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Solving Stand-Level Planning Problems that Involve Multiple Criteria and a Single-Tree Growth Model

Peder Wikström

SWEDISH UNIVERSITY OF AGRICULTURAL SCIENCES

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Abstract

Today's forestry faces a complex situation where one must consider not only economic profit but also non-marketed values such as biological diversity, recreation and aesthetics. This thesis presents a new method to help answer the question: How should we manage a stand or a forest in order to meet some stated objective? This objective may include a variety of values. The values dealt with in this thesis are related to economic efficiency and biological diversity, but other values that can be described numerically, directly or indirectly, and integrated into a growth-and-yield model could be considered as well.

The thesis is comprised of four papers. The first, which deals with even-aged management, develops and analyses a solution method for stand-level planning that incorporates concerns for biological diversity. The model is based on Tabu search and greedy heuristics in conjunction with a single-tree growth-and-yield model. This solution method is used again to deal with uneven-aged management in the second paper. The third paper shows that computational efficiency can be improved considerably by a proper choice of decision variables, simplification of the solution procedure and data aggregation. The last paper describes a column generation procedure that integrates stand-level optimisation into a forest-level planning problem.

The stand-level planning model presented enables analysis of a wide range of objectives and constraints. The model is suggested as an analysis framework for deriving managerial guidelines or as a generator of stand-level plans in forest-level planning. Economically efficient measures can be found to preserve or create stand structures and elements that are associated with an increased biological diversity. Indirectly, such measures can be related to a monetary cost by comparison with a case that has a purely economic objective.

Keywords: optimisation, biodiversity, coarse woody debris, deciduous, individual-tree, Picea abies, Pinus sylvestris, tree retention, tree size diversity.

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ABSTRACT

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Today's forestry faces a complex situation where one must consider not only economic profit but also non-marketed values such as biological diversity, recreation and aesthetics. This thesis presents a new method to help answer the question: How should we manage a stand or a forest in order to meet some stated objective? This objective may include a variety of values. The values dealt with in this thesis are related to economic efficiency and biological diversity, but other values that can be described numerically, directly or indirectly, and integrated into a growth-and-yield model could be considered as well.

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*Take the course opposite to custom
and you will almost always do well.*

Jean Jacques Rousseau (1712 – 1778)

*The diversity of the phenomena of nature is so great,
and the treasures hidden in the heavens so rich,
precisely in order that the human mind shall never be
lacking in fresh nourishment.*

Johannes Kepler (1571-1630)

CONTENTS

APPENDIX
Papers I – IV

This thesis is based on the following papers, which will be referred to by their Roman numerals.

I. Wikström, P., and Eriksson, L.O. 2000[1]. Solving the stand management problem under biodiversity-related considerations. *Forest Ecology and Management* 126: 361-376.

II. Wikström, P. 2000[2]. A solution method for uneven-aged management applied to Norway spruce. *Forest Science* 46: 452-463

III. Wikström, P. 2000. Effect of decision variable definition and data aggregation on a search process applied to a single-tree simulator. Manuscript.

IV. Wikström, P., and Eriksson, L.O. 2000. Integrating stand-level optimisation into a multiple-criteria forest-level planning problem. Manuscript.

INTRODUCTION

Background

Forest planning is about making decisions on which activities to perform in the near future for a given forest resource in order to meet some stated objective given by a decision-maker. An activity that affects the current state of a forest resource will have an impact on the future state of the resource, and, consequently, will affect the freedom of action in the future. Also, the best decision today is dependent on what is planned in the future, meaning that decisions at different times are linked to each other. Therefore, both short-term and long-term consequences of an activity, or a series of activities over time, should be forecasted and evaluated before actually deciding to implement them.

The planning problem dealing with the management of forest resources has traditionally been separated into stand-level and forest-level problems. A stand is an administrative unit of a forest that is spatially delineated, and the stand-level problem consists of determining the sequence of management activities for an existing stand. The forest-level problem is to determine the best management regime for each stand or management unit that is part of the forest in order to meet an overall objective for the forest.

This objective reflects the decision-makers' appreciation of forest values, which may change over time according to trends and public attitudes (see, e.g., Bengston 1994). For example, a few decades ago, forestry in many countries was primarily considered a purely economic activity. Today, numerous reports on a rapid extinction of plant and animal species as a consequence of prevalent forestry practices have caused an anxious concern for biological diversity (biodiversity), which is usually defined as the diversity within and between species and of ecosystems (United Nations 1992). Forest values can be divided into two categories; tangible and intangible (Osmaston 1968). Today's forestry faces a variety of both tangible and intangible values that must be, or could be, considered in the planning process; these include timber, habitats for different species, recreation, and aesthetics.

