Development of a prototype model for optimizing silvicultural investment on a diverse forest ownership in central Maine.

by

Kris Martin Reyner

submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Forest Management and Economics.

APPROVED:

Jay Sullivan, Chairman

W. David Klemperer

Daniel B. Taylor

December, 1991

Blacksburg, Virginia

Development of a prototype model for optimizing silvicultural investment on a diverse forest ownership in central Maine.

by

Kris Martin Reyner

Jay Sullivan, Chairman

Forest Management and Economics.

(ABSTRACT)

This research project developed a prototype model for optimizing silvicultural investment on an industrial ownership in central Maine. The model was based on the Model I harvest scheduling formulation of Johnson and Scheurman (1977). The linear programming based model incorporated a choice of three objective functions (cost minimization, present net worth maximization, and woodflow maximization) subject to limited land area, investment levels, and required woodflows. The model incorporated data from a 150,000 acre study area but was developed with the intention that it be easily expandable to the entire 920,000 acre ownership as data becomes available. The study also considered the possibility of moving the ownership to a more balanced age class distribution. This consideration is overshadowed at the present time by an impending softwood shortage.

Acknowledgements

Many thanks to the following:

The members of my committee: Dr. W. David Klemperer, and Dr. Daniel B. Taylor for their time and helpful suggestions.

Dr. William A. Leuschner for his work as my major professor during the first 18 months of my program.

Dr. Jay Sullivan for his efforts as my major professor during the last 6 months of my program, and for help in bringing this project to completion.

My parents for their ongoing encouragement, support, and optimism.

The Lord, for being there when I needed it most.

Table of Contents

List of Tables

List of Illustrations

Chapter 1

Introduction:

Background:

S.D. Warren, Northeast Timberlands (N.E.T.) owns over 900,000 acres in central Maine. Around 80 percent of the ownership is manageable in that it does not consist of roads, streams and ponds, or State of Maine Land Use Regulation Commission (LURC) zones[1]. The ownership contains five natural stand types ranging from predominantly softwood stands to predominately hardwood stands, and five plantation types including black and white spruce, red and jack pine, and larch. The bulk of the ownership (over 95 percent) is in the natural stand types. The ownership provides roundwood and biomass chips (boiler fuel) for the S.D. Warren pulp mill in Skowhegen, Maine, as well as sawtimber and utility poles to the open market.

---

[1] LURC zones include: great ponds, streams, high mountain areas, deer yards, eagle nests, remote recreation areas, and unique geologic features.

Problem Statement and Justification:

Over the past decade, N.E.T has invested several million dollars annually in silvicultural treatments to compensate for the age class imbalance on the ownership. The ownership exhibits a roughly "U" shaped age class distribution, with large acreages in the 0 to 20 and 50 to 60 age classes. The 20 to 30 and 40 to 50 age classes have far fewer acres and the age 30 to 40 class has very few acres. The age 30 to 40 class will be called on in the 2005 to 2015 period to provide softwood, however this age class lacks the acreage to provide the needed volume. This shortage will be most acute between 2005 and 2015 on company lands and a decade later in the state overall. With this softwood shortage only a decade away, additional investment in intermediate silvicultural treatments can no longer impact the shortage. With the passage of this investment window, the investment trend of the past decade is coming under scrutiny. To study the merits of the components of the silvicultural program, N.E.T. has expressed interest in a financial analysis of plantation establishment and tending. However, the financial analysis and planning advantages of a whole or multiple rotation harvest schedule approach have been noted. These advantages include the optimization of the timing of harvest and other silvicultural treatments of present and future stands. A couple of options were discussed concerning the acquisition or development of a harvest scheduling model. The adaptation of MaxMillion (Clutter et al., 1978) or other commercial harvest scheduling packages was discussed, but N.E.T. preferred to avoid an off-the-shelf package in favor of a model that they could customize as their management situation changes. Development of a model specifically for their situation was the approach they selected.

Study Objectives:

The primary objective of the study is to develop a linear programming (LP) based model capable of optimally allocating annual silvicultural investment to maximize woodflow. The model must accommodate a variety of management regimes across the covertypes present over a 100 year planning horizon. A second objective is to apply a present value maximand to the model to provide a finance based measure of solution effectiveness which includes the time value of money. This will take into account the opportunity cost of capital invested in silvicultural activities. A third objective is to investigate model enrichments such as addressing the age class imbalance on the ownership. A fourth objective is to make recommendations concerning expansion of the model across the balance of the 920,000 acre ownership.

Proposed model:

A variety of modeling approaches have been used for harvest scheduling. LP has been selected for this study due to N.E.T.'s interest in the approach, its past use in timber management scheduling problems, and the availability of software packages for the solution of LP based models.

In pursuit of N.E.T.'s woodflow objectives, the model has been formulated to maximize the woodflow from the existing growing stock and the anticipated stream of annual silvicultural and land management investments, over the planning horizon. However, to provide additional flexibility and management decision support, the model also includes the choice of two other objective functions: cost minimization and present net worth maximization. These both address the financial aspects of providing woodflow to the company's pulp mill.

The model is bounded by resource constraints of land area and annual silvicultural investment; and decision maker goal constraints of woodflow requirements and woodflow objectives. The choice variables in the model are acres of a given cover type allocated to a given management regime, following the Model I formulation described by Johnson and Scheurman (1977).

This study has been limited to the development of a prototype model for a sub-unit of the ownership in question. This has been done due to limited data availability and computational restrictions of personal computer (PC) based LP software. The model has also been developed with the intention that it be used for strategic rather than tactical planning. The model should be considered strategic due to the management unit definition used: acres in a given cover type / site class combination throughout the study area, as well as the current imprecision of some data used in the model, most notably the growth and yield projections. The results the model generates, could be used in planning, forecasting, and financial analysis for the study area. Direct application on the ground may prove difficult due to these simplifications, which have been adopted to limit the size of the development effort. Also, LP does not lend itself well to tactical modeling due to the impracticalities of including all possible combinations of management regimes in the model. Such an approach is theoretically possible but exceeds the computational capabilities of available computer hardware and software.

Thesis Overview:

The following chapter (2) is a brief overview of the current literature on timber management scheduling. Chapter 3 outlines the methods used in developing this model. Chapter 4 reviews the results of the model developed in this study, including discussions of the results produced by the various objective functions. The final chapter (5) summarizes the work of this study relative to the objectives, and notes the conclusions and recommendations from this study. The appendices contain the source code and the output file for a simplified example of the model developed here, to demonstrate the structure of the model.

Chapter 2

Literature Review:

Timber Management Scheduling:

Timber management or harvest scheduling models examine the timing of cultural treatments and harvests of present and future stands of timber to optimize landowner objectives. Curtis (1962) did early work in this area with an LP based model for optimally scheduling the management of 22,000 acres of leased land. In recent years several studies have expanded on that work. The models developed in these studies evolved along several lines. The most widely used approaches have been developed around binary search, dynamic programming, and linear programming.

Binary search (BS) is a search routine that begins with a bounded (restricted) solution space and reduces this space by repeatedly dividing it into two parts, and determining which of the parts must contain the optimal value. It will accommodate only one system configuration, that is one management regime in a forest management application. BS applications have included SORAC (Chappelle, 1966) and TREES (Tedder et al., 1980) which have been used to set harvest levels on public lands, ECHO (Walker, 1971) which has been used to find harvest schedules when the producer faces a downward sloping demand function for timber, and SIMAC (Sassman et al., 1972) which has been used to set timber harvest levels and investment levels on Bureau of Land Management lands in the West.

Dynamic programming (DP) is another approach used in harvest scheduling. To use DP, the problem must be divisible into discrete stages, points in time when decisions are required. At each stage in deterministic DP, possible deterministic states of nature are identified. Each state of nature is a set of conditions or situations resulting from the decision at that stage, given the conditions resulting from previous stages. Management decisions at each stage then alter the state of the system under examination at that stage. DP determines the combination of decisions that maximizes overall effectiveness by eliminating suboptimal paths to each node. At any stage, the optimal policy for the remaining stages is independent of previously adopted policy for the given system. Due to the step by step nature of DP as it moves between stages, it can readily handle non-linear variable relationships as well as discrete variables. These attributes are less easily handled by other optimization techniques. Uncertainty also can be readily accommodated by DP (Martell and Fullerton, 1988). An important drawback of DP is the lack of a standard algorithm form. The solution software must be developed for each specific system to which it is applied. Key here is the "curse of dimensionality" which refers to the complexity involved in the DP structure as the number of states and stages increases. A problem can become too complex to be translated into the DP computer code. In theory, a model can be constructed to include all possible states and stages, but even simplified problems may be impractical to encode.

DP applications have focused on stand level analyses. Examples include a univariate allocation algorithm for use in forestry problems (Hool, 1968); simultaneous determination of the optimal thinning schedule and rotation for an even-aged forest (Schreuder, 1971); analysis of regeneration costs, initial stocking level, site quality, and variable logging costs on thinning and rotation for Douglas-fir using DP (Brodie et al., 1978); and derivation of optimal stand density over time, a discrete stage, continuous state dynamic programming solution (Chen et al., 1980).

Linear programming (LP) is a modeling approach that optimizes a guiding equation known as the objective function, subject to a set of linear constraints. LP has a standard solution technique, known as the simplex method, which facilitates the use of this modeling approach. As the name implies, all mathematical relationships in the objective function and the constraints of an LP must be linear in the decision variables. However, linearity in the decision variables does not prohibit the consideration of non-linear considerations such as stand growth equations which may be handled in stepwise linear fashion.

LP applications have included MAXMILLION (Clutter et al., 1968; Clutter et al., 1978) a computerized forest management planning system capable of incorporating inventory data and accounting for taxes, which was developed for private lands in the Southeast; Timber RAM (Navon, 1971), a long range planning method for commercial timber lands under multiple-use management which was developed for public lands in the West; MUSYC (Johnson and Jones, 1979), a multiple use sustained yield resource scheduling package serving as the predecessor to FORPLAN; FORPLAN (Kent et al., 1986; Johnson and Stuart, 1985) the U.S. Forest Service multiple use sustained yield planning model that incorporates the linkage of plans to budgets, and aggregate emphasis options.

Selection of a modeling approach, from LP, DP, and BS, depends on the nature of the model and system under study. A major consideration in modeling approach selection is the time and cost associated with development of that technique for a specific application. In addressing timber management scheduling problems similar to that under investigation in this study, LP seems to be the preferred solution technique. LP is more capable than other optimization techniques of dealing with such management considerations as a variety of constraints on harvest volume and pattern (Johnson and Tedder, 1983), as well as accommodating various management regimes over numerous stands. LP is also capable of handling a variety of budgetary and present value constraints. Finally, there are several commercially available software packages for the solution of LP based models, thus facilitating the solution step of model application.

Linear Programming Based Timber Management Schedules:

Linear programming based models consist of an objective function and a series of constraints. The objective function describes the contribution of each decision variable to the optimand. The optimand is the overall measure of effectiveness for the model solution. A variety of measures have been used as the optimand including present net worth, woodflow, and cost minimization. Decision variables are typically defined as acres of a given cutting unit to be managed by a given management regime. Constraints are the restrictions placed on the decision variables in the model. The constraints in harvest scheduling applications fall into three basic categories: resource constraints, decision maker goal constraints, and policy and regulatory constraints. Resource constraints include: land area available, technological limits, budgetary restrictions, and woodflow requirements. Decision maker goal constraints can include: desired woodflow patterns, intertemporal smoothing of operations, ending inventory conditions, and level of forest regulation. Policy and regulatory constraints are imposed by laws, regulations, political necessity, or other external influences and include: chemical use regulations, runoff restrictions, and various other environmental considerations.

When using LP models, several assumptions are made about the objective function, constraints, decision variables, and decision variable coefficients to enforce the required model linearity in the decision variables. There is assumed to be a direct linear relationship between the decision variables and the objective function and constraint levels. Decision variable coefficients are assumed to be additive and independent in their contribution to the objective function and constraints. All variables are assumed to be continuous and positive, thus integer and negative values are not typically accommodated. All treatments are assumed to occur at a single point in each planning period. The LP model treats all included relationships as deterministic. Because of these assumptions, the modeler must be careful when idealizing and simplifying the problem to ensure that the model reasonably represents the original problem.

Model I versus Model II:

LP based timber management models generally take one of two forms, designated as Model I and Model II by Johnson and Scheurman (1977). Both can utilize LP to locate optimal solutions, but each approaches the problem differently. In Model I, the decision variables are acres assigned to a given management type over the entire planning horizon, where a management type is a cover type / age class / management regime combination. Model I applications include: MaxMillion (Clutter, 1968), Timber RAM (Navon, 1971), MaxMillion II Theo (Clutter et al, 1978), MUSYC (Johnson and Jones, 1979), and FORPLAN (Kent, Kelly, and King, 1985; Johnson and Stuart, 1985).

Model II decision variables also are acres assigned to a given management type, but here the management type definitions contain age class and period of regeneration harvest, as opposed to the Model I management types that are cover type / age class / management regime combinations. Model II management types include covertypes and management regimes for current stands, but future stands, within the planning horizon, are considered separate decision variables. Model II tends to less easily accommodate variations in management regimes than Model I, particularly in the case of commercial thinning and selection cuts which produce woodflow but are not regeneration harvests (Johnson and Scheurman, 1977). Model II applications include: ECHO (Walker, 1971), SIMAC (Sassman et al, 1972), SORAC (Chappelle, 1966), TREES (Johnson et al, 1975; Tedder et al, 1980), MUSYC (Johnson and Jones, 1979), and FORPLAN (Johnson and Stuart, 1985).

Model Components:

LP based timber management scheduling models typically consist of three linked computer programs: a matrix generator, an LP solver, and a report writer (Clutter et al, 1983). The matrix generator converts the raw cost, revenue, yield, land base, and investment data into the equation format required by the LP. The LP solver then optimizes the objective function relative to a set of constraints. Finally, the report writer compiles and summarizes the LP output to make pertinent data readily accessible.

Implementation:

Interpretation of the LP solution by decision makers is the first step toward implementing the solution. The report writer provides the information necessary to make informed decisions. This information must be compared to overall organizational goals to see if the solution makes sense and is what was anticipated (Massam, 1988). If the solution seems peculiar, it should be examined to see if it meets the constraints placed on the system. If the constraints are met, the model has solved correctly, and either the intuition of the decision maker in anticipating the solution was misleading, or some pertinent information was incorrectly represented or not included in the model. The model solution will contain whatever imprecision or inaccuracy the data used in developing the model contained. The data used in developing the model then need to be as accurate as is feasible. Data omissions also can bias the solution, and may need to be incorporated in the model or at least its absence noted before proceeding. If a peculiar solution fails to meet the constraints, a model flaw or omission may be present. These types of errors can however be very difficult to locate, particularly in large models.

LP provides several indications of the relative importance of various data used in the model. Sensitivity analysis indicates the relative impact of changes in various input parameters on the solution. Sensitivity analysis also can be used to identify critical values of various parameters. These critical values are values beyond which the solution becomes unstable. Parametric linear programming is a variation on sensitivity analysis in which one or more parameters are systematically changed to determine their impact on the solution. This technique can be used like sensitivity analysis to identify critical parameter values. Retrospective testing can be used by comparing model results for past period data against actual performance to see if the model outperforms the actual results for the period. The LP solution process provides what are known as dual prices. These values indicate how the objective function would be impacted for a change in any individual constraint right hand side or individual decision variable. For example, the dual price on a binding constraint indicates how much the objective function would change if that constraint were relaxed by one unit, assuming nothing else in the model changed.

Once these sensitivity analysis techniques have been applied and the model has been revised to better reflect the system under study, the solution can then be implemented. The analysis should be documented sufficiently to allow duplication of results. The model also should be monitored over time and revised as necessary to ensure continued adequacy of solutions (Hillier and Lieberman, 1986).

Chapter 3

Methods:

Methods:

The model developed in this study is based on the Model I timber harvest scheduling formulation. The basic structure of Model I consists of an objective function of the form:

$$\text{maximize } Z = \sum_{i=1}^{m} \sum_{j=1}^{n} c_{ij} \, x_{ij} \qquad [1]$$

where:

Z = optimand

i = individual cutting units

m = number of cutting units in model

j = individual management regimes

n = number of management regimes in model

c = contribution of a given management type to the objective function

x = choice variables (acres of a cutting unit to be managed by a given management regime)

subject to:

$$\sum_{j=1}^{n} x_{ij} \leq r_i \quad \forall i = 1,m \qquad [2]$$

where: r_i = acres in cutting unit i

The model has been formulated to accommodate a choice of optimands, including: woodflow maximization, present net worth (PNW) maximization, or cost minimization for a required woodflow. Woodflow maximization is included due to the role of the ownership in providing roundwood and boiler fuel to a pulp mill. PNW is included due to the consideration of the time value of money which accounts for the opportunity cost of capital tied up in silvicultural investments. This allows these investments to be compared with uses of capital other than in silvicultural activities. Cost minimization is included to supplement the woodflow maximization. The ownership under study has a strongly skewed age class distribution and the sponsor is facing a softwood shortage during certain periods in the future. Cost minimization can assist in evaluating the cost of providing a particular woodflow in a given future period. These various objectives are incorporated with the use of different coefficient (c) vectors in the objective function (eq. 1).

In this study, several constraints are needed in addition to the Model I acreage constraints. These constraints fall into two categories: 1) cutting period resource restrictions or requirements, and 2) accounting constraints required to accommodate the variable cutting period lengths included in the model.

Within each cutting period, the total investment level is restricted by the amount of capital available, and requirements are placed upon the quantities of softwood, hardwood, and biomass provided to the company pulp mill./ The cutting period dependent restriction and requirement constraints are included in the model as inequalities and take the form:

$$\sum_{i=1}^{m} \sum_{j=1}^{n} a_{ijk}\ x_{ijk}\ \geq \text{or} \leq\ rhs_k \quad \forall k = 1,q \qquad [3]$$

where: k = individual cutting periods

q = number of cutting periods in the model

a_{ijk} = contribution of x_{ij} to constraint in cutting period k

rhs_k = resource requirement / restriction in cutting period k

Note: The direction of the inequality depends on the constraint. In the investment constraints, ≤ applies; while in the woodflow constraints, ≥ applies.

