Approaches to Integrated Strategic/Tactical Forest Planning

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Abstract

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Traditionally forest planning is divided into a hierarchy of planning phases. Strategic planning is conducted to make decisions about sustainable harvest levels while taking into account legislation and policy issues. Within the frame of the strategic plan, the purpose of tactical planning is to schedule harvest operations to specific areas in the immediate few years and on a finer time scale than in the strategic plan. The operative phase focuses on scheduling harvest crews on a monthly or weekly basis, truck scheduling and choosing bucking instructions. Decisions at each level are to a varying degree supported by computerized tools.

A problem that may arise when planning is divided into levels and that is noted in the literature focusing on decision support tools is that solutions at one level may be inconsistent with the results of another level. When moving from the strategic plan to the tactical plan, three sources of inconsistencies are often present; spatial discrepancies, temporal discrepancies and discrepancies due to different levels of constraint.

The models used in the papers presented in this thesis approaches two of these discrepancies. To address the spatial discrepancies, the same spatial resolution has been used at both levels, i.e., stands. Temporal discrepancies are addressed by modelling the tactical and strategic issues simultaneously.

Integrated approaches can yield large models. One way of circumventing this is to aggregate time and/or space. The first paper addresses the consequences of temporal aggregation in the strategic part of a mixed integer programming integrated strategic/tactical model. For reference, linear programming based strategic models are also used. The results of the first paper provide information on what temporal resolutions could be used and indicate that outputs from strategic and integrated plans are not particularly affected by the number of equal length strategic periods when more than five periods, i.e. about 20 year period length, are used.

The approach used in the first paper could produce models that are very large, and the second paper provides a two-stage procedure that can reduce the number of variables and preserve the allocation of stands to the first 10 years provided by a linear programming based strategic plan, while concentrating tactical harvest activities using a penalty concept in a mixed integer programming formulation. Results show that it is possible to use the approach to concentrate harvest activities at the tactical level in a full scale forest management scenario. In the case study, the effects of concentration on strategic outputs were small, and the number of harvest tracts declined towards a minimum level. Furthermore, the discrepancies between the two planning levels were small.

Keywords: Forest planning, Hierarchical, Integrated, linear programming, mixed integer programming, operations analysis, strategic, tactical.

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Appendix

Papers I – II

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

I. Andersson, D. and Eriksson, L.O. Effects of temporal aggregation in integrated strategic/tactical and strategic forest planning. Manuscript.

II. Andersson, D. and Eriksson, L.O. Spatially concentrating tactical harvest activities in integrated strategic/tactical forest planning: a hierarchical two-level approach. Manuscript.

Introduction

Of the Swedish landmass, 55 percent is covered with productive forest (Anon., 2004). Forests and forestry have traditionally contributed significantly to the country's welfare through utilities such as food, fuelwood and industrial wood (Stridsberg, 1984; Fritzböger and Söndergaard, 1995), and this continues. Large expenses are associated with forestry operations. When competing on a global market, the operations need to be effective and well planned to reduce costs and increase profitability. Forest planning by major companies is a process involving large organizations, vast forest areas, many people and many activities at different levels. Important issues in forest planning include long-term sustainability of the forest resource as well as a steady flow of timber over time. Also important are shorter term issues related to accessibility of stands and the road system. The utilization of machinery and their allocation to harvest areas over time should also be considered in the planning process. Historically, issues related to timber supply have been the most important. However, in recent decades, the greater interest in and knowledge of environmental issues, such as habitats for endangered species, has increased the demand for higher levels of detail in forest planning processes. The trends toward customer-oriented management and just-in-time thinking also require planning processes to be more effective (Karlsson, 2002).

The many different processes that are involved should be jointly planned to avoid suboptimal solutions. Many factors, among them the organizational structure of forest companies and the sheer magnitude of data and complexities of systems, have led to the establishment of a hierarchy of planning phases: strategic, tactical and operational (Karlsson and Rönnqvist, 2005). Strategic planning is traditionally conducted to make decisions about sustainable harvest levels while taking into account legislation and policy issues. Within the frame of the strategic plan, the purpose of tactical planning is to schedule harvest operations to specific areas in the immediate few years and on a finer time scale than in the strategic plan. The operative phase focuses on scheduling harvest crews on a monthly or weekly basis, truck scheduling and choosing bucking instructions.

