Project:

Land Management Planning Methods to Maximize Environmental, Societal and Economic Benefits

Final Report:

A Multi-period Optimization Method for Balancing SFM Criteria and Indicators in Land Use Planning

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Abstract

A multi-objective, multi-period optimization method for balancing SFM criteria and indicators was created for tactical land use planning for two integrated forest products companies located in the East Kootenay area of British Columbia. The model includes a harvest block creation model that aggregates GIS polygons with similar attributes to create decision units for the model. A set of SFM criteria and indicators were developed based on information that could be collected from regional GIS databases, and potential outputs from the model. Clearcut, 50% selection and no-treatment options were available to each decision unit to satisfy stakeholder objectives. The mathematical model uses a fuzzy-set approach with a MAXMIN optimization strategy. User specified Targets, Thresholds and Triggers establish the membership functions necessary to determine the degree of objective satisfaction. A case study is presented that demonstrates the use of the model in a sustainable forest planning context. Results indicate that the method holds promise for developing scenarios and determining opportunity costs of SFM criteria in a stakeholder review process.

Key Words: forest planning, Criteria and Indicators, fuzzy sets

Acknowledgments

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Background

To balance the objectives of Sustainable Forest Management and the priorities of stakeholders, land managers must often create a large number of planning scenarios. Each scenario must be evaluated for timber and non-timber outputs, sustainability, and public acceptance. The ability to explore tradeoffs between often competing objectives is essential for creating these integrative management scenarios for review.

The downfall is that there are too many potential scenarios to comprehensively review, and the public's preferences can change with increasing information about the outcomes of those preferences. This is because public judgments are provisional: there is a difference between what the public prefers to happen, and what they believe should happen when faced with the facts, the costs, and the tradeoffs (Shindler 2000; Shindler et al. 2002).

Because of this complexity, the development and use of decision support tools is an integral part of developing SFM plans. Decision support tools can be used for both comprehensive analysis and for scenario building, with the primary purpose of forecasting and valuing outcomes from different plans. Therefore, the purpose of this type of tool is more strategic than operational. The tool doesn't make specific management decisions; it prepares "best case" scenarios and evaluates options based on the planner's directions.

Over the years there have been many planning models developed that respond to the challenges of their time. As computer power increases, the complexity of the models has correspondingly increased. However, most forest-level models in use today have been developed for maximizing a single output, such as Net Present Value (NPV) or timber volume. Non-timber objectives are included in these models through constraints, using trial and error to find acceptable solutions.

We are developing a planning tool that uses a more integrative approach. In our approach, experts can prepare scenarios which can then be reviewed and “valued” by stakeholders in an iterative process (see Shindler et al 1999, Toman et al. 1998). The 7-step process is shown in Table 1.

Our planning model balances a set of objectives related to the criteria and indicators (C&I) of sustainable forest management. We have conducted a comprehensive review of the C&I published by the Canadian Council of Forest Ministers (1997, 2000), and the C&I developed by a local study in the West Kootenay region of BC (Robinson 2002). For inclusion in our model, the indicators were required to meet operational standards adapted from Bunnell (1997). A full description of the indicators and rationale for choosing them can be found in Maness (2003). This project further refines and adds new indicators based on the collaborative work of the project team as explained in next section.

The model users direct the model by setting targets and thresholds for each indicator. The research conducted by our integrated team establishes how the indicators are affected by management decisions such as silvicultural prescriptions and special management zones as well as forest growth.

The concepts of sustained yield and multiple-use have been the foundation of planning for decades. However, the development of our decision support system requires specialized operation research techniques to deal with multiple criteria that are measured on different scales. Historically, the two most widely used models used for multi-objective forest management planning have been multi-objective linear programming (MOLP) and goal programming (GP) (see Weintraub and Bare 1996 for a review of these types of models). Both MOLP and GP methods can be interactive in the sense that multiple non-inferior solutions can be generated and presented to decision makers for evaluation, in a technique known as modeling to generate alternatives (MGA).

A great deal of research was conducted in forest planning with both MOLP and GP in the late 1980’s and early 1990’s (Weintraub and Bare 1996), but none of this early research has found its way into practice. There are several reasons for this. The first and most important reason is that these models did not consider manufacturing and products. Therefore, it is difficult to see the financial and socio-economic impact from forest management decisions.

Table 1. Seven step iterative process to evaluate management scenarios using the multi-period optimization model and public participatory processes.

Step	Process	Information Source
1.	*Determine where we are:* Define and quantify SFM indicators based on expert evaluation of presented data	GIS data, economic data, company data
2.	*Determine where we want to be:* Present current status report and conduct stakeholder preferences	Public participatory process
3.	*Set targets and thresholds:* Based on preferences, experts set targets, thresholds and triggers	Expert assessments
4.	*Conduct sensitivity analyses:* Using the multi-period optimization model, determine costs of achieving goals and prepare scenarios for evaluation and ranking	Data collected from steps 1, 2 and 3
5.	*Review with stakeholders:* Review scenarios, costs and tradeoffs with stakeholders	Model output, interactive maps, graphs
6.	*Check for acceptable solution:* If no acceptable scenario is found go to step 3.	Public participatory process
7.	*Develop management plans:* Develop management and monitoring plans based on scenario and preferences.	Scenario used as management guideline

We deal with this problem by embedding very detailed and thoroughly tested manufacturing optimization models into the decision support system.

Secondly, a huge amount of data is required for these models. Only recently has the availability of extensive GIS data made this type of model relevant. Our model will access the GIS data directly; we are creating computer programs to pre-process and clean the data. Thirdly, the SFM criteria itself did not really exist at that time. Recent research related to forest certification schemes and sustainable forest management C&I have made this part of the problem much better understood.

Liu et al. (2000) developed an interesting integer-based planning model that combines short- and long-term planning. The model used a target-oriented approach with indicators for the spatial arrangement of cut blocks, even-flow timber and age-class structure. The model did not consider manufacturing or stand-structure objectives, and objective weights were required for each of the objectives used.

The main difficultly associated with using these types of methods in practice is the need to determine and fix weights for each of the objectives. This requires stakeholders to make judgments about the relative value of different objectives with different units -- exceedingly difficult to do in practice. Also, as mentioned, stakeholders' preferences can change when presented with the likely outcomes based on their initial preferences.