Rational decisions require tools for analysis that can handle a range of objectives and are able to simulate the effects of the decisions that are made. The complexity of a forest ecosystem and the long time-horizons that are typically involved make such projections difficult. Projection models available for forestry applications are basically confined to growth-and yield models that describe the physical dynamics of a stand or its trees. If intangible values such as aesthetic beauty are to be recognised, these must therefore be described indirectly by the physical conditions that are associated with beauty. Similarly, the preservation or promotion of species in practical forestry is about providing the necessary conditions for these (see, e.g., Kangas and Pukkala 1996).

This thesis deals with a solution method for stand-level planning problems in a multiple-criteria context. Even though within-stand biodiversity and economic efficiency are considered to be the main objectives, other non-economic values such as aesthetics and recreation could be dealt with as well, as long as these, directly or indirectly, can be numerically quantified.

Objectives of the thesis

This thesis presents a new solution method for dealing with various objectives and constraints in stand-level planning, and a number of applications of this method. The work is motivated from an inability of the present models to handle problems that are too complex (see next sections). Apart from economic efficiency, conditions that are correlated to biodiversity are considered a primary interest, and are incorporated into the planning problems either in the form of constraints (Papers I and II) or as an objective (Paper IV). The specific purpose of each paper is:

Paper I. Develop a stand-level planning model that recognises non-timber outputs of relevance for biodiversity. A wide range of problem formulations should be possible. Only even-aged management is addressed.

Paper II. Extend the model presented in Paper I to deal with uneven-aged management. Objectives such as mimicking the naturally occurring structure of a virgin stand are included.

Paper III. Reduce the size of the stand-level planning problem so that computational effort is limited when the model presented in Papers I and II is applied to real-world data. The paper is aiming at a subsequent use of the model in Paper IV.

Paper IV. Establish a linkage between stand-level and forest-level optimisation. To do this, a column generation procedure is developed that enables the selection of a management regime for each individual stand so that an overall objective for a forest holding is optimised.

STAND-LEVEL MANAGEMENT PLANNING

Concepts and purpose

The stand-level planning problem usually involves the choice of one of two management systems, even-aged or uneven-aged, and the determination of what treatments to undertake and the timing of these. Even-aged management refers to plantation management. A plantation regime starts with planting, followed by thinnings (sometimes preceded by a pre-commercial thinning) and ends with clear-cutting. Uneven-aged management refers to stands that are never clear-cut, but repeatedly harvested with selective cuttings; new trees are naturally generated.

Traditional economic analyses propose three different measures of economic efficiency to evaluate a management system: land expectation value (LEV), managed forest value (MFV) and forest value (FV) (see Getz and Haight 1989, p. 272).

- *LEV* is, for even-aged management, the net present value (NPV) of a perpetual series of rotations, starting from bare land. For uneven-aged management, LEV is the present value of a harvest regime that converts to a perpetual series of steady-state harvests minus the liquidation value of the existing stand.

- *MFV* (Rideout 1985) is the present value of an infinite series of steady-state harvests; for even-aged management, it is the same as LEV.

- *FV* is a term introduced by Faustmann (1849) as being the NPV of harvests during and after the conversion of a stand to plantation management. FV is maximised when maximising the NPV of the general, any-aged, management problem with an infinite planning horizon (Haight 1987). Even-aged and uneven-aged management are special cases of this general problem, where constraints are imposed to require a clear-cut and conversion to plantation management or, for uneven-aged management, to convert to a steady-state uneven-aged management regime after one or more harvests (Getz and Haight 1989, Haight 1987).

FV is the correct measure to use to compare the economic efficiency of even-aged and uneven-aged management when applied to a given stand (Haight 1987), because MFV ignores the conversion cost of an existing stand and LEV can be used only in the case when the even-aged alternative involves an immediate clear-cut.

If the purpose of stand-level analysis is to determine or explore some guidelines for how a certain type of stand should be managed, then a single-stand analysis can be made for one or several representative stands. On the other hand, in forest-level planning there are usually constraints such as harvest flow that link the management of individual stands. Therefore, with such constraints, an optimal solution to a forest-level planning problem may not be attained by solving individual stand-level problems (e.g., Reed 1986). A linkage is, however, necessary between stand-level and forest-level analyses (Paredes and Brodie 1989).