A problem that may arise when planning is divided into levels is that solutions at one level may be inconsistent with the results of another level, and thus their meaning could be doubted (Weintraub and Davis, 1996). When moving from the strategic plan to the tactical plan, three sources of inconsistencies are often present; spatial discrepancies, temporal discrepancies and discrepancies due to different levels of constraint.

The purpose of an integrated planning approach is to reduce the possible inconsistencies between the levels and thereby, in abstract terms, bring the planning levels ‘closer to each other’. This is achieved by identifying and addressing the possible sources of inconsistencies. The purpose of this thesis is to present approaches to this end. This thesis focuses on the integration of strategic and tactical planning; it does not deal with operational planning.

The next section will give a more detailed description of forest planning and the nature of the planning stages. Thereafter, several approaches to coping with the inconsistency problem are reviewed, followed by a broader review of work in the field, given these approaches. Lastly, summaries of papers are presented.

Basic concepts of traditional forest planning

Theories, concepts and mathematics to support forest management have a long history, with some significant work occurring in the nineteenth century. af Ström (1829) provides an early Swedish reference to forestry planning. An approach to forest management in those days was the central European concept of a well-regulated forest. Using such a concept, the forest is divided into a number of blocks equal to the desired rotation plus one year, and one block is harvested each year and replanted the following year. Another pioneer was Faustmann. By using the calculus of Faustmann (1849), it became possible to compute and compare the effects of different rotation periods or thinning intervals. The invention of the simplex method (Dantzig, 1963) for linear programming and the computer revolution, which started in the 1960s, were two prerequisites for making mathematical programming the important base for decision support for forest planning that it is today. Weintraub and Davis (1996) provide an overview of the forest planning problem from a US Forest Service perspective and its coevolution with planning tools and computer power, amongst other things, from the 1960s to 1995.

Irrespective of the support tools used, an intuitively reasonable way to manage planning of a complex system such as forestry and to adapt the planning to the organizational structure is to divide the planning into different phases. Planning and decision making in forestry is traditionally performed in a hierarchical structure, where information is passed from the top down and the decisions taken are based on the information available at each level. The levels in this hierarchy from the top down are usually denoted strategic, tactical or operational, depending on the time scale to which they are applied (Weintraub and Bare, 1996; Martell *et al.*, 1998). In Sweden, the structures date back to the 1960s (Lönner, 1968; Andersson, 1971). Planning processes differ because of structural differences between organizations; however, the general scheme is applicable to all the major forest companies (Söderholm, 2002).

Strategic planning is traditionally conducted to make decisions about sustainable harvest levels while taking into account legislation and policy issues (Martell *et al.*, 1998). Although the considerations vary between organizations and nations, traditional industrial strategic planning usually includes the goal of ensuring long-term stability in the wood supply to industries while maximizing the net present value (NPV) (Martell *et al.*, 1998). The time horizon of the strategic planning stage is largely determined by the growth rate of the trees. One rotation, or approximately 100 years, is commonly used under Swedish conditions. In decision support models, time is often aggregated into periods of five or 10 years. Data are often aspatial. Examples of information supplied from this level of planning are net revenues and the levels of harvest in final felling and thinning (Söderholm, 2002). Early strategic decision support systems were mainly concerned with timber production. The trend in the ongoing development of decision support systems in forestry has turned to a wider view of the forest resource as not being only a timber supply, but also incorporating other aspects such as biodiversity and recreation (Vertinsky *et al.*, 1994; Weintraub and Bare, 1996; Fries *et al.*, 1998). Examples of strategic planning decision support systems are the Forest Management Planning Package (Jonsson *et al.*, 1993) in Sweden, MELA (Siitonen *et al.*, 1999) in Finland, FORPLAN (Johnsson *et al.*, 1986) and SPECTRUM (Camenson *et al.*, 1996) in the USA and FOLPI (Manley and Threadgill, 1990) in New Zealand.