Our optimization approach eliminates the need to establish objective weights by using fuzzy set theory. The idea behind fuzzy set theory is that human objectives are often imprecise, conflicting and non-commensurable. Instead of using weights, each goal can be modeled with a desired outcome (target), and minimum allowable outcome (threshold). A membership function can then be created that determines the degree of satisfaction of the desired result (Bellman and Zadeh 1970). The membership function serves as a surrogate to model the stakeholders' preferences for desired outcomes. These are mathematical relationships that can be linear, piecewise linear, or non-linear.

Fuzzy set theory has been used in forest planning problems. Hof et al. (1986) presented an early application of fuzzy constraints to a single objective harvest scheduling problem with non-declining even flow constraints. Mendoza et al. (1993) solved a multi-objective planning problem with a linear membership function that quantified the degree of satisfaction of each of the objectives. However, these attempts fell short of considering measures for ecological representation, recreation or any other indicators of SFM beyond non declining harvest volumes.

While the basic mathematical structure for solving these types of problems exists, no one has attempted to develop a planning model that integrates a complex set of economic, ecological and social objectives. There are two reasons for this: 1) it is enormously complex to determine how to model the impact of management decisions on a wide array of disparate indicators, and 2) the resulting model could be mathematically intractable. We have solved both of these problems by using a hierarchical planning technique that integrates existing models to deal with the separate indicators.

Methods

Planning Area

The Invermere Timber Supply Area (TSA) is an area of 1,110,700 hectares located in the interior dry belt of Southeastern British Columbia. It contains 6 biogeoclimatic zones. The current allowable annual cut for the Invermere TSA was set in 1996 at 581,570 cubic meters (m^3). The long term sustainable cut level is currently projected to decline to 426,880 m^3 over the next 3 decades as older stands in the area are harvested.

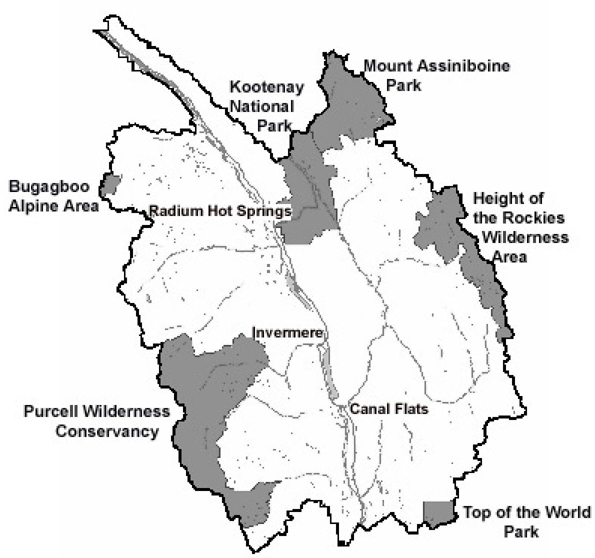

Figure 1. Location map of the Invermere TSA.

A general location map of the TSA is shown in Figure 1. The TSA is divided into 34 Landscape Units (LU), based roughly on watershed boundaries as shown in Figure 2. Each LU contains approximately 24,000 hectares.

Each landscape unit consists of approximately 12,000 polygons, each with an average size of 2 hectares, but a great deal of variation size. GIS data for the TSA is organized by polygon. The next section describes how polygons were merged to create management units.

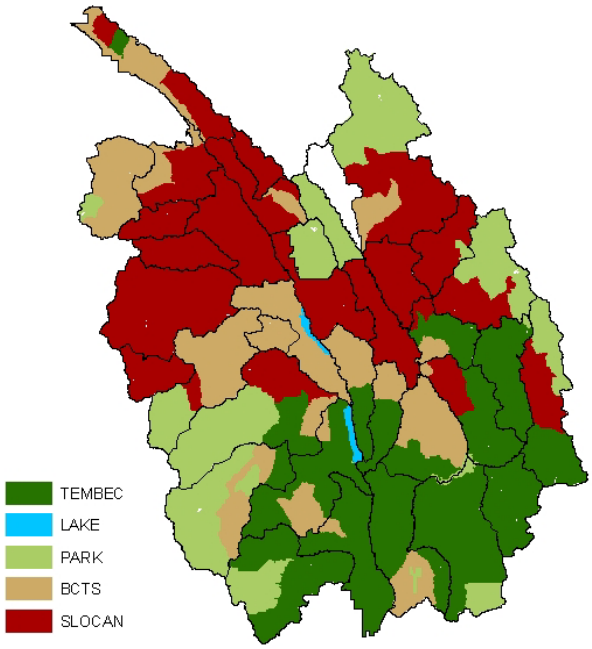

Figure 2. Invermere TSA showing the division into Landscape Units (black contours), and the area designated to parks, lakes and forest licensees

There are 6 species listed as endangered and 19 species listed as vulnerable that potentially occur in the TSA. These include the southern population of woodland caribou, grizzly bear, Rocky Mountain bighorn sheep, Swainson's hawk, sandhill crane and bull trout.

The TSA is surrounding by highly scenic national and provincial parks and an important wetlands area for migratory waterfowl. The TSA includes the communities of Invermere, Windermere, Canal Flats and Radium Hot Springs. These are small communities that are highly dependent on employment from the mill, tourism and guiding services. Tourism accounts for approximately 33% of the labor force, and forestry related activities about 20%.

Timber from the TSA supplies three sawmills. This northern portion of the TSA is licensed to Slocan Forest Products Company, which has one sawmill located in Radium Hot Springs, BC. The southern portion of the TSA is licensed to Tembec Forest Products, with sawmills located in Canal Flats (inside the Invermere TSA) and Elko (outside the Invermere TSA). Tembec also has a pulp mill located at Skookumchuck BC. In addition logs are traded to an LVL plant located in another region of BC. The different forest licensees and their respective allotted areas are shown in Figure 2.

The forest types on the TSA range from dry open stands of ponderosa pine (PP Zone) and interior Douglas-fir at low elevations (IDF) to Englemann spruce – subalpine fir (ESSF) at higher elevations. Lodgepole pine commonly occurs in the montane spruce zone (MS) due to the fire history in the region.

The quality of life benefits on the region are enormous; consequently the area is undergoing rapid development as a recreational playground for residents from the Calgary metropolitan area, 3 hours away by automobile. The population has increased by approximately 25% over the last 10 years.

GIS Data

The GIS dataset for the Invermere TSA was obtained from Interior Reforestation Co. Ltd. in Cranbrook BC, in January 2004. The timber type inventory data was obtained from the BC Ministry of Sustainable Resource Management in February 2002. The GIS data containing the recreational information was contained in the Invermere Forest District Recreation Features Inventory Dataset and obtained from the British Columbia Ministry of Forests in January 2003.

