash_table
     done = .false.
     call hashfn(numread)
     do while (.not.done)
     if((hash_table(hash_add).eq.-1).or.              !empty slot
    > (config_info(hash_table(hash_add)).sol_value -
```

```
     > cur_feasible.lt. 0.0001))then                    !match
      done = .true.
     else
      hash_add = mod((hash_add+1),itable_size)          !linear probe
     endif
     end do
c if it is a new configuration, add it
c otherwise, do nothing
     if(hash_table(hash_add).eq.-1) then          !existing configuration
      config_point=config_point+1
      if(config_point.gt.10000)then
           write(21,*) '*** error *** config_point > 10000'
           write(*,*) '*** error *** config_point > 10000'
       stop
      endif
      hash_table(hash_add)=config_point
      config_info(config_point).time_last_found = move_count
      config_info(config_point).sol_value = cur_feasible
     endif
     return
     end
```

subroutine choose_a_link(ilink,iperiod)

```
c  Choose link from the leaves in the current road structure
c and return the link id and the period to shift the link to.
     include 'params.f'
     include 'com_tabu2.f'
     include 'road_com.f'
     include 'search_status.f'
     integer*2 ilink,iperiod,l,l_period
     real*4 cost,least_cost
     least_cost = 999999.0
     do l=1,numroads
      if((roads(l).required_by_harvest)
    >  .and.(roads(l).numsons.eq.0)) then  !link in road net and is a leaf
       if ((move_count-roads(l).time).gt. link_tenure) then !if not tabu
       l_period = roads(l).period_assigned + 1
       call calc_r_cost_sngl(l,cost,l_period)
        if(cost.lt.least_cost)then
         least_cost=cost
         ilink = l
         iperiod = l_period
        endif
       endif
      endif
     end do
     return
     end
```

subroutine new_escape_routine

```
      include 'params.f'
      include 'search_status.f'
      include 'road_com_sol.f'
      include 'com_tabu2.f'
      include 'road_com.f'
      integer*2 ilink, l_period
      if (cur_road_cost.eq.0.0)then
          call stand_escape_routine
      else
          call choose_a_link(ilink,l_period)
          if(ilink.eq.-1)then
           write(21,*) 'no link found amongst leaves'
           message = 'no link found amongst leaves'
           at_end = .true.
       return
      endif
      do i=st_point(ilink),st_point(ilink+1)-1
          tabu_tenure = tabu_tenure + st_point(ilink+1)-st_point(ilink)
       if (x(st_list(i)).lt.l_period) then  !retime the stand
        x(st_list(i))=l_period
            if(l_period .eq. ifuture)then
         call del_stand2(st_list(i))
            else
             call del_stand2(st_list(i))
         call ADD_STAND2 (st_list(i),l_period)
            endif
        call tabu_add(st_list(i))
           endif
       end do
      endif
      roads(ilink).period = l_period
      roads(ilink).time = move_count
      if(l_period.eq.ifuture)roads(ilink).required_by_harvest = .false.
      call build_roads
      call calc_objective
      return

            end
```

subroutine link_escape

```
c This routine deletes links until a large enough set of stands have been deleted
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'com_data.f'
```

```
      include 'road_com_sol.f'
      include 'com_move.f'
      include 'com_tabu2.f'
      include 'search_status.f'
      include 'com_reactive.f'
      integer*2 ilink
      integer*2 link_list(numroads)
      integer*2 link_len
      logical test_sol_feas
      integer stand_count
      num_esc_steps =min(60,int((1+rand())*moving_average)/5.0)
      stand_count=0
      num_tries=0
 10   num_tries=num_tries+1
      ilink = int(rand()*numroads)+1
      if(roads(ilink).period.eq.ifuture)goto 10
       call get_all_links(ilink,link_list,link_len)
c now, re-assign all the stands that are involved to ifuture
c for each link in the list
      do k = 1, link_len
       ilink=link_list(k)
       do i=st_point(ilink),st_point(ilink+1)-1
        if (x(st_list(i)).gt.0.and.x(st_list(i)).lt.ifuture) then
            stand_count=stand_count+1
         x(st_list(i))=ifuture
         call tabu_add(st_list(i))
           endif
       end do
       roads(ilink).period = ifuture  ! assign the road link
       roads(ilink).required_by_harvest = .false.
      end do
c if not enough stands have been deleted, get another link
       if (stand_count.lt.num_esc_steps.and.num_tries.lt.10) goto 10
       call init_opens!re-do the openings
      call make_opens2
      call build_roads       ! re-build the roads
      cur_road_cost=cur_road_cost*r_factor
      call calc_objective    !calculate the objective
      move_feas = test_sol_feas()
      call update_best
      tabu_tenure = tabu_tenure+ float(stand_count)!increase tabu_tenure
      return
      end
```

Utility Routines and Functions

```
      real*4 function rtrunc(rreal_number)
      real*4 epsilon
      real*4 rreal_number
```

```
 parameter(epsilon=.01)
 if (abs(rreal_number).lt.epsilon) then
 rtrunc=0.0
 else
 rtrunc=rreal_number
 endif
 return
 end function rtrunc

 real*8 function dtrunc(dreal_number)
 real*8 epsilon
 real*8 dreal_number
 parameter(epsilon=.01)
 if (dabs(dreal_number).lt.epsilon) then
 dtrunc=0.0
 else
 dtrunc=dreal_number
 endif
 return
 end function dtrunc
```

subroutine reinstal !reinstal the best solution found

```
 include 'params.f'
 include 'road_com_sol.f'
 include 'best_sol.f'
 include 'road_com.f'
 include 'com_data.f'
 call init_roads
 do i=1,numread
  x(i)=x_save(i)
  if(x(i).gt.0.and.x(i).lt.ifuture)then
   if (stand_info(i).link_req.ne.0)then
        roads(stand_info(i).link_req).period = min(x(i),
>       roads(stand_info(i).link_req).period)
        roads(stand_info(i).link_req).required_by_harvest = .true.
   endif
  endif
 end do
 call build_roads
 call init_opens
 call make_opens2
 call calc_objective
 return
 end
```

subroutine write_sol(icount)

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'road_com.f'
      include 'sol_param2.f'
      include 'com_data.f'
      include 'com_open.f'
      integer icount
c use best solution
      call reinstal
c write out parameters
      write(61,*) 'r_factor = ',r_factor,'stream = ',icount
      write(71,*) 'r_factor = ',r_factor,'stream = ',icount
      write(81,*) 'r_factor = ',r_factor,'stream = ',icount
c solution now in current
c write out totals to each file
      write(61,800)cur_loss_penalty,cur_road_cost,cur_feasible,
     > hvol
      write(71,800)cur_loss_penalty,cur_road_cost,cur_feasible,
     > hvol
      write(81,800)cur_loss_penalty,cur_road_cost,cur_feasible,
     > hvol
800   format(10(f12.2,','))
c write harvest and openings
      do i=1,numread
      write(81,1000)stand_info(i).stand_no,
     > x(i),stand_info(i).opening(1),
     > stand_info(i).opening(2)
      end do
      do i=1,numread
      write(61,1000)stand_info(i).stand_no,x(i)
      end do
c write roads
      do i=1,numroads
      write(71,1100) i,roads(i).period_assigned
      end do
1000  format(4(i6,','))
1100  format(i4,',',i2)
      return
      end
```

subroutine write_data_rts(icount)

```
      include 'params.f'
      include 'search_status.f'
      include 'road_com_sol.f'
      include 'com_reactive.f'
      include 'sol_param2.f'
      integer icount
      write(11,9000)r_factor,best_loss_penalty,
```

```
     >best_road_cost,
     >(best_loss_penalty+best_road_cost),
     >total_time,
     >imp_time,
     >move_count,icount,
     >message
9000  format (5(f20.2,','),3(i6,','),a30)
      return
      end
```

subroutine save_init_sol

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'init_sol.f'
      include 'com_data.f'
      do i=1,numread
      i_sol(i)=x(i)
      end do
      return
      end
```

subroutine get_init_sol

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'init_sol.f'
      include 'com_data.f'
      include 'road_com.f'
      call init_roads
      do i=1,numread
       x(i)=i_sol(i)
          if(stand_info(i).link_req.ne.0)then
           if(x(i).gt.0)then
            roads(stand_info(i).link_req).period=min0(x(i),
     >      roads(stand_info(i).link_req).period)
           if(x(i).lt.ifuture)
     >   roads(stand_info(i).link_req).required_by_harvest=.true.
            endif
           endif
       end do
      call init_opens
      call make_opens2

     return
     end
```

subroutine init_best_values

```
      include 'params.f'
      include 'road_com_sol.f'
      best_feasible=999999999.
      best_infeasible=999999999.
      best_loss_penalty=999999999.
      best_road_cost=999999999.
      return
      end
```

subroutine write_iter

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'search_status.f'
      include 'com_move.f'
      write(91,1000)move_count,move_feas,
     > cur_loss_penalty,cur_road_cost,
     >dtrunc(cur_dev_fr_total),
     >(dtrunc(cur_dev_fr_periodic(j)),j=1,numperiods),
     >dtrunc(cur_dev_fr_maxopen),
     >best_feasible
1000  format(i5,',',l4,10(f12.2,','))
      return
      end
```

subroutine init_move_counters2

```
      include 'params.f'
      include 'search_status.f'
      include 'sol_param2.f'
      cur_alpha=upper_bound
      cur_beta=upper_bound
      cur_gamma=upper_bound
      move_count = 1
      moves_since_improve = 0
      escape_time=0
      message = 'No Message'
      feas_count_total = 0
      feas_count_per = 0
      feas_count_open = 0
      infeas_count_total = 0
      infeas_count_per = 0
      infeas_count_open = 0
      return
      end
```

subroutine update_move_counters2

```
      include 'params.f'
      include 'sol_param2.f'
      include 'search_status.f'
      include 'com_move.f'
      include 'road_com_sol.f'
      move_count = move_count + 1
      if(move_feas)then                                    !last move was feasible
       feas_count_per=feas_count_per+1
       feas_count_total=feas_count_total+1
       feas_count_open=feas_count_open+1
      else
      if(dtrunc(cur_dev_fr_total).ne.0.0)then
            infeas_count_total=infeas_count_total+1
      else
            feas_count_total=feas_count_total+1
      endif
      if(dtrunc(cur_dev_fr_maxopen).ne.0.0)then
            infeas_count_open=infeas_count_open+1
      else
            feas_count_open=feas_count_open+1
      endif
      if(dtrunc(dabs(cur_infeasible - cur_beta*cur_dev_fr_total -
     >    cur_gamma*cur_dev_fr_maxopen -
     >     cur_loss_penalty - cur_road_cost)).ne.0.0)then
            infeas_count_per=infeas_count_per+1
      else !
           feas_count_per=feas_count_per+1
      endif
      endif
      return
      end
```

subroutine update_obj_coeff2

```
      include 'params.f'
      include 'search_status.f'
      include 'sol_param2.f'
      if (infeas_count_total .eq. check_interval )then          !last 10 infeasible
           cur_beta = dmin1(upper_bound,cur_beta*2.0)
      else if (feas_count_total.eq.check_interval) then         !last 10 feasible
       cur_beta = dmax1(lower_bound,cur_beta/2.0)
      endif
      if (infeas_count_per .eq. check_interval )then!last 10 infeasible
           cur_alpha = dmin1(upper_bound,cur_alpha*2.0)
      else if (feas_count_per.eq.check_interval) then           !last 10 feasible
```