At the tactical level, the purpose is to schedule harvest operations to specific areas and on a finer time scale (Martell *et al.*, 1998). The time horizon is usually from five years up to two decades. The input to the tactical planning from the strategic planning often comes in the form of volume targets that must be achieved. A number of other considerations need to be taken into account in tactical planning. The building of new roads and restoration of existing roads are frequently regarded as tactical matters (Davis *et al.*, 2001). Another issue in tactical planning is the formation of harvest blocks (Davis *et al.*, 2001), which could be, for example, concentrated areas of stands to be harvested at the same time by the same harvest crew. Harvest block formation reduces costs associated with harvest activities, such as the cost of trailing harvest equipment (Gustafsson *et al.*, 2000). The reduction of clear-cut size by stipulating that some time must pass between the final felling of adjacent stands is sometimes regarded as tactical (Martell *et al.*, 1998; Davis *et al.*, 2001). An even workload for the harvest crews, and industry requirements for an even flow of different log assortments over time and that ground conditions of stands should match planned harvest seasons, may be regarded as tactical considerations (Gustafsson *et al.*, 2000).

An output from the tactical plan is a set of stands to be further inventoried in detail and passed to the operative planning level. Directions with respect to improvements of the forest road network are also given. In Sweden, most tactical planning is conducted manually with GIS-based tools (Söderholm, 2002). Internationally, there are some models for tactical planning, such as TEAMS (Covington *et al.*, 1988), SNAP (Sessions and Sessions, 1992) and the models RELMdss (Church *et al.*, 2000a) and BAM (Church *et al.*, 2000b).

The operational level is not considered in this study and is not described in detail. However, at this level, the time scale is about one year or less, and issues such as scheduling of harvest crews on a monthly or weekly basis, truck scheduling and bucking are considered (Karlsson, 2002), given the prerequisites from the tactical plan. OPTICORT and PLANEX (Epstein *et al.*, 1999) are two Chilean examples of operational planning systems.

Problems with the hierarchical strategic-tactical planning setting and approaches for the integration of the planning levels

A problem that may arise when planning is divided into levels is that solutions at one level may be inconsistent with the results of another level and thus their meaning could be doubted. Weintraub and Davis (1996) stress that: "A very critical question is how to obtain consistency between results of decision models defined at two or more hierarchal levels. An optimal or near optimal solution at one level may not be meaningful if it is not logically or empirically consistent with results obtained at another. For example if statements about forest harvest levels repeatedly do not match the realized harvests on operating units." An effort to group the sources of inconsistency between the strategic and tactical planning levels can, based on what has been mentioned in the literature, yield three categories, of which the first two appear to be the most frequently addressed:

- Spatial discrepancies due to different area resolutions. There is often no stand-level information at the strategic level of planning, whereas such information is required at the tactical level because of the spatial nature of the issues handled.
- Temporal discrepancies due to different planning horizons. The time horizon of tactical planning is often shorter than that of strategic planning, which means that the implications of the actions according to the tactical plan are unknown with respect to strategic objectives.
- Discrepancies due to different levels of constraint. Other criteria are used in the tactical planning phase compared with the strategic phase, which can potentially lead to inconsistent solutions to the two phases.

Several approaches have been devised to cope with these discrepancies. They can generally be grouped into three main categories based on the information flow:

- The all-embracing or monolithic approach. The most straightforward approach to the integrated planning problem is to incorporate all aspects of the problem into one model. Using this approach, all information is available to both strategic and tactical levels simultaneously. The main disadvantage is that the models can become very large; hence, a negative tone is often coupled to the term monolithic. This and other disadvantages of the monolithic approach are outlined in Weintraub and Cholaky (1991).
- Hierarchical or top-down approach. With this approach, information is passed from the top down, i.e., from the strategic to the tactical level (Weintraub and Davis, 1996). This approach takes the same standpoint as the traditional planning structure described earlier using upper-level information as targets for lower-level planning phases. However, the approach is undergoing continuous refinements to address the discrepancy problems. The literature on top-down systems describes both explicit two-level approaches (strategic and tactical), and one-level approaches (tactical) that only describe the lower-level model

and operate on information that are assumed to have been provided by a preceding strategic-level process.

- The bottom-up approach. Here, the more detailed level is modeled first. This information is utilized to build what can be regarded as an upper-level solution. Two variants of this approach can be discerned. In the first simulation-based approach, lower-level considerations are taken into account periodwise over the strategic time horizon to build the strategic harvest level. In the second, a number of feasible lower-level alternatives are identified, which in turn are used as decision variables in an optimization-based model that considers strategic goals. Hence, the information flow is directed from the lower (tactical) to the upper (strategic) level. This approach comes naturally when modeling nonindustrial private forest owners under forest-wide constraints such as habitat requirements.