Spatial data used to map Indicator 1 (Representation) ecosystem groupings were developed by Wells et al. (2004). Ecosystem grouping mapping was developed from Predictive Ecosystem Mapping (PEM) data provided by JMJ Holdings Inc of Nelson, B.C. Data are dated March 31, 2002. Further details can be found in Wells et al. (2004).

Manufacturing Sources

The lumber mills modeled in this study are Slocan's Radium Division sawmill located in Radium Hot Springs, BC, and Tembec Forest Industries' sawmill located in Canal Flats, BC. Their respective operating areas within the timber harvesting land base are shown in Figure 3.

The Slocan Radium mill produces commodity dimension, J-Grade and machine stress rated (MSR) lumber products with 50% of their production in the latter two categories. The mill has 240 employees and produces 120 million board feet per year. The mill also produces 71,000 bone dry units of wood chips annually.

Logs are trucked over public roads to the mill's log yard. About 50% of the mill's logs are cut-to-length, the balance are cross cut in 2 manual bucking lines. Primary breakdown consists of 3 sawing lines: a high speed small log canter, a canter twin and a carriage headrig for larger high quality logs. Three large kilns provide adequate drying capacity.

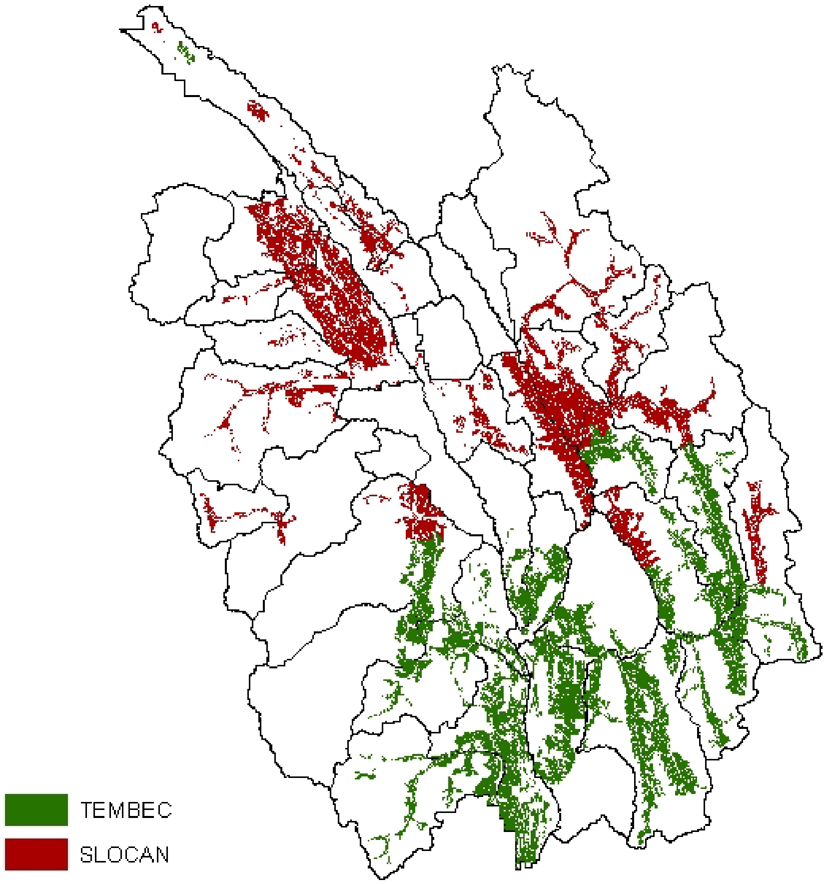

Figure 3. Invermere TSA showing the Timber Harvesting Land Base (THLB) for the 2 licensees.

The Tembec Canal Flats mill produces commodity dimension, machine stress rated and J-Grade lumber. Almost 50% of the production is MSR lumber. This mill produces about 100 million board feet per year, and the two groups of species processed here are Fir-Larch and Spruce-Pine-Fir (SPF), with the latter accounting for about 80% of the production. The logs are trucked on highway (to a maximum of 53' length) and off-highway (to 70' length). Three manual bucking lines prepare the logs to standard lengths, for logs with a butt diameter between 6" to 25". Oversized logs (>25") are peeled off on site to 23". The two primary breakdown lines consist of a Reducer Twin/Cant Optimizer combination, and a Double Length Infeed Canter. Lumber is dried in 4 double-track kilns, each with a capacity of about 250,000 MBF.

Sawmill Data

The majority of the data for the Slocan Radium sawmill was already collected in the previous year's project. The project team visited Tembec Canal Flats sawmill in November 2003 and collected financial, technical and production data about the operations of that plant. Examples of the technical data used in the current project are shown in Table 2, Table 3 and Table 4.

Table 2. Bucking line information

		BUCKING LINE INFORMATION					**LOG SIZE LIMITS**		**BUCKING LINE PERFORMANCE SETTINGS**
		Bucking Method	**Valid Log Length Group**	**Down Time [%]**	**Saw Kerf [in]**	**Log Trim Allowance [in]**	**Min SED [in]**	**Max SED [in]**	**Capacity [stems/min]**
Sawmill 1	**Bucking Line 1**	Mill Bucking 16 ft. preferred	Common Lengths (10'-20')	10	0.375	6.0	6.0	42.0	5
	Bucking Line 2	Mill Bucking 16 ft. preferred	Common Lengths (10'-20')	10	0.375	8.0	4.0	42.0	10
	Bucking Line 3	Mill Bucking 16 ft. preferred	Common Lengths (10'-20')	10	0.375	6.0	4.0	42.0	12
Sawmill 2	**Bucking Line 1**	Mill Bucking 20 ft. preferred	Common Lengths (8'-20')	35	0.250	6.0	4.0	42.0	3
	Bucking Line 2	Mill Bucking 20 ft. preferred	Common Lengths (8'-20')	35	0.250	8.0	4.0	42.0	5