```
 cur_alpha = dmax1(lower_bound,cur_alpha/2.0)
endif
if (infeas_count_open .eq. check_interval )then          !last 10 infeasible
     cur_gamma = dmin1(upper_bound,cur_gamma*2.0)
else if (feas_count_open.eq.check_interval) then         !last 10 feasible
 cur_gamma = dmax1(lower_bound,cur_gamma/2.0)
endif
 feas_count_total=0
 feas_count_per=0
 feas_count_open=0
 infeas_count_total=0
 infeas_count_per=0
 infeas_count_open=0
 return
 end
```

subroutine init_x

```
include 'params.f'
include 'road_com_sol.f'
do i=1,numstands
 x(i)=ifuture
end do
return
end
```

subroutine init_stands

```
include 'params.f'
include 'com_data.f'
do  i=1,numstands
  stand_info(i).stand_no=0
 do j=1,2
  stand_info(i).opening(j)=0
 end do
 stand_info(i).dead=0
 stand_info(i).for_non=0
 stand_info(i).ageclass=0
 stand_info(i).site=0
 stand_info(i).numadj=0
 stand_info(i).cover_type=0
 do j=1,maxvert
 stand_info(i).adj(j)=0
 end do
 stand_info(i).acres=0.0
 stand_info(i).stocking=0.0
 stand_info(i).ivol=0.0
 stand_info(i).unass_penalty = 0.0
```

```
 stand_info(i).link_req = 0
 end do
 numread=0  !number of stands read
 return
 end
```

subroutine init_opens

```
 include 'params.f'
 include 'com_open.f'
 include 'com_data.f'
c this routine initializes the opening structures and
c clears all opening numbers from stand info.
 do  i=1,numread
 stand_info(i).opening(2)=0
 stand_info(i).opening(1)=0
 end do
c clear the openings
 o_avail=1
 o_last=0
 o_top=1
 do  i=1,num_opens
 opens(i).operiod=0
 opens(i).acres=0.0
 opens(i).numvert=0
 opens(i).numedges=0
 opens(i).pointer_fwd=0
 opens(i).pointer_back=0
 do  j=1,maxvert
  opens(i).v(j)=0
  opens(i).epointer(j)=0
  opens(i).e(j)=0
 end do
 end do
 do  i=1,num_opens-1
 av_list(i)=i+1
 end do
 av_list(num_opens)=0
 return
 end
```

subroutine get_data(dataset)

```
 include 'params.f'
 include 'com_data.f'
 include 'road_com_sol.f'
 include 'com_move.f'
 character*12 dataset
```

```
      integer*2 maxstand
      real*4 tot_vol
      integer*2 i,j,k,
     > INDX(23000),ADJ(NUMSTANDS,MAXADJ),numadj
      real*4 tot_acres
      character*16 species
      integer cover_type,for_non,ios
      real*4 unass_penalty
      character*8 mapin
      integer*2 stand_list(0:numroads,300)
      integer*2 link_point(0:numroads)
      logical good_one
      mapin = 'shulkell'
      do i=0,numroads
       link_point(i)=0
       do j=1,300
            stand_list(i,j)=0
       end do
      end do
      tot_acres=0.0
      tot_vol=0.0
      maxstand=0
      numread=0
      do  i=1,23000
      indx(i)=0
      end do
      do  i=1,numstands
      do j=1,maxadj
       adj(i,j)=0
      end do
      end do
      write(*,*) 'reading road data ...'
      call read_road
      write(*,*) 'opening file',dataset
      open(unit=20,file=dataset)
      istart = 1
      do 200, i=1,numstands
       read (20,10,end=100,iostat=ios) stand_info(i).stand_no,
     > stand_info(i).ACRES,
     > stand_info(i).ageclass,
     > stand_info(i).site,
     > stand_info(i).stocking,
     > stand_info(i).ivol,
     > stand_info(i).cover_type,
     > stand_info(i).for_non,
     > stand_info(i).link_req
10     format(i5,f10.2,i4,i4,f6.2,f12.6,i3,i5,i5)
      INDX(STAND_info(I).stand_no)=I
      tot_acres=tot_acres+stand_info(i).acres
      tot_vol=tot_vol+stand_info(i).ivol*stand_info(i).acres
```

```
      if((stand_info(i).for_non.ge.9907).and.
     >  (stand_info(i).for_non.le.9909))then
       stand_info(i).dead=1
      else
          stand_info(i).dead=0
      endif
      if(stand_info(i).for_non.eq.9960) then !existing clearcut
          x(i)=0
          stand_info(i).unass_penalty = 0.0
      else
          x(i)=ifuture                                    !unassigned
c  calculate unass penalty and volumes for the planning periods
c  and determine whether to add to st_list
          good_one = .false.
       move_stand = i
       call calc_unass_penalty(unass_penalty)
       stand_info(i).unass_penalty = unass_penalty
          do k=1,numperiods
           call calc_volume(i,k,stand_info(i).volume(k))
           stand_info(i).volume(k)=rtrunc(stand_info(i).volume(k))
           if(stand_info(i).volume(k).gt.0.)good_one=.true.
           call calc_ass_penalty(i,k,stand_info(i).ass_penalty(k))
          end do
          if(good_one)then                          !if volume, add to st_list
       link_point(stand_info(i).link_req)=
     >  link_point(stand_info(i).link_req)+1
       stand_list(stand_info(i).link_req,
     >  link_point(stand_info(i).link_req))=i
          endif
      endif
200   continue
100   if(ios.eq.-1) then
      numread=i-1
      else
      numread=numstands
     endif
     close(20)
     write(*,*) 'number of stands read ',numread
     maxstand=stand_info(numread).stand_no !since they are in order
c  make up the stand to road lists
     call make_st_list(link_point,stand_list)
c  Read the adjacency file and update stand adjacency list
     open (unit=10,file='/home3/richarew/thesis/data/'//mapin//
    > '/'//mapin//'.adj')
     do while (iSTAND.le.MAXstand)
          read (10,*,end=300) inum,istand,(ADJ(indx(istand),J),j=1,INUM)
          numadj=0       !pointer to adjacency list members
          do  k=1,inum
           if (adj(indx(istand),k).le.maxstand) then
            numadj=numadj+1
```

```
            stand_info(indx(istand)).adj(numadj)=
     >       indx( adj(indx(istand),k))
            endif
          end do
          stand_info(INDX(iSTAND)).numadj=numadj
      end do
300   close(10)
      return
      end
```

subroutine calc_parameters

```
      include 'params.f'
      include 'sol_param2.f'
      real*4 periodic_per,total_per
c set cost to $5000/km (road lengths stored in meers)
c discount rate is .10
c period is 5 years
      d_factor(1)=.7879*5.
      d_factor(2)=.4893*5.
      d_factor(3)=.3038*5.
      d_factor(4)=.1886*5.
      d_factor(5)=0.0
      ptarget =  500.0        !thousands of cubic feet
      htarget = 2000.0        !thousands of cubic feet
      periodic_per = 0.05
      total_per    = 0.02
      periodic_all = periodic_per*ptarget
      total_all = total_per*htarget
      r_factor = 1.0
      return
      end
```

subroutine init_move_values

```
      include 'params.f'
      include 'sol_param2.f'
      include 'com_move.f'
      move_road_cost = 0.0
      move_feas = .false.
      return
      end
```

subroutine init_search_params

```
      include 'params.f'
      include 'search_status.f'
```

```
c call this routine after data file has been read so that
c numread is known
      maxiters = 5000
      check_interval = 10
      return
      end
```

subroutine init_objective

```
      include 'params.f'
      include 'sol_param2.f
      include 'com_data.f'
      include 'road_com_sol.f'
      cur_sol = 0.0                        !no harvest
      cur_infeasible = 0.0          !
      cur_feasible = 0.0            !
      cur_loss_penalty = 0.0               !none yet
      cur_road_cost = 0.0
      cur_dev_fr_maxopen=0.0
c since there is no volume at this point
      do j=1,numperiods
       cur_dev_fr_periodic(j)=ptarget-periodic_all
       cur_infeasible=cur_infeasible+cur_dev_fr_periodic(j)
      end do
      cur_dev_fr_total=htarget-total_all
      cur_infeasible=cur_beta*cur_infeasible+cur_alpha*cur_dev_fr_total
c calculate the unassigned penalty for all stands
      do stand=1,numread
           cur_loss_penalty=cur_loss_penalty+stand_info(stand).unass_penalty
      end do
c  update the total penalties
      cur_infeasible = cur_infeasible+cur_loss_penalty
c reduce the loss penalty by the unavoidable penalty
       call calc_base_loss
      cur_loss_penalty = cur_loss_penalty - min_loss_penalty
      return
      end
```

subroutine save_sol

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'com_data.f'
      include 'search_status.f'
      include 'best_sol.f'
      include 'road_com.f'
      do i=1,numread
       x_save(i)=x(i)
```

```
      end do
      do i = 1,numroads
       road_save(i) = roads(i).period_assigned
      end do
      return
      end
```

subroutine clear_solution

```
      include 'params.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      do i=1,numread
      if (x(i).ne.0)then
       x(i)=ifuture
      endif
      end do
      cur_sol = 0.0
      do j=1,numperiods
       hvol(j) = 0.0
      end do
      call init_roads
      return
      end
```

subroutine time_stats(elapsed)

```
      include 'search_status.f'
      real*4 elapsed
      elapsed = etime_(etime_struct)
      return
      end
```

subroutine read_growth

```
      include 'com_growth.f'
      open (unit=51,file='/home3/richarew/thesis/data/mai.dat')
      do isite = 1,6  !corresponds to index 3-8
       read(51,'(i4)') mai_max_age(isite)
       read(51,100) (mai(isite,iage),iage = 1,22)  !22 age classes
      end do
100   format (22f7.2)
      close(unit=51)
      return
      end
```

```
logical function test_sol_feas()
include 'params.f'
include 'road_com_sol.f'
test_sol_feas=.false.
if(dtrunc(cur_dev_fr_maxopen).ne.0.0)then
 return
 else if(dtrunc(cur_dev_fr_total).ne.0.0)then
 return
 else
 do j=1,numperiods
 if(dtrunc(cur_dev_fr_periodic(j)).ne.0.0)return
 end do
 endif
 test_sol_feas=.true.
 return
end function

logical function test_move_feas()
include 'params.f'
include 'com_move.f'
test_move_feas=.false.
if(dtrunc(move_dev_fr_maxopen).ne.0.0)then
 return
 else if(dtrunc(move_dev_fr_total).ne.0.0)then
 return
 else
 do j=1,numperiods
 if(dtrunc(move_dev_fr_periodic(j)).ne.0.0)return
 end do
 endif
 test_move_feas=.true.
 return
end function
```