The model has been formulated to include 16 cutting periods to span the 100 year planning horizon. The first decade of the harvest schedule is composed of 6 one year cutting periods for years 0 through 5 and 1 five year cutting period for years 6 through 10. This has been done to allow year by year examination of investment in the current and next five years. However, the age class data for the study area consists of 10-year age classes. This grouping of stands into age classes is necessary to keep the model small enough to work with. These accounting constraints allow woodflows and acreages in any of the first 7 cutting periods to meet the constraints for that decade. Elimination of these constraints should be a priority in N.E.T.'s continuing development of the model. These constraints could be eliminated via inclusion of management regime sequences for one year increment age classes to span the first decade of stand existence. The accounting constraints currently take the form:

$$\sum_{k=1}^{7} \sum_{i=1}^{m} \sum_{j=1}^{n} a_{ijk} \, x_{ij} = \sum_{k=1}^{7} rhs_k \qquad [4]$$

To address the age class imbalance on the N.E.T. ownership, constraints have been included in the model to enforce area regulation as an alternate set of equations which can be used in solving the model. This consideration requires two sets of equations. One set of equations are required to sum the acres in each covertype that are clearcut in each cutting period. These areas are then compared with the area of that cutting unit that would be cut in a regulated forest, which is the total acreage in a cutting unit divided by average rotation age for that cutting unit. The differences between areas cut in each period and the regulated forest areas are summed over all cover types and the total constrained to a user selected area control acreage variation.

Study Area:

The study area consists of a 150,000 acre administrative unit of N.E.T.'s 920,000 acre ownership. This area provides a good representation of the management complexity of the entire ownership, and thus maintains the programming difficulty of the whole, while significantly reducing the data requirements for the study. This will make the expansion of the model to the whole ownership easy to accomplish as the balance of the data become available.

The initial assumptions under which the model has been developed include: investment of $4,200,000 per decade; woodflow requirements of 1,000,000 thousand weight

(MWT)[2] of softwood per decade, 500,000 MWT of hardwood per decade, and 125,000 MWT of biomass per decade; a real discount rate of 6 percent; and 100 year planning horizon. The costs and prices used in the model have been omitted here due to their proprietary nature.

The decision variables used in the model are acres of a given covertype, site productivity class, and age class to be allocated to a given management regime. The covertypes included in the model appear in Table 1. They include four natural types, precommercially thinned softwood, and five plantation types. The site productivity classes are denoted 1, 2, 3, 4, and 5, with 5 being the most productive and 1 being the least. The ownership is classified into twelve 10-year age classes, which are named for the average age of the class. For example, the 0 to 10 age class is age class 5, the 11 to 20 age class is age class 15 and so forth. The decision variable acreages are total acres across the study area consisting of a given covertype / site class / age class. The model thus does not allocate prescriptions to specific physical locations.

The management regimes included in the model are a compilation of the most promising and most historically successful management regimes. The rotation lengths were selected by projecting the age necessary to produce a given woodflow per acre. The management regimes considered are composed of combinations of the following treatments: biomass harvest (whole tree chipping), mechanical or chemical site preparation, natural or artificial regeneration, chemical release, mechanical or chemical precommercial thinning, and commercial thinning. Table 2 contains a listing of the management regimes used in formulating the model. The table lists the applicable management regimes for each covertype / site class combination. Each row on the table consists of one management regime. The numbers in the columns indicate the number of years after the previous harvest that a certain treatment occurs. The first

[2] A thousand weight is 1,000 pounds of material.

Table 1. Covertypes.

Stand Origin	Covertype	Species
Natural:	Mixed Softwood (S)	spruce *Picea spp.*
		fir *Abies balsamea* (L.) Mill.
	Mixed Hardwood (H)	maple *Acer spp.*
		beech *Fagus grandifolia* Ehrh.
		birch *Betula spp.*
		aspen *Populus spp.*
	Softwood / Hardwood (SH)	predominantly softwood
	Hardwood / Softwood (HS)	predominantly hardwood
	Precommercially thinned softwood (ST)	(same species as mixed softwood)
Plantation:	Red pine (RP)	red pine *Pinus resinosa* Ait.
	Jack pine (JP)	jack pine *Pinus banksiana* Lamb.
	Larch (L)	larch *Larix spp.*
	White spruce (WS)	white spruce *Picea glauca* (Moench)
	Black spruce (BS)	black spruce *Picea mariana* (Mill.)

Table 2. Management Regimes.

cover type[1]	site class	Treatment Age (years since previous harvest): site prep	plant	first release	second release	PCT[2]	first comm. thin[3]	second comm. thin[4]	harvest
S	5								50 or 60
S	5			4					40 or 50
S	5			4		13			32 or 42
S	4								60 or 70
S	4			6					50 or 60
S	4			6		15			40 or 50
S	3								75 or 85
S	3			7					65 or 75
S	3			7		18			54 or 64
S	3	3	4[5]	6					55 or 65
S	3	3	4[6]	6					55 or 65
S	3	3	4[7]	6					55 or 65
S	3	3	4[7]	6			35	50	65 or 85
S	2								100 or 110
S	2			9					90 or 100
S	2			9		21			77 or 87
S	1								120 or 130
SH	5								50 or 60
SH	5			4					40 or 50
SH	5			4		13			32 or 42
SH	4								60 or 70
SH	4			6					50 or 60
SH	4			6		15			40 or 50
SH	3								75 or 85
SH	3			7					65 or 75
SH	3			7		18			54 or 64
SH	3	3	4[5]	6					55 or 65
SH	3	3	4[6]	6					55 or 65
SH	3	3	4[7]	6					55 or 65
SH	3	3	4[7]	6			35	50	65 or 75
SH	2								100 or 110
SH	2			9					90 or 100
SH	2			9		21			77 or 87
SH	1								120 or 130
HS	5								60 or 70
HS	5			4					40 or 50
HS	5			4		13			32 or 42
HS	5		1[6]	3					45 or 55
HS	5		1[6]	3	5				45 or 55
HS	5		1[7]	3					45 or 55
HS	5		1[7]	3	5				45 or 55
HS	5		1[7]	3			25	35	45 or 55

Table 2. Management Regimes (continued).

cover type[1]	site class	site prep	plant	first release	second release	PCT[2]	first comm. thin[3]	second comm. thin[4]	harvest
		Treatment Age (years since previous harvest)							
HS	5		1[7]	3	5		25	35	45 or 55
HS	5	2	3[8]	5			18		28 or 38
HS	4								75 or 85
HS	4			6					50 or 60
HS	4			6		15			40 or 50
HS	4		1[6]	3					50 or 60
HS	4		1[6]	3	5				50 or 60
HS	4		1[7]	3					50 or 60
HS	4		1[7]	3	5				50 or 60
HS	4		1[7]	3			30	40	50 or 60
HS	4		1[7]	3	5		30	40	50 or 60
HS	4		1[9]	3					50 or 60
HS	4		1[9]	3	5				50 or 60
HS	4	2	3[8]	5			23		33 or 43
HS	3								90 or 100
HS	3			7					65 or 75
HS	3			7		18			54 or 64
HS	3		1[5]	3					55 or 65
HS	3		1[5]	3	5				55 or 65
HS	3		1[6]	3					50 or 60
HS	3		1[6]	3	5				50 or 60
HS	3		1[7]	3					50 or 60
HS	3		1[7]	3	5				50 or 60
HS	3		1[7]	3			30	40	50 or 60
HS	3		1[7]	3	5		30	40	50 or 60
HS	3		1[9]	3					55 or 65
HS	3		1[9]	3	5				55 or 65
HS	3		1[10]	3					55 or 65
HS	3		1[10]	3	5				55 or 65
HS	2								115 or 125
HS	2			9					90 or 100
HS	2			9		21			77 or 87
HS	2		1[10]	3					60 or 70
HS	2		1[10]	3	5				60 or 70
H	5								60 or 70
H	5		1[6]	3					55 or 65
H	5		1[6]	3	5				45 or 55
H	5		1[7]	3					55 or 65
H	5		1[7]	3	5				45 or 55
H	5		1[7]	3			25	35	45 or 55
H	5		1[7]	3	5		25	35	45 or 55

Table 2. Management Regimes (continued).

cover type[1]	site class	site prep	plant	first release	second release	PCT[2]	first comm. thin[3]	second comm. thin[4]	harvest
		Treatment Age (years since previous harvest)							
H	5	2	3[8]	5			18		28 or 38
H	4								75 or 85
H	4		1[6]	3					50 or 60
H	4		1[6]	3	5				50 or 60
H	4		1[7]	3					50 or 60
H	4		1[7]	3	5				50 or 60
H	4		1[7]	3			30	40	50 or 60
H	4		1[7]	3	5		30	40	50 or 60
H	4		1[9]	3					50 or 60
H	4		1[9]	3	5				50 or 60
H	4	2	3[8]	5			23		33 or 43
H	3								90 or 100
H	3		1[5]	3					55 or 65
H	3		1[5]	3	5				55 or 65
H	3		1[6]	3					50 or 60
H	3		1[6]	3	5				50 or 60
H	3		1[7]	3					50 or 60
H	3		1[7]	3	5				50 or 60
H	3		1[7]	3			30	40	50 or 60
H	3		1[7]	3	5		30	40	50 or 60
H	3		1[9]	3					55 or 65
H	3		1[9]	3	5				55 or 65
H	3		1[10]	3					55 or 65
H	3		1[10]	3	5				55 or 65
H	2								115 or 125
H	2		1[10]	3					60 or 70
H	2		1[10]	3	5				60 or 70
ST	2								77 or 87
ST	3								54 or 64
ST	4								40 or 50
ST	5								32 or 42
RP	3			3					50 or 60
RP	3			3	5				50 or 60
RP	3			3			30	40	50 or 60
RP	3			3	5		30	40	50 or 60
RP	4			3					50 or 60
RP	4			3	5				50 or 60
RP	4			3			30	40	50 or 60
RP	4			3	5		30	40	50 or 60
RP	5			3					45 or 55
RP	5			3	5				45 or 55

Table 2. Management Regimes (continued).

cover type[1]	site class	site prep	plant	first release	second release	PCT[2]	first comm. thin[3]	second comm. thin[4]	harvest
		Treatment Age (years since previous harvest)							
RP	5			3			25	35	45 or 55
RP	5			3	5		25	35	45 or 55
JP	3			3					55 or 65
JP	3			3	5				55 or 65
L	4			3			23		33 or 43
L	5						18		28 or 38
WS	3			3					55 or 65
WS	3			3	5				55 or 65
WS	4			3					50 or 60
WS	4			3	5				50 or 60
BS	2			3					60 or 70
BS	2			3	5				60 or 70
BS	3			3					55 or 65
BS	3			3	5				55 or 65

1. see Table 1 for covertype definitions
2. precommercial thinning
3. first commercial thinning
4. second commercial thinning
5. plant jack pine
6. plant red pine, 400 trees per acre
7. plant red pine, 600 trees per acre
8. plant larch
9. plant white spruce
10. plant black spruce

row of the table then indicates for a site class 5 natural softwood stand, nothing is done following harvest until it is again harvested at either age 50 or 60. The second row, also for site class 5 natural softwood, adds a herbicide release four years after harvest, which reduces the rotation length by 10 years to 40 or 50 years. Eliminating management regimes *a priori* has the potential to limit the optimal solution, but inclusion of all possible regimes is not practical. Even with a paring down of regimes, over 9,600 management regime sequences (combinations of management regimes to span the planning horizon) are considered, still a significant programming effort.

In the model, the management regimes are broken down into treatments which are the portion of a management regime that occurs within a cutting period. The model contains seven coefficients for each treatment. Those seven coefficients are value (revenue - cost), cost, revenue (based on initial, non-inflated product prices), total woodflow, softwood woodflow, hardwood woodflow, and biomass woodflow.

The Model:

The data supporting the model have been compiled on a series of electronic spreadsheets to render them compatible with the matrix generation language included in the GAMS LP package (General Algebraic Modeling System {Brooke et al., 1988}) selected for this study. This package was selected for its matrix generation language and matrix size capabilities on the PC platform. The model consists of over 9600 decision variables in 354 equations. On a 20 megahertz 80386 PC, the model runs in from 9.5 to 11 hours, depending on the model version involved. The PC version of GAMS successfully handles the matrix generation tasks called for in the code. This task entails the identification and generation of over 1.2 million coefficients and consumes nearly 95 percent of the model run time.

The model developed in this study seeks to optimize one of three objective functions (woodflow maximization, PNW maximization, or cost minimization) subject to limited land base, limited investment, and required softwood, hardwood, and biomass woodflows. It also considers the timing interactions of the various management regime sequences in meeting the constraints. The model currently includes acreage data for the mixed softwood, mixed softwood and hardwood, mixed hardwood and softwood, mixed hardwood, and precommercially thinned softwood covertypes (Table 1).

The data provided for the study by N.E.T. proved to be difficult to deal with. When they generated age classes for all stands in the study area, stands that were not known to have been harvested since 1923 were lumped into the 61 to 70 year old age class. This generalization however does not accurately represent the ownership. There are appreciable acreages of older age classes. In order to more closely mirror the ownership, half of the acreage in the 61 to 70 year old age class has been shifted to the 71 to 80 year old age class. The need for this change was brought to light by the initial formulation of the model, which proved to be infeasible. The management regimes incorporated into the model specify a minimum rotation age for site class 3 of 75 years in softwood and 90 years in hardwood. The woodflow requirements during the first two decades of the planning horizon could not be met with the older stands lumped into the 61-70 year old age class. The data base supporting the model does not acknowledge the 71-80 year old stands present on the ownership. This is further reason why this model should be considered strategic rather than tactical.

The biomass (boiler fuel) woodflow constraints also caused model infeasibility initially. The constraint levels provided were current biomass utilization levels. However, biomass yield was incorporated into the model as a fixed percentage of the hardwood woodflow produced by each management regime sequence. Currently a moderate quantity of higher use material (pulpwood and low quality sawtimber) is being chipped for use as biomass due to the convenience of acquiring the material internally. This use of higher valued products is not currently included in the model, and thus the model is incapable of meeting the required levels of biomass. The biomass requirements have been reduced to achieve a feasible solution as a stop gap measure. Further model development should focus on the endogenous determination of end-product use, including biomass.

Chapter 4

Results and Discussion:

Overview of Results:

The three objective functions produce markedly different results (Table 3). Under cost minimization, projected woodflow is 19,306,000 MWT over the planning horizon, at a present value of $14,687,000, with no investment required during the planning horizon. Under PNW maximization, at a real discount rate of 6 percent, projected woodflow is 39,824,000 MWT, with a present value of $30,345,947 for a non-discounted total investment of $10,301,850. Under woodflow maximization, projected woodflow is 67,776,000 MWT, with a present value of $20,269,000 for a non-discounted total investment of $41,003,956. Cost minimization then is the least costly, by its nature, but also produces the least woodflow and the lowest PNW. PNW and woodflow maximizations provide a mixed picture. Under PNW maximization, only 57 percent of the woodflow maximization volume is projected, but the total woodflow projected under PNW maximization is worth 1.5 times as much as the total woodflow projected under woodflow maximization. Under PNW maximization then, the production of a smaller

Table 3. **Baseline Model Results Summary.**

		Strategy:	
	Woodflow max	PNW max	Cost min
Investment (MM$)	41.00	10.30	0
PNW (MM$)	20.27	30.35	14.69
Woodflow (MWT)	67.78	39.82	19.31
% of acres treated:			
hardwood	100	100	22
hard & softwood	100	100	50
soft & hardwood	100	100	66
softwood	100	100	61
thinned softwood	100	100	92

volume of higher valued material is projected. N.E.T. then will need to examine their situation to determine if volume or value is more important in their decision process.

The woodflow maximization model looks only at the woodflow produced by the various management regime sequences. This objective would be of most interest if the woodflow needs of the pulp mill were of primary concern. However, in N.E.T.'s situation, their ownership currently provides around 25 percent of the mill's requirements, thus even moderate changes in woodflow from the ownership would have little impact in the total wood supply to the mill. In this situation, cost minimization would be less expensive than woodflow maximization for meeting the ownership woodflow requirements. Present net worth maximization also examines the costs of providing a given woodflow but in addition gives consideration to the opportunity cost of the capital used in the silvicultural investments. This allows for comparison with other possible investments. One note of caution, the prices included in the model for various product are market prices and thus may not reflect the true internal value of the various products to the pulp mill. This may make silvicultural investments appear less attractive than they actually are.

Baseline Analyses:

To review, the initial conditions under which the model was run included investment limit of $4,200,000 per decade; woodflow requirements of 1,000,000 MWT of softwood per decade, 500,000 MWT of hardwood per decade, and 125,000 MWT of biomass per decade; a real discount rate of 6 percent; and a 100 year planning horizon. The covertype / age class / site class acreages represent a 150,000 acre administrative unit of the N.E.T. ownership.

Woodflow maximization: This model version results in a highly investment intensive solution. There are only three cutting periods in which less than 95 percent of the available capital is invested. Contrast this with cost minimization where no capital is invested and PNW maximization in which there are only four periods in which more than 50 percent of the available capital is invested. Woodflow maximization calls for intensive use of intermediate treatments, as well as plantations. The woodflow produced by this model, however, is strongly skewed toward the end of the planning horizon (Figure 1) compared to the PNW maximization and cost minimization formulations (Figures 2 and 3).