Spatial discrepancies

A conventional approach to strategic planning is to use aspatial data formed by aggregating stands based on some characteristics such as site index, species composition, etc.. Terms such as “strata” (Nelson *et al.* 1991) or “analysis area” (Davis *et al.*, 2001), “croptype” (McNaughton *et al.*, 1998), “macro stand” (Cea and Jofré, 2000) or “macro area” (Weintraub and Cholaky, 1991) are used to denote these aspatial decision units. The terms macro stand and macro area include a crude spatial dimension (stands are aggregated within predefined zones), while the other terms frequently (but not always, cf. Nelson *et al.* (1991)) do not. These more or less aspatial enities are subsequently used as decision units when long-term plans are established. At the tactical level, the considerations on road building, harvest block formation, etc., require greater spatial detail. Often individual stands are used as the decision unit. Nelson *et al.* (1991) note that strata based plans may be infeasible because they lack specific area information. Cea and Jofré (2000) note that two-level decisions could cause under- or overestimations of the costs or different forecasts of the land area to be harvested and stress that the aggregation and disaggregation process must be carried out carefully. Deficiencies in the aggregation process of stands, activities and time are also noted by Weintraub *et al.* (1986) as the cause of discrepancies when results from the strategic model are taken into account in disaggregated models at lower levels.

The use of monolithic models is a straightforward way of addressing the discrepancy problem. Since the strategic and tactical issues are handled in the same model, this approach does not induce spatial discrepancies. The approach of Weintraub and Navon (1976) is quite aggregated and uses a subdivision of strata into access zones instead of individual stands. McNaughton *et al.* (1998) retains stand identities in the tactical part of the plan but uses strata in the strategic part.

The spatial discrepancy problem is primarily associated with the top-down approaches. One of the more elaborate methods of addressing the spatial (and other) discrepancies in this setting is to use top-down bottom-up approaches iteratively, starting with a top-down process. Weintraub and Cholaky (1991) used stands aggregated into macro areas at the strategic level and stands at the tactical level and tried to modify the strategic plan using the road building plans from the tactical level to define new strategic road building sequences, and thereby stand selections, in an iterative process. Cea and Jofré (2000) used cluster analysis based on stand properties to create strategic macro stand management units. These are disaggregated to stands at the tactical level. By using stand properties and tactical-level information on harvest costs, transportation and returns, new macro stands can be formed and the strategic problem resolved. This procedure can be repeated in an iterative process to try to reduce the differences between strategic and tactical planning levels. The approach of Nelson *et al.* (1991) could be defined as an iterative approach using only one iteration. The strata based strategic plan provides volume and net revenue targets. The tactical second phase operate on harvest units manually delineated based on the "age class distribution of the forest". A simulation procedure identified five feasible tactical plans, which were bottom-up fed to a third stage. In the third stage, the strata area allocated in a strategic model similar to the first phase, is forced by constraints to equal the area specified by the tactical stand based plan.

Many top-down systems are not very elaborate in their management of spatial discrepancies. Often a surplus of stands is selected more or less subjectively or given some priority function. Another approach is to use all stands in the tactical planning phase. Regardless of the approach, the systems strive to fulfill some strategic goal, such as harvest volume, as closely as possible. Davis and Martell (1993) subjectively delineate harvest blocks for the tactical planning phase and note that "a surplus of harvest blocks was delineated to provide flexibility to the tactical model". Tactical area selection is not constrained, as in Nelson *et al.* (1991). The top-down method by Weintraub *et al.* (1986) uses macro stands aggregated from individual stands at the strategic level and all stands at the tactical level, and does not explicitly address the spatial discrepancy issues. The tactical planning approaches by Nelson and Brodie (1990), Yoshimoto (1996) and Richards and Gunn (2000), used all stands and no area targets for tactical planning. The systems of Covington *et al.* (1988) and Church *et al.* (2000a) used all stands but is not specific about which targets should be specified by the user. The tactical models of Church *et al.* (2000b) used strategic model data in the form of strata within predefined zones. The tactical models used goal programming to allocate the zone/strata areas to finer scale subunits with as little deviation as possible from the areas allocated in the strategic plan. The simulation-based tactical planning approaches by Jamnick and Walters (1993) used all stands and no area targets, when given seven different priority measures for scheduling stands to different periods. Sessions and Sessions (1992) also use priority functions and no area targets. Eriksson (1987) tested three priority measures and used these to select stands to fulfill strategic strata-based plan.area outputs.