Table 3. Sawing lines information

		LOG SIZE LIMITS				MACHINE SPEED SETTINGS			
		Min SED [mm]	**Max SED [mm]**	**Minimum Log Length [in]**	**Maximum Log Length [in]**	**Down Time [%]**	**Saw Kerf [mm]**	**Log Gap [ft]**	**Chain Speed [ft/min]**
Sawmill 1	**Canter A**	4.0	10.0	120.0	240.0	13.30	3.0	7.0	438.0
	Canter B	6.0	25.0	120.0	240.0	19.6	4.0	12.0	239.0
Sawmill 2	**Canter A**	4.0	14.0	96.0	240.0	24	5.0	13.0	290.0
	Canter B	4.0	8.0	96.0	240.0	24	4.0	12.0	400.0

Table 4. Edgers/trimmer information

		INFORMATION		PERFORMANCE SETTINGS		
		Type	**Saw Kerf [in]**	**Down Time [%]**	**Feed Speed**	**Gap / Fill**
Sawmill 1	**Edger A**	Board Edger	0.140	10	200 lugs/min	85% fill
	Edger B	Board Edger	0.120	15	200 lugs/min	70% fill
	Trimmer	Double End	--	10	92 lugs/min	80% fill
Sawmill 2	**Edger A**	Cant Edger	0.120	10	200 ft/min	100 in gap
	Edger B	Cant Edger	0.120	15	200 ft/min	20 in gap
	Edger C	Board Edger	0.140	10	200 lugs/min	85% fill
	Trimmer	Double End	--	15	105 lugs/min	80% fill

Structure of the Decision Support System

The Decision Support System consists of interactive scenario building model nested inside a stakeholder review process. This approach integrates a suite of models in a hierarchical fashion to optimize the overall problem. This allows each model to focus on the objectives that are important at that level. To ensure global optimality the models are linked, often through the use of shadow prices on resources.

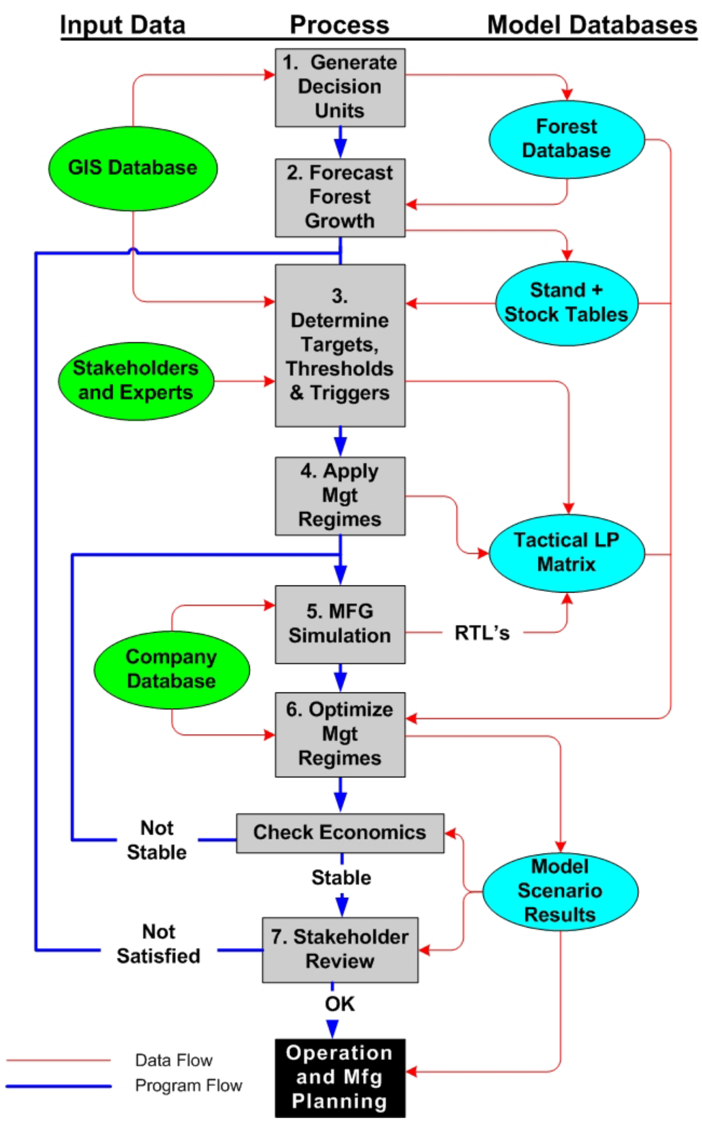

Figure 4. Flow Chart of the Scenario Analysis Model.

The basic structure of the model is shown in Figure 4. The structure is hierarchical in the sense that there are several linked optimizers, each working in a different temporal realm. The models are executed iteratively, and are driven toward a global solution by the sensitivity results from previous runs. Stakeholders and experts drive the search for new solutions by reviewing model the output, and changing the targets and thresholds for the individual SFM indicators. Using this approach, the indicators do not have to be valued – in fact the system provides the opportunity cost of the indicators as an output.

A brief description of the model from a practical standpoint follows. The model will create strategic, tactical and operational management plans that are linked together and sustainable. We have created a heuristic optimization model that partitions the landscape into homogeneous and contiguous decision units that are between 10 and 100 hectares in size. We build stand and stock tables for each decision unit, and apply a set of user-defined management regimes to them. The regimes include preservation, partial cutting, and clear cuts with varying levels of reserve. We project a set of indicators related to the important sustainable forest management criteria, and assign management regimes to decision units in a manner that optimizes the overall set of indicators over the planning period. The resulting timber from the harvested blocks is then "manufactured" with an embedded forest to product manufacturing optimization model. Therefore we understand the impact of the management decisions on mill productivity, profitability and the type of products. This drives a set of SFM economic indicators like investment potential, employment, and tax revenues. We produce reports for each planning period, and show the opportunity cost of each of the SFM indicators. Stakeholders can review this information, modify the targets and thresholds and re-run the scenario until they are satisfied that no improvements are possible.

Flow of the Scenario Builder

The Scenario Builder is the automated optimization model that constructs a management plan based on the Targets, Thresholds and Triggers specified by the stakeholders in process 3. The Scenario Builder consists of processes 1, 2, 4, 5, 6 in Figure 4. The overall model is solved using a hierarchical planning framework. The process starts in process 1 by analyzing the GIS polygons and aggregating polygons into similar stewardship units (SU's) with a heuristic model. Once stakeholders have specified Targets, Thresholds and Triggers, forest cover type data is used to generate a stand and stock table for each harvest unit in process 3. The harvest units are grown over time using a growth yield simulator so the full set of opportunities is available. In process 4 a harvest simulation model applies management regimes to each potential harvest unit. Trees are bucked into woods length logs - initially based on company sawmill profile information, and later based on shadow prices if optimal bucking can occur in the field. At this point all of the data is prepared for the tactical model.