On natural hardwood stands, natural regeneration is selected for the site class 2 stands and the younger site class 3 stands. On the older site class 3 stands, conversion to red pine followed by commercial thinning is selected. Site class 4 and 5 stands are all converted to either larch or red pine and commercially thinned in most cases. Under the objective of maximizing woodflow, plantations are selected, particularly on more productive sites.

On natural hardwood/softwood mixed stands, the 5 year old site class 2 and 3 stands are prescribed to a release and precommercial thinning regime to secure a harvest before the end of the planning horizon. The 5 year old site class 3 stands are also converted to red pine following harvest. The older site class 2 stands are naturally regenerated. The older site class 3 stands are converted to red pine. Site class 4 and 5 offer a mixture of conversion to red pine or larch, and natural regeneration with herbicide release and precommercial thinning. If more capital were available, more stands would likely be converted to plantations. It should be noted that this solution emphasizes moving through as many rotations over the planning horizon as are financially possible. This forcing of additional rotations into the planning horizon is a characteristic of LP based models, due to the lack of consideration for activities beyond the planning horizon. This is not however, a problem as long as the model is

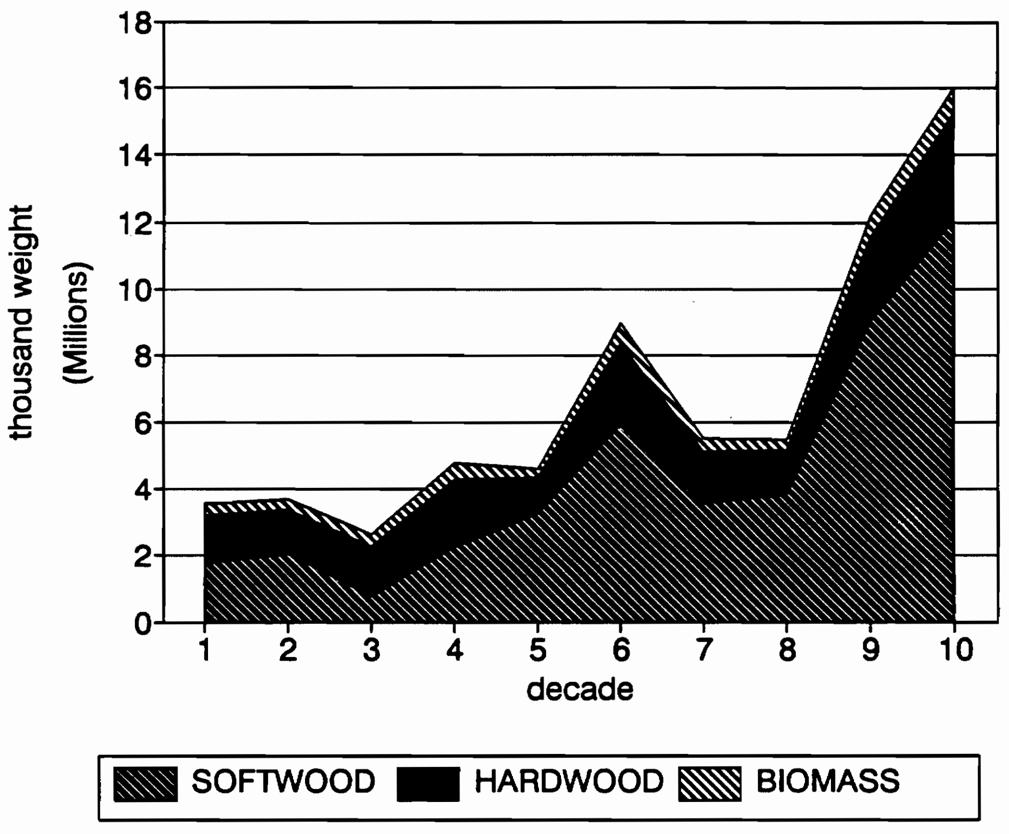

Figure 1. Woodflow Maximization - woodflow trajectory.

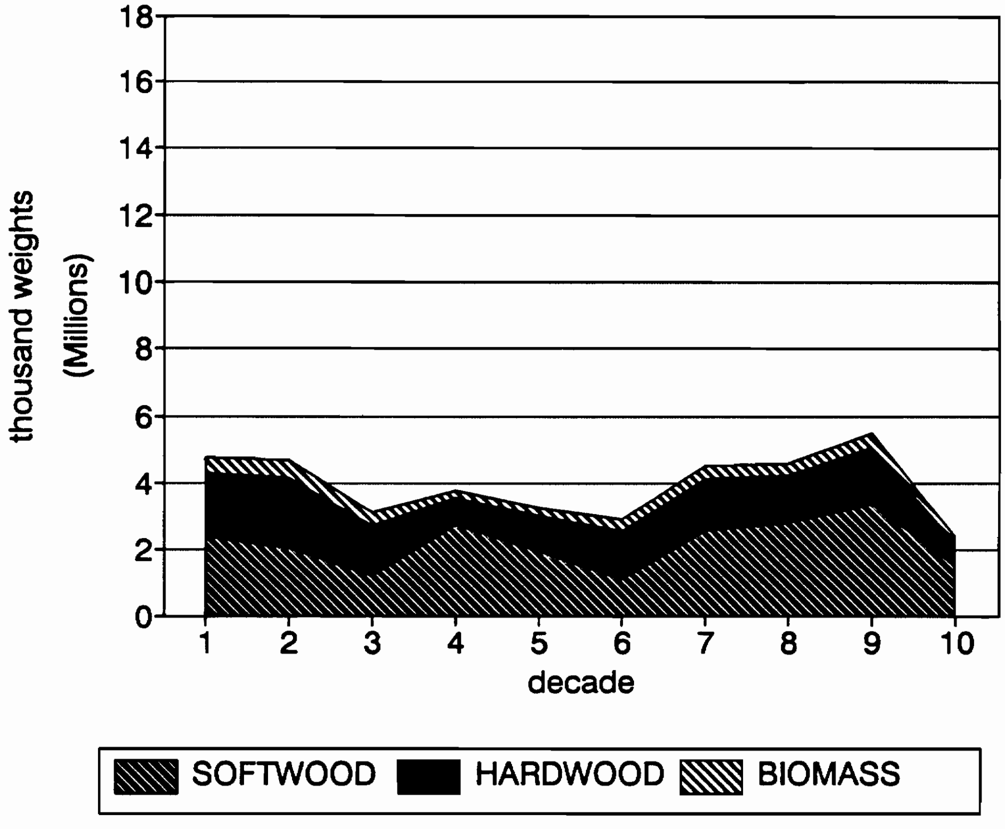

Figure 2. **PNW Maximization - woodflow trajectory.**

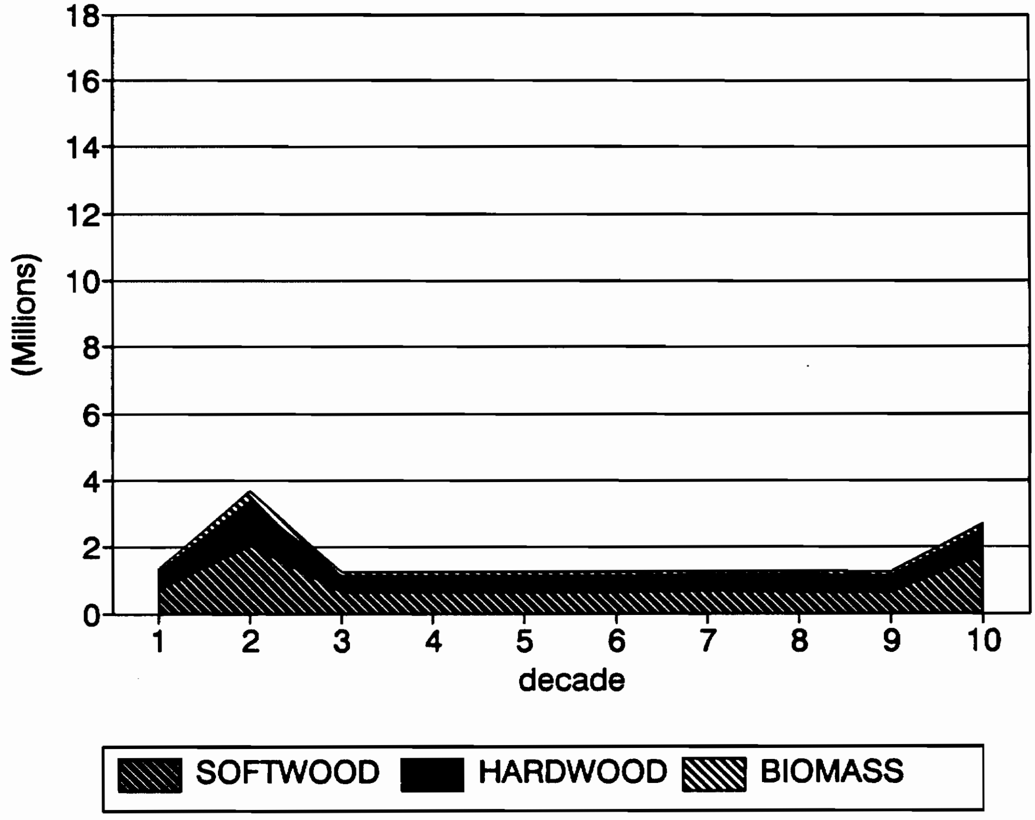

Figure 3. Cost Minimization - woodflow trajectory.

updated and continually run so it is always allocating over the next 100 year planning horizon.

On natural softwood/hardwood mixed and natural softwood, the model selects primarily natural regeneration. The exceptions include site class 3 where some conversion to red pine is selected. The site class 4 and 5 stands also are allocated to herbicide release and precommercial thinning management regime sequences. This fairly closely mirrors the PNW maximization solution, except that here the longer of the 2 available rotation lengths is selected. This correspondence between the models indicates that these management regime sequences offer both good financial returns and favorable woodflow quantities, and thus seem reasonable as a guide for future land management decisions.

On the precommercially thinned softwood stands, the site class 3 stands are cut and converted to red pine. The site class 4 and 5 stands however are maintained in the current covertype and undergo precommercial thinning in following rotations. Again, this contrasts with the PNW maximization solution where only site class 5 is maintained in the current covertype and thinning regime. In the PNW model, site classes 3 and 4 are allocated to natural regeneration without thinning. Treatment of these stands will depend on the priorities of N.E.T. If woodflow is the objective, then this precommercial thinning sequence should be used on the upper two site classes. If return on investment is the key decision criteria, then the thinning should only be applied to the site class 5 stands.

The non-zero dual prices for the binding constraints in this initial solution occur on the upper bound on investment in cutting periods 1, 2, 4, 8, 9, 10, 12, 13, 14, 15, and 16, with positive dual prices in a range between 2.16 to 0.104. The cutting period 8 softwood woodflow constraint has a dual price of -1.18, while the cutting period 8 hardwood woodflow constraint has a dual price of -0.306. Dual prices indicate how the solution would be impacted if each of the constraints individually were relaxed or tightened. Dual prices also indicate the relative impact of the binding constraints on the solution, with larger dual prices (absolute value) more severely restricting the solution. The manager can then examine the constraints with the largest dual prices to see if those constraints can be relaxed at a cost smaller than the constraint dual price. In the case of the cutting period 4 investment constraint at 2.16, if an additional dollar could be secured for investment in that period, it would yield 2.16 MWT of additional woodflow over the balance of the planning horizon. Conversely, if some constraint must be tightened, the dual price indicates how that tightening will affect the objective function value. The danger however, is that the dual prices indicate the effect of only a one unit change in the constraint. They do not necessarily indicate the impact of a multiple unit change, and thus in this example, a constraint change of 10 units may not yield 21.6 MWT of additional yield across the planning horizon. The impact of such a change would have to be assessed by changing the constraint level and resolving the model.

Present Net Worth Maximization: This model version provides a less investment intensive solution than the woodflow maximization solution, due to the consideration of the time value of money. Figure 2 shows the woodflow trajectory for this model version. It has much less variation than the woodflow maximization solution (Figure 1), but generally higher levels than the cost minimization case, shown in Figure 3.

On natural hardwood stands, natural regeneration is selected regardless of site class, and on all but 55 and 65 year old site class 5 stands, the model selects the shorter of the two available rotation ages. On 55 and 65 year old site class 5 stands, the model selects 70 years for the first rotation and 60 years for the second rotation. Because all available acres are treated with these management regimes, this solution could be easily applied to the ownership.

On natural hardwood/softwood mixed site class 2 stands, the 115 year rotation is selected on all acres available. Site class 3 stands are treated with a 90 year rotation on the 15 and 55 year old stands. Precommercial thinning is selected for the existing 15 year old stands and herbicide release for the next rotation on the 55 year old stands. On site class 4, the 5 year old stands are released and precommercially thinned in the first rotation only. The stands that are currently 15, 25, 35, 45, 55, and 65 years old are released and precommercially thinned in the second rotation only. The 75 year old stands are cut immediately and given an herbicide release followed by precommercial thinning before being harvested in each of the next two rotations. On site class 4, intensive management is selected, including precommercial thinning and herbicide release. The 55 year old site class 5 stands are cut immediately and converted to red pine. The balance of the age classes of site class 5 stands are treated with a release followed by precommercial thinning regime, thereby shortening the rotation length. This solution then primarily involves the use of natural regeneration on hardwood/softwood sites, followed by herbicide release and precommercial thinning on site classes 4 and 5. The conversion of 55 year old site class 5 to red pine represents an exception to the rule.

On natural softwood / hardwood mixed stands, much the same picture as hardwood / softwood stands exists. Site classes 1, 2, and 3 are allocated to natural regeneration following harvest, using the shorter available rotation age in all but about $\frac{4}{5}$ of the 75 year old site class 3 stands, which are allocated to the longer available rotation age. Even on site class 4, only the 5 year old stands are allocated to management regimes that include intermediate treatments, and then only herbicide release and precommercial thinning in the first rotation. However, all six age classes of site class 5 stands are prescribed to release and precommercial thinning in the first rotation. The older age classes, also are assigned to the same regime in the second rotation. No plantation options are selected for this covertype, though the herbicide release followed by precommercial thinning regime does cause the conversion to a softwood covertype by eliminating the hardwood component in the treated stands. Softwood/hardwood stands then are allocated to natural regeneration, and only the site class 5 stands are allocated to be herbicide released and precommercially thinned.

On natural softwood stands, harvest is selected for all site class 1, 2, and 3 stands as soon as they are available and the sites are subsequently naturally regenerated. The age 5 and 15 site class 4 softwood stands are herbicide released and precommercially thinned in the first rotation. The balance of the age classes and rotations are harvested as soon as they are available. The only exception is the 55 year old stands that are cut at age 70, which is the longer of two available rotations, in the first rotation. All age classes of site class 5 stands are herbicide released and precommercially thinned in their first rotation, and in the second rotation if the benefits occur within the planning horizon. Here, as with the softwood/hardwood mix, site classes 1, 2, 3, and 4 should be naturally regenerated and allowed to grow. On site class 5, benefits are derived from herbicide release and precommercial thinning.

On the precommercially thinned softwood stands, only 15 year old stands are present on the ownership. On site classes 3 and 4 these stands are allocated to harvest as soon as they are available and receive no intermediate treatments in succeeding rotations. On site class 5, the existing stands are harvested as soon as available, herbicide released, and precommercially thinned in the next two rotations before being naturally regenerated. This indicates that, except on site class 5, precommercial thinning is not recommended except to meet woodflow requirements.

The non-zero dual prices for the binding constraints on this solution are investment in the first cutting period at 3.4, and the cutting period 8 softwood woodflow constraint at -3.6. As in the woodflow maximization case, the cutting period 8 softwood woodflow constraint is binding. However, in this case, only the cutting period 1 investment constraint is binding. In the woodflow maximization, the investment constraint was binding in 11 of the cutting periods. This confirms the less investment intensive nature of the PNW maximization formulation.

Cost minimization: Under the initial conditions, only management regimes that include natural regeneration following harvest are included in the solution. The solution includes a mix of the rotation ages available for each of the site classes. This contrasts with PNW maximization that includes primarily the shorter available rotations and woodflow maximization that includes primarily the longer available rotations. Also, in the cost minimization case, the solution includes no management regime sequences requiring intermediate treatments (chemical or mechanical site prep, chemical release, chemical or mechanical precommercial thinning). This solution provides a fairly steady stream of required woodflows (Figure 3) which follows the required woodflow levels very closely. It however fails to utilize the entire ownership, leaving many acres untreated. Taxes and administrative costs, which tend to make this under-utilization of the ownership less desirable, are not incorporated in this prototype model. Both PNW and woodflow maximization utilize all acres available. The dual prices on the binding constraints to this solution were not particularly enlightening since very few constraints were binding, and those that were binding had dual prices of epsilon, which GAMS defines as "very close to zero, but different from zero".

Parametric Analysis:

In examining the sensitivity of the model to various parameters, woodflow maximization was observed in the presence of decreasing silvicultural investment levels, present net worth maximization was observed in the presence of various discount rates, and cost minimization was observed in the presence of increasing woodflow requirements. Woodflow maximization was observed under 10, 20, 30, 40, 50, and 100 percent decreases in available cutting period investment levels. PNW maximization was observed under discount rates of 0, 2, 4, 6, 8, and 10 percent. Cost minimization was observed in the face of 10, 20, 30, and 40 percent increases in the required woodflows in each of the cutting periods. In each case, the following quantities were observed: total investment, PNW, total woodflow, per period woodflow, and total acreage treated. The binding constraints were also noted. Table 4. summarizes these parametric analyses.

Woodflow maximization: Woodflow maximization, is examined in the presence of decreasing available investment. At 90 percent of the initial level of $4.2 million per decade, the prescription includes fewer plantations and less precommercial thinning but still provides 98 percent of the woodflow that the full investment provided, while PNW increases by 3 percent. The binding constraints on this solution are the investment level in all but cutting periods 3, 5, 6, and 7; cutting period 8 and 9 softwood woodflow constraints; and the cutting period 8 hardwood woodflow constraint.