Models for stand growth projection

A forest ecosystem is a dynamic resource system: its development over time is a result of human inventions and biotic conditions. The kind of model used to project the growth and value of trees is decisive for the kind of optimisation technique that can be applied. Based on Clutter (1963) and Munro (1974), Davis and Johnson (1987) distinguish three principal types of growth-and-yield models to project stand development. A *whole-stand model* is the most aggregated and uses stand variables such as age and basal area as input variables to predict future stand (volume, basal area, number of trees). The simplest form of a whole-stand model is univariate, where the stand volume or value is expressed as a function of stand age. *Diameter distribution models* also classify as whole-stand models since the number of stems in each diameter class is a function of the aggregate stand characteristics.

The second type of model defined by Davis and Johnson (1987) is a *diameter-class model*, which can be considered a special form of the more general *stage-structured model*. A stage-structured model acts on classes of trees and projects the growth and volume for the average tree of each class. The classes could be based on, for example, diameter, age or height. For practical reasons, the diameter-class model is the most common form of a stage-structured model. A stage-structured model can be either linear or non-linear. The former assumes that transition probabilities between classes are fixed and independent of the stand density. In a non-linear model, tree growth, mortality, and ingrowth are dependent on stand density and are expressed as non-linear functions.

A *single-tree model* (also called the individual-tree model), is the most complex model and projects the growth of each tree on a sample tree list as a result of competition with other trees (based on a calculated competition index), biotic conditions and harvest activities. A single-tree model can be distance-dependent, meaning that the competition index is based on the position of a tree in relation to all trees within its zone of competition. Because of the complexity of such a model and the associated cost of mapping trees, distance-independent models are the most used single-tree models. In this model, the competition index is calculated from stand characteristics. The less aggregated a model is, the more structural information is available for exploitation in stand management analysis. The drawback is that the difficulty of solving a problem increases with the level of resolution.

Any of the models described can be deterministic or stochastic. A *deterministic model* assumes that a future state of the forest and the forest's outputs can be predicted with certainty. These predictions are fundamentally unrealistic because there are many sources of uncertainties such as tree growth and mortality, natural generation, catastrophic events, timber prices, model assumptions, and measurement errors, all accentuated by the long time-horizons that are typically dealt with in forest planning. A more realistic model is a *stochastic model* in which an output of the model is associated with a certain probability. However, using a stochastic model in an optimisation framework is much more complicated than using a deterministic model. Also, a stochastic model is seldom purely stochastic; it can be partially deterministic due to difficulties to access the probabilities of the parameters to be predicted.

Model choice depends on (i) the purpose and (ii) the availability of an applicable model. If the purpose is to make a strategic plan for a large forest area, then a more aggregated model may be sufficient. However, even if one kind of model would be preferred for a given purpose, there may be no applicable models available for the stand types or tree species that are present in the forest. Similarly, if the purpose is to make an optimal management plan, the model must be applicable in an optimisation framework.

In this thesis, the *single-tree deterministic* model of Söderberg (1986) is used to predict five-year growth of the tree basal area under unmanaged conditions. Response to thinning is then predicted as a function of thinning intensity according to Jonsson (1980). This model is found in a wide variety of applications, such as long-range forest planning (Jonsson et al. 1993) and forecasts of national timber supply (Lundström and Söderberg 1996).

Mathematical programming

Mathematical programming is a collective term for methods that are used for solving mathematical problems. The problem dealt with is that of minimising or maximising an objective function by a proper choice of decision variable values (activities).

Using whole-stand models enhances, in comparison with other growth models, the possibility of finding an optimal solution by derivation (e.g., Cawrse et al. 1984, Chang 1981, Clark 1976). For more complex growth-models and problems, *dynamical programming* (DP) has been the most used. DP requires a discrete solution space that is attained by defining a finite set of stand states. DP has been applied to whole-stand models (e.g., Amidon and Akin 1968, Brodie and Kao 1979, Schreuder 1971), stage-structured models (e.g., Riitters et al. 1982) and single-tree models (Haight et al. 1985, Martin and Ek 1981). The drawback of DP is a "curse of dimensionality" described by Bellman (1957), the inventor of DP, which means that the number of states in the DP network must be limited for computational reasons. DP has therefore not explicitly included diameter class distributions in the state-space definition. For the same reason, most studies with DP have involved single-species stands only.