Road Subroutines

subroutine init_roads

```
include 'params.f'
include 'road_com.f'
do i=1,numroads
roads(i).period = ifuture
roads(i).required_by_harvest = .false.
roads(i).required_by_connect = .false.
roads(i).time=-32766
```

```
      end do
      return
      end
```

subroutine build_roads

```
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'road_com_sol.f'
      include 'search_status.f'
      include 'best_move.f'
      integer*2 i,j,k,t,imin      !local variables
      integer*2 ilink
      real*4 new_pr                  !used to put closest node or
      real*4 cost_to_add(2)        ! to calc min cost path to add link in cycle.
      integer*2 knode(2)
      do i=1,numnodes+1              !init the val array
       val(i) = 9999.0               !indicates whether nodes have been parsed
       dad(i) = 0
       link(i) = -1
      end do
      call const_road_heap           !init the heap
      do i=1,numroads                    !clear the previous solution
       roads(i).period_assigned = ifuture
       roads(i).nhops=0
       roads(i).dad_link=-1
       roads(i).numsons = 0
      end do
c compute the shortest path network for the roads
c val(t) stores the length of the shortest path from t to the root
c priority(t) is used to arrange the heap
      k = inv(numnodes+1)                      !remove the root node
      priority(k) = 0.0                        !root of tree
      val(k)=0.0
      link(numnodes+1)=0
10    call pqremove(k)                        !k will point to the element removed
      do ipoint = adj_point(k),adj_point(k+1)-1   !get all adjacent nodes
          t = adj(ipoint,1)                    !adjacent node
          ilink = adj(ipoint,2)                !link #
          if(inv(t).le.heap_size)then          !still on heap
           if(roads(ilink).required_by_harvest)then !required
            new_pr=0.0
           else
            new_pr= priority(k) + roads(ilink).lgth   !distance to k
           endif
           if(priority(t).gt.new_pr)then       !shorter?
            call pqchange(t,new_pr)            !update priority
```

```
            val(t)=val(k)+roads(ilink).lgth              !update length of path
            dad(t)=k                                     !father
            link(t)=ilink                                !simpler
            roads(ilink).dad_link = link(k)
            roads(ilink).period_assigned=roads(ilink).period !assign period
            roads(ilink).required_by_connect=
     >      .not.roads(ilink).required_by_harvest       !true if a steiner link
          endif
            endif
          end do                                         !next adjacent node
          if(heap_size.gt.0)then                         !not finished
            k=1                                          !get top element
            goto 10                                      !and continue
          else
          endif
 c fix up the period required
          do i=1,numnodes                                !all but root node
           if(val(i).ne.9999.0)then                      !in, parse the path
           j = i                                         !save node index
           imin = roads(link(i)).period_assigned         !period for the last link
              do while (dad(j).ne. 0 )                   !parse all connections
               j = dad(j)                                !father
               imin = min(imin,roads(link(j)).period_assigned) !min period required
               roads(link(j)).period_assigned=imin       !update
           end do
          endif
         end do                                          !next node
c find any missing links
         do i=1,numroads
         if((roads(i).dad_link.eq.-1)
        >  .and.(roads(i).required_by_harvest))then
          roads(i).period_assigned=roads(i).period       !assign it to its period
          knode(1)=roads(i).x
          knode(2)=roads(i).y                            !two directions
          do ii=1,2                                      !find the cheapest path
           if ( roads(i).period .lt.
        >       roads(link(knode(ii))).period_assigned)then
            call calc_r_cost_sngl(link(knode(ii)),
        >    cost_to_add(ii),roads(i).period_assigned)
            else
             cost_to_add(ii)=val(knode(ii))
               endif
          end do
         costdiff = cost_to_add(1)-cost_to_add(2)
         if ( costdiff.lt.0) then
          k = 1
         else if (costdiff.gt.0.)then
          k=2
         else !tie
          rval=rand()
```

```
      k=int(rval)+1
     endif
       k = knode(k)  !finally got it!
c  path chosen, implement
     roads(i).dad_link = link(k) ! Assign dad link
     imin = roads(i).period_assigned
     k = dad(k)
     do while( (k.ne.0).and.(imin.lt.roads(link(k)).period_assigned) )
      roads(link(k)).period_assigned = imin
      k=dad(k)
      imin = min(roads(link(k)).period_assigned,imin)
     end do
    endif
    end do                                    !next link
    cur_road_cost = 0.0
    do i=1,numroads
     if(roads(i).period_assigned.ne.ifuture)then
          cur_road_cost = cur_road_cost +
   >      roads(i).lgth * d_factor(roads(i).period_assigned)
     endif
    end do
    cur_road_cost = cur_road_cost*r_factor
c  find and store the sons for each link
    do i = 1, numroads
     k = roads(i).dad_link
     if(k.ne.0)then
          roads(k).numsons = roads(k).numsons + 1
          roads(k).sons(roads(k).numsons)=i
          endif
    end do
    return
    end
```

subroutine make_st_list(link_point,stand_list)

```
    include 'params.f'
    include 'road_com.f'
    include 'com_data.f'
    integer*2 link_point(0:numroads)
    integer*2 stand_list(0:numroads,300)
    integer*2 ipoint
     ipoint=0
     st_point(0)=1
     do i=0,numroads
          do j=1,link_point(i)
           st_list(ipoint+j)=stand_list(i,j)
          end do
          ipoint=link_point(i)+ipoint
```

```
        st_point(i+1)=ipoint+1
      end do
      return
      end
```

subroutine read_road

```
      include 'params.f'
      include 'road_com.f'
      integer*2 adjlist(numnodes+1,300,2),adj_pt(numnodes+1)
      do i=1,numnodes +1            !init the adjacency lists
      adj_pt(i)=0
      end do
      open (unit=10,
     > file='/home3/richarew/thesis/data/shulkell/roads.txt') !open road data file
10    read(10,*,end=99)i, roads(i).x,roads(i).y,roads(i).lgth
          adj_pt(roads(i).x)=adj_pt(roads(i).x)+1
          adj_pt(roads(i).y)=adj_pt(roads(i).y)+1
          adjlist(roads(i).x,adj_pt(roads(i).x),1)=roads(i).y
          adjlist(roads(i).y,adj_pt(roads(i).y),1)=roads(i).x
          adjlist(roads(i).x,adj_pt(roads(i).x),2)=i
          adjlist(roads(i).y,adj_pt(roads(i).y),2)=i
          roads(i).period = ifuture
          roads(i).required_by_harvest = .false.
          roads(i).required_by_connect = .false.
          roads(i).period_assigned = ifuture
      i=i+1
      goto 10
99    close(unit=10)
c build the adjacency list (pack it)
      istart = 0
      do i=1,numnodes+1
      adj_point(i)=istart+1
      do j=1,adj_pt(i)
       adj(istart+j,1)=adjlist(i,j,1)
       adj(istart+j,2)=adjlist(i,j,2)
      end do
      istart=adj_pt(i)+istart
      end do
      adj_point(numnodes+2)=adj_point(numnodes+1)+adj_pt(numnodes+1)
      return
      end
```

subroutine const_road_heap

```
c Since all priorities are the same, simply construct the array
      include 'params.f'
```

```
      include 'road_com.f'
      integer*2 i
      heap_size = numnodes+1
      do i=0,numnodes+1
      road_heap(i)=i
      inv(i)=i
      priority(i)=32767.0
      end do
      priority(numnodes+1)=0.0    !ROOT NODE represents mainroad access
      priority(0)=-10                    !sentinel value for node 0
      return
      end
```

subroutine pqdownheap(k)

```
      include 'params.f'
      integer*2 k,j
      integer*2 vert
      include 'road_com.f'
      vert=road_heap(k)
      do while (k.le.heap_size/2)
       j=k+k
       if(j.lt.heap_size)then
            if(priority(road_heap(j)).gt.priority(road_heap(j+1))) j=j+1
       endif
       if (priority(vert).le.priority(road_heap(j))) goto 10
       road_heap(k)=road_heap(j)
       inv(road_heap(j))=k
       k=j
      end do
10    road_heap(k)=vert
      inv(vert)=k
      return
      end
```

subroutine pqremove(k)

```
c  remove the kth element of the heap
      include 'params.f'
      integer*2 k,ksave
      include 'road_com.f'
      ksave=road_heap(k)
      inv(road_heap(k))=heap_size
      road_heap(k)=road_heap(heap_size)
      inv(road_heap(heap_size))=k
      heap_size=heap_size-1
```

```
      call pqdownheap(k)
      k=ksave
      return
      end
```

subroutine pqchange(t,new_pr)

```
c change element t to have priority new_pr
      include 'params.f'
      integer*2 t,k
      real*4 new_pr,old_pr
      include 'road_com.f'
      old_pr=priority(t)
      priority(t)=new_pr
      k = inv(t)
      if(new_pr.lt.old_pr)then
       call pqupheap(k)
      else
       call pqdownheap(k)
      endif
      return
      end
```

subroutine pqupheap(k)

```
      include 'params.f'
      integer*2 vert,k
      include 'road_com.f'
      vert=road_heap(k)
      do while (priority(road_heap(int(k/2))).ge.priority(vert))
       road_heap(k)=road_heap(int(k/2))
       inv(road_heap(k))=k
       k=int(k/2)
       road_heap(k)=vert
       inv(road_heap(k))=k
      end do
      return
      end
```

subroutine calc_retime_cost(link_to_change)

```
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'com_move.f'
```

```
      integer*2 link_to_change,ilink,l_period,imin,p_link,path_period
      integer*2 knode(2)
      real*4 cost_to_add(2)
c calculate the re_timing costs for link_to_change,each l_period
c the base cost is the re-timing of the link_to_change
      if ((link_to_change.le.0).or.(link_to_change.gt.numroads))then
       write(*,*) 'error in link ',link_to_change
       stop
       endif
      do l_period = 1, ifuture
c check to see if the link is in a path
      if (roads(link_to_change).dad_link.eq.-1) then          !link is not in a path
       r_cost(l_period)=roads(link_to_change).lgth*
     >      d_factor(l_period)                                 !cost to build the new link
       knode(1)=roads(link_to_change).x
       knode(2)=roads(link_to_change).y
       do kk=1,2
            k=knode(kk)
            ilink = link(k)
            if(roads(ilink).period_assigned.lt.l_period)then
             call calc_r_cost_sngl(ilink,cost_to_add(kk),l_period)
            else
             cost_to_add(kk)=0.0
            endif
       end do
       r_cost(l_period)=r_factor*(r_cost(l_period)+
     >  min(cost_to_add(1),cost_to_add(2)))
       else! just do it
       ilink = link_to_change
       call calc_r_cost_sngl(ilink,cost_to_add(1),l_period)
       r_cost(l_period)=cost_to_add(1)*r_factor
      endif
      end do
      return

            end
```