At an investment level of 80 percent, not quite as many intensive management regimes are selected, but the solution remains largely unchanged from the solution at the 90 percent investment level. Total woodflow drops to 95 percent of the initial level while PNW increases another 5 percent. The binding constraints are investment in all cutting periods except 3, 5, and 6; cutting period 8 and 9 softwood woodflow constraints; and cutting period 8 hardwood woodflow constraint.

At the 70 percent investment level, total woodflow dropped to 92 percent of the initial woodflow level while PNW increases to 111 percent of the initial level. This is a result of less conversion of mixed softwood / hardwood stands to plantations. The binding constraints are investment in all cutting periods except 3 and 6; and cutting period 8

Table 4. **Parametric Analyses Results Summary.**

Optimand	Parameter changed			Woodflow		PNW	
	Invest. level	Discount rate	Woodflow requirement	level MM MWT	% of initial	level $MM	% of initial
Woodflow	$4.2MM			67.78		20.27	
Woodflow	$3.8MM			66.42	98%	20.88	103%
Woodflow	$3.4MM			64.39	95%	21.89	108%
Woodflow	$2.9MM			62.36	92%	22.50	111%
Woodflow	$2.5MM			59.65	88%	23.51	116%
Woodflow	$2.1MM			56.94	84%	23.66	116.7%
Woodflow	$0			35.92	53%	23.11	114%
PNW		10%		33.85	85%		
PNW		8%		34.64	87%		
PNW		6%		39.82	initial case		
PNW		4%		47.78	120%		
PNW		2%		54.95	138%		
PNW		0%		62.12	156%		
Cost			100%	19.31		14.69	
Cost			110%	20.75	107%	16.27	110%
Cost			120%	23.74	123%	18.31	125%
Cost			130%	24.91	129%	19.74	134%
Cost			140%	infeasible			

and 9 softwood woodflow constraints. An investment level of 60 percent yields 88 percent of the initial woodflow, with a PNW of 116 percent of the initial solution. The binding constraints are investment in all cutting periods except 3 and 6; and cutting period 8 and 9 softwood woodflow constraints.

At the 50 percent investment level, total woodflow drops to 84 percent of the initial, while PNW increases to 116.7 percent. At this investment level natural regeneration with herbicide release and in some cases precommercial thinning is predominantly selected. The binding constraints are investment in all cutting periods except 3 and 6, and cutting period 8 and 9 softwood woodflow constraints. In the zero investment woodflow maximization solution, woodflow remains at 53 percent of what it was initially, but PNW remains at 114 percent of the PNW of the initial woodflow maximization solution. The binding constraints are investment in all cutting; cutting period 8 and 9 softwood woodflow constraints; and the cutting period 11 biomass woodflow constraint. These analyses indicate that as investment decreases, woodflow drops a much smaller percentage than investment, thus indicating the woodflow is not extremely sensitive to changes in investment.

Present Net Worth Maximization: PNW has been maximized in the presence of discount rates of 2, 4, 8, and 10 percent and compared with the initial 6 percent discount rate solution. At 4 percent, plantations are increasingly used. This results in a 20 percent increase in woodflow over the initial level of slightly less than 40 million MWT. PNW is not noted in this parametric analysis section due to the role fo the discount rate in the PNW calculation. PNW increases drastically as the discount rate decreases and drops similarly as the discount rate increases. At zero percent, the PNW is $280 million while at 10 percent it drops to $20.4 million. The binding constraints on this solution are investment in cutting periods 1, 4, 8, and 11; and the cutting period 8 softwood woodflow constraint. At 2 percent, woodflow increases to 138 percent of the initial woodflow. Conversion to plantations becomes the rule for the mixed hardwood stands, unlike runs at higher discount rates. The balance of the cover types remain allocated primarily to herbicide release and precommercial thinning of naturally regenerated stands. The binding constraints on this solution are investment in cutting periods 1, 2, 4, 8, 9, 10, 11, and 13; and the cutting period 8 softwood woodflow constraint. At zero percent, the mixed hardwood / softwood stands, mixed softwood / hardwood stands and mixed softwood stands are heavily allocated to plantations. This produces woodflow of 156 percent of the initial level. This 61 million MWT is 91 percent of the woodflow generated by the initial woodflow maximization formulation. The binding constraints on this solution include investment in all but cutting periods 3, 5, and 15; and the cutting period 8 softwood woodflow constraint.

In the case of discount rates above the initial 6 percent, less investment intensive management regimes are selected. This is due to the relatively greater penalty being placed on the time differential between the investment and the return, at the higher interest rate. At 8 percent, the solution follows this less intensive trend by reducing the use of herbicide release and precommercial thinning on mixed hardwood stands. The exceptions are the 55 and 65 year old site class 5 mixed hardwood stands which are converted to larch. This solution results in 13 percent less total woodflow than the solution at a discount rate of 6 percent. The binding constraints on this solution are investment in the first cutting period; cutting period 8 softwood woodflow constraint; and cutting period 10 biomass woodflow constraint. At 10 percent, two additional plantation prescriptions are selected for site class 5 mixed hardwood / softwood stands, due to the shorter rotation length resulting from the plantation option. This solution results in an additional 2 percent reduction in total woodflow, to 85 percent of the initial solution. The binding constraints on this solution are investment in cutting period 1; cutting period 8 softwood woodflow constraint; and cutting period 10 biomass woodflow constraint. The woodflow produced under PNW maximization is thus quite sensitive to changes in the discount rate.

Cost minimization: Both 10 and 20 percent increases in required woodflow could still be met at an investment level of zero. This is accomplished by actively managing a larger number of acres than in the initial cost minimization case, though including no management regimes that require intermediate treatments. These two increases in woodflow requirement also raise both the PNW and total woodflow produced by the ownership. The constraints in these scenarios are either minimally or not binding at all as in the initial case.

At a 30 percent increase in required woodflow, the solution is no longer feasible at an investment level of zero. The model enhances natural stand yields with some release of mixed hardwood / softwood stands, which thus eliminates the hardwood component and reduces competition, some precommercial thinning in mixed hardwood/softwood stands which reduces the rotation length, and use of conversion to red pine and white spruce of some mixed hardwood/softwood stands. Despite the required investment, this increase in woodflow requirement also increases PNW. Surprisingly though, some acres are still left untreated and in some cases these acres are in the most productive site classes. This may be a matter of the woodflow from those acres being available in cutting periods that have surplus wood available. For this solution, the only significantly binding constraint is the cutting period 8 softwood constraint. Cutting period 8 has a woodflow requirement level about twice that of any other cutting period in order to help meet the pulp mill's wood demands during the softwood shortage between 2005 and 2015 (cutting period 8). Thus, this constraint would be expected to be a problem.

At a 40 percent increase in required woodflow, the problem becomes infeasible. This likely is due to the large single period woodflow required to meet the softwood supply shortage in the 2005 - 2015 decade. If that requirement spike were reduced or simply not increased with the balance of the woodflow requirements, the ownership could likely produce in excess of 40 percent more woodflow than the initially required levels, as is evidenced by the woodflow maximization model. In that formulation, 3.95 times as much woodflow is produced by the initial solution than in the initial cost minimization solution. The cost of meeting the woodflow requirements then is quite sensitive to changes in those requirements, particularly beyond the 120 percent level.

Area Regulation:

The costs of imposing area regulation on the ownership have also been investigated. Area regulation has been approximated by requiring that the area harvested in each cutting period be within a specified interval around the ideal regulated forest condition, in which an equal area is cut in each cutting period. Deviations of plus or minus 10, 15, 20, 25, and 30 percent have been used for each period of the planning horizon. However, using the baseline analysis woodflow requirements, the model maximands showed little reduction due to the area regulation constraints, as shown in Table 5 by the runs with a 0 percent WRI (woodflow requirement increase).

To further constrain the solution, the required woodflows in each period were also increased. In combination, these area regulation and woodflow constraints provided sufficient restriction on the solution to provide contrasting solutions as the constraints tightened. Table 5 summarizes the results of the area regulation model runs. As the allowed area regulation deviation decreased from ± 25 percent to ± 10 percent under the 110 percent required woodflow level the total woodflow drops 2 million MWT in the woodflow maximizing formulation, see Table 5 where WRI equals 10 percent. The PNW of this solution, however, rose as the ARD (area regulation deviation) got smaller. In the case of the PNW maximizing formulation, the PNW drops $1.6 million between the ± 25 and ± 10 percent intervals, while the woodflow from this formulation

Table 5. Area Regulation Model Results Summary.

Maximand	ARD[1]	WRI[2]	Woodflow million MWT	PNW million $	Cost million $
Woodflow	± ∞	0%	67.78	20.27	41.00
PNW	± ∞	0%	39.82	30.35	10.30
Woodflow	±25%	0%	63.63	20.00	41.69
Woodflow	±20%	0%	63.09	20.20	41.05
Woodflow	±15%	0%	62.40	20.58	41.03
Woodflow	±10%	0%	61.49	21.35	39.37
Woodflow	±05%	0%	60.34	21.55	39.53
PNW	±25%	0%	39.28	29.80	10.13
PNW	±20%	0%	38.84	29.59	10.00
PNW	±15%	0%	38.79	29.31	9.95
PNW	±10%	0%	38.99	29.00	9.78
PNW	±05%	0%	38.22	28.62	8.37
Woodflow	±25%	10%	63.14	20.49	41.68
Woodflow	±20%	10%	62.61	20.52	41.28
Woodflow	±15%	10%	61.91	20.86	40.43
Woodflow	±10%	10%	61.06	21.21	39.76
Woodflow	± 5%	10%	-	infeasible	-
PNW	±25%	10%	39.11	28.74	10.07
PNW	±20%	10%	39.42	28.47	10.08
PNW	±15%	10%	39.60	28.17	10.02
PNW	±10%	10%	38.77	27.16	8.83
PNW	± 5%	10%	-	infeasible	-
Woodflow	±35%	20%	63.14	21.03	41.20
Woodflow	±30%	20%	62.79	20.95	41.68
Woodflow	±25%	20%	62.37	20.96	41.42
Woodflow	±20%	20%	-	infeasible	-
PNW	±35%	20%	39.23	28.10	10.09
PNW	±30%	20%	39.16	27.86	10.03
PNW	±25%	20%	39.70	26.67	10.13
PNW	±20%	20%	-	infeasible	-

[1]ARD - area regulation deviation allowed per period

[2]WRI - woodflow requirement increase

drops some 0.4 million MWT. In both cases, costs drop along with the maximand. At 120 percent of the initial required woodflow level, both formulations become infeasible at the ±20 percent WRI. At broader intervals, both the woodflow and present net worth drop along with the maximand as the ARD got smaller. In general, area regulation does not appear to be an overly expensive constraint on this problem. This is despite the marked age class imbalances existing on the ownership. This conslusion may however be biased by the reduction in the biomass woodflow requirements that has been used in this modeling effort to achieve feasibility.

Implementation:

The three objective functions examined here offer confirming solutions in some cases, but more commonly, contrasting solutions. However, this is the intended result of having all three in the model, that is, to provide alternative perspectives from which to judge the system under study. Each objective function offers a different set of criteria on which to evaluate the alternatives. Another reason for including three objective functions is to demonstrate that there is no single "right answer" to the question of optimizing silvicultural investment. Too often, computer generated solutions are taken too literally.

The management regime sequences selected by the model can be used as general guidelines for on-the-ground management of the area in question. However, the model may allocate, for example, 764.317 acres of a covertype / site class / age class to a particular management regime sequence. What is important is the percentage of the total available acres of the cover type that these 764.317 acres represent. If it is 18.372 percent, for example, then about $\frac{1}{5}$ of the covertype acres should be so treated. Usually, the model allocates all acres of a covertype / age class to the same management regime sequence, making application of the model solution easy.

It is vital to keep in mind that the model is operating on average yields, costs, prices, anticipated woodflow requirements, and silvicultural investment levels. Exceptional situations may well warrant different treatment. Also, this model contains a very limited amount of information about each management regime sequence, and thus cannot foresee all possible interactions on the ground such as, adjacency considerations, harvesting operations plans, and seasonal restrictions. The model contains seven coefficients for each treatment. Treatments are the portions of a management regime that occurs within one cutting period. This is a sparse bit of information, but to consider over 9600 possible management regime sequences simultaneously, much realism must be suppressed. The model will achieve global optimality over the entire area considered, and thus at the local or individual management regime level it may select options that on their own seem not to make sense. However, from the whole ownership perspective, these management regime sequences will be optimal.

Finally, the model is only as good as the information it contains. This means that the model solution should be viewed with skepticism, not unrealistically so, but a critical evaluation is necessary. If the solution makes sense, use it. If the solution seems odd or amiss, question it, and look more closely to determine whether the model is considering something the user is not, or if the user is considering something the model is not. The model solution then should be used as a guide, but where it diverges from the status quo, should serve as a challenge to that status quo, and prompt the user to try to gain further understanding of the system. However, if considerations beyond the scope of the model conflict with the solution obtained, then those considerations may warrant incorporation into the model for future runs.

Chapter 5

Summary and Conclusions:

Summary:

This study set out to develop a prototype linear programming based timber management scheduling model capable of optimally allocating annual silvicultural investment to maximize woodflow. This model was developed around the Model I formulation of Johnson and Scheurman (1977) and was coded to utilize the GAMS LP software package. Some 200 management regimes were incorporated into the model and concatenated to span the 100 year planning horizon of interest in the study. The model was formulated to accommodate five site productivity classes. The model was restricted to a 150,000 acre administrative unit of the N.E.T. ownership due to data availability, but has been developed with the intention that it be easily expandable to accommodate the balance of the 920,000 acres in the ownership.

Once developed, the model was run repeatedly to identify and eliminate errors and to test the sensitivity of the model to changes in model parameters. This sensitivity analysis phase was limited somewhat by availability of suitable computer hardware. At only 1 model run per day, this phase spanned several months and that was why it was limited in scope. Only the more critical parameters were examined over the range most likely to be used, or values that could be used to contrast those of the other initial formulation solutions, such as woodflow maximization under zero investment compared with the cost minimization solution. Additional sensitivity analysis should be considered a priority in further developing and applying the model.

The second objective of the study was to apply a present value maximand to the model. PNW includes more factors in its examination of the alternatives than woodflow maximization by incorporating a) the time value of money, b) the disparity in the values of various products including: hardwood sawlogs, pulpwood, biomass boiler fuel, and c) the costs associated with treatments relative to their returns. This objective function was added to the model early in the development effort as was a third cost minimization objective function. The cost minimization objective function was included as a third measure of the effectiveness of the solution in providing woodflow to the pulp mill. The addition of these objective functions to the model was expedited by the matrix generation language included in the GAMS LP package. The final model includes a choice of these three objective functions. Also, each of the formulations includes the other two objective functions simply as accounting constraints. This provides a yardstick for comparing the solutions derived under various objective functions. For instance, when running the model to maximize PNW, the model also will provide a summary of the costs and total woodflows anticipated.

The third objective of the study was to investigate ways to address the age class imbalance on the ownership. This was accomplished by imposing a set of constraints requiring the area cut in each of the cutting periods to be within a user specified interval around a regulated forest condition, that is, an equal area harvested in each cutting period. The results of this set of model formulations indicated that a regulated condition would be relatively inexpensive to impose. Less than about 6 percent of PNW would be lost to go from the present condition of the study area to regulation within a 5 percent interval around ideal. At this time, however, exogenous variables, particularly irregular short-term woodflow requirements by the company's pulp mill, may preclude implementation of such a schedule now. Also, over time the model will tend to move the ownership toward such a condition by seeking to meet constraints placed on it, as evidenced by, steady to gradually increasing long term minimum woodflow requirements.

The fourth objective of the study was to make recommendations concerning expansion of the model across the ownership. The study area selected for the project includes the physical land management regimes necessary to treat the whole ownership. This is key to incorporation of the balance of the ownership into the model. The expansion will require only the addition of a) covertype / age class acreages, b) woodflow requirements, and c) investment restrictions for the 920,000 acre ownership rather than 150,000 acres considered in the prototype model. The balance of the model is formulated to accommodate these changes. Parametric analyses will be necessary once these new data are included in the model due to the change in scale of the problem.

Conclusions and Recommendations:

The model developed here has the flexibility necessary to accommodate changes in the management situation. It provides reasonable ease of access to data most likely to need modification. It provides a prototype base on which further development can build. There are several topics that should be addressed by N.E.T. in further development. 1) A means of allocating acreages to the first 7 cutting periods (first decade) individually rather that as a lump sum as has been done for the woodflow and investment constraints in the current formulation. 2) Improvement of the yield functions available for the ownership to better reflect the productivity of the various sites and covertypes. Of particular concern here is the lack of a yield function for biomass. A biomass yield function, not directly proportional to the hardwood yield function, would possibly eliminate the biomass infeasibility problem encountered in this modeling effort. 3) Incorporation of more of the background data into the model itself or more closely tying the model to the spreadsheets that contain such coefficients as product prices, yield functions, product recovery rates, regeneration and harvest covertype percentages, and cord to MWT conversion factors should be another area of development. Fortunately, this is not a problem unique to this model. GAMS Development Corporation is working to establish closer ties between GAMS and particularly Lotus 1-2-3. 4) Examine the sensitivity of the model to alternate projections in the prices of the various materials produced on the ownership. 5) Consider the inclusion in the model of a greater number of possible rotation lengths in the model. Especially look at shorter rotations, and rotations based on some economic base rather than rotations yielding a certain volume of material. 6) Investigate the incorporation of taxes into the model. These efforts may facilitate this development goal for this model. These modifications will make the model easier to use and modify, as well as making it a more realistic representation of N.E.T.'s management situation.

Literature Cited:

Brooke, A., D. Kendrick, A. Meersaus. 1988. GAMS: a user's guide. Scientific Press, S. San Francisco. 290 p.