Linear stage-structured models are easily solved with *linear programming* (LP) (e.g., Buongiorno and Michie 1980). Adams and Ek (1974) were pioneers in solving the management problem while recognising size-specific harvest rates. The growth dynamics were projected with a non-linear stage-structured model and the problem was solved with the gradient projection method. Using the same growth model as Adams and Ek (1974), Haight (1985) used a version of the method of steepest descent to optimise the sequence of diameter distribution and selection harvests.

Due to the complex nature of a single-tree model and the difficulty or impossibility in obtaining gradients, the choice of solution method when using such a model for growth projection is restricted to derivate-free solution methods. After DP, the remaining alternatives are search techniques, such as random search (Bullard et al. 1985) or, what has become the most popular technique, the coordinate search method of Hooke and Jeeves (1961) (the H&J method).

The *H&J method* was introduced in forestry applications for a whole-stand model by Roise (1986a), and extended to single-tree models by Roise (1986b), Haight and Monserud (1990) and (Valsta 1992). The method approximates the objective function gradient by the evaluation of small discrete steps taken in the solution domain (exploratory search) and make moves (pattern search) along this direction to find local optima. The procedure requires several starting points in order to draw any conclusion about the global optima, but it can never guarantee that such a point is reached. In all single-tree applications, decision variables have been defined for classes of trees or as parameters to describe thinning form and intensity, even though the trees were kept as discrete units in the growth projections. Eriksson (1994) explored the special structure of a single-tree model and structured the problem into four levels. The first three levels dealt with the determination of harvest periods; different solution methods involving gradient and combinatorial methods were evaluated.

The lowest level consisted of determining which trees should be harvested and was solved with LP, since the non-linear objective function could be replaced by a first-order approximation at each solution point. The solution found with any procedure was always within 1 % of the best solution. The procedures were applied on small problems with five tree records representing a stand.

Planning in a biodiversity context

The conditions for biodiversity appear at different scales and thus affect forest planning in different ways. At a landscape level, a management plan can deal with the spatial allocation of activities to consider, for example, migration of species and edge effects. Also, non-spatial concerns, such as the need for a variety of ecosystem types to be represented in the landscape could be involved. At a lower level, there are structures, elements and processes within a stand that are considered as key factors for a large biodiversity, such as the occurrence of dead wood, the abundance of deciduous trees, diversity of trees sizes and fires (e.g., Esseen et al. 1992, Franklin et al. 1987, Ambuel and Temple 1983, Berg et al. 1994, Fries et al. 1997).

Only a few studies devoted to stand management optimisation recognise concerns for biodiversity. An early attempt by Calish et al. (1978) was to find the optimal rotation lengths for a modified SEV that included non-timber values such as wildlife. The non-timber values were simple functions of stand age priced in monetary terms. Haight et al. (1992) presented a method to optimise timber yields while satisfying stand density targets required for non-timber objectives. A single-tree model was used to simulate stand development and the problem was solved with the H&J method. Buongiorno et al. (1994) examined the trade-off between tree size diversity and economic returns. A matrix stand-growth model was used to project stand development and methods involving linear and non-linear programming were used to solve the problem. Gove et al. (1995) presented a non-linear programming model for optimising the LEV while maintaining tree size diversity in uneven-aged northern hardwood stands. The growth dynamics were simulated with a diameter class model. In common for the studies of Calish et al. (1978), Buongiorno et al. (1994) and Gove et al. (1995) is that their application are limited to specific problems and growth models.

An example where concerns for stand-level biodiversity are explicitly recognised without involving stand-level optimisation is presented by Pukkala et al. (1997). They proposed a forest-level planning procedure where both forest-level and stand-level indices of species diversity were involved. The criteria used to estimate stand-level diversity were the volume of dead wood and deciduous trees, old forest, and within-stand variety. A finite set of stand management alternatives was simulated at the start of the forest-level solution procedure.

Hence, consideration of biodiversity in stand-level analysis (as well as in forest-level analysis) has been confined to provide quantitative conditions or indices that should favour an increased or preserved biodiversity. This is consistent with the discussion of intangible values presented in the Introduction.