RTS Subroutines

subroutine check_for_reps(escape)

```
      include 'params.f'
      include 'road_com_sol.f'
      include 'com_hash.f'
      include 'com_reactive.f'
      include 'search_status.f'
      include 'com_tabu2.f'
      include 'com_data.f'
```

```
 logical escape,done
 integer*2 length
 escape = .false.
 done = .false.
 call hashfn(numread)
 do while (.not.done)
 if((hash_table(hash_add).eq.-1).or.              !empty slot
> (config_info(hash_table(hash_add)).sol_value -
> cur_feasible.lt. 0.0001))then                   !match
  done = .true.
 else
  hash_add = mod((hash_add+1),itable_size)        !linear probe
 endif
 end do
 if(hash_table(hash_add).ne.-1) then              !existing configuration
  length = move_count -
>  config_info(hash_table(hash_add)).time_last_found
  config_info(hash_table(hash_add)).num_rep =
> config_info(hash_table(hash_add)).num_rep + 1
  config_info(hash_table(hash_add)).time_last_found =
>  move_count
  if (config_info(hash_table(hash_add)).num_rep
>  .gt. rep)then
   chaotic=chaotic+1
   if(chaotic .gt.chaos)then
        chaotic=0
        escape = .true.
        return
   endif
  endif
  if (length .lt. cycle_max) then
      if(moving_average .eq. 0.0)then
       moving_average = length
   else
    moving_average = 0.1*length + 0.9*moving_average
      endif
   tabu_tenure =min(600.0,increase*tabu_tenure)
      steps_since_size_change = 0
  endif
 else                      !new configuration, instal it
  config_point=config_point+1
  if(config_point.gt.10000)then
      write(21,*) '*** error *** config_point > 10000'
      message='config_point > 10000'
      at_end = .true.
  endif
  hash_table(hash_add)=config_point
  config_info(config_point).time_last_found = move_count
  config_info(config_point).sol_value = cur_feasible
 endif
```

```
      if (steps_since_size_change .gt.moving_average)then
          tabu_tenure = max(tabu_tenure*decrease,1.0)
          steps_since_size_change = 0
      endif
      return
      end
```

subroutine init_reactive

```
      include 'params.f'
      include 'com_reactive.f'
      chaotic=0
      chaos=3
      rep=3
      cycle_max=50
      increase = 1.1
      decrease = 0.9
      return
      end
```

subroutine del_one_link

```
      include 'params.f'
      include 'sol_param2.f'
      include 'road_com.f'
      include 'com_data.f'
      include 'road_com_sol.f'
      include 'com_move.f'
      include 'com_tabu2.f'
      include 'search_status.f'
      include 'com_reactive.f'
      integer*2 ilink
      integer*2 link_list(numroads)
      integer*2 link_len
      logical test_sol_feas
      integer stand_count
      num_esc_steps =1
      stand_count=0
      num_tries=0
10      ilink = int(rand()*numroads)+1
      num_tries=num_tries+1
      if(roads(ilink).period.ne.ifuture)then
       call get_all_links(ilink,link_list,link_len)
c now, re-assign all the stands that are involved to ifuture
      do k = 1, link_len
       ilink=link_list(k)
       do i=st_point(ilink),st_point(ilink+1)-1
        if (x(st_list(i)).gt.0.and.x(st_list(i)).lt.ifuture) then
```

```
            stand_count=stand_count+1
          x(st_list(i))=ifuture
          call tabu_add(st_list(i))
            endif
        end do
 c assign the road link
        roads(ilink).period = ifuture
        roads(ilink).required_by_harvest = .false.
       end do
       endif
 c re-do the openings
       call init_opens
       call make_opens2
 c re-build the roads
       call build_roads
       cur_road_cost=cur_road_cost*r_factor
 c calculate the objective
       call calc_objective
 c update best
       move_feas = test_sol_feas()
       call update_best
 c  now set tabu_tenure to be equal to tabu_tenure plus number of stands deleted
       tabu_tenure = tabu_tenure+ float(stand_count)
       return
       end
```

Tabu Subroutines

subroutine init_tabu_rts

```
      include 'params.f'
      include 'com_tabu2.f'
      include 'com_reactive.f'
      tabu_point = 0    !points to tabu list
      do  i=1,itabu_len
       tabu_list(i)= -20000.0          !zero tabu list
      end do
      steps_since_size_change = 0
      tabu_tenure = 1.0
      moving_average=0.0
      return
      end
```

subroutine get_aspiration2(asp)

```
      include 'params.f'
      include 'sol_param2.f'
      include 'com_move.f'
      include 'road_com_sol.f'
      logical asp,tabu
      asp = .false.
c check feasibility
      if (move_feas) then  !feasible
       if((move_loss_penalty+move_road_cost).lt.
     > (best_feasible))then
            asp = .true.
       endif
      else                      !infeasible
      endif
      return
      end
```

subroutine check_tabu(tabu) !move tabu?

```
      include 'params.f'
      include 'com_tabu2.f'
      include 'com_move.f'
      include 'search_status.f'
      logical tabu
      if(tabu_list(move_stand).ge.(move_count-tabu_tenure))then
       tabu=.true.
      else
       tabu = .false.
      endif
      return
      end
```

subroutine tabu_add(stand)

```
      include 'params.f'
      include 'com_tabu2.f'
      include 'search_status.f'
      integer*2 stand
      tabu_list(stand)=move_count
      return
      end
```

APPENDIX D

NUMERICAL RESULTS

Table D.1. Statistics for SHULKELL Dataset

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	310,945	292,843	372,456	6,678	15,345	4.94%
0.20	326,495	307,979	385,927	6,978	15,055	4.61%
0.30	336,019	325,392	361,142	6,464	8,245	2.45%
0.40	349,632	337,224	373,660	7,233	8,786	2.51%
0.50	360,851	352,301	374,346	6,793	6,125	1.70%
0.60	374,729	361,901	388,906	6,758	7,188	1.92%
0.70	385,847	373,681	410,644	6,881	8,551	2.22%
0.80	398,580	386,656	410,775	7,191	5,914	1.48%
0.90	409,719	399,135	436,416	6,451	9,781	2.39%
1.00	415,975	406,966	423,622	6,804	4,847	1.17%
2.00	498,386	488,556	508,032	5,214	4,585	0.92%
3.00	563,860	556,021	572,178	4,771	4,400	0.78%
4.00	624,297	606,125	646,247	5,053	7,828	1.25%
5.00	664,834	655,268	686,107	4,048	7,527	1.13%
6.00	715,875	695,961	743,025	6,055	8,583	1.20%
7.00	760,205	744,499	775,101	5,970	6,551	0.86%
8.00	795,396	773,852	809,759	6,758	9,077	1.14%
9.00	819,104	800,514	846,428	6,662	10,718	1.31%
10.00	853,648	818,568	889,636	3,681	18,839	2.21%
11.00	885,892	840,961	948,920	3,052	29,769	3.36%
12.00	897,555	854,537	944,427	3,518	24,916	2.78%
13.00	917,688	881,089	963,015	2,621	22,390	2.44%
14.00	932,470	895,660	976,755	2,492	23,588	2.53%
15.00	942,137	890,176	976,755	2,265	20,408	2.17%
16.00	947,501	908,036	972,957	1,987	16,742	1.77%
17.00	955,875	917,468	976,167	1,144	13,854	1.45%
18.00	960,366	939,916	976,755	1,159	9,577	1.00%
19.00	960,306	928,798	977,427	775	12,006	1.25%
20.00	957,839	927,437	976,755	998	11,938	1.25%

Table D.2. Statistics for Dataset 1

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	360,857	338,866	384,548	6,168	10,382	2.88%
0.20	379,005	360,060	410,944	5,841	13,818	3.65%
0.30	393,293	374,518	410,082	6,814	9,674	2.46%
0.40	404,577	381,821	438,954	6,440	13,050	3.23%
0.50	415,884	398,342	434,981	5,497	9,555	2.30%
0.60	428,350	409,974	454,439	6,566	10,479	2.45%
0.70	441,935	426,785	466,691	6,604	9,026	2.04%
0.80	452,602	432,697	480,064	6,561	9,970	2.20%
0.90	461,269	446,691	480,184	5,782	7,904	1.71%
1.00	475,363	459,349	539,950	5,539	14,242	3.00%
2.00	562,926	549,637	597,428	2,520	10,132	1.80%
3.00	614,589	606,351	629,500	2,152	5,706	0.93%
4.00	659,084	645,503	671,910	2,768	6,768	1.03%
5.00	699,763	683,391	719,396	2,463	9,038	1.29%
6.00	746,484	720,503	773,359	2,147	14,786	1.98%
7.00	755,519	741,558	780,129	2,757	8,566	1.13%
8.00	782,239	766,783	797,354	3,011	7,355	0.94%
9.00	808,379	797,860	837,692	3,179	7,878	0.97%
10.00	831,165	823,341	864,308	3,043	7,250	0.87%
11.00	873,470	836,711	946,006	3,362	30,789	3.52%
12.00	896,640	856,632	943,514	3,529	24,124	2.69%
13.00	915,713	868,072	968,544	3,183	28,094	3.07%
14.00	927,446	878,286	996,905	3,154	28,616	3.09%
15.00	952,331	886,250	993,704	2,864	27,924	2.93%
16.00	958,513	902,042	1,005,713	2,255	26,337	2.75%
17.00	972,134	914,686	995,357	1,681	20,507	2.11%
18.00	976,229	924,221	1,012,702	1,838	18,815	1.93%
19.00	982,175	942,033	1,001,490	1,359	15,009	1.53%
20.00	986,732	957,224	1,005,713	1,025	12,744	1.29%

Table D.3. Statistics for Dataset 2

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	360,857	338,866	384,548	6,168	10,382	2.88%
0.20	379,005	360,060	410,944	5,841	13,818	3.65%
0.30	393,293	374,518	410,082	6,814	9,674	2.46%
0.40	404,577	381,821	438,954	6,440	13,050	3.23%
0.50	415,884	398,342	434,981	5,497	9,555	2.30%
0.60	428,350	409,974	454,439	6,566	10,479	2.45%
0.70	441,935	426,785	466,691	6,604	9,026	2.04%
0.80	452,602	432,697	480,064	6,561	9,970	2.20%
0.90	461,269	446,691	480,184	5,782	7,904	1.71%
1.00	475,363	459,349	539,950	5,539	14,242	3.00%
2.00	562,926	549,637	597,428	2,520	10,132	1.80%
3.00	614,589	606,351	629,500	2,152	5,706	0.93%
4.00	659,084	645,503	671,910	2,768	6,768	1.03%
5.00	699,763	683,391	719,396	2,463	9,038	1.29%
6.00	746,484	720,503	773,359	2,147	14,786	1.98%
7.00	755,519	741,558	780,129	2,757	8,566	1.13%
8.00	782,239	766,783	797,354	3,011	7,355	0.94%
9.00	808,379	797,860	837,692	3,179	7,878	0.97%
10.00	831,165	823,341	864,308	3,043	7,250	0.87%
11.00	873,470	836,711	946,006	3,362	30,789	3.52%
12.00	896,640	856,632	943,514	3,529	24,124	2.69%
13.00	915,713	868,072	968,544	3,183	28,094	3.07%
14.00	927,446	878,286	996,905	3,154	28,616	3.09%
15.00	952,331	886,250	993,704	2,864	27,924	2.93%
16.00	958,513	902,042	1,005,713	2,255	26,337	2.75%
17.00	972,134	914,686	995,357	1,681	20,507	2.11%
18.00	976,229	924,221	1,012,702	1,838	18,815	1.93%
19.00	982,175	942,033	1,001,490	1,359	15,009	1.53%
20.00	986,732	957,224	1,005,713	1,025	12,744	1.29%

Table D.4. Statistics for Dataset 3

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	355,194	335,891	374,366	5,982	8,544	2.41%
0.20	371,896	353,456	398,604	6,247	11,175	3.00%
0.30	388,706	372,072	407,381	6,827	9,012	2.32%
0.40	404,450	378,911	432,390	6,976	11,955	2.96%
0.50	410,688	392,100	422,212	5,826	7,823	1.90%
0.60	422,519	410,298	448,384	6,342	7,810	1.85%
0.70	434,268	423,831	450,199	5,938	6,406	1.48%
0.80	446,268	432,693	473,403	6,060	9,199	2.06%
0.90	463,583	448,590	485,551	6,565	9,850	2.12%
1.00	469,649	449,190	495,752	6,269	12,073	2.57%
2.00	557,068	543,643	567,350	4,674	6,081	1.09%
3.00	615,291	602,303	631,406	4,512	6,831	1.11%
4.00	680,258	658,974	689,415	4,723	6,538	0.96%
5.00	718,303	702,290	739,007	4,302	9,040	1.26%
6.00	753,642	737,045	768,181	3,662	9,562	1.27%
7.00	764,900	757,288	784,556	5,114	6,206	0.81%
8.00	778,061	771,395	785,279	5,796	3,181	0.41%
9.00	793,832	787,248	804,584	6,292	3,781	0.48%
10.00	822,095	803,078	862,365	3,674	15,961	1.94%
11.00	848,080	821,686	909,755	4,233	21,753	2.57%
12.00	867,672	835,343	935,164	3,905	24,324	2.80%
13.00	891,471	858,850	946,548	3,510	24,294	2.73%
14.00	903,398	847,807	953,705	3,595	24,035	2.66%
15.00	927,238	889,962	953,558	2,847	18,175	1.96%
16.00	937,320	897,694	955,927	2,248	15,002	1.60%
17.00	937,979	894,679	982,767	1,603	20,388	2.17%
18.00	944,940	905,066	989,687	1,062	16,307	1.73%
19.00	939,611	900,463	960,953	959	17,717	1.89%
20.00	942,897	911,864	961,315	1,018	12,829	1.36%