Brodie, J.D., D.M. Adams, and C. Kao. 1978. Analysis of Economic Impacts on Thinning and Rotation Age for Douglas- Fir, Using Dynamic Programming. Forest Science 24:513-522.

Chappelle, D.E. 1966. A Computer Program for Scheduling Allowable Cut Using either Area or Volume Regulation during Sequential Planning Periods. U.S. Forest Service Research Paper PNW-33.

Chen, C.M., D.W. Rose, and R.A. Leary. 1980. Derivation of Optimal Stand Density over Time - a Discrete Stage, Continuous State Dynamic Programming Solution. Forest Science 26:217-227.

Clutter, J.L., et al. 1968. MAX MILLION - A Computerized Forest Management Planning System. School of Forest Resources, University of Georgia, Athens.

_____, J.C. Fortson, and L.V. Pienaar. 1978. MAX MILLION II - A Computerized Forest Management Planning System, User's Manual. School of Forest Resources, University of Georgia, Athens. 54 p.

_____, J.C. Fortson, L.V. Pienaar, G.H. Brister, R.L. Bailey. 1983. Timber management: A quantitative approach. Wiley, New York. 333 p.

Curtis, F.H. 1962. Linear programming in the management of forest property. Journal of Forestry. 60(9):611-616.

Hillier, F.S., and G.J. Lieberman. 1986. Introduction to operations research, 4th ed. Holden-Day, Inc. Oakland, California. 888 p.

Hool, J.N. 1968. An Univariate Allocation Algorithm for Use in Forestry Problems. Journal of Forestry. 66:492-493. Kent, B.M., J.W. Kelly, and J.J. King. 1986. FORPLAN Version 1: Mathematical Programmer's Guide. Land Management Planning, U.S. Forest Service, Washington, D.C. 378 p.

Johnson, K.N., and D.B. Jones. 1979. A User's Guide to Multiple Use-Sustained Yield Resource Scheduling Calculation (MUSYC). Timber Management, U.S. Forest Service, Fort Collins, CO.

_____, and H.L. Scheurman. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives - discussion and synthesis. Forest Science Monograph No. 18. 32 p.

_____, and T. Stuart. 1985. FORPLAN Version 2: Mathematical Programmer's Guide. Land Management Planning, U.S. Forest Service, Washington, D.C. 134 p.

_____, and P.L. Tedder. 1983. LP vs. binary search in periodic harvest level calculation. Forest Science 29(3):569-581.

Martell, D.L., and J.M. Fullerton. 1988. Decision analysis for jack pine management. Canadian Journal of Forest Research 18(4):444-452.

Massam, B.H. 1988. Multiple-criteria decision making (MCDM) techniques in planning. Pergamon Press, New York. 84p.

Navon, D.I. 1971. Timber RAM ... A Long Range Planning Method for Commercial Timber Lands under Multiple-Use Management. U.S. Forest Service Research Paper PSW-70. 22p.

Sassman, R.W., E. Hold, and K. Bergsvick. 1972. User's manual for a Computer Program for Simulating Intensively Managed Allowable Cut. U.S. Forest Service General Technical Report PNW - 1. 50 p.

Schreuder, G.F. 1971. The simultaneous Determination of optimal Thinning Schedule and Rotation for an Even-aged Forest. Forest Science. 17:333-338.

Tedder, P.L., J.S. Schmidt, and J. Gourley. 1980. TREES: Timber Resource Economic Estimation System, Volume I - A User's Guide for Forest Management and Harvest Scheduling. Forest Research Laboratory Research Bulletin 31a, Oregon State University, Corvallis. 81 p.

Walker, J.L. 1971. An Economic Model for Optimizing the Rate of Timber Harvesting. Ph.D. Thesis. University of Washington, Seattle, Diss. Abstr. 32(5):2276A (microfilm no. 71-28489). 117 p.

Appendix A
Example Source Code:

```
* To illustrate the model developed in this study, a small
* example has been extracted from the code.  The model is
* structured as required by the GAMS LP package.  This
* example is a two cover type by two site class model.  The
* cover types used here are naturally regenerated softwood
* (noted as "S") and naturally regenerated softwood /
* hardwood mix with predominantly softwood (noted as "SH").
* The site classes are noted as simply "1" and "2", with 2
* being more productive.

* The following 3 lines are GAMS control statements, a.
* setting the page header, b. telling it to ignore upper and
* lower case differentiation, and c. controlling output.

$TITLE  THESIS
$OFFUPPER
$OFFSYMXREF OFFSYMLIST OFFUELLIST OFFUELXREF

* The model begins with a series of what gams calls SETS.
* (Uppercase words indicate what GAMS calls reserved words.
* These are words that have special significance to the
* GAMS compiler.  This syntax is used here for clarity
* only and is not necessary in the GAMS language.)  These
* SETS are the basic building blocks on which the remainder
* of the model is built.

SETS

* Cutting periods (CP) are the time intervals on which the
* model is based.  There are six - 1 year CP, one - 5 year
* CP, and nine - 10 year CP, which together span the 100
* year planning horizon used in the model.  The six - one
* year and one - 5 year CP are included to facilitate
* examination of investment in the short term.


    CP       cutting periods      / 1   year 0
                                    2   year 1
                                    3   year 2
```

```
                         4   year 3
                         5   year 4
                         6   year 5
                         7   years 6 - 10
                         8   years 11 - 20
                         9   years 21 - 30
                         10  years 31 - 40
                         11  years 41 - 50
                         12  years 51 - 60
                         13  years 61 - 70
                         14  years 71 - 80
                         15  years 81 - 90
                         16  years 91 - 100/;

* PARAMETERS are one dimensional tables used to specify
* limiting values of various coefficients.

PARAMETER

  CPI(CP) period index - used in woodflow constraints
  / 1 0, 2 1, 3 2, 4 3, 5 4, 6 5, 7 8, 8 15, 9 25, 10 35,
    11 45, 12 55, 13 65, 14 75, 15 85, 16 95 /;

* Age classes (AC) are the age groups used in the cover
* typing of the ownership.

SET
  AC      age classes         / 1  age 0 to 10
                          2  age 11 to 20
                          3  age 21 to 30
                          4  age 31 to 40
                          5  age 41 to 50
                          6  age 51 to 60
                          7  age 61 to 70
                          8  age 71 to 80
                          9  age 81 to 90
                          10 age 91 to 100
                          11 age 101 to 110
                          12 age 111 to 120
                          13 age 121 to 130/;

* This index creates a parameter which matches the age class
* SET but by being a PARAMETER, this index can be used in
* calculations.

PARAMETER
   ACI(AC) age class index used in acreage constraints
   / 1 1,2 2,3 3,4 4,5 5,6 6,7 7,8 8,9 9,10 10,11 11,12
   12,13 13 /;

* SCALARS are unique multipliers used to adjust the
* magnitude of a value.  In this case, the DR SCALAR is the
* discount rate used in the present value calculations.

SCALAR    DR   discount rate as decimal percent   / .06 /;
SCALAR    ACBOUND area control bound          / .5 /;
```

```
* The following four parameters define the acreages
* available in the four cover type/site class combinations
* included in this model.  These parameters act as the
* limiting values in the area constraints later in the
* model.

PARAMETER

  SHS1AREA(AC) soft and hard wood site 1 areas by age class
                          / 1      1000,
                            2       900,
                            3       700,
                            4       600,
                            5       400,
                            6       100,
                            7         0,
                            8       200,
                            9       200,
                            10      300,
                            11      700,
                            12      900,
                            13     1100 /

  SHS2AREA(AC) soft and hard wood site 2 areas by age class
                          / 1      2000,
                            2      1950,
                            3      1600,
                            4      1300,
                            5      1000,
                            6       600,
                            7       200,
                            8       800,
                            9      1000,
                            10     1000,
                            11     1400,
                            12     1700,
                            13     1750 /

  SS1AREA(AC) softwood site 1 areas by age class
                          / 1       800,
                            2      1000,
                            3      1100,
                            4       700,
                            5       400,
                            6       100,
                            7       210,
                            8       300,
                            9       400,
                            10      800,
                            11      700,
                            12      500,
                            13      600 /

  SS2AREA(AC) softwood site 2 areas by age class
```

```
                  / 1     1100,
                    2     1000,
                    3     1200,
                    4      600,
                    5      400,
                    6        0,
                    7      100,
                    8      300,
                    9      250,
                    10     400,
                    11     700,
                    12    1000,
                    13    1300 /

* Investment is another PARAMETER.  This is simply the
* maximum investment level for each of the cutting periods
* included in the model.

          INVEST(CP)    / 1       -80000,
                    2       -80000,
                    3       -80000,
                    4       -80000,
                    5       -80000,
                    6       -80000,
                    7      -400000,
                    8      -800000,
                    9      -800000,
                    10     -800000,
                    11     -800000,
                    12     -800000,
                    13     -800000,
                    14     -800000,
                    15     -800000,
                    16     -800000    /

* SWWFREQ(CP) - softwood woodflow requirement in the domain
* of cutting period.
          SWWFREQ(CP)   / 1       10000,
                    2       10000,
                    3       10000,
                    4       10000,
                    5       10000,
                    6       10000,
                    7       50000,
                    8      100000,
                    9      100000,
                    10     100000,
                    11     100000,
                    12     100000,
                    13     100000,
                    14     100000,
                    15     100000,
                    16     100000    /;

* In formulating the model, the management regimes contained
* in Fig. 1 have to be concatenated to span the 100 year
```

```
* planning horizon of interest in the study. This process
* produces a number of management regime sequences (MRS).
*
* Figure 1.
*     Site #   Herbicide   Pct   Harvest    Volume    Harvest
*              Release     Age   Age        (CDS)     Stand
*              Age
* Types
* S     1    --        --   120       35         50%S,50%SH
* S     1    --        --   130       37.92      50%S,50%SH
* S     2    --        --   100       35         50%S,50%SH
* S     2    --        --   110       38.5       50%S,50%SH
* S     2    9         --   90        35         100%S
* S     2    9         --   100       38.89      100%S
* S     2    9         21   77        40         100%S
* S     2    9         21   87        45.19      100%S
* SH    1    --        --   120       35         50%S,50%SH
* SH    1    --        --   130       37.92      50%S,50%SH
* SH    2    --        --   100       35         50%S,50%SH
* SH    2    --        --   110       38.5       50%S,50%SH
* SH    2    9         --   90        35         100%S
* SH    2    9         --   100       38.89      100%S
* SH    2    9         21   77        40         100%S
* SH    2    9         21   87        45.19      100%S
*
* Each of the MRS define a decision variable in the model.
* GAMS requires that decision variables be defined in the
* domain of a set. For this reason, there must be a set
* defining the decision variables for each cover type/site
* class combination. For programming ease the decision
* variables have been defined as 4 digit integers. The
* first digit defines the age class to which the decision
* variable applies and the remaining 3 are simply the MRS's
* ordinal position in the listing of MRS for a given cover
* type/site class combination. In the case of MRS for 5
* year old stands, the first digit has been omitted.

SETS
  SHS1MR softwood & hardwood site 1 mgmt regime sequences
     / 1, 1001, 2001, 3001*3002, 4001*4002,
       5001*5002, 6001*6002, 7001*7002, 8001*8002,
       9001*9002, 10001*10002, 11001*11002, 12001 /

  SHS2MR softwood & hardwood site 2 mgmt regime sequences
     / 1*10, 1001*1009, 2001*2005, 3001*3006, 4001*4006,
       5001*5006, 6001*6006, 7001*7006, 8001*8007,
       9001*9010, 10001*10006 /

  SS1MR softwood site 1 management regime sequences
     / 1, 1001, 2001, 3001*3002, 4001*4002, 5001*5002,
       6001*6002, 7001*7002, 8001*8002, 9001*9002,
       10001*10002, 11001*11002, 12001 /

  SS2MR softwood site 2 management regime sequences
     / 1*10, 1001*1009, 2001*2005, 3001*3006, 4001*4006,
       5001*5006, 6001*6006, 7001*7006, 8001*8007,
```

```
     9001*9010, 10001*10006 /;

PARAMETERS

  SHS1I(SHS1MR) soft&hard wood site 1 mgmt rgm seq'nce index
  / 1 1, 1001 2, 2001 3, 3001*3002 4, 4001*4002 5,
  5001*5002 6, 6001*6002 7, 7001*7002 8, 8001*8002 9,
  9001*9002 10, 10001*10002 11, 11001*11002 12, 12001 13 /

  SHS2I(SHS2MR) soft&hard wood site 2 mgmt rgm seq'nce index
  / 1*10 1, 1001*1009 2, 2001*2005 3, 3001*3006 4,
    4001*4006 5, 5001*5006 6, 6001*6006 7, 7001*7006 8,
    8001*8007 9, 9001*9010 10, 10001*10006 11 /

  SS1I(SS1MR) softwood site 1 mgmt regime sequence index
  / 1 1, 1001 2, 2001 3, 3001*3002 4, 4001*4002 5,
    5001*5002 6, 6001*6002 7, 7001*7002 8, 8001*8002 9,
    9001*9002 10, 10001*10002 11, 11001*11002 12,
    12001 13 /

  SS2I(SS2MR) softwood site 2 mgmt regime sequence index
  / 1*10 1, 1001*1009 2, 2001*2005 3, 3001*3006 4,
    4001*4006 5, 5001*5006 6, 6001*6006 7, 7001*7006 8,
    8001*8007 9, 9001*9010 10, 10001*10006 11 /;

* In order to operate on (calculate and collate with) the
* MRS, they had to defined as integers. Since the various
* MRS have silvicultural treatments occurring in different
* periods and the models need to allocate investment dollars
* and woodflows into various periods, the MRS need to be
* further divided into segments occurring in each of the
* cutting periods spanned by the model. The portion of a
* MRS occurring within one cutting period is defined as a
* treatment, and each treatment for a given cover type/site
* class has been assigned an integer value. Figure 2 below
* defines the treatments for each of the cover type / site
* class combinations.
*
* Figure 2. Treatment definitions.
* treatment #  SS1         SS2         SHS1        SHS2
*    1      Bs130s1,R  Bs100rs2,R  Bsh130s1,R Bsh100rs2,R
*    2      Bs120s1,R  Bs100r2,R   Bsh120s1,R Bsh100s2,R
*    3                 Bs110s2,R              Bsh110s2,R
*    4                 Bs77rps2,R             Bsh77rps2,R
*    5                 Bs87rps2,R             Bsh87rps2,R
*    6                 Bs90rs2,R              Bsh90rs2,R
*    7                   Pct                  Pct
*    8                   RelH                  RelH
*
* As with MRS, these treatments must have a set defining the
* treatments applicable to a given cover type/site class.
* Despite using the same integer for the various cover
* type/site class combinations, the actual treatments
* differ. The integers are duplicated for programming ease.

SET
```

```
    T     TREATMENTS                 / 1*8 /

    SHS1T(T) soft & hard wood site 1 treatments   / 1*2 /
    SHS2T(T) soft & hard wood site 2 treatments   / 1*8 /

    SS1T(T) softwood site 1 treatments          / 1*2 /
    SS2T(T) softwood site 2 treatments          / 1*8 /;

* TI creates a parameter for use in calculations as is done
* in the CPI and ACI indexes.

PARAMETER
    TI(T)    TREATMENT INDEX
        /1 1,2 2,3 3,4 4,5 5,6 6,7 7,8 8 /;

* The treatments for a given cover type/site class can have
* up to five coefficients associated with them.  This TC set
* defines these coefficients and will act as one of the
* defining sets in the coefficient tables below.

SET
    TC    TREATMENT COEFFICIENTS
     / VALUE in period of occurrence
       COST  in period of occurrence
       REVENUE in period of occurrence
       WDFL total woodflow
       SWWF softwood woodflow /;

* TCI converts the treatment coefficient names to integers
* for computations purposes.

PARAMETER
    TCI(TC) TREATMENT COEFFICIENT INDEX
       / VALUE 1, COST 2, REVENUE 3, WDFL 4, SWWF 5 / ;

* The following four cover type/site class coefficient
* tables define the 5 coefficient values associated with
* each MRS.

TABLE SHS1COEFF(SHS1T,TC) soft & hard wood site 1
coefficients
       VALUE   COST REVENUE  WDFL   SWWF
1       897.3   0.0   897.3  187.2  115.8
2       828.3   0.0   828.3  172.8  106.9 ;

TABLE SS1COEFF(SS1T,TC) softwood site 1 coefficients
       VALUE   COST REVENUE  WDFL   SWWF
1       897.3   0.0   897.3  187.2  115.8
2       828.3   0.0   828.3  172.8  106.9 ;

TABLE SHS2COEFF(SHS2T,TC) soft & hard wood site 2 coefficients
       VALUE   COST   REVENUE  WDFL    SWWF
  1    905.0   0.0    905.0    181.8   138.8
  2    828.3   0.0    828.3    172.8   106.9
  3    911.1   0.0    911.1    190.1   117.5
  4   1344.4    0.0   1344.4    187.0   142.8
```

```
 5  1519.0   0.0  1519.0  211.2  161.3
 6   814.5   0.0   814.5  163.6  124.9
 7  -208.0 -208.0   0.0    0.0    0.0
 8   -45.0  -45.0  0.0    0.0    0.0 ;


TABLE SS2COEFF(SS2T,TC) softwood site 2 coefficients
      VALUE   COST   REVENUE  WDFL    SWWF
  1    947.6   0.0    947.6   189.8   146.9
  2    861.1   0.0    861.1   179.0   113.1
  3    947.2   0.0    947.2   196.9   124.4
  4   1403.0   0.0   1403.0   195.3   151.1
  5   1585.2   0.0   1585.2   220.6   170.7
  6    852.9   0.0    852.9   170.9   132.2
  7   -208.0 -208.0    0.0     0.0     0.0
  8    -45.0  -45.0   0.0     0.0     0.0  ;

* The following four cover type/site class coefficient
* tables define the treatments by cutting period for each
* management regime sequence.  The numbers in the body of
* the tables correspond to the treatment numbers in
* Fig. 2 above for the respective cover type and site class
* combinations.

TABLE SHS1MRS(SHS1MR,CP) soft & hard wood site 1 mrs
         1    2    3    4    5    6    7    8
 12001   0    0    0    0    0    1    0    0
 11001   0    0    0    0    0    0    0    1
 11002   0    0    0    0    0    2    0    0
 10001   0    0    0    0    0    0    0    0
 10002   0    0    0    0    0    0    0    2
 9001    0    0    0    0    0    0    0    0
 9002    0    0    0    0    0    0    0    0
 8001    0    0    0    0    0    0    0    0
 8002    0    0    0    0    0    0    0    0
 7001    0    0    0    0    0    0    0    0
 7002    0    0    0    0    0    0    0    0
 6001    0    0    0    0    0    0    0    0
 6002    0    0    0    0    0    0    0    0
 5001    0    0    0    0    0    0    0    0
 5002    0    0    0    0    0    0    0    0
 4001    0    0    0    0    0    0    0    0
 4002    0    0    0    0    0    0    0    0
 3001    0    0    0    0    0    0    0    0
 3002    0    0    0    0    0    0    0    0
 2001    0    0    0    0    0    0    0    0
 1001    0    0    0    0    0    0    0    0
  1    0    0    0    0    0    0    0    0

  +      9   10   11   12   13   14   15   16
 12001   0    0    0    0    0    0    0    0
 11001   0    0    0    0    0    0    0    0
 11002   0    0    0    0    0    0    0    0
 10001   1    0    0    0    0    0    0    0
 10002   0    0    0    0    0    0    0    0
 9001    0    1    0    0    0    0    0    0
```

```
9002   2   0   0   0   0   0   0   0
8001   0   0   1   0   0   0   0   0
8002   0   2   0   0   0   0   0   0
7001   0   0   0   1   0   0   0   0
7002   0   0   2   0   0   0   0   0
6001   0   0   0   0   1   0   0   0
6002   0   0   0   2   0   0   0   0
5001   0   0   0   0   0   1   0   0
5002   0   0   0   0   2   0   0   0
4001   0   0   0   0   0   0   1   0
4002   0   0   0   0   0   2   0   0
3001   0   0   0   0   0   0   0   1
3002   0   0   0   0   0   0   2   0
2001   0   0   0   0   0   0   0   2
1001   0   0   0   0   0   0   0   0
  1    0   0   0   0   0   0   0   0    ;

TABLE SHS2MRS(SHS2MR,CP) soft & hard wood site 2 mrs
        1   2   3   4   5   6   7   8
10001   0   0   0   0   0   3   0   0
10002   0   0   0   0   0   3   0   8
10003   0   0   0   0   0   3   0   8
10004   0   0   0   0   0   3   0   8
10005   0   0   0   0   0   3   0   8
10006   0   0   0   0   0   3   0   8
9001    0   0   0   0   0   0   0   3
9002    0   0   0   0   0   0   0   3
9003    0   0   0   0   0   0   0   3
9004    0   0   0   0   0   0   0   3
9005    0   0   0   0   0   2   0   0
9006    0   0   0   0   0   2   0   8
9007    0   0   0   0   0   2   0   8
9008    0   0   0   0   0   2   0   8
9009    0   0   0   0   0   2   0   8
9010    0   0   0   0   0   2   0   8
8001    0   0   0   0   0   0   0   0
8002    0   0   0   0   0   0   0   0
8003    0   0   0   0   0   0   0   0
8004    0   0   0   0   0   0   0   2
8005    0   0   0   0   0   0   0   2
8006    0   0   0   0   0   0   0   2
8007    0   0   0   0   0   0   0   2
7001    0   0   0   0   0   0   0   0
7002    0   0   0   0   0   0   0   0
7003    0   0   0   0   0   0   0   0
7004    0   0   0   0   0   0   0   0
7005    0   0   0   0   0   0   0   0
7006    0   0   0   0   0   0   0   0
6001    0   0   0   0   0   0   0   0
6002    0   0   0   0   0   0   0   0
6003    0   0   0   0   0   0   0   0
6004    0   0   0   0   0   0   0   0
6005    0   0   0   0   0   0   0   0
6006    0   0   0   0   0   0   0   0
5001    0   0   0   0   0   0   0   0
5002    0   0   0   0   0   0   0   0
```