SUMMARY OF PAPERS I-IV

A new solution method for the stand-level planning problem (Papers I-III)

Paper I

The H&J method, due to its reported efficiency, is one natural choice of a mathematical programming method of optimisation that involves a single-tree simulator. The justification for developing a new solution method is essentially threefold. First, the H&J method, as well as other heuristic search methods, requires sensitivity analysis in the form of repeated solutions with different starting points (Haight and Monserud 1990, Roise 1986b).

Second, the number of decision variables that can be dealt with is limited and is proportional to the number of thinnings. The largest number of active decision variables, which are those variables that are associated with species and diameter classes that contain trees, was about 50 in Roise (1986b) corresponding to about 30% of all variables. Haight and Monserud (1990) solved an any-aged problem. The largest number of decision variables used was about 60 but the number of active variables was not given. Valsta (1992) solved an even-aged problem by specifying thinning form and intensity with three parameters for each thinning. The time lengths between thinnings were, as in Roise (1986a, 1986b), treated as continuous decision variables. The largest problem solved involved 17 decision variables.

Third, the convergence of the algorithm is problematic when there are non-convexities and discontinuities in the objective function (Haight and Monserud 1990). As an example, Haight and Monserud (1990) observed a particular poor behaviour of the algorithm when a discrete event in the form of a fixed planting was included in the problem. The optimisation problem that occurred when plantings were included as decision variables was considered too complicated and excluded from the analysis.

Another possible choice is the method of Eriksson (1994), but the use of LP limits its applicability in the sense that the objective function must be differentiable.

The solution technique developed here aims at the analysis of the special structure of a single-tree model to design a more efficient search procedure than the H&J method. First, the discrete-time property of a single-tree model was utilized to specify a two-level hierarchy of the planning problem (cf. Eriksson 1994), where the first level is to determine in what periods harvesting should be performed, and the second level is concerned with the choice of trees to harvest. The first level is a combinatorial problem where the number of thinnings (for an even-aged problem) is limited due to a fixed entry cost associated with harvesting. With the H&J method, the number of thinnings must be given before starting the solution procedure, and therefore repeated solutions are necessary with different number of thinnings. With a suitable method, the search of harvest periods could involve any number thinnings. The choice of harvest periods for a finite time horizon is in essence equivalent to a *travelling purchaser problem* (TPP), and was solved by Voß (1996) with a DROP/ADD-heuristic in conjunction with Tabu search (TS). The same approach was chosen to solve the first level problem dealt with here (Paper I, p. 366 and Paper II, p. 455). The reason for choosing TS, which was first proposed by Glover (1989), is its reputation as a very efficient so-called meta-heuristic. A meta-heuristic is a technique to guide a local search algorithm to explore the solution space beyond local optimality. See, e.g., Glover and Laguna (1997) for more information on TS. No random starting points were used but a search always started with an unmanaged alternative, i.e., with no active harvest periods.

For the second level, assume the following: The problem is to maximise the present value of a sequence of selection harvests, and there is a restriction for a minimum residual stand volume after harvest. Then, for each harvest period, the tree-selection problem concerns "filling up a basket" or a quota of the extracted volume. Because the best time for cutting varies between trees, such a quota will be unlikely to hold a portion of every tree record in the tree list, but more likely to hold only a subset of tree records. With the H&J method, every gradient approximation requires that a small, discrete change in each active decision variable (i.e., each coordinate axis) must be evaluated, after which a pattern move, still small, aligning to the direction of the approximation is performed. As a result, excessive computation for changes in variable values that will seldom lead to any improvement of the best solution is likely. Instead, to improve efficiency, the search method designed here concentrates its moves (changes of variable values) on those that give the largest improvement of the objective function value. This is accomplished by avoiding the gradient approximation used in the H&J method, and instead scanning the solution space and moving more rapidly in the solution domain with the help of a greedy heuristic (Paper I, p. 366-368). As on the first level, no random starting points were used, but an initial solution was either to cut no trees or "inherited" from a previous solution (Paper I, p. 367).

Only even-aged management was considered and the problem was to maximise the NPV of harvests subject to biodiversity-related considerations. The latter were formulated as constraints and expressed in terms of stand attribute targets for coarse woody debris (CWD), tree size diversity and tree retention. In addition, a comparison was made with traditional thinning guides. All constraints were augmented into the objective function as penalty functions. The performance of the model was demonstrated with a case example, where the model was applied to fictional mixed stands of Norway spruce and birch.