Table D.5. Statistics for Dataset 4

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	366,261	354,864	381,534	6,922	6,160	1.68%
0.20	384,998	370,591	414,147	6,313	8,929	2.32%
0.30	399,396	381,835	423,952	6,359	8,463	2.12%
0.40	409,673	396,506	429,372	6,247	7,255	1.77%
0.50	422,068	410,248	437,666	6,846	5,678	1.35%
0.60	435,168	420,995	455,677	6,908	6,825	1.57%
0.70	449,218	440,076	462,712	6,621	5,446	1.21%
0.80	460,658	452,428	470,878	6,602	4,959	1.08%
0.90	472,336	464,832	482,635	6,826	3,900	0.83%
1.00	482,379	472,945	491,034	5,957	5,205	1.08%
2.00	567,462	555,134	579,355	4,044	5,768	1.02%
3.00	622,883	615,186	636,696	5,197	6,044	0.97%
4.00	690,574	682,609	697,660	5,338	3,807	0.55%
5.00	728,796	715,991	737,008	4,998	3,727	0.51%
6.00	763,545	751,860	774,774	5,018	5,965	0.78%
7.00	781,114	773,313	798,890	4,738	5,171	0.66%
8.00	802,559	794,073	819,313	5,760	5,989	0.75%
9.00	828,755	814,255	888,197	5,422	15,123	1.82%
10.00	852,096	831,461	901,572	3,410	15,142	1.78%
11.00	880,564	854,286	917,273	4,140	17,559	1.99%
12.00	905,166	872,018	934,516	3,170	17,875	1.97%
13.00	919,062	881,542	946,337	2,566	14,560	1.58%
14.00	930,489	908,317	961,527	2,182	14,856	1.60%
15.00	937,316	915,160	989,872	2,337	15,224	1.62%
16.00	953,857	925,140	989,872	1,528	16,711	1.75%
17.00	959,202	920,233	991,829	1,340	19,110	1.99%
18.00	958,573	924,642	1,000,944	999	19,877	2.07%
19.00	959,642	937,699	993,785	1,065	18,771	1.96%
20.00	967,168	938,089	989,872	1,104	16,119	1.67%

Table D.6. Statistics for Dataset 5

ρ	Average	Best	Worst	Av. # Moves	Std. Dev	Coeff. Var
0.10	344,628	330,192	357,913	6,118	5,595	1.62%
0.20	361,575	341,517	377,259	6,580	9,134	2.53%
0.30	375,309	364,907	390,505	5,644	6,060	1.61%
0.40	391,333	370,908	411,908	6,625	8,628	2.20%
0.50	399,814	389,354	415,610	6,706	5,920	1.48%
0.60	414,245	399,905	448,469	6,864	9,267	2.24%
0.70	425,136	417,442	439,919	7,086	5,627	1.32%
0.80	436,861	426,332	458,270	6,678	6,199	1.42%
0.90	447,766	434,661	464,597	5,509	6,745	1.51%
1.00	454,232	447,463	467,514	6,444	5,388	1.19%
2.00	542,253	528,390	554,351	4,448	6,135	1.13%
3.00	601,378	591,256	615,316	4,491	5,904	0.98%
4.00	664,709	644,091	679,496	5,129	10,942	1.65%
5.00	706,097	685,099	717,748	4,418	10,646	1.51%
6.00	743,660	726,986	771,410	5,198	9,934	1.34%
7.00	772,190	759,618	795,489	6,262	7,672	0.99%
8.00	791,913	778,900	808,442	5,142	6,660	0.84%
9.00	816,544	792,232	901,418	5,812	18,948	2.32%
10.00	837,555	822,173	886,514	3,806	14,584	1.74%
11.00	865,040	830,367	911,879	3,235	21,831	2.52%
12.00	886,153	856,992	943,031	3,669	23,247	2.62%
13.00	894,590	846,698	925,418	3,282	19,390	2.17%
14.00	917,359	879,364	947,761	2,859	18,376	2.00%
15.00	923,271	891,688	948,356	2,728	17,017	1.84%
16.00	932,717	893,634	993,459	2,254	17,470	1.87%
17.00	945,827	921,361	993,459	954	15,662	1.66%
18.00	942,210	907,107	976,215	1,647	16,492	1.75%
19.00	946,440	923,327	993,459	1,199	15,843	1.67%
20.00	949,299	925,648	993,459	1,081	15,900	1.67%

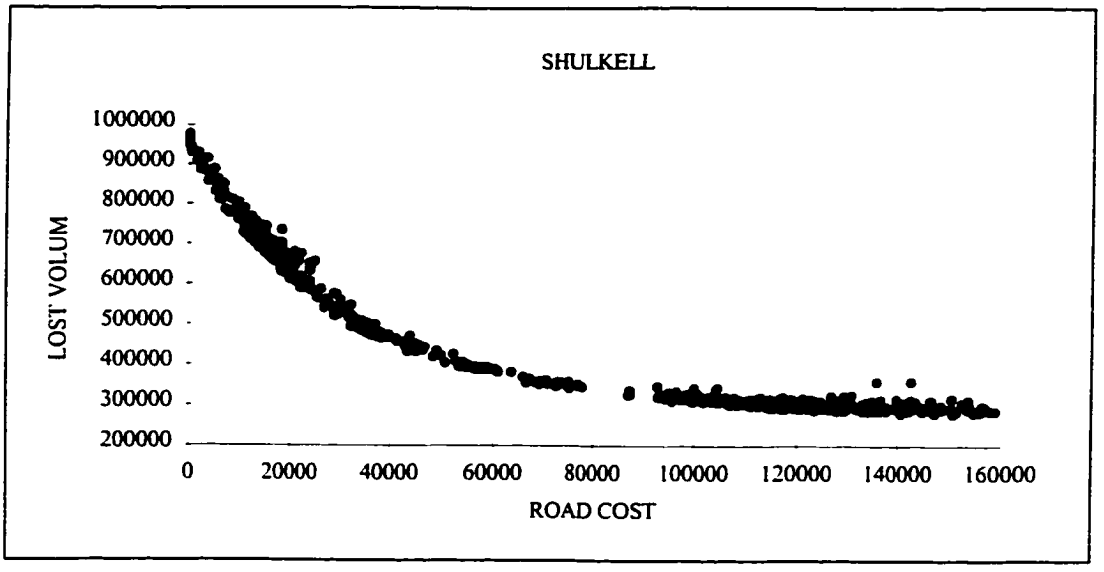


Figure D.1. Solutions for Shulkell Dataset

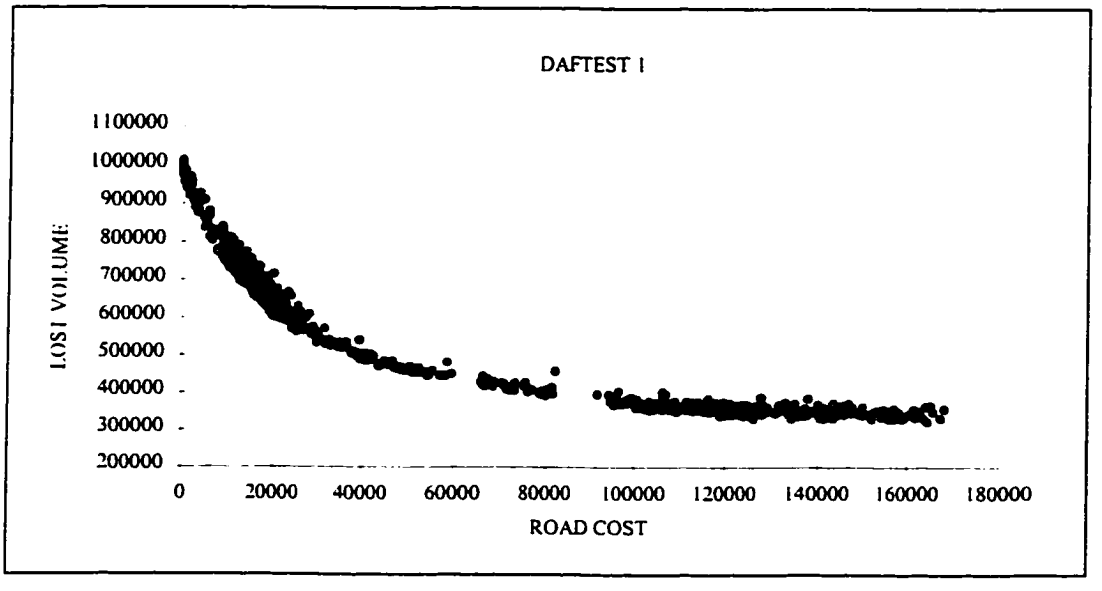


Figure D.2. Solutions for Dataset 1.

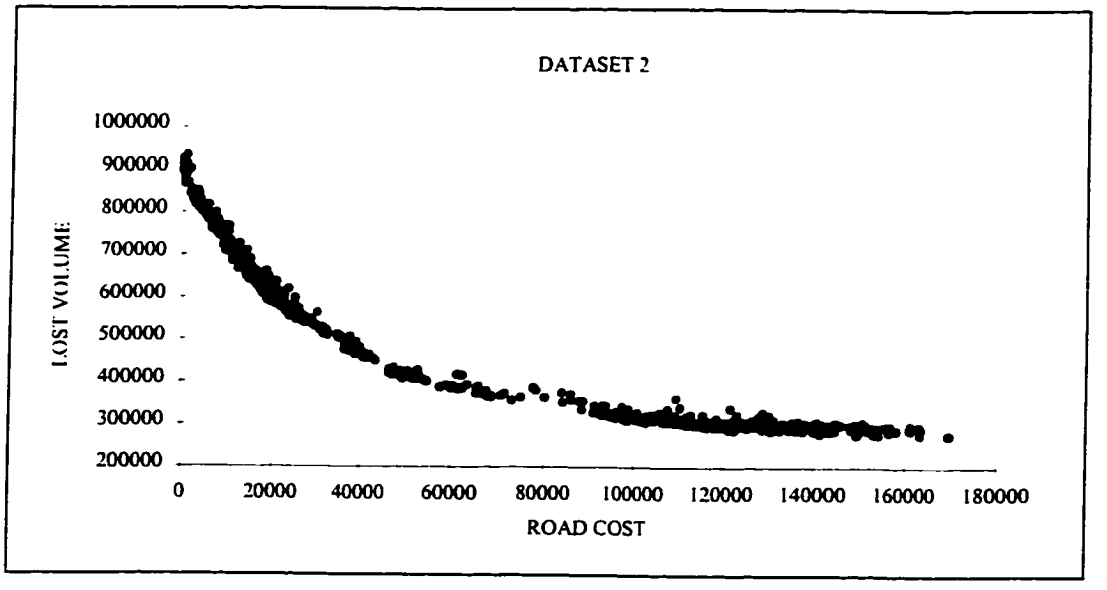


Figure D.3. Solutions for Dataset 2.