5003	0	0	0	0	0	0	0	0
5004	0	0	0	0	0	0	0	0
5005	0	0	0	0	0	0	0	0
5006	0	0	0	0	0	0	0	0
4001	0	0	0	0	0	0	0	0
4002	0	0	0	0	0	0	0	0
4003	0	0	0	0	0	0	0	0
4004	0	0	0	0	0	0	0	0
4005	0	0	0	0	0	0	0	0
4006	0	0	0	0	0	0	0	0
3001	0	0	0	0	0	0	0	0
3002	0	0	0	0	0	0	0	0
3003	0	0	0	0	0	0	0	0
3004	0	0	0	0	0	0	0	0
3005	0	0	0	0	0	0	0	0
3006	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0
1001	0	0	0	0	0	0	0	0
1002	0	0	0	0	0	0	0	0
1003	0	0	0	0	0	0	0	0
1004	0	0	0	0	0	0	7	0
1005	0	0	0	0	0	0	7	0
1006	0	0	0	0	0	0	7	0
1007	0	0	0	0	0	0	7	0
1008	0	0	0	0	0	0	7	0
1009	0	0	0	0	0	0	7	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	8	0	0	0
4	0	0	0	0	8	0	0	0
5	0	0	0	0	8	0	0	0
6	0	0	0	0	8	0	0	7
7	0	0	0	0	8	0	0	7
8	0	0	0	0	8	0	0	7
9	0	0	0	0	8	0	0	7
10	0	0	0	0	8	0	0	7

+	9	10	11	12	13	14	15	16
10001	0	0	0	0	0	0	0	0
10002	0	0	0	0	0	0	0	0
10003	0	0	0	0	0	0	0	6
10004	7	0	0	0	0	0	0	5
10005	7	0	0	0	0	0	4	0
10006	7	0	0	0	0	0	4	8
9001	0	0	0	0	0	0	0	0
9002	8	0	0	0	0	0	0	0
9003	8	7	0	0	0	0	0	0
9004	8	7	0	0	0	0	0	4
9005	0	0	0	0	0	0	0	0
9006	0	0	0	0	0	0	0	0
9007	0	0	0	0	0	0	0	6
9008	7	0	0	0	0	0	0	5

9009	7	0	0	0	0	0	4	0
9010	7	0	0	0	0	0	4	8
8001	3	0	0	0	0	0	0	0
8002	3	8	0	0	0	0	0	0
8003	3	8	7	0	0	0	0	0
8004	0	0	0	0	0	0	0	0
8005	8	0	0	0	0	0	0	0
8006	8	7	0	0	0	0	0	0
8007	8	7	0	0	0	0	0	4
7001	0	3	0	0	0	0	0	0
7002	0	3	8	0	0	0	0	0
7003	0	3	8	7	0	0	0	0
7004	2	0	0	0	0	0	0	0
7005	2	8	0	0	0	0	0	0
7006	2	8	7	0	0	0	0	0
6001	0	0	3	0	0	0	0	0
6002	0	0	3	8	0	0	0	0
6003	0	0	3	8	7	0	0	0
6004	0	2	0	0	0	0	0	0
6005	0	2	8	0	0	0	0	0
6006	0	2	8	7	0	0	0	0
5001	0	0	0	3	0	0	0	0
5002	0	0	0	3	8	0	0	0
5003	0	0	0	3	8	7	0	0
5004	0	0	2	0	0	0	0	0
5005	0	0	2	8	0	0	0	0
5006	0	0	2	8	7	0	0	0
4001	0	0	0	0	3	0	0	0
4002	0	0	0	0	3	8	0	0
4003	0	0	0	0	3	8	7	0
4004	0	0	0	2	0	0	0	0
4005	0	0	0	2	8	0	0	0
4006	0	0	0	2	8	7	0	0
3001	0	0	0	0	0	3	0	0
3002	0	0	0	0	0	3	8	0
3003	0	0	0	0	0	3	8	7
3004	0	0	0	0	2	0	0	0
3005	0	0	0	0	2	8	0	0
3006	0	0	0	0	2	8	7	0
2001	0	0	0	0	0	0	3	0
2002	0	0	0	0	0	0	3	8
2003	0	0	0	0	0	2	0	0
2004	0	0	0	0	0	2	8	0
2005	0	0	0	0	0	2	8	7
1001	0	0	0	0	0	0	0	3
1002	0	0	0	0	0	0	2	0
1003	0	0	0	0	0	0	2	8
1004	0	0	0	0	0	5	0	0
1005	0	0	0	0	0	5	8	0
1006	0	0	0	0	0	5	8	7
1007	0	0	0	0	4	0	0	0
1008	0	0	0	0	4	8	0	0
1009	0	0	0	0	4	8	7	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	2
3	0	0	0	0	0	0	0	1

Example Source Code:

```
  4    0    0    0    0    0    0    6    0
  5    0    0    0    0    0    0    6    8
  6    0    0    0    0    0    0    5    0
  7    0    0    0    0    0    0    5    8
  8    0    0    0    0    0    4    0    0
  9    0    0    0    0    0    4    8    0
 10    0    0    0    0    0    4    8    7    ;

TABLE SS1MRS(SS1MR,CP) softwood site 1 mrs
        1    2    3    4    5    6    7    8
 12001  0    0    0    0    0    1    0    0
 11001  0    0    0    0    0    0    0    1
 11002  0    0    0    0    0    2    0    0
 10001  0    0    0    0    0    0    0    0
 10002  0    0    0    0    0    0    0    2
 9001   0    0    0    0    0    0    0    0
 9002   0    0    0    0    0    0    0    0
 8001   0    0    0    0    0    0    0    0
 8002   0    0    0    0    0    0    0    0
 7001   0    0    0    0    0    0    0    0
 7002   0    0    0    0    0    0    0    0
 6001   0    0    0    0    0    0    0    0
 6002   0    0    0    0    0    0    0    0
 5001   0    0    0    0    0    0    0    0
 5002   0    0    0    0    0    0    0    0
 4001   0    0    0    0    0    0    0    0
 4002   0    0    0    0    0    0    0    0
 3001   0    0    0    0    0    0    0    0
 3002   0    0    0    0    0    0    0    0
 2001   0    0    0    0    0    0    0    0
 1001   0    0    0    0    0    0    0    0
  1     0    0    0    0    0    0    0    0

  +     9    10   11   12   13   14   15   16
 12001  0    0    0    0    0    0    0    0
 11001  0    0    0    0    0    0    0    0
 11002  0    0    0    0    0    0    0    0
 10001  1    0    0    0    0    0    0    0
 10002  0    0    0    0    0    0    0    0
 9001   0    1    0    0    0    0    0    0
 9002   2    0    0    0    0    0    0    0
 8001   0    0    1    0    0    0    0    0
 8002   0    2    0    0    0    0    0    0
 7001   0    0    0    1    0    0    0    0
 7002   0    0    2    0    0    0    0    0
 6001   0    0    0    0    1    0    0    0
 6002   0    0    0    2    0    0    0    0
 5001   0    0    0    0    0    1    0    0
 5002   0    0    0    0    2    0    0    0
 4001   0    0    0    0    0    0    1    0
 4002   0    0    0    0    0    2    0    0
 3001   0    0    0    0    0    0    0    1
 3002   0    0    0    0    0    0    2    0
 2001   0    0    0    0    0    0    0    2
 1001   0    0    0    0    0    0    0    0
  1     0    0    0    0    0    0    0    0 ;
```

TABLE SS2MRS(SS2MR,CP) softwood site 2 mrs

	1	2	3	4	5	6	7	8
10001	0	0	0	0	0	3	0	0
10002	0	0	0	0	0	3	0	8
10003	0	0	0	0	0	3	0	8
10004	0	0	0	0	0	3	0	8
10005	0	0	0	0	0	3	0	8
10006	0	0	0	0	0	3	0	8
9001	0	0	0	0	0	0	0	3
9002	0	0	0	0	0	0	0	3
9003	0	0	0	0	0	0	0	3
9004	0	0	0	0	0	0	0	3
9005	0	0	0	0	0	2	0	0
9006	0	0	0	0	0	2	0	8
9007	0	0	0	0	0	2	0	8
9008	0	0	0	0	0	2	0	8
9009	0	0	0	0	0	2	0	8
9010	0	0	0	0	0	2	0	8
8001	0	0	0	0	0	0	0	0
8002	0	0	0	0	0	0	0	0
8003	0	0	0	0	0	0	0	0
8004	0	0	0	0	0	0	0	2
8005	0	0	0	0	0	0	0	2
8006	0	0	0	0	0	0	0	2
8007	0	0	0	0	0	0	0	2
7001	0	0	0	0	0	0	0	0
7002	0	0	0	0	0	0	0	0
7003	0	0	0	0	0	0	0	0
7004	0	0	0	0	0	0	0	0
7005	0	0	0	0	0	0	0	0
7006	0	0	0	0	0	0	0	0
6001	0	0	0	0	0	0	0	0
6002	0	0	0	0	0	0	0	0
6003	0	0	0	0	0	0	0	0
6004	0	0	0	0	0	0	0	0
6005	0	0	0	0	0	0	0	0
6006	0	0	0	0	0	0	0	0
5001	0	0	0	0	0	0	0	0
5002	0	0	0	0	0	0	0	0
5003	0	0	0	0	0	0	0	0
5004	0	0	0	0	0	0	0	0
5005	0	0	0	0	0	0	0	0
5006	0	0	0	0	0	0	0	0
4001	0	0	0	0	0	0	0	0
4002	0	0	0	0	0	0	0	0
4003	0	0	0	0	0	0	0	0
4004	0	0	0	0	0	0	0	0
4005	0	0	0	0	0	0	0	0
4006	0	0	0	0	0	0	0	0
3001	0	0	0	0	0	0	0	0
3002	0	0	0	0	0	0	0	0
3003	0	0	0	0	0	0	0	0
3004	0	0	0	0	0	0	0	0
3005	0	0	0	0	0	0	0	0
3006	0	0	0	0	0	0	0	0

2001	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	0
2003	0	0	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	0	0
1001	0	0	0	0	0	0	0	0
1002	0	0	0	0	0	0	0	0
1003	0	0	0	0	0	0	0	0
1004	0	0	0	0	0	0	7	0
1005	0	0	0	0	0	0	7	0
1006	0	0	0	0	0	0	7	0
1007	0	0	0	0	0	0	7	0
1008	0	0	0	0	0	0	7	0
1009	0	0	0	0	0	0	7	0
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
3	0	0	0	0	8	0	0	7
4	0	0	0	0	8	0	0	7
5	0	0	0	0	8	0	0	7
6	0	0	0	0	8	0	0	7
7	0	0	0	0	8	0	0	7
8	0	0	0	0	8	0	0	0
9	0	0	0	0	8	0	0	0
10	0	0	0	0	8	0	0	0

+	9	10	11	12	13	14	15	16
10001	0	0	0	0	0	0	0	0
10002	0	0	0	0	0	0	0	0
10003	0	0	0	0	0	0	0	6
10004	7	0	0	0	0	0	0	5
10005	7	0	0	0	0	0	4	0
10006	7	0	0	0	0	0	4	8
9001	0	0	0	0	0	0	0	0
9002	8	0	0	0	0	0	0	0
9003	8	7	0	0	0	0	0	0
9004	8	7	0	0	0	0	0	4
9005	0	0	0	0	0	0	0	0
9006	0	0	0	0	0	0	0	0
9007	0	0	0	0	0	0	0	6
9008	7	0	0	0	0	0	0	5
9009	7	0	0	0	0	0	4	0
9010	7	0	0	0	0	0	4	8
8001	3	0	0	0	0	0	0	0
8002	3	8	0	0	0	0	0	0
8003	3	8	7	0	0	0	0	0
8004	0	0	0	0	0	0	0	0
8005	8	0	0	0	0	0	0	0
8006	8	7	0	0	0	0	0	0
8007	8	7	0	0	0	0	0	4
7001	0	3	0	0	0	0	0	0
7002	0	3	8	0	0	0	0	0
7003	0	3	8	7	0	0	0	0
7004	2	0	0	0	0	0	0	0
7005	2	8	0	0	0	0	0	0
7006	2	8	7	0	0	0	0	0
6001	0	0	3	0	0	0	0	0