The tactical model executes and determines which areas will be harvested with which treatments. The resulting log information is passed to the operational model which runs the sawmill optimally based on that log distribution. Return-to-log values are then determined, and the tactical/operational sequence is re-executed until a global optimum is reached. At this point the scenario is prepared for stakeholder review.

Stakeholders review the output to determine if criteria have been sufficiently met. If not, targets, thresholds and triggers are reviewed, negotiated and modified, and a new scenario is built as above. The process continues until stakeholders are satisfied or all options have been explored. Multi-criteria decision methods such as the Analytic Hierarchy Process or other methods can be used in the stakeholder review to determine preferences.

The details of the model will be presented in the order of numbered modules in the figure above.

1. Creation of Decision Units

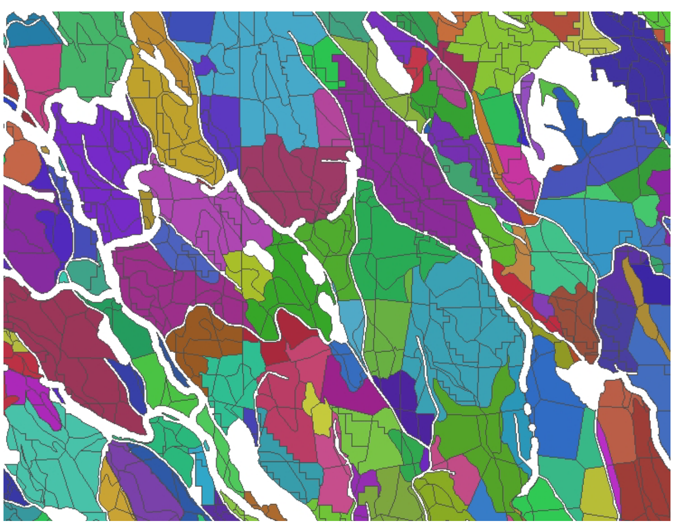

Figure 5. Example of Decision Units (in colour) located in LU29 – Steamboat, also showing polygon boundaries

We built a fuzzy simulated annealing model to optimize the aggregation of polygons into operationally-sized harvest units (Boyland 2004). The forest planning model requires these harvest units as an input, spatially defining the contiguous areas where a single silvicultural treatment will be applied. Using single polygons for this purpose is impractical: they are too small, and there are too many of them. Therefore we grouped them together into contiguous units of 10 to 100 hectares (Figure 5), called decision units (DU).

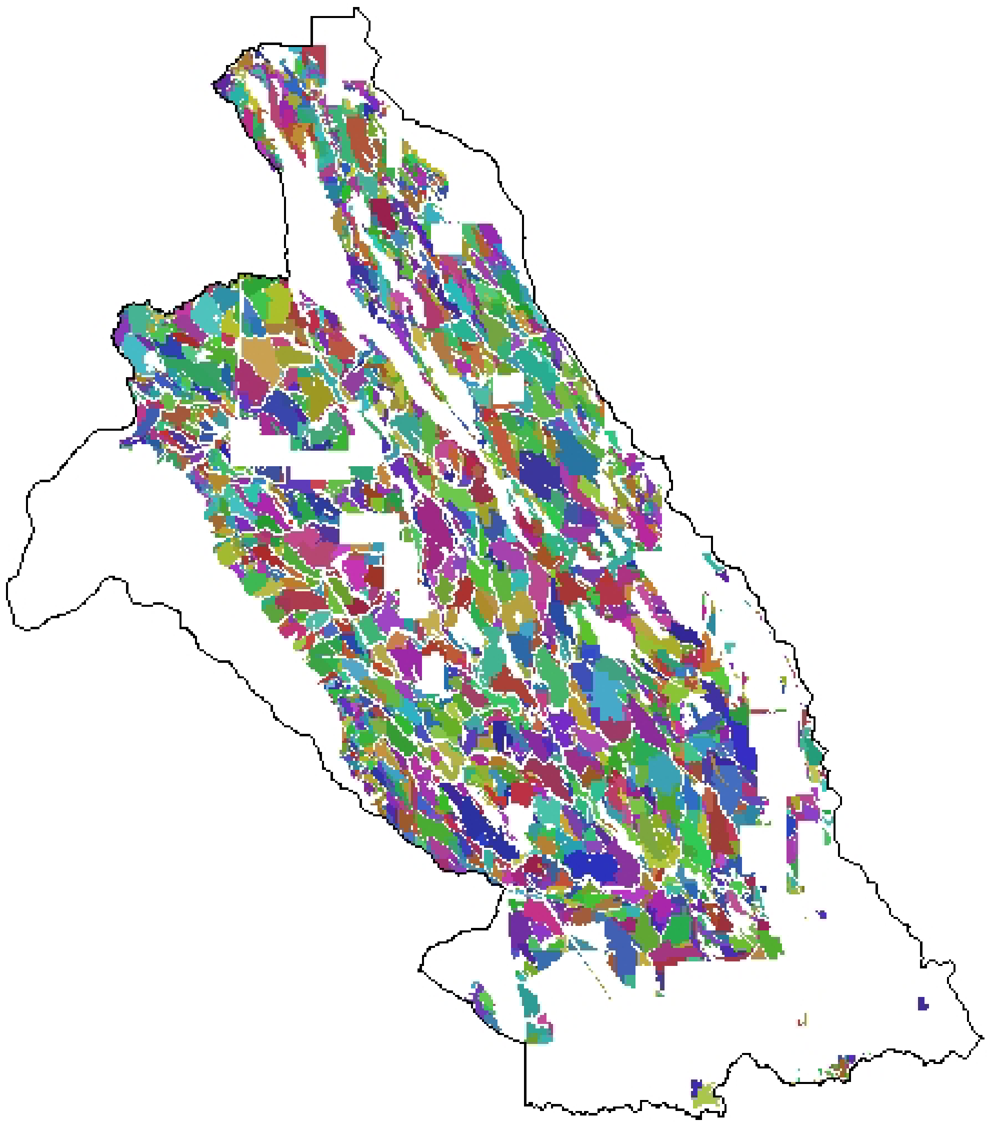

Figure 6. Example of a landscape unit (LU29 - Steamboat) of the Invermere TSA, showing the aggregated Decision Units on the THLB area

The initial step of creating decision units for harvest scheduling models has been approached through a variety of methods. Random harvest unit creation is the most widely used approach (Remsoft 1994, Remsoft 1996, Walters et al. 1999. Gustafson 1998; Nelson 2001; Murray and Weintraub 2002). Many variations exist, however most algorithms begin by randomly choosing a polygon, and then randomly choosing contiguous neighbouring polygons to build up a harvest unit to the size target. A seed point approach was used by Murray and Weintraub (2002). Seed points were randomly positions across the landbase, and polygons were grouped into harvest units based on the closest seed point to the polygon centroid. Harvest unit size was controlled by controlling the number of initial seed points. An example of these aggregated decision units for one landscape is shown in Figure 6.