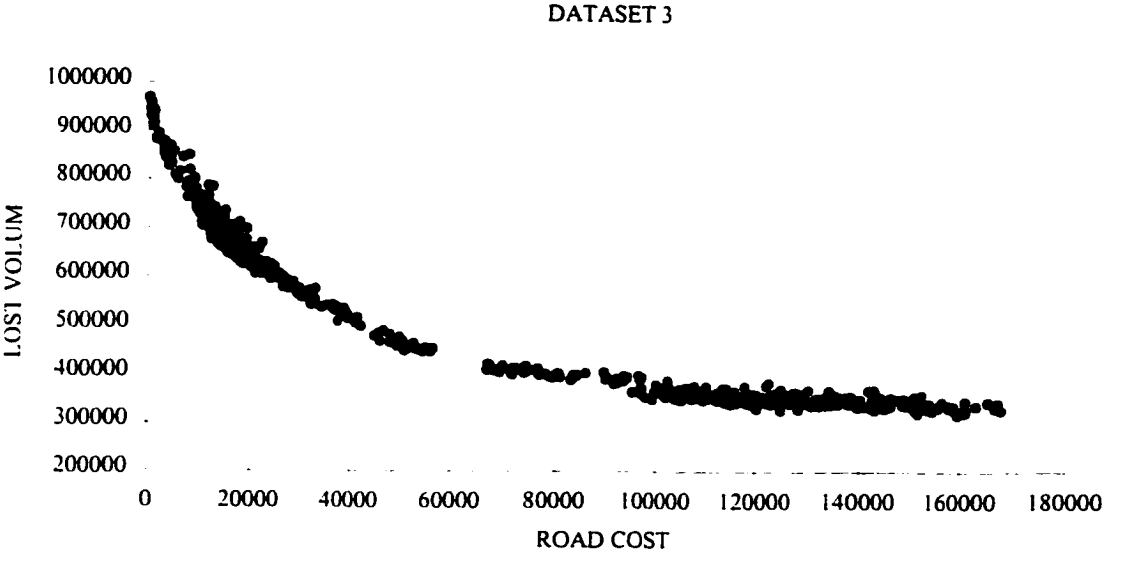


Figure D.4. Solutions for Dataset 3.

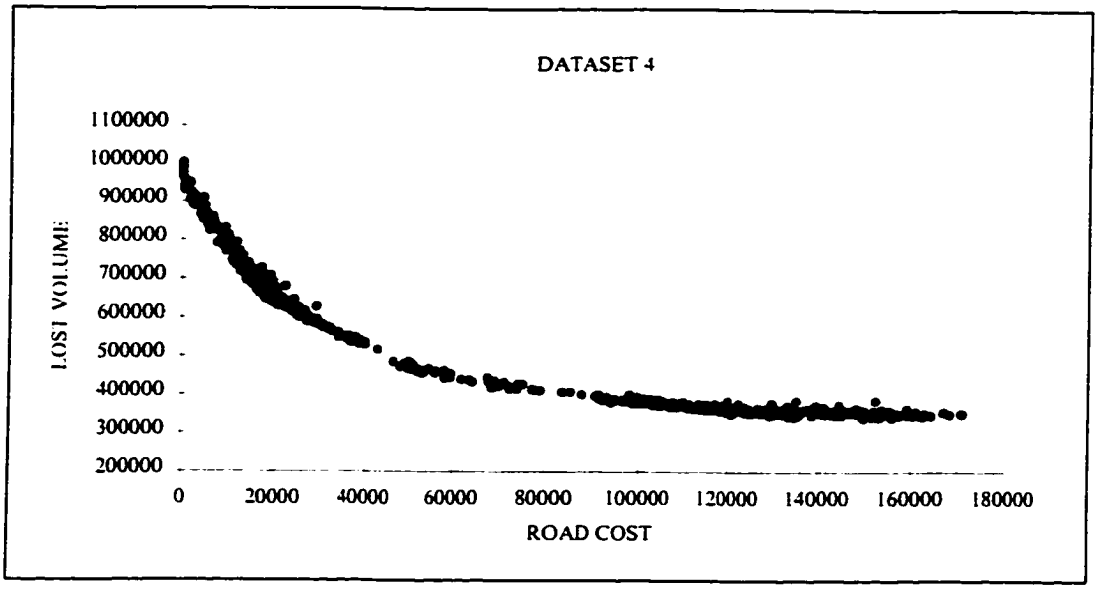


Figure D.5. Solutions for Dataset 4.

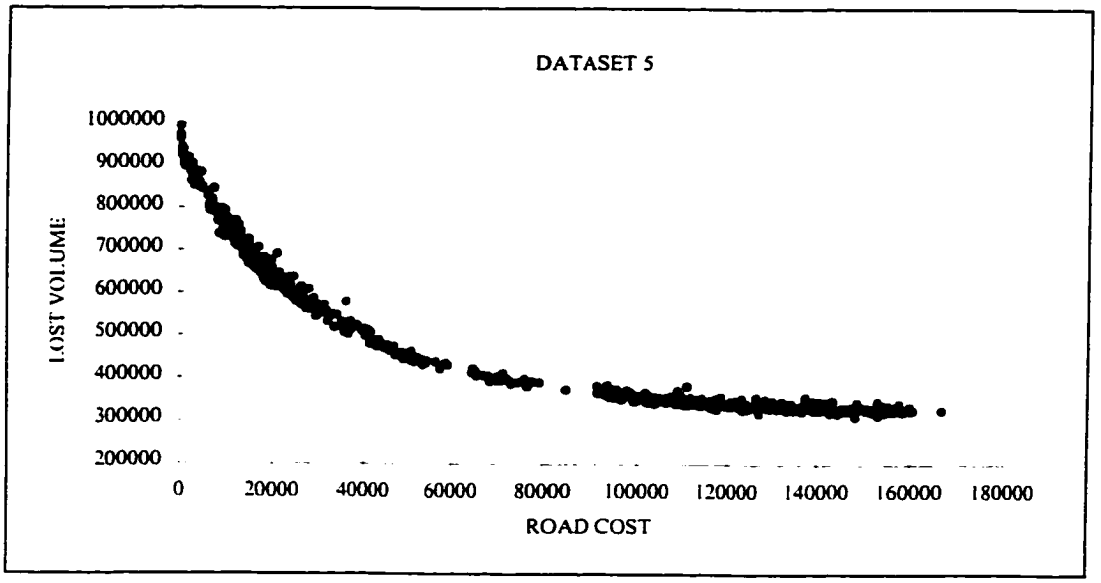


Figure D.6. Solutions for Dataset 5.

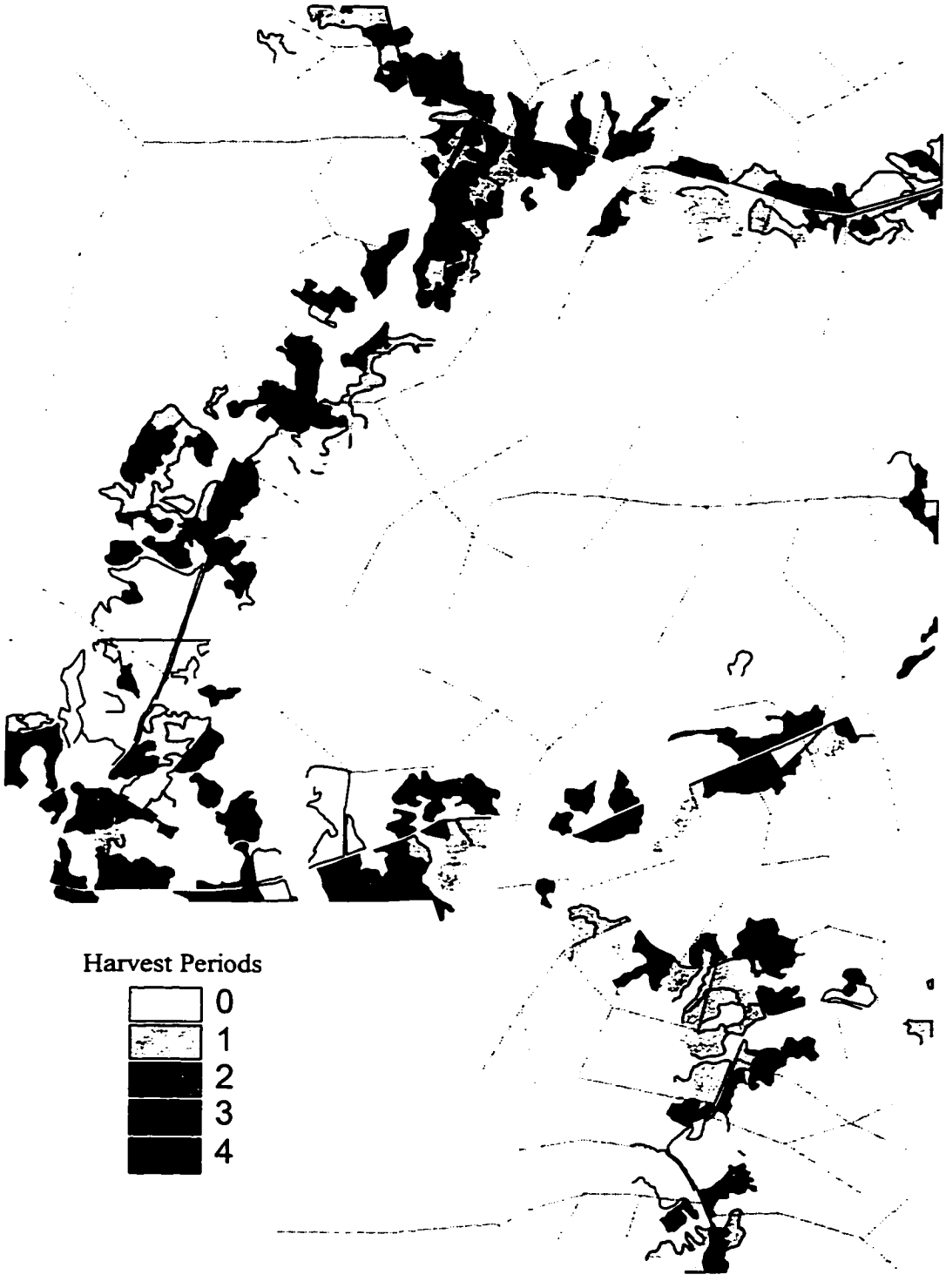


Figure D.7. Zero Roading Cost Solution
Lost Volume 947, 468.