Example Source Code:

```
6002   0   0   3   8   0   0   0   0
6003   0   0   3   8   7   0   0   0
6004   0   2   0   0   0   0   0   0
6005   0   2   8   0   0   0   0   0
6006   0   2   8   7   0   0   0   0
5001   0   0   0   3   0   0   0   0
5002   0   0   0   3   8   0   0   0
5003   0   0   0   3   8   7   0   0
5004   0   0   2   0   0   0   0   0
5005   0   0   2   8   0   0   0   0
5006   0   0   2   8   7   0   0   0
4001   0   0   0   0   3   0   0   0
4002   0   0   0   0   3   8   0   0
4003   0   0   0   0   3   8   7   0
4004   0   0   0   2   0   0   0   0
4005   0   0   0   2   8   0   0   0
4006   0   0   0   2   8   7   0   0
3001   0   0   0   0   0   3   0   0
3002   0   0   0   0   0   3   8   0
3003   0   0   0   0   0   3   8   7
3004   0   0   0   0   2   0   0   0
3005   0   0   0   0   2   8   0   0
3006   0   0   0   0   2   8   7   0
2001   0   0   0   0   0   0   3   0
2002   0   0   0   0   0   0   3   8
2003   0   0   0   0   0   2   0   0
2004   0   0   0   0   0   2   8   0
2005   0   0   0   0   0   2   8   7
1001   0   0   0   0   0   0   0   3
1002   0   0   0   0   0   0   2   0
1003   0   0   0   0   0   0   2   8
1004   0   0   0   0   0   5   0   0
1005   0   0   0   0   0   5   8   0
1006   0   0   0   0   0   5   8   7
1007   0   0   0   0   4   0   0   0
1008   0   0   0   0   4   8   0   0
1009   0   0   0   0   4   8   7   0
  1    0   0   0   0   0   0   0   0
  2    0   0   0   0   0   0   0   2
  3    0   0   0   0   0   0   5   0
  4    0   0   0   0   0   0   5   8
  5    0   0   0   0   0   4   0   0
  6    0   0   0   0   0   4   8   0
  7    0   0   0   0   0   4   8   7
  8    0   0   0   0   0   0   0   1
  9    0   0   0   0   0   0   6   0
 10    0   0   0   0   0   0   6   8 ;

* VARIABLES are the choice variables in the model.  The
* cover type/site class variables correspond to the MRS for
* the respective cover type/site class sequences.

VARIABLES

    XSHS1(SHS1MR) soft & hard wood site 1 mgmt rgm acreages
```

```
    XSHS2(SHS2MR) soft & hard wood site 2 mgmt rgm acreages
    XSS1(SS1MR) softwood site 1 management regime acreages
    XSS2(SS2MR) softwood site 2 management regime acreages

* SWYIELD(CP) - softwood yield.  This is the total softwood
* woodflow produced by all management regime sequences
* selected by the model, in a given cutting period.  This
* value is used in the CP softwood constraints.

    SWYIELD(CP) softwood woodflow per cutting period

* CPCST is an accounting VARIABLE used to record the total
* cost of selected MRS's.  This is of interest in the cost
* minimization case where investment level is otherwise
* unrestricted.

    CPCST(CP)   cutting period investment

* D1SWY - decade 1 softwood yield.  This is an accounting
* VARIABLE which is the sum of woodflows occurring in the
* first decade.  This is used in the decade one softwood
* constraint.

    D1SWY        decade one softwood yield

* D1SWWF - decade 1 softwood woodflow.  This VARIABLE is the
* sum of softwood woodflow requirements for the first decade
* and is used in the decade 1 softwood woodflow constraint.

    D1SWWF       decade one softwood woodflow requirement

* N - net present worth.  This is the maximand used in the
* NPW objective function and represents the NPW of all model
* selected treatments across the planning horizon.

     N           MAXIMAND (NET PRESENT VALUE)

* W - woodflow.  This is the maximand used in the woodflow
* objective function and represents the woodflow produced by
* all model selected treatments across the planning horizon.

    W            MAXIMAND (WOOD FLOW)


* C - cost.  This is the minimand (the opposite of maximand)
* used in the cost minimization objective function and
* represents the cost of producing a required set of
* woodflows across the planning horizon.

    C            MINIMAND (COST)

* ?*s?REGSUM - covertype / site class acreage sum for use in
* area regulation equations.

SHS1REGSUM(CP)  soft & hard wood site 1 area reg acreage sum
SHS2REGSUM(CP)  soft & hard wood site 2 area reg acreage sum
```

```
SS1REGSUM(CP)   softwood site 1 area regulation acreage sum
SS2REGSUM(CP)   softwood site 2 area regulation acreage sum

CPCUTAREAL(CP)  cutting period cut area lower limit
CPCUTAREAU(CP)  cutting period cut area upper limit;

* The following statements restrict the solution space by
* disallowing such things as negative acreages.

POSITIVE VARIABLES
        XSHS1, XSHS2, XSS1, XSS2,
        SWYIELD,
        D1SWY, D1SWWF,
        SHS1REGSUM, SHS2REGSUM, SS1REGSUM, SS2REGSUM,
        CPCUTAREAL;

NEGATIVE VARIABLE CPCST, CPCUTAREAU;

* EQUATIONS define the objective function and constraints to
* be used in the model.  In this model, there is a choice of
* three objective functions including:  cost minimization,
* present value maximization, and woodflow maximization.

EQUATIONS

* NPW - net present worth (one of three possible objective
* functions).  This EQUATION (declared here and defined
* below) calculates the present value of each selected MRS
* and thereby guides the model in its efforts to minimize
* NPW across the planning horizon.

    NPW        net present worth (opt objective function)

* WOODFLOW - woodflow (one of three possible objective
* functions).  This EQUATION (declared here and defined
* below) sums the woodflows produced by model selected MRS's
* and guides the model in its efforts to maximize woodflow
* across the planning horizon.

    WOODFLOW   woodflow (optional objective function)

* COSTMIN - cost minimization (one of three possible
* objective functions).  This EQUATION (declared here and
* defined below) sums the costs of model selected MRS's and
* guides the model in its efforts to minimize costs for a
* given woodflow across the planning horizon.

    COSTMIN     cost minimization (opt objective function)

* ?*S?AREAC(AC) - cover-type/site-class/age-class area
* constraints.  The following 32 "equations" actually define
* 416 GAMS EQUATIONS.  These EQUATIONS are the area
* constraints which prevent the model from allocating
* more acres of each cover-type/site-class/age-class to
* various MRS's than exist.  These are a model necessity but
* are of minimal management interest beyond whether of not
```

```
* all available acres were allocated.

    SHS1AREAC(AC) soft & hard wood site 1 acreage constr.

    SHS2AREAC(AC) soft & hard wood site 2 acreage constr.
    SS1AREAC(AC)  softwood site 1 acreage constraint
    SS2AREAC(AC)  softwood site 2 acreage constraint

* S*S?AREARG(CP) - covertype / site class area regulation
* summation equations.  These equations sum the acreage
* clearcut in each cutting period.

    SHS1AREARG(CP)  soft & hard wood site 1 cp area sum eq.
    SHS2AREARG(CP)  soft & hard wood site 2 cp area sum eq.
    SS1AREARG(CP)   softwood site 1 cp area sum equations
    SS2AREARG(CP)   softwood site 2 cp area sum equations

* AREAREGUL(CP) and AREAREGLL(CP) - area regulation upper
* and lower limits.  These equations require that the total
* area cut in each cutting period does not deviate more than
* ACBOUND(see under scalar)% up or down in any cutting
* period.

    AREAREGUL(CP)   area regulation upper limit
    AREAREGLL(CP)   area regulation lower limit

* INVESTMENT(CP) - cutting period investment.  This
* "equation" defines 16 GAMS equations - one for each
* cutting period.  These restrict the cost of all selected
* MRS's to the investment available in the given period.
* This is of interest in seeing how much of the total
* available money is spent by the model.  Also, the cutting
* period available investment levels (in the PARAMETERS
* section at the top of the model - see INVEST(CP)) can be
* adjusted to reflect administrative changes and the model
* re-solved.

    INVESTMENT(CP)  cutting period investment restrictions

* CPCOST(CP) - cutting period cost.  Used with the cost
* minimization objective function to track investment levels
* for each of the cutting periods as required to produce the
* required woodflows.

    CPCOST(CP)            cutting period cost

* CPSWWF(CP) - cutting period softwood woodflow.  This
* EQUATION (actually a set of 9 equations) sums the
* woodflows occurring in each of the 10 year long cutting
* periods (numbers 8-16) and sets the softwood woodflow
* VARIABLE equal to this total.  CPHWWF(CP) and
* CPBIOMASS(CP) are the hardwood and biomass equivalents of
* this EQUATION set.

    CPSWWF(CP)    cutting period softwood woodflow
```

```
* CPSWWFREST(CP) - cutting period softwood woodflow
* restriction (or constraint). This set of 9 EQUATIONS (one
* for each of the ten-year cutting periods) requires that
* the woodflow produced meets or exceeds the woodflow
* required for that cutting period as defined by SWWFREQ(CP)
* above.

    CPSWWFREST(CP)  cutting period softwood constraint

* D1SWWDFL - decade 1 softwood woodflow. This EQUATION sums
* the woodflows occurring in the first decade and sets the
* decade 1 softwood woodflow VARIABLE to this sum.

    D1SWWDFL    decade one softwood woodflow

* D1SWWFREQ - decade 1 softwood woodflow requirement. This
* EQUATION sums the woodflow requirements (SWWFREQ(CP)) for
* the first decade. This sum is used in the decade 1
* woodflow constraint below.

    D1SWWFREQ   decade one softwood woodflow requirement

* D1SWWFREST - decade 1 softwood woodflow restriction (or
* constraint). This EQUATION requires that the decade 1
* softwood woodflows meet of exceed the decade 1 softwood
* woodflow requirements.

    D1SWWFREST   DECADE ONE SOFTWOOD CONSTRAINT;

* Following are the GAMS definitions of each of the
* equations declared above. This is the GAMS structured
* algebra of the model and includes the algebra as well as
* the matrix generation algorithms. This matrix generation
* capability greatly facilitates data modification in the
* model. Changes are made in the tables at the top of the
* model and GAMS then generates the new constraints
* including the new data.

NPW ..   N =E=
    SUM(CP,(SUM(TC$(TCI(TC) EQ 1),
    (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
    XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC)
     /((DR+1)**CPI(CP)))))) +
    SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
    XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC)
     /((DR+1)**CPI(CP)))))) +
    SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
    XSS1(SS1MR)*(SS1COEFF(SS1T,TC)
     /((DR+1)**CPI(CP)))))) +
    SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
    XSS2(SS2MR)*(SS2COEFF(SS2T,TC)
     /((DR+1)**CPI(CP)))))))))));

WOODFLOW ..   W =E=
    SUM(CP,(SUM(TC$(TCI(TC) EQ 4),
    (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
```

```
    XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC))))) +
    SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
    XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC))))) +
    SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
    XSS1(SS1MR)*(SS1COEFF(SS1T,TC))))) +
    SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
    XSS2(SS2MR)*(SS2COEFF(SS2T,TC)))))))));

COSTMIN ..   C =E=
    SUM(CP,(SUM(TC$(TCI(TC) EQ 2),
    (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
    XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC))))) +
    SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
    XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC))))) +
    SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
    XSS1(SS1MR)*(SS1COEFF(SS1T,TC))))) +
    SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
    XSS2(SS2MR)*(SS2COEFF(SS2T,TC))))))))));

CPCOST(CP) ..   CPCST(CP) =E=
    SUM(TC$(TCI(TC) EQ 2),
    (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
    XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC))))) +
    SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
    XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC))))) +
    SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
    XSS1(SS1MR)*(SS1COEFF(SS1T,TC))))) +
    SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
    XSS2(SS2MR)*(SS2COEFF(SS2T,TC)))))));

SHS1AREAC(AC) ..     SUM(SHS1MR $(SHS1I(SHS1MR) EQ ACI(AC)),
               XSHS1(SHS1MR)) =L= SHS1AREA(AC);

SHS2AREAC(AC) ..     SUM(SHS2MR $(SHS2I(SHS2MR) EQ ACI(AC)),
               XSHS2(SHS2MR)) =L= SHS2AREA(AC);

SS1AREAC(AC) ..     SUM(SS1MR $(SS1I(SS1MR) EQ ACI(AC)), XSS1(SS1MR))
               =L= SS1AREA(AC);

SS2AREAC(AC) ..     SUM(SS2MR $(SS2I(SS2MR) EQ ACI(AC)), XSS2(SS2MR))
               =L= SS2AREA(AC);

SHS1AREARG(CP) .. SUM(SHS1T $(TI(SHS1T) LE 2),
             (SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
             XSHS1(SHS1MR)))) =E= SHS1REGSUM(CP);

SHS2AREARG(CP) .. SUM(SHS2T $(TI(SHS2T) LE 6),
             (SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
             XSHS2(SHS2MR)))) =E= SHS2REGSUM(CP);

SS1AREARG(CP) .. SUM(SS1T $(TI(SS1T) LE 2),
             (SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
             XSS1(SS1MR)))) =E= SS1REGSUM(CP);

SS2AREARG(CP) .. SUM(SS2T $(TI(SS2T) LE 6),
             (SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
```

```
          XSS2(SS2MR)))) =E= SS2REGSUM(CP);

AREAREGUL(CP)$(CPI(CP) GE 10) ..
   (SHS1REGSUM(CP) - (1 + ACBOUND) * ((SUM(AC,SHS1AREA(AC)))/12.5)) +
   (SHS2REGSUM(CP) - (1 + ACBOUND) * ((SUM(AC,SHS2AREA(AC)))/10.5)) +
   (SS1REGSUM(CP) - (1 + ACBOUND) * ((SUM(AC,SS1AREA(AC)))/12.5)) +
   (SS2REGSUM(CP) - (1 + ACBOUND) * ((SUM(AC,SS2AREA(AC)))/10.5))
   =E= CPCUTAREAU(CP);

AREAREGLL(CP)$(CPI(CP) GE 10) ..
   (SHS1REGSUM(CP) - (1 - ACBOUND) * ((SUM(AC,SHS1AREA(AC)))/12.5)) +
   (SHS2REGSUM(CP) - (1 - ACBOUND) * ((SUM(AC,SHS2AREA(AC)))/10.5)) +
   (SS1REGSUM(CP) - (1 - ACBOUND) * ((SUM(AC,SS1AREA(AC)))/12.5)) +
   (SS2REGSUM(CP) - (1 - ACBOUND) * ((SUM(AC,SS2AREA(AC)))/10.5))
   =E= CPCUTAREAL(CP);

INVESTMENT(CP) .. INVEST(CP) =L=
   SUM(TC$(TCI(TC) EQ 2),
   (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
   XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC))))) +
   SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
   XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC))))) +
   SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
   XSS1(SS1MR)*(SS1COEFF(SS1T,TC))))) +
   SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
   XSS2(SS2MR)*(SS2COEFF(SS2T,TC)))))));

CPSWWF(CP) .. SWYIELD(CP) =E=
   SUM(TC$(TCI(TC) EQ 5),
   (SUM(SHS1T,(SUM(SHS1MR$(SHS1MRS(SHS1MR,CP) EQ TI(SHS1T)),
   XSHS1(SHS1MR)*(SHS1COEFF(SHS1T,TC))))) +
   SUM(SHS2T,(SUM(SHS2MR$(SHS2MRS(SHS2MR,CP) EQ TI(SHS2T)),
   XSHS2(SHS2MR)*(SHS2COEFF(SHS2T,TC))))) +
   SUM(SS1T,(SUM(SS1MR$(SS1MRS(SS1MR,CP) EQ TI(SS1T)),
   XSS1(SS1MR)*(SS1COEFF(SS1T,TC))))) +
   SUM(SS2T,(SUM(SS2MR$(SS2MRS(SS2MR,CP) EQ TI(SS2T)),
   XSS2(SS2MR)*(SS2COEFF(SS2T,TC)))))));

CPSWWFREST(CP)$(CPI(CP) GE 10) ..SWYIELD(CP) =G= SWWFREQ(CP);

D1SWWDFL .. SUM(CP$(CPI(CP) LT 10),SWYIELD(CP)) =E= D1SWY;

D1SWWFREQ .. SUM(CP$(CPI(CP) LT 10),SWWFREQ(CP)) =E= D1SWWF;

D1SWWFREST .. D1SWY =G= D1SWWF;

* The MODEL statement allows the user to specify which of
* the EQUATIONS defined in the model to use in solving the
* problem. This is useful in this case where there are 3
* possible objective functions to choose from (max NPW, max
* woodflow, min cost). For each of these cases, a few of
* the equations defined in the code are omitted - most
* notable the other objective functions. It is however
* interesting to leave one of both of the other objective
* functions in to see what their levels are given a
* different objective function.
```

```
MODEL AX1C  COST MINIMIZATION
   / COSTMIN, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, WOODFLOW, CPCOST, NPW /

  AX1N  NPW MAXIMIZATION
   / NPW, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     INVESTMENT, CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, WOODFLOW, COSTMIN /

  AX1W  WOODFLOW MAXIMIZATION
   / WOODFLOW, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     INVESTMENT, CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, NPW, COSTMIN /

  AX1Car  COST MINIMIZATION
   / COSTMIN, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     SHS1AREARG, SHS2AREARG, SS1AREARG, SS2AREARG,
     AREAREGLL, AREAREGUL,
     CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, WOODFLOW, CPCOST, NPW /

  AX1Nar  NPW MAXIMIZATION
   / NPW, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     SHS1AREARG, SHS2AREARG, SS1AREARG, SS2AREARG,
     AREAREGLL, AREAREGUL,
     INVESTMENT, CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, WOODFLOW, COSTMIN /

  AX1War  WOODFLOW MAXIMIZATION
   / WOODFLOW, SHS1AREAC, SHS2AREAC, SS1AREAC, SS2AREAC,
     SHS1AREARG, SHS2AREARG, SS1AREARG, SS2AREARG,
     AREAREGLL, AREAREGUL,
     INVESTMENT, CPSWWF, CPSWWFREST, D1SWWDFL, D1SWWFREQ,
     D1SWWFREST, NPW, COSTMIN / ;

* SOLVE - this statement tells GAMS which MODEL to solve,
* what solver to use, what VARIABLE is the maximand, and
* which way (maximize or minimize) is improving.  A glance
* at the first solve statement (cost minimization) may
* cause you to do a double take - why maximize cost?  Costs
* are included in the model as negative numbers so
* maximizing their sum pushes that sum toward zero.  The
* other two solve statements are as would be expected.
*
* These models are solved as discontinuous non-linear
* programs in order to accommodate the exceptions called for
* by the dollar control operator in some of the equations
* (see GAMS manual) as well as to utilize the MINOS5 solver
* (which is quick and handles large problems).

*  SOLVE AX1C USING DNLP MAXIMIZING C;

 SOLVE AX1N USING DNLP MAXIMIZING N;
```

```
* SOLVE AX1W USING DNLP MAXIMIZING W;
* SOLVE AX1Car USING DNLP MAXIMIZING C;
* SOLVE AX1Nar USING DNLP MAXIMIZING N;
* SOLVE AX1War USING DNLP MAXIMIZING W;
```