Targets for harvest unit size (10-100 hectares), shape (globular rather than linear), and similarity (age, species type) were included in the aggregation process. The simulated annealing algorithm was used to minimize the total deviation away from the sum of all targets. Age objectives were specified using fuzzy sets, eliminating the need to specify age classes. We tested the fuzzy simulated annealing model against a random block building algorithm, the seed point algorithm, and crisp simulated annealing methods, and found that the fuzzy simulated annealing algorithm consistently produced decision units that created higher NPV values when included into an integer programming harvest scheduler (Boyland 2004).

2. Forecast Forest Growth

In the previous year's FII project, stem size distribution data were extracted from a network of regional BC Ministry of Sustainable Resource Management (MSRM) permanent sample plots (PSPs) summarized using a four-part stratification system designed to facilitate the assignment of a representative stratum to each polygon within the resultant database. One of the primary objectives for this year's model development project was to expand the capability of the model to conduct an analysis for multiple time periods. To meet this objective, it was necessary to devise a method for projecting the development of stand attributes through time including temporal sequences of stand table data. Due to time limitations resulting from the delay in funding, an interim methodology was developed to meet the short-term requirements of the multi-objective multi - period optimization model. The interim method was a based on a chronosequence approach using the existing PSP stratification system in combination with VDYP to project temporal sequences for PSP strata for a series of analysis units linked to the resultant forest cover database. Each PSP stratum was linked to a set of representative stand table data which were used as input to the scenario optimization model. While the interim method provides a reasonable approximation of the temporal trends in stand table data, it is subject to a number of errors that may result in inaccuracies. The method and its limitations are described in greater detail in Seely (2004).

In addition to the development and application of the interim approach, a long-term solution for projecting stand attribute was developed using the FORECAST model as a simulation tool. The use of FORECAST for projecting stand attribute curves, including stand table data avoids many of the shortcomings of the interim approach and also provides the potential to expand the model analysis to include a broader range of non-economic indicators (see Seely, 2004). There was insufficient time available to calibrate and apply the model for the forest types within the Invermere TSA. Plans for continued development of the model include this task.

3. Determine Criteria and Indicators

The choice of criteria and indicators used for SFM depends on the scale on which our judgments about sustainability are made. The broad principals for international sustainable development were developed in the 1992 Earth Summit (United Nations 1992). An international initiative, known as the Montreal Process (Montreal Process 1995), endorsed a system of 7 criteria and 67 indicators for the conservation and sustainable management of temperate and boreal forests. More recently, the Canadian Council of Forest Ministers (1997, 2000) endorsed a set of 6 criteria and 62 indicators to guide forest management at national level.

While the CFFM criteria and indicators provide a good framework of the important principles for sustainable development, they fall short of defining operational criteria for local or regional management decisions (Reynolds 2001; Brang et al. 2002). Effective criteria for management planning must be practical and simple, and they must make common sense (Bunnell 1997).

Due to the massive amounts of data required, our planning model must obtain the input regarding the goals from GIS data sources. A comprehensive review of the SFM Criteria and Indicators was completed to determine the set of objectives to be used in our model (see Maness 2004). This study reviewed C&I published by the Canadian Council of Forest Ministers (1997, 2000), as well as the C&I developed from a local study down in the West Kootenay region of BC (Robinson 2002). For inclusion in our model, the indicators were required to meet the following standards adapted from Bunnell (1997).

1. Available:

   To meet this standard for the purposes of this project the indicator data must either: a) currently exist in an available GIS database, or b) exist as output from the planning model.

2. Measurable:

   To meet this standard the indicator must be a metric that is clearly understood and measurable on the ground. Many CCFM indicators failed to meet this standard, something that has been noted by other researchers in this area.

3. Operable:

   To meet this standard the indicator must be usable in the planning model. This means that the relationship between the indicator and management decisions made on the ground must be clearly understood. In other words, it must be something from which it is possible to actually identify targets, thresholds, and triggers. This standard is also strongly restrictive; however, as these types of models evolve, it is expected that research will be conducted to identify targets, thresholds and triggers for additional indicators.

4. Credible & Relevant:

   To meet this standard, the indicator must be relevant to the intent of the original SFM criteria adopted at the Montreal Process (Montreal Process 1995). This standard is applied for new indicators were created at the local level in response to special regional needs.

A team of experts was assembled to develop the operational C&I used for this study. The experts worked together in a series of team meetings that culminated in a Criteria and Indicators workshop held at the University of British Columbia in 2004. The workshop was attended by important stakeholders and professional planners. Each indicator was proposed and discussed. Modifications were made as required.

Our study uses 4 criteria and 9 indicators that could be included in the context of our planning model. The criteria and indicators are listed below in Table 5. Targets and thresholds were developed for each indicator based on expert judgment using the model output as a guideline. When the model is used in a stakeholder participatory process, the targets and thresholds would be iteratively evaluated and changed to generate alternative solutions for evaluation. A full description of the indicators and rationale for choosing them can be found in Maness (2004).

Table 5. Criteria and indicators chosen for the planning model.