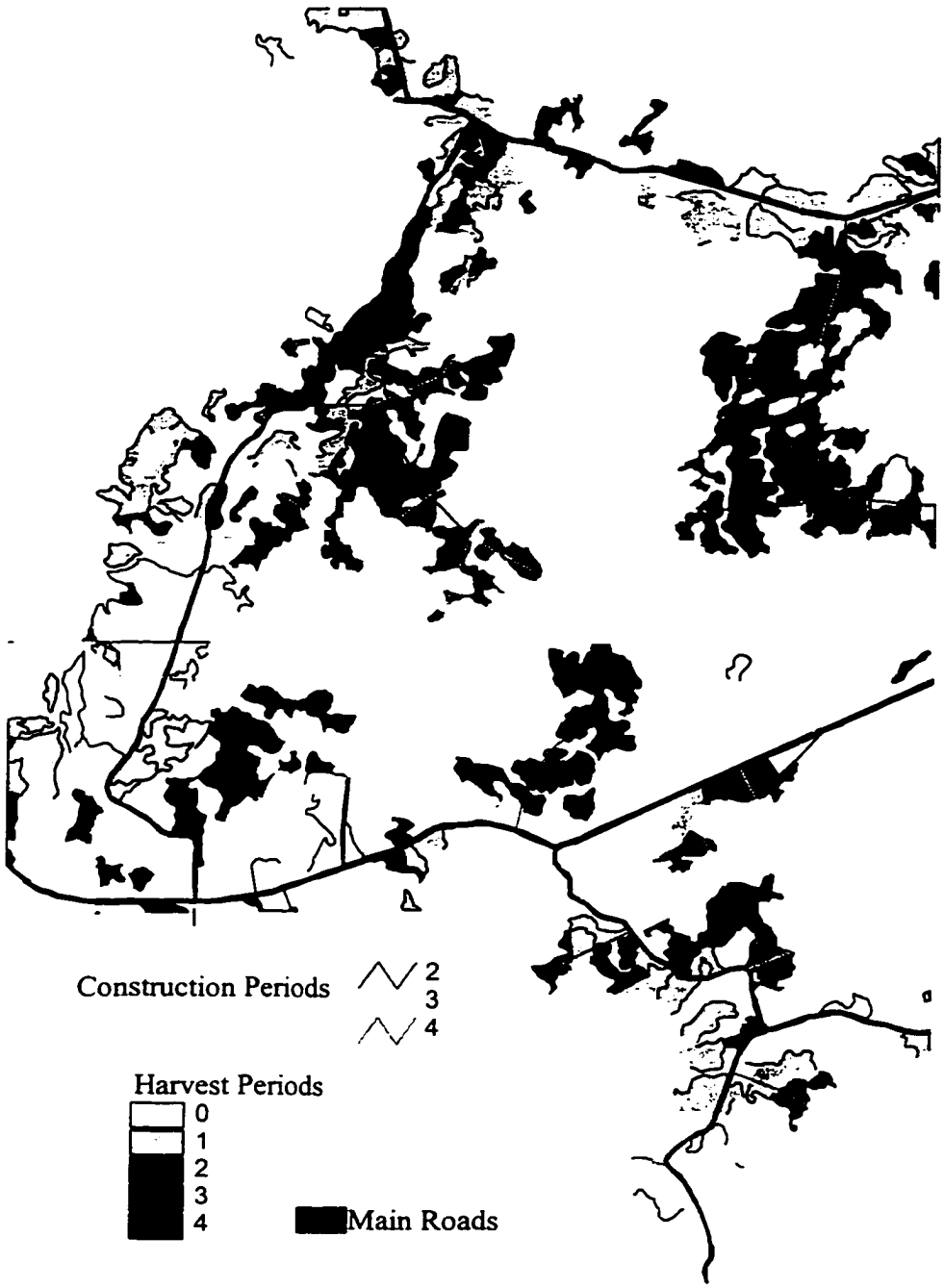


Figure D.8. Low Roading Cost Solution
Road Cost $15,062, Lost Volume 674,410.4.

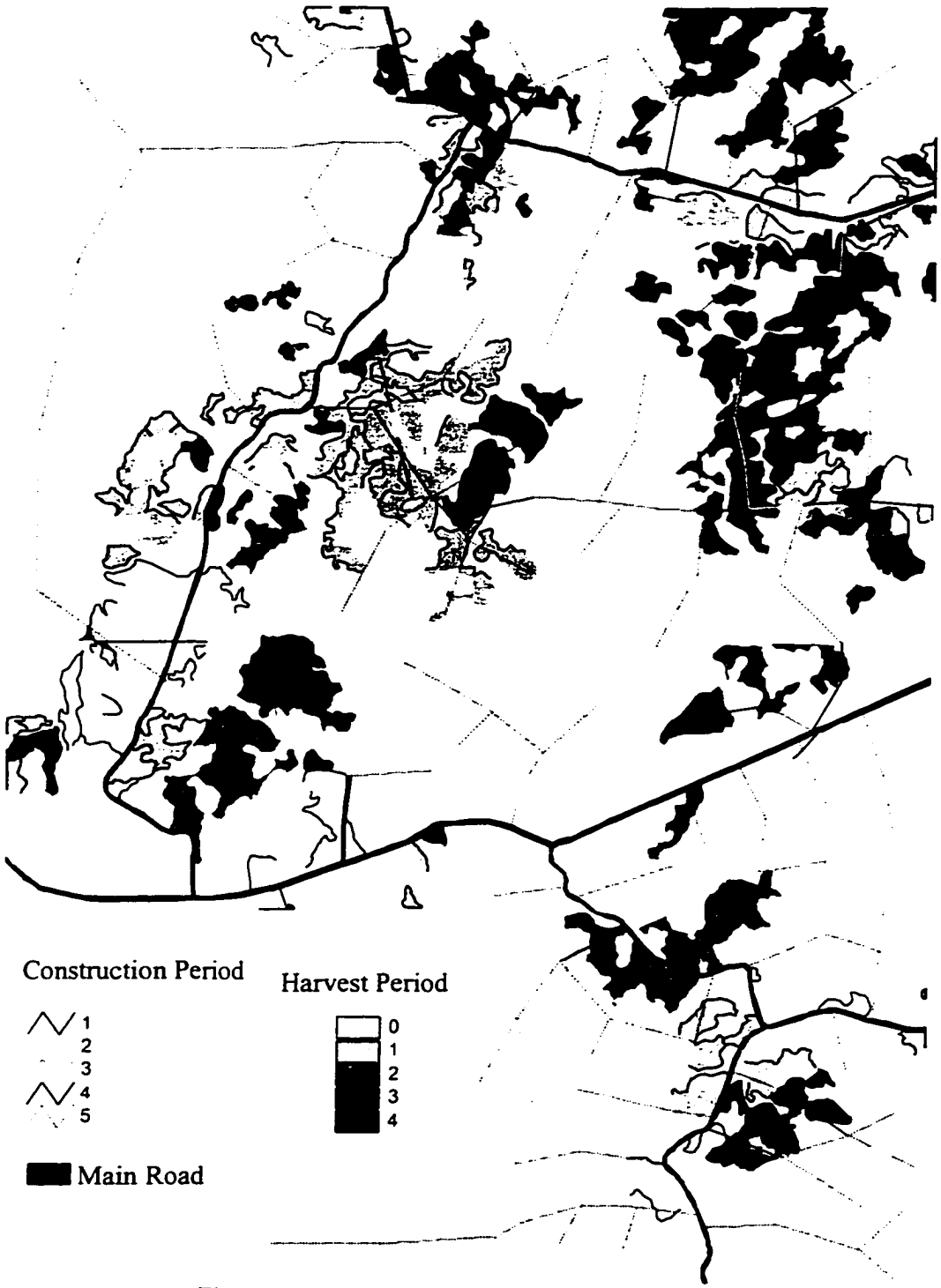


Figure D. 9 Medium-low Roading Cost Solution
Roading cost $30,030, Lost Volume 561,148