Appendix B
Example Output File

```
MODEL STATISTICS

BLOCKS OF EQUATIONS    13     SINGLE EQUATIONS     90
BLOCKS OF VARIABLES    10     SINGLE VARIABLES    219
NON ZERO ELEMENTS    1137     NON LINEAR N-Z        0
DERIVATIVE POOL         3     CONSTANT POOL         0
CODE LENGTH             1

GENERATION TIME     =       30.270 SECONDS


EXECUTION TIME      =       32.620 SECONDS        VER: 386-EK-009

          S O L V E    S U M M A R Y

    MODEL    AX1N            OBJECTIVE  N
    TYPE     DNLP            DIRECTION  MAXIMIZE
    SOLVER   MINOS5          FROM LINE  1091

**** SOLVER STATUS      1 NORMAL COMPLETION
**** MODEL STATUS       1 OPTIMAL
**** OBJECTIVE VALUE         6013142.5596

 RESOURCE USAGE, LIMIT          6.000      1000.000
 ITERATION COUNT, LIMIT       148          1000

    M I N O S    5.2    (Jun 1989)
    = = = = =

    B. A. Murtagh, University of New South Wales
      and
    P. E. Gill,  W. Murray,  M. A. Saunders and M. H. Wright
    Systems Optimization Laboratory, Stanford University.


 WORK SPACE NEEDED (ESTIMATE)  --    6153 WORDS.
 WORK SPACE ALLOCATED          --    7384 WORDS.
```

EXIT -- OPTIMAL SOLUTION FOUND

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU NPW	.	.	.	1.000

NPW NET PRESENT WORTH (OPT OBJECTIVE FUNCTION)

---- EQU SHS1AREAC SOFT & HARD WOOD SITE 1 ACREAGE CONSTRAINT

	LOWER	LEVEL	UPPER	MARGINAL
1	-INF	1000.000	1000.000	EPS
2	-INF	900.000	900.000	EPS
3	-INF	700.000	700.000	3.267
4	-INF	600.000	600.000	5.850
5	-INF	400.000	400.000	10.477
6	-INF	100.000	100.000	18.763
7	-INF	.	.	33.602
8	-INF	200.000	200.000	60.176
9	-INF	200.000	200.000	174.277
10	-INF	300.000	300.000	192.993
11	-INF	700.000	700.000	345.621
12	-INF	900.000	900.000	618.954
13	-INF	1100.000	1100.000	670.515

---- EQU SHS2AREAC SOFT & HARD WOOD SITE 2 ACREAGE CONSTRAINT

	LOWER	LEVEL	UPPER	MARGINAL
1	-INF	2000.000	2000.000	3.267
2	-INF	1950.000	1950.000	5.850
3	-INF	1600.000	1600.000	10.477
4	-INF	1300.000	1300.000	18.763
5	-INF	1000.000	1000.000	33.602
6	-INF	600.000	600.000	60.176
7	-INF	200.000	200.000	174.277
8	-INF	800.000	800.000	192.993
9	-INF	1000.000	1000.000	345.621
10	-INF	1000.000	1000.000	618.954
11	-INF	1400.000	1400.000	680.827

---- EQU SS1AREAC SOFTWOOD SITE 1 ACREAGE CONSTRAINT

	LOWER	LEVEL	UPPER	MARGINAL
1	-INF	800.000	800.000	EPS
2	-INF	1000.000	1000.000	EPS
3	-INF	1100.000	1100.000	3.267
4	-INF	700.000	700.000	5.850
5	-INF	400.000	400.000	10.477
6	-INF	100.000	100.000	18.763
7	-INF	210.000	210.000	33.602

8	-INF	300.000	300.000	60.176
9	-INF	400.000	400.000	174.277
10	-INF	800.000	800.000	192.993
11	-INF	700.000	700.000	345.621
12	-INF	500.000	500.000	618.954
13	-INF	600.000	600.000	670.515

---- EQU SS2AREAC SOFTWOOD SITE 2 ACREAGE CONSTRAINT

	LOWER	LEVEL	UPPER	MARGINAL
1	-INF	1100.000	1100.000	3.396
2	-INF	1000.000	1000.000	6.082
3	-INF	1200.000	1200.000	10.892
4	-INF	600.000	600.000	19.506
5	-INF	400.000	400.000	34.933
6	-INF	.	.	62.559
7	-INF	100.000	100.000	182.402
8	-INF	300.000	300.000	200.635
9	-INF	250.000	250.000	359.307
10	-INF	400.000	400.000	643.464
11	-INF	700.000	700.000	707.803

---- EQU INVESTMENT CUTTING PERIOD INVESTMENT RESTRICTIONS

	LOWER	LEVEL	UPPER	MARGINAL
5	-INF	.	80000.000	.
7	-INF	.	4.0000E+5	.
8	-INF	.	8.0000E+5	.
9	-INF	.	8.0000E+5	.
10	-INF	.	8.0000E+5	.
11	-INF	.	8.0000E+5	.
12	-INF	.	8.0000E+5	.
13	-INF	.	8.0000E+5	.
14	-INF	.	8.0000E+5	.
15	-INF	.	8.0000E+5	.
16	-INF	.	8.0000E+5	.

---- EQU CPSWWF CUTTING PERIOD SOFTWOOD WOODFLOW

	LOWER	LEVEL	UPPER	MARGINAL
1	.	.	.	EPS
2	.	.	.	EPS
3	.	.	.	EPS
4	.	.	.	EPS
5	.	.	.	EPS
6	.	.	.	EPS
7	.	.	.	EPS
8	.	.	.	EPS
9	.	.	.	EPS
10	.	.	.	0.622

11	.	.	.	EPS
12	.	.	.	EPS
13	.	.	.	EPS
14	.	.	.	EPS
15	.	.	.	EPS
16	.	.	.	EPS

---- EQU CPSWWFREST CUTTING PERIOD SOFTWOOD CONSTRAINT

	LOWER	LEVEL	UPPER	MARGINAL
8	1.0000E+5	2.8484E+5	+INF	.
9	1.0000E+5	2.3416E+5	+INF	.
10	1.0000E+5	1.0000E+5	+INF	-0.622
11	1.0000E+5	1.1759E+5	+INF	.
12	1.0000E+5	1.7459E+5	+INF	.
13	1.0000E+5	2.2821E+5	+INF	.
14	1.0000E+5	3.9228E+5	+INF	.
15	1.0000E+5	4.6053E+5	+INF	.
16	1.0000E+5	5.3063E+5	+INF	.

	LOWER	LEVEL	UPPER	MARGINAL
---- EQU D1SWWDFL	.	.	.	EPS
---- EQU D1SWWFREQ	-1.100E+5	-1.100E+5	-1.100E+5	EPS
---- EQU D1SWWFREST	.	6.4024E+5	+INF	.
---- EQU WOODFLOW	.	.	.	EPS
---- EQU COSTMIN	.	.	.	EPS

D1SWWDFL DECADE ONE SOFTWOOD WOODFLOW
D1SWWFREQ DECADE ONE SOFTWOOD WOODFLOW REQUIREMENT
D1SWWFREST DECADE ONE SOFTWOOD CONSTRAINT
WOODFLOW WOODFLOW (OPTIONAL OBJECTIVE FUNCTION)
COSTMIN COST MINIMIZATION (OPT OBJECTIVE FUNCTION)

---- VAR XSHS1 SOFT & HARD WOOD SITE 1 MGMT RGM ACREAGES

	LOWER	LEVEL	UPPER	MARGINAL
1	.	1000.000	+INF	.
1001	.	900.000	+INF	.
2001	.	700.000	+INF	.
3001	.	.	+INF	-2.311
3002	.	600.000	+INF	.
4001	.	.	+INF	-4.139
4002	.	400.000	+INF	.
5001	.	.	+INF	-7.413
5002	.	100.000	+INF	.
6001	.	.	+INF	-13.276
6002	.	.	+INF	.
7001	.	.	+INF	-23.775
7002	.	200.000	+INF	.
8001	.	.	+INF	-109.089
8002	.	200.000	+INF	.

9001	.	.	+INF	-4.201
9002	.	300.000	+INF	.
10001	.	.	+INF	-136.551
10002	.	700.000	+INF	.
11001	.	.	+INF	-244.542
11002	.	900.000	+INF	.
12001	.	1100.000	+INF	.

---- VAR XSHS2 SOFT & HARD WOOD SITE 2 MGMT RGM ACREAGES

	LOWER	LEVEL	UPPER	MARGINAL
1	.	.	+INF	-3.267
2	.	2000.000	+INF	.
3	.	.	+INF	-35.342
4	.	.	+INF	-33.158
5	.	.	+INF	-33.336
6	.	.	+INF	-114.973
7	.	.	+INF	-115.151
8	.	.	+INF	-108.697
9	.	.	+INF	-109.015
10	.	.	+INF	-109.835
1001	.	.	+INF	-2.257
2001	.	.	+INF	-4.042
3001	.	.	+INF	-7.239
3002	.	.	+INF	-7.556
4001	.	.	+INF	-12.963
4002	.	.	+INF	-13.532
5001	.	.	+INF	-23.215
5002	.	.	+INF	-24.234
6001	.	.	+INF	-108.086
6002	.	.	+INF	-109.911
7001	.	.	+INF	-1.348
7002	.	.	+INF	-4.617
8001	.	.	+INF	-133.336
8002	.	.	+INF	-139.190
9001	.	.	+INF	-238.784
9002	.	.	+INF	-249.269
10001	.	1400.000	+INF	.
10002	.	.	+INF	-18.777
1002	.	1950.000	+INF	.
1003	.	.	+INF	-0.177
1004	.	.	+INF	-117.138
1005	.	.	+INF	-117.456
1006	.	.	+INF	-118.276
1007	.	.	+INF	-105.898
1008	.	.	+INF	-106.467
1009	.	.	+INF	-107.936
2002	.	.	+INF	-4.219
2003	.	1600.000	+INF	.
2004	.	.	+INF	-0.318
2005	.	.	+INF	-1.138
3003	.	.	+INF	-8.377
3004	.	1300.000	+INF	.
3005	.	.	+INF	-0.569

3006	.	.	+INF	-2.038
4003	.	.	+INF	-15.002
4004	.	1000.000	+INF	.
4005	.	.	+INF	-1.019
4006	.	.	+INF	-3.650
5003	.	.	+INF	-26.865
5004	.	600.000	+INF	.
5005	.	.	+INF	-1.826
5006	.	.	+INF	-6.537
6003	.	.	+INF	-114.623
6004	.	200.000	+INF	.
6005	.	.	+INF	-3.269
6006	.	.	+INF	-11.707
7003	.	.	+INF	-13.055
7004	.	800.000	+INF	.
7005	.	.	+INF	-5.855
7006	.	.	+INF	-20.966
8003	.	.	+INF	-154.302
8004	.	1000.000	+INF	.
8005	.	.	+INF	-10.485
8006	.	.	+INF	-37.547
8007	.	.	+INF	-32.244
9003	.	.	+INF	-276.331
9004	.	.	+INF	-271.028
9005	.	1000.000	+INF	.
9006	.	.	+INF	-18.777
9007	.	.	+INF	-15.564
9008	.	.	+INF	-61.250
9009	.	.	+INF	-57.745
9010	.	.	+INF	-57.922
10003	.	.	+INF	-15.564
10004	.	.	+INF	-61.250
10005	.	.	+INF	-57.745
10006	.	.	+INF	-57.922

---- VAR XSS1 SOFTWOOD SITE 1 MANAGEMENT REGIME ACREAGES

	LOWER	LEVEL	UPPER	MARGINAL
1	.	800.000	+INF	.
1001	.	1000.000	+INF	.
2001	.	1100.000	+INF	.
3001	.	.	+INF	-2.311
3002	.	700.000	+INF	.
4001	.	.	+INF	-4.139
4002	.	400.000	+INF	.
5001	.	.	+INF	-7.413
5002	.	100.000	+INF	.
6001	.	.	+INF	-13.276
6002	.	210.000	+INF	.
7001	.	.	+INF	-23.775
7002	.	300.000	+INF	.
8001	.	.	+INF	-109.089
8002	.	400.000	+INF	.
9001	.	.	+INF	-4.201

9002	.	800.000	+INF	.
10001	.	.	+INF	-136.551
10002	.	700.000	+INF	.
11001	.	.	+INF	-244.542
11002	.	500.000	+INF	.
12001	.	600.000	+INF	.

---- VAR XSS2 SOFTWOOD SITE 2 MANAGEMENT REGIME ACREAGES

	LOWER	LEVEL	UPPER	MARGINAL
1	.	.	+INF	-3.396
2	.	1100.000	+INF	.
3	.	.	+INF	-114.635
4	.	.	+INF	-114.812
5	.	.	+INF	-108.085
6	.	.	+INF	-108.403
7	.	.	+INF	-109.223
8	.	.	+INF	-35.303
9	.	.	+INF	-33.016
10	.	.	+INF	-33.194
1001	.	.	+INF	-2.346
2001	.	.	+INF	-4.202
3001	.	.	+INF	-7.525
3002	.	.	+INF	-7.843
4001	.	.	+INF	-13.476
4002	.	.	+INF	-14.045
5001	.	.	+INF	-24.134
5002	.	.	+INF	-25.153
6001	.	.	+INF	-113.588
6002	.	.	+INF	-115.414
7001	.	25.482	+INF	.
7002	.	.	+INF	-3.269
8001	.	.	+INF	-138.611
8002	.	.	+INF	-144.465
9001	.	.	+INF	-248.231
9002	.	.	+INF	-258.715
10001	.	700.000	+INF	.
10002	.	.	+INF	-18.777
1002	.	1000.000	+INF	.
1003	.	.	+INF	-0.177
1004	.	.	+INF	-116.533
1005	.	.	+INF	-116.850
1006	.	.	+INF	-117.671
1007	.	.	+INF	-104.802
1008	.	.	+INF	-105.371
1009	.	.	+INF	-106.841
2002	.	.	+INF	-4.379
2003	.	1200.000	+INF	.
2004	.	.	+INF	-0.318
2005	.	.	+INF	-1.138
3003	.	.	+INF	-8.663
3004	.	600.000	+INF	.
3005	.	.	+INF	-0.569
3006	.	.	+INF	-2.038

4003	.	.	+INF	-15.514
4004	.	400.000	+INF	.
4005	.	.	+INF	-1.019
4006	.	.	+INF	-3.650
5003	.	.	+INF	-27.784
5004	.	.	+INF	.
5005	.	.	+INF	-1.826
5006	.	.	+INF	-6.537
6003	.	.	+INF	-120.126
6004	.	100.000	+INF	.
6005	.	.	+INF	-3.269
6006	.	.	+INF	-11.707
7003	.	.	+INF	-11.707
7004	.	274.518	+INF	.
7005	.	.	+INF	-5.855
7006	.	.	+INF	-20.966
8003	.	.	+INF	-159.577
8004	.	250.000	+INF	.
8005	.	.	+INF	-10.485
8006	.	.	+INF	-37.547
8007	.	.	+INF	-32.013
9003	.	.	+INF	-285.777
9004	.	.	+INF	-280.244
9005	.	400.000	+INF	.
9006	.	.	+INF	-18.777
9007	.	.	+INF	-15.413
9008	.	.	+INF	-60.989
9009	.	.	+INF	-57.331
9010	.	.	+INF	-57.508
10003	.	.	+INF	-15.413
10004	.	.	+INF	-60.989
10005	.	.	+INF	-57.331
10006	.	.	+INF	-57.508

---- VAR SWYIELD SOFTWOOD WOODFLOW PER CUTTING PERIOD

	LOWER	LEVEL	UPPER	MARGINAL
1	.	.	+INF	.
2	.	.	+INF	.
3	.	.	+INF	.
4	.	.	+INF	.
5	.	.	+INF	.
6	.	7.5024E+5	+INF	.
7	.	.	+INF	.
8	.	2.8484E+5	+INF	.
9	.	2.3416E+5	+INF	.
10	.	1.0000E+5	+INF	.
11	.	1.1759E+5	+INF	.
12	.	1.7459E+5	+INF	.
13	.	2.2821E+5	+INF	.
14	.	3.9228E+5	+INF	.
15	.	4.6053E+5	+INF	.
16	.	5.3063E+5	+INF	.

```
                    LOWER     LEVEL      UPPER    MARGINAL

---- VAR D1SWY          .    7.5024E+5     +INF      .
---- VAR D1SWWF         .    1.1000E+5     +INF      .
---- VAR N            -INF   6.0131E+6     +INF      .
---- VAR W            -INF   5.2676E+6     +INF      .
---- VAR C            -INF       .         +INF      .

  D1SWY     DECADE ONE SOFTWOOD YIELD
  D1SWWF    DECADE ONE SOFTWOOD WOODFLOW REQUIREMENT
  N         MAXIMAND (NET PRESENT VALUE)
  W         MAXIMAND (WOOD FLOW)
  C         MINIMAND (COST)


**** REPORT SUMMARY :        0    NONOPT
                             0 INFEASIBLE
                             0  UNBOUNDED
                             0    ERRORS


**** FILE SUMMARY

INPUT   C:\REYNER\THESIS.GMS
OUTPUT  C:\REYNER\THESIS.LST


EXECUTION TIME      =       3.790 SECONDS       VER: 386-EK-009
```

Vita.

The author was born in West Union, Iowa on September 15, 1966, where he lived until leaving for college. He received a Bachelor of Science degree in Forest Administration from the University of Wisconsin - Stevens Point in December 1989. While enrolled there he spent a summer working for the USDI-BLM in Salem, Oregon and 8 months on a Coop position with S.D. Warren Co. in Fairfield, Maine. He began his graduate work at Virginia Polytechnic Institute and State University in January 1990 and anticipates completion in December 1991. Upon completion the author plans to seek employment in forest industry.

Kris M. Reyner