The solution method was validated by comparing it with the most reliable solution procedure of Eriksson (1994). As a result, solutions for maximum NPV for four fictional stands were within 0.5% and computation times were about one third of the Eriksson procedure. Economic losses due to the addition of non-timber constraints were measured as the percentage loss in NPV compared to a solution that maximises NPV only. Management proposals to meet the constraints are discussed. As an example, the proposed measures to supply more CWD were first to delay the final harvest, second to decrease the number of thinnings and third to decrease thinning intensity. Another example is tree retention, for which it appeared more costly to retain birch than spruce. This may seem counter-intuitive, since the price for spruce was higher than for birch. However, birch achieves maximum growth in value sooner than spruce, and therefore contributes considerably to the net revenues in early thinnings. These examples can possibly represent situations where optimisation can result in non-intuitive management proposals. Finally, the thinning guides gave poor solutions in terms of both NPV and the non-timber outputs dealt with.

Paper II

The model presented in Paper I is extended to incorporate uneven-aged management. To make this possible, an ingrowth component was added to the growth-and-yield model. Different problem formulations were adopted to maximise the NPV of harvested trees, with or without steady-state constraints. With no such constraints, a finite time horizon approximated the general management problem, while the steady-state constraints involved fixed and equilibrium endpoints. The fixed endpoint was a reverse J-shaped diameter distribution, and its purpose was to mimic the structure of a virgin stand. Analysis of economic efficiency, productivity and managerial implications was made for three fictional stands with different initial states. With the method used and for the endpoint problems, the conversion strategy, conversion length and steady-state diameter distribution were determined simultaneously. A Kolmogorov-Smirnov measure was used to describe the similarity between diameter distributions and was put directly into the constraints.

The case study in Paper II gave insight into investigations that must be carried out in order to compare even-aged and uneven-aged management of Norway spruce. For example, assumptions had to be made for ingrowth (treated as a constant), mortality, harvest costs and damages. Also, the growth-and-yield model probably underestimates the growth of regenerated trees, because the growth functions do not recognise the chance for recovery of trees that have once been suppressed. With the stated assumptions, even-aged management gave the largest NPV but no general conclusions about the best management system should be made solely on the basis of the case study.

For uneven-aged management, an infinite time horizon approximation was considered the most reliable solution approach as it, in contrast to a steady-state approach, does not assume that a resource system reaches a climax, eliminates the need to define a diameter class width and involves no fixed cutting cycles. For infinite time horizon approximations, differences in NPV for planning horizons of 100, 150 and 200 years were small. This is due to discounting and, consequently, a small contribution to the total NPV of harvests that occur in distant time.

Paper III

While Papers I and II present solutions for fictional stands with limited numbers of tree records, Paper III explores different approaches to make the solution method amenable for real stands with many sample trees in the tree lists. The impact on computation times and solution values were evaluated for (i) different groupings of tree-selection harvest controls, (ii) alternatives to the Tabu seach procedure to determine harvest timing, and (iii) data aggregation. Approaches (i) and (ii) aim at limiting the number of function evaluations (each evaluation involves a call to the growth-and-yield model) while still projecting the growth of every registered tree record. With (iii) the purpose is to limit the number of tree records that must be projected. Sensitivity analysis was made for a selection of stands in southern Sweden, where each stand was represented by a set of inventoried plots and each plot was represented by a tree list holding all trees in the plot. Both even-aged and uneven-aged management was considered.

Solutions improved with the number of decision variables, but the solution improvement levelled out when the number of decision variables per species group was more than five. The Tabu search procedure proved very efficient at determining harvest periods for the even-aged problem. For the uneven-aged problem, fixed cutting cycles approximated the harvest timing problem, but at considerably shorter execution times. Hence, the use of predefined, fixed, cutting cycles was useful when computation effort was recognised (cf. Paper II where computation time was not considered a problem). The optimal management regimes for the aggregated data gave NPVs that deviated considerably from the solutions for the non-aggregated data. Using the harvest timing given by the aggregated data solutions, applying it to the non-aggregated data and resolving the tree-selection problem, gave solutions within a few per cent of the solutions for the non-aggregated data.

Integrating stand-level optimisation into a multiple-criteria forest-level planning problem (Paper IV)

A forest-level planning problem is to determine the best combination of activities for the forest stands or management units in order to reach an overall objective for the forest. As mentioned previously, solving individual stand-level problems does not, usually, give an optimal forest-level plan. Large size is an obstacle when attempting to solve the problem, as each stand can be managed in almost an infinite number of ways (at least when thinning is an option). To overcome the size problem the conventional tactic is to define only a limited set of alternatives for each stand or unit. The drawback of this approach is that the solution space is not explored, meaning that in all probability management alternatives exist for the stands that better reflect the objectives for the forest. As a consequence, the attained solution may be far from optimal.