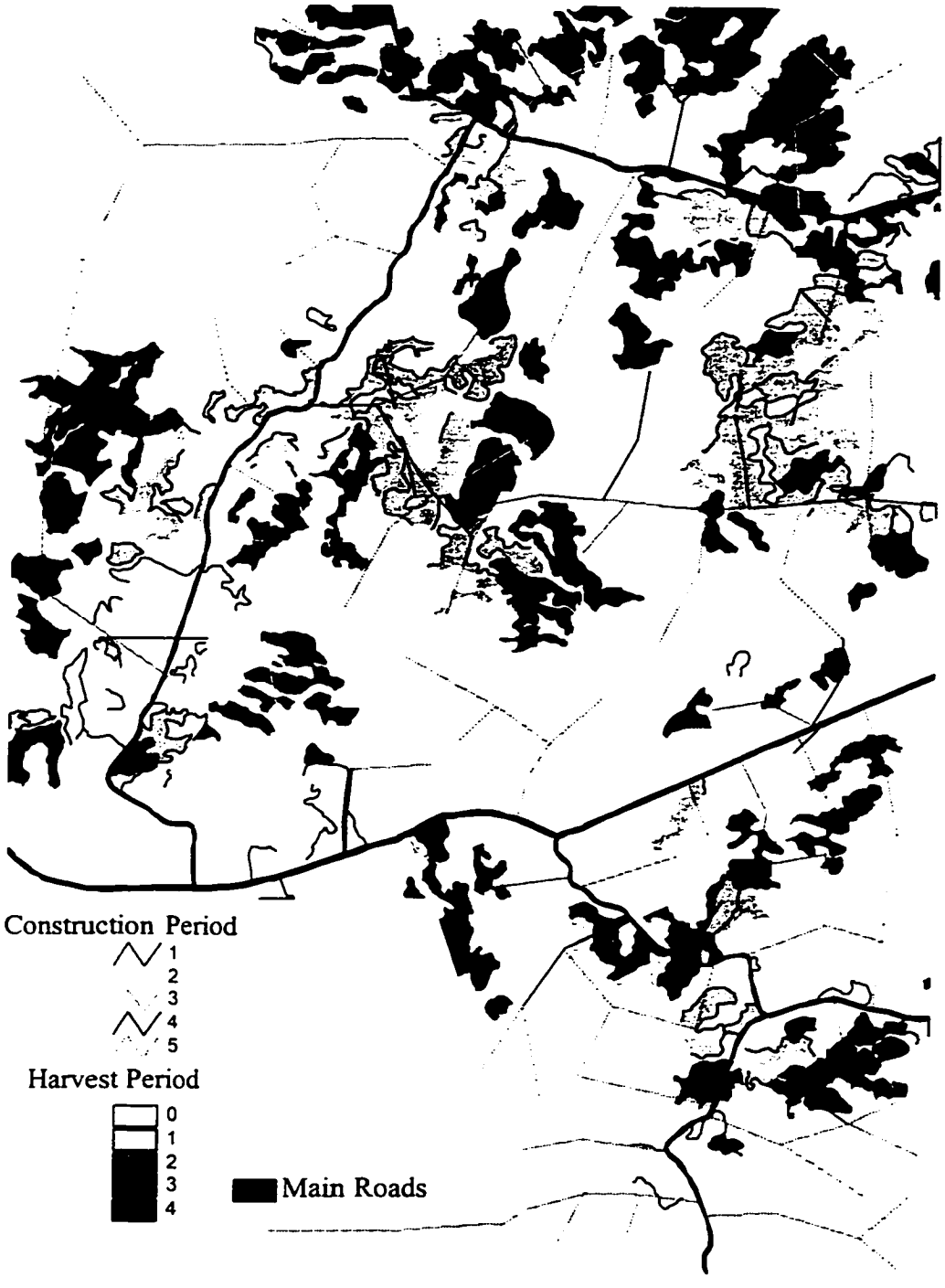


Figure D.10. Medium Roading Cost Solution
Cost $54,390, Lost Volume 404,876

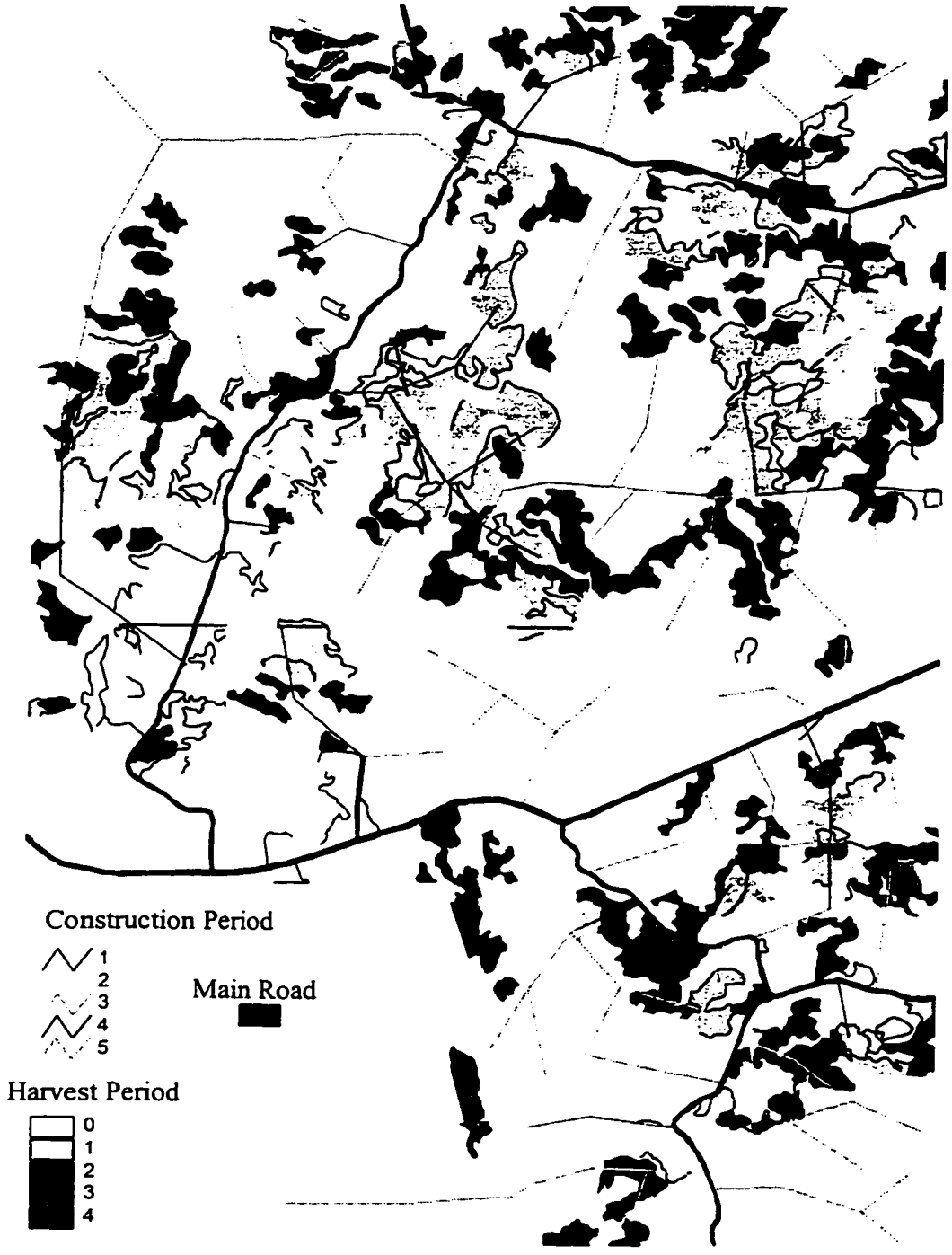


Figure D.11. High Roading Cost Solution
Road Cost $ 105,419, Lost volume 315,782

50COST

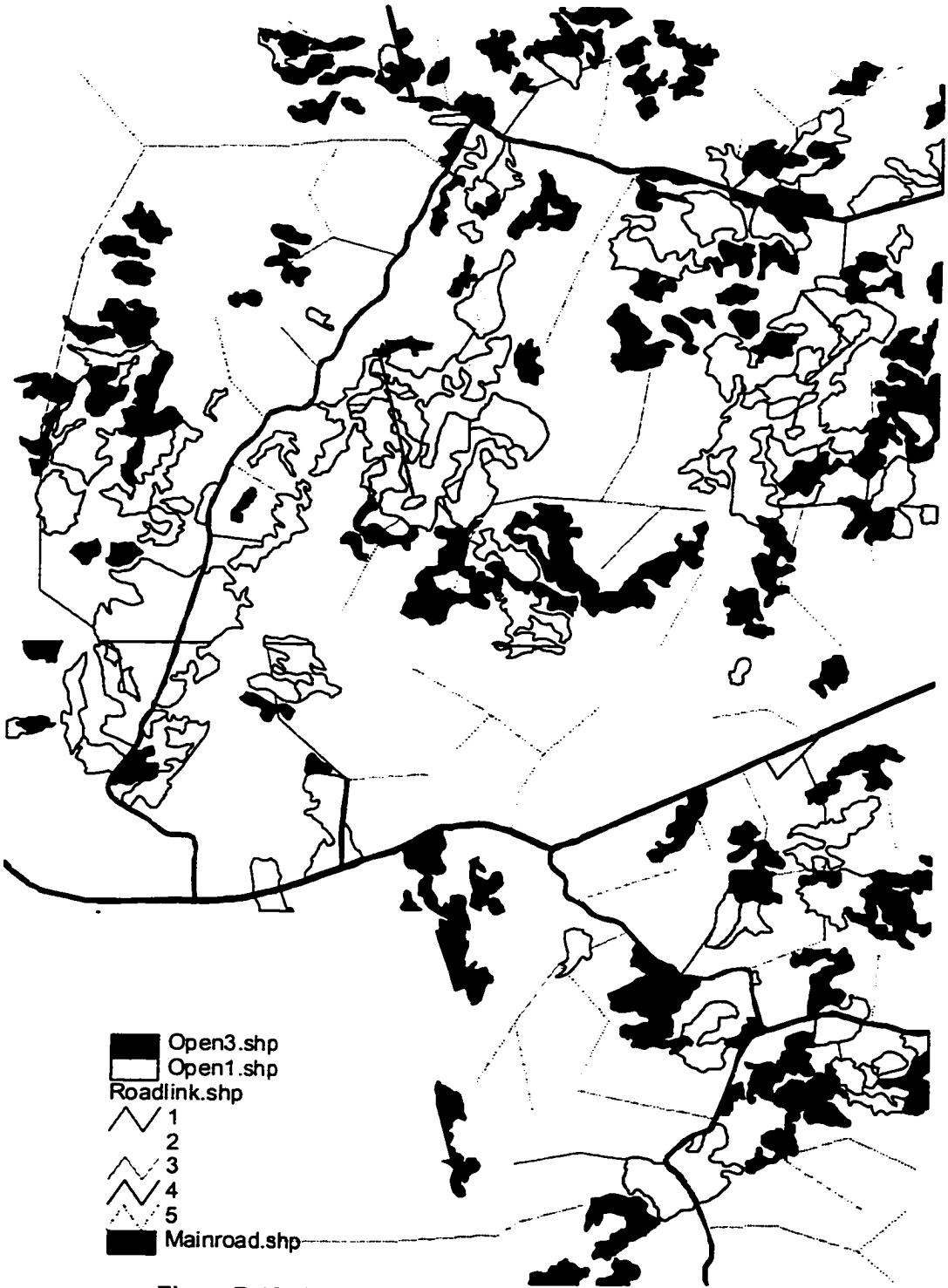
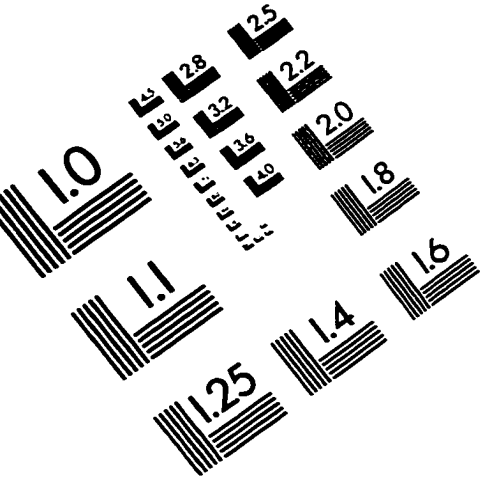


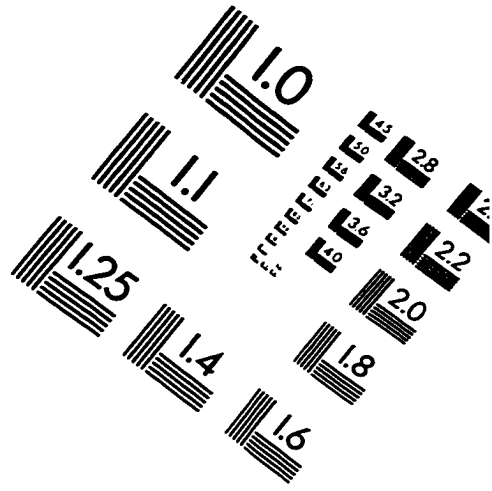
Figure D.12. Openings, Periods 1 and 3, Solution D.10

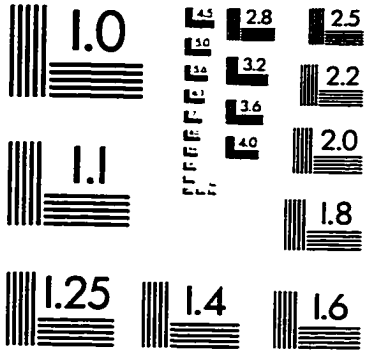
50COST

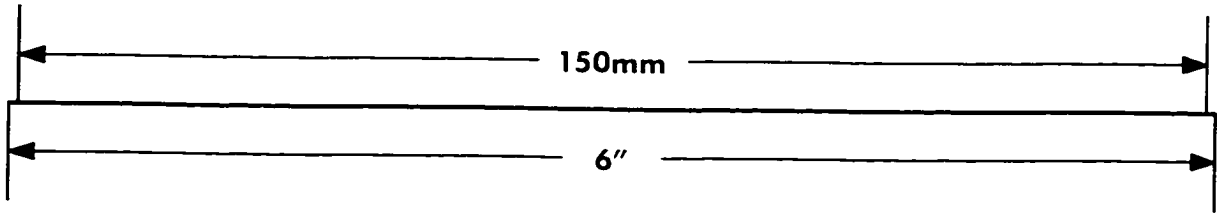
Figure D.13. Openings, Periods 2 and 4, Solution D.10

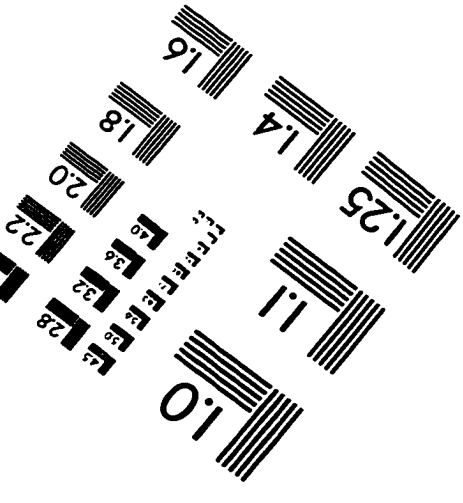
IMAGE EVALUATION TEST TARGET (QA-3)

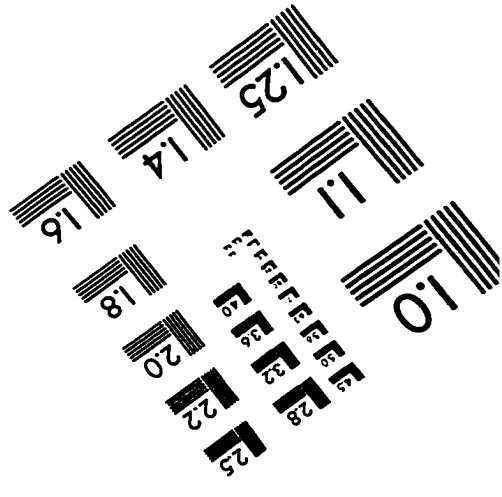












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