Indicator	Measured Variable	Trigger
Criterion I – Biological richness and its associated vales are sustained within the management unit (e.g. Invermere Timber Supply Area)		
1. Ecologically distinct ecosystem types are represented in the non-harvestable land base[1]	Percentage of area (hectares) reserved from harvest to achieve target	Indicator value is retained by preserving a minimum of 20% of ecosystem type in NHLB
2. Stand and forest-level habitat elements are represented[1]	Percentage of area (hectares) in required forest types considered to belong to Old Growth Management Areas (OGMA)	Indicator value is retained by preserving a minimum of 90% of basecase OGMA area requirements
Criterion II – Forest productivity is sustained		
3. Annual removal of forest products relative to the volume determined to be sustainable	Annual harvests	Harvest volumes are constrained by the Annual Allowable Cut (AAC)
Criterion III – The flow of economic benefits from the forest is sustained		
4. Net profitability is sustained (proxy tax revenues)	4. Net profitability is sustained (proxy tax revenues)	4. Net profitability is sustained (proxy tax revenues)
5. Total employment in all forest sectors is sustained	5. Total employment in all forest sectors is sustained	5. Total employment in all forest sectors is sustained
6. The provincial government continues to receive portion of benefits	6. The provincial government continues to receive portion of benefits	6. The provincial government continues to receive portion of benefits

[1] Wells, R.A. 2004. Thresholds and Targets for Representation and OGMA Indicators in the Invermere TSA. Technical report prepared for Forest Innovation Investment Ltd. Faculty of Forestry, University of British Columbia, Vancouver, BC.

Table 5. Continued.

Indicator	Measured Variable	Trigger
Criterion IV – Forest management supports ongoing opportunities for quality of life benefits		
7. Availability of recreation opportunities are sustained[2]	Recreation value score for each decision unit as a function of recreational significance, sensitivity to development, and proximity to water	Indicator value is retained by maintaining scores greater than the threshold
8. Visual quality of managed landscape is acceptable to stakeholders[3]	Visual quality objective (VQO) scores as given by visual prescriptions in visual management areas	Indicator value is retained by meeting visual prescriptions and green-up restrictions
9. Community watersheds are sustained and protected[4] - see below	Number of hectares of equivalent clearcut area (ECA) by watershed type	Indicator value is retained up to a 30% ECA harvest removal by landscape unit and watershed type

A discussion about the community watershed indicator is presented in the next section of this final report, as no individual technical report was produced on this subject. For detailed descriptions of other indicators, please refer to the technical reports pertaining to this project, as referenced in previous footnotes.

Community Watershed indicator

Forest vegetation is known to play an important role in maintaining and regulating hydrological cycles. It has been demonstrated that the removal of forest cover through harvesting can have a significant impact on the timing and magnitude of

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[2] Harshaw, H.W. 2004. Outdoor Recreation Indicator Formulation, Targets & Threshold Levels for the Invermere TSA. Technical report prepared for Forest Innovation Investment Ltd. Faculty of Forestry, University of British Columbia, Vancouver, BC.

[3] Picard. P. 2004. Targets & Threshold Levels and Formulation for the Visual Quality Indicator for Invermere TSA. Technical report prepared for Forest Innovation Investment Ltd. Faculty of Forestry, University of British Columbia, Vancouver, BC.

[4] Forsite Consultants Ltd. 2004. Invermere Timber Supply Area Timber Supply Review #3. Data Package Draft v3.0. Report prepared for Invermere Timber Supply Area, Defined Forest Area Management Group.

peak flows and, thus, has the potential to increase the likelihood of extreme flooding events which can result in erosion and an associated decline in water quality. As the forest canopy develops following harvesting it gradually regains its capacity to regulate hydrological cycles.

Equivalent clearcut area (ECA) is a calculated term that reflects the cumulative effect of harvesting within a watershed that is equivalent to the impact of a clearcut (Anon., 1999). Depending on the characteristics of a particular watershed, the rate of recovery of forest vegetation following harvesting will determine the degree to which harvesting can take place within the watershed without having a significant impact on water quality, quantity and flow patterns. Thresholds for ECA for a given watershed or local group of watersheds are typically determined by regional hydrologists on a case by case basis.

The measure chosen for this indicator is the number of hectares of equivalent clearcut area (ECA) of forested area within each landscape unit (LU) by watershed type.

Where:
1. The area of given polygon added to the total ECA area for a given watershed until trees regrow to (6m) in height (see Table 6).
2. Watersheds are defined by LU boundaries and the watershed type field in the Invermere TSR3 Resultant database.
3. Cumulative ECA is calculated as a percentage of the total area for each watershed.
4. ECA thresholds were based on those established for the Invermere TSR3 (See Table 6).

Table 6. A description of ECA thresholds showing forest cover objectives by watershed type from Table 47 of the Invermere TSA Timber Supply Review Data Package v3.0.

Watershed Type	Forest cover objectives	Area of Application	Comments
Community Watersheds	Max 30% < 6m (22 yrs)	Crown forested area within each LU by watershed type (CWS / DWS).	22 yrs used as a surrogate for the 6m ht – based on a Fd stand with an SI of 18.3.
Domestic Watershed – Class 1	Max 30% < 6m (22 yrs)		
Domestic Watershed – Class 2	Max 30% < 6m (22 yrs)		
Domestic Watershed – Class 3	Max 30% < 6m (22 yrs)		
Domestic Watershed – Class 3s	Max 30% < 6m (22 yrs)		

The trigger for this indicator is based on the calculation of ECA (as a % of total forested area) within specified watersheds as described above.

The following equation is used to determine whether a polygon should be included or excluded as an ECA area:

> if height < 6 then 1 else 0
>
> where:
>
> 1 = Add to ECA area
>
> 0 = Do not include in ECA area

The effects of specific harvesting treatments on the trigger are as follows:

Clearcut: The polygon age is reset and the entire area of the polygon is included as ECA until the tree height from the associated growth curve reaches >6m.

Partial harvest (50%): Since age is not reset under this treatment, time since harvesting is used as a surrogate. Fifty percent of the polygon area (based on 50% tree removal) is included in the ECA calculation until the time since harvest reaches > 22 years (See Table 6).

The threshold ECA for all watersheds was set at 30% based on recommendations for the Invermere TSR3 analysis from Dave Glunn, the MoF Regional Hydrologist. For the purposes of the scenario evaluation model, the ECA target was set at 25% for all watersheds.

4. Apply Management Regimes

Harvesting treatments

The model considers two types of harvest prescriptions, clear-cut and partial cut. The harvest block can also be cut at a varying level of intensity. For example, a 40 hectare block could have less than 40 hectares actually harvested. The level of intensity is a continuous variable. Partial cuts are 50% retention level. This means that 50% of the volume is removed in each polygon that make up the harvest block.

The model assigns harvesting prescriptions to stewardship units taking account of the targets, thresholds and triggers for each criteria and indicator.

All decision units on private land and those identified as inoperable are removed from the harvestable area. However these decision units may still contribute to satisfy non economic criteria and indicators. We assume that this area is undisturbed over the planning period, so this is considered outside the decision support system.