An alternative approach establishes a linkage between the forest-level and stand-level planning problems, where an individual stand-level solution explicitly reflects the objectives and constraints of the forest-level problem. With an LP formulation for the forest-level planning problem, it is possible to apply *column generation* (CG), which is a two-level method for solving LP problems with many variables. For a forest-level planning problem, a two-level hierarchy arises very naturally, where the master problem corresponds to forest-level constraints such as non-declining flow constraints or the total amount of dead wood, and the subproblems correspond to the stand-level activities. LP is probably the most used method for optimising forest-level planning problems, and is used in the Finnish MELA, the United States SPECTRUM and the New Zealand FOLPI systems (see Nabuurs and Paivinen 1996 for review). These systems have in common a finite set of stand-level management alternatives that are generated before solving a planning problem.

A CG procedure is presented in Paper IV. The objective was to maximise an overall objective for a forest, including NPV and a MAXMIN formulation for CWD; the problem was subject to non-declining inventory and even-net-flow constraints. The even-net-flow constraints were expressed with a Kolmogorov-Smirnov measure. The CG procedure was used to produce management regimes for the stands. These regimes were attained with the single-tree model and solution method presented in Papers I and II, using the measures proposed in Paper III to improve computational efficiency. In a case study, the model was demonstrated by solving the planning problem for a forest holding of 39 stands in northern Sweden, where each stand was represented by about nine survey plots. The total number of projected trees was more than 9000.

The CG procedure proved successful in finding stand-level management regimes so that an overall forest-level objective was fulfilled. For the first time, a long-term forest-level planning problem has been solved that simultaneously considers the optimisation of an overall objective of a forest, and, using a single-tree model for stand growth projection, the optimisation of stand-level treatments. Even though forest planning is often strategic with the purpose of not identifying the best management regime for every individual stand but, for example, getting a realistic proposal of sustainable harvest volumes, the outcomes for a forest ultimately depend on the outcomes from the stands that are part of the forest. Therefore, if the production potential of the individual stands was not considered, decisions may be based on solutions that are from optimal.

CONCLUSIONS

With the development of the solution method, a wide range of objectives and constraints can now be handled, given that they can be described numerically and integrated into a growth-and yield model. Economically efficient measures can be found to preserve or create stand structures and elements that are associated with an increase in biodiversity. Indirectly, such measures can be related to a monetary cost by comparison to a case with a purely economic objective.

The method can be used for both single-stand analysis and as a generator of stand-specific treatments in forest-level planning problems. The solution methods presented reflect a philosophy that the objectives are user-defined and, hence, it is the decision-maker who determines to what extent different criteria are involved.

FUTURE RESEARCH

Relations between stand and tree characteristics and biodiversity must be established and described in functional form for integration into the growth-and-yield model. In addition, a decision-maker (DM) is dependent on recommendations to specify a planning problem in a biodiversity context. For example, if the DM intends to provide the habitat for an endangered, wood-inhabiting species, information is needed on the amount of dead wood that is required by the species. Also, the properties of dead wood, such as tree species, size and decay class, are of great importance for wood-inhabiting organisms (e.g., Kruys et al. 1999). Mortality functions only give an indirect measure of the occurrence of dead wood. More adequate forecasts of the amount and the properties of it require models that describe its decay over time.

Reliable estimates of the economic efficiency of uneven-aged management require, for example, models that describe natural regeneration of Norway spruce, damages on remaining trees and plants after harvesting, harvesting costs and critical stocking levels to maintain the uneven-aged system (Paper II).

Although an effort has been made to make the solution method computationally efficient, computation times can still be considerable. Further studies to deal with this problem are motivated. For example, it would be interesting to compare the performance of the solution method when involving different kinds of growth models. A stage-structured model is more tractable for optimisation analysis than a single-tree model and may give sufficiently accurate and detailed growth projections (cf. Ek and Monserud 1979, and Haight and Getz 1987). Also, a stage-structured model is more amenable than a single-tree model to the incorporation of stochastic sources of variation, such as for mortality, timber prices, and tree growth.

Finally, recognising biodiversity at different scales is important, and there is a need for operations research in the simultaneous consideration of both within-stand and between-stand conditions.

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