Each harvesting prescription has an associated harvesting cost based on the harvest method (clear-cut or selection-cut) and the net harvest volume. Partial-cuts are more expensive than clear-cut systems and cost increases are incurred as net harvest volume decreases.

Costs are also adjusted according to the likely harvesting system that would be used in each stewardship unit. For example a cable system will be more expensive than a ground based harvest system. The likely harvest system for each stewardship unit is determined by analysis of terrain data extracted from the GIS. This process is automated in the model.

The model simulates the harvesting process, and bucks tree length logs into long logs or short logs as specified by each mill. The logs are merchandised and routed to the appropriate mill.

Table 7. Harvesting treatments currently considered by the model.

Prescription ID	Method	Harvest Intensity
1	Clear-cut	100%
2	Partial Cut	50%
3	Preserve	0%

5. Manufacturing Simulation

The operational planning model is called by the tactical planning model as a subroutine. The purpose of the operation planning model is to determine the economic indicator levels that could be generated from harvesting each possible harvest unit. These indicators are the company revenue, total employment and tax revenues.

The operation planning model used is a decomposed crisp linear programming model that maximizes net revenue from sawmilling operations given a log distribution. The model contains a bucking and sawing simulation model that generates activities using column generation. The mathematical formulation and full details of the model can be found in Maness and Norton (2002).

The economic indicators values will change as a function of the species and size of the logs that are delivered to the mills. Consequently, the two models must be solved iteratively using a hierarchical framework.

Post-optimization analysis from this yields information useful to decisions made by the tactical planning model, including the full set of products made by each mill, and the Return to Log values (RTLs) by species, size and mill.

6. Optimize Management Regimes

The purpose of the planning model is to assign management treatments to harvest units over time to maximize the SFM indicators. However, it is not possible to maximize all of the indicators simultaneously since the indicators are often expressed in different units of measure. The solution used in this research is to maximize the "degree of goal satisfaction". The degree of goal satisfaction is the actual achievement for each indicator expressed as a percentage.

Instead of maximizing a summation of all indicators, we instead maximize the least achieved goal. For example, if visual quality is the hardest indicator to meet, the model will maximize all indicators so that they at least meet the visual quality indicator. The principle here is one of adaptive management. We undertake those management activities that bring the indicators into balance rather than maximizing one at the expense of others.

Mathematical Formulation

Given this idea, a formulation based on fuzzy set theory is constructed. We use a MAXMIN formulation which maximizes the degree of satisfaction with the least satisfied indicator. The formulation[5] is:

Maximize λ (1)

Subject to:

$$\sum_{j}^{J}\sum_{k=1}^{K} t_{ijkp}\, x_{jkp} - tx_{pi} \qquad = 0 \qquad \forall\, i, p \tag{2}$$

$$tx_{ip}\, \mu_{pi}\left(Ta_{ip}, Th_{ip}\right) - \lambda \qquad \geq 0 \qquad \forall\, i, p \tag{3}$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K} c_{ljkp}\, x_{jkp} \qquad \leq b_l \qquad \forall\, l, p \tag{4}$$

Where:

- λ = minimum degree of satisfaction over all indicators
- x = hectares in stewardship unit k treated with operation treatment j
- t = trigger for impacting how management activity affects indicator i
- μ_i = fuzzy membership function for indicator i
- Ta = target for indicator i
- Th = threshold for indicator i
- c = fixed coefficients for normal "crisp" resource constraints
- b = right hand sides for normal "crisp" resource constraints
- i = subscript for indicator
- j = subscript for operation treatment
- k = subscript for decision unit
- p = subscript for period
- l = subscript for constraint

[5] For ease in understanding, the mathematical formulation is given here exactly as it is implemented. For a discussion of the theoretical background and development of the "fuzzified" equations the reader is referred to Mendoza and Sprouse (1989).

The “fuzzy” model structure consists of two types of constraints. Eq. 2 determines the achievement level for each indicator. This equation contains the “trigger” (t) which is a scoring coefficient applied to the management activity variable. This allows each management prescription to differentially impact the indicator. There is a constraint for each indicator and each period.

Eq. 3 determines the degree of satisfaction (λ) through the membership function (μ). The equation for every indicator and every period relates to the same variable (λ). The greater than or equal to constraint ensures that every degree of satisfaction level be at least as high as the least satisfied indicator. This relates the actual level of the indicator to the target and threshold levels. With this formulation, the objective function (Eq. 1) will maximize the indicator that is satisfied the least.

The model also contains constraints to ensure feasibility of the solution. One set of constraints ensure that no more hectares are cut than are available, and a harvest unit is harvested only once.

The basic structure of the forest level model in terms of how the harvest units are modeled over time is based on the Model 1 formulation (Davis et al. 2000). The primary difference is that economic indicators are determined by a sub-model that is called by the forest level model. Forest growth is determined exogenously by the operational model.

Membership Functions for Indicators

The membership function is the essential component of optimization with fuzzy sets. In our example, the membership function gives the degree of satisfaction of a given indicator between the target and the threshold value. If the indicator is fully satisfied (meets the target) the membership will be 1. Likewise, if the indicator is at the threshold the membership will be 0. The indicator is not permitted to go below the threshold.

The membership function gives values for λ between the target and threshold. The membership functions can take on many different shapes according to the value structure of stakeholders for each indicator. Currently a linear membership function is used for each indicator with the following form:

$$\mu_{ip}(\mathbf{tx}) = \begin{bmatrix} \dfrac{1 - Th_{ip}}{Ta_{ip} - Th_{ip}} & if \;\; \mathbf{tx}_{ip} > Th_{ip} \\ \\ 0 & if \;\; \mathbf{tx}_{ip} \leq Th_{ip} \end{bmatrix} \tag{5}$$

Additional research is needed to determine the appropriate shape of the membership function for different indicators.

Linking the Models

Division of the planning problem into strategic, tactical and operational temporal realms is useful because both the objectives and the level of detail required are quite different in each realm. The hierarchical planning applications developed to date divide the planning problem spatially, for example between levels of an organization such as headquarters and division, or stands and forest level (examples are Hof and Baltic 1991, Schreier et al. 1993, Palander 1997). Our model is a significant advancement in that we are the first to solve such a complex hierarchical model for land use planning.

Our modeling approach integrates a suite of models in a hierarchical fashion to optimize the overall problem. This allows each model to focus on the objectives that are important at that level. To ensure global optimality the models are linked, often through the use of shadow prices on resources.

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