The bottom-up approach avoids spatial discrepancies since it builds an upper-level solution from feasible lower-level, often stand-based, solutions. The approaches by Yoshimoto *et al.* (1994), Baskent and Jordan (1991) and Kurttila *et al.* (2001) are examples of stand-based bottom up approaches. The bottom-up approach by Davis and Liu (1991) uses data from existing plans of several landowners without specifying their spatial resolution.

Temporal discrepancies

The second matter that may be considered as a possible source of inconsistencies is that the tactical planning phase in the traditional hierarchical planning setting is often conducted without knowledge of the temporal dependencies ahead in time. This problem occurs because the tactical planning time horizon is often much shorter than the strategic time horizon. All actions in forestry have effects on long-term development (Jacobsson, 1986), and so actions taken in the first years may affect the actions to be taken later.

In Sweden, for example, where objective methods for data acquisition for strategic planning are traditionally used (Eriksson and Lämås, 2003), temporal rather than spatial discrepancies is the main issue. Planning with the forest management planning package (Jonsson *et al.*, 1993) is based on a stratified sample of stands. Calculations on these stands are made to establish harvest levels and thinning quotas that are deemed feasible and in compliance with company strategies and policy. Stands are selected for tactical planning using priority functions to fulfil the harvest levels of the first period established with the forest management planning package. Means of prioritizing without linkage to the strategic plan can be used (Ericsson and Westerling, 1981). A link between the sample stands of the strategic planning phase and the total set of stands used in the tactical phase can be established using regression functions and the concept of inoptimality losses (Jacobsson, 1986). For the sample stands, the inoptimality loss incurred by harvest shifts can be calculated. Given selected stand characteristics as independent variables, regression functions using the inoptimality losses as the dependent variable can be established for the sample stands. The problems that can arise are temporal discrepancies. When using inoptimality losses, the long-term effects of the selection of stands are only statically known, given that the marginality assumptions hold. That is, the changes implied by the stand selection at the tactical level are not so large as to require a recalculation of the strategic plan. When prioritizing without linkage to the strategic plan, the long-term effects are unknown. In either case though, the harvest volumes targets of the first strategic period can probably be met through a thorough selection of stands.

The monolithic models by Weintraub and Navon (1976) and McNaughton *et al.* (1998) address this problem by the problem formulation itself, since the monolithic approach incorporates both strategic and tactical time scales in a single model.

The iterative top-down bottom-up process of Cea and Jofré (2000) addresses this problem as the data are fed from the bottom up to the strategic level. When the strategic problem defined by the bottom-up process is solved, the consequences of the actions at the lower level affect the strategic decisions. The models of Nelson *et al.* (1991) and Davis and Martell (1993) explicitly model the strategic problem as a part of the tactical model. Weintraub and Cholaky (1991) and Weintraub *et al.* (1986) also incorporate the strategic issues and time horizon in the tactical model. The one-level tactical models of Covington *et al.* (1988), Nelson and Brodie (1990), Sessions and Sessions (1992), Jamnick and Walters (1993), Yoshimoto

(1996), Church *et al.* (2000a,b) and Richards and Gunn (2000) do not explicitly address this issue. Richards and Gunn (2000) may have addressed it through their lost volume concept. However, this is not described in detail in their paper. Eriksson (1987) uses priority functions based on the reduced cost of the strategic plan and thus takes into account the long-term effect statically, given that the marginality assumptions hold.

Yoshimoto *et al.* (1994) and Baskent and Jordan (1991) address this issue bottom up, as harvest levels are built using lower-level information. The solutions are built by allocating harvests stepwise, moving ahead from period to period until a feasible harvest level for the entire planning horizon is found. The bottom-up goal programming approaches by Davis and Liu (1991) and Kurttila *et al.* (2001) also do this since the long-term effects are incorporated into the decision variables.

Discrepancies due to different levels of constraint

Decisions at the tactical level of planning require the consideration of more, or other, criteria than those used in strategic planning. The consequences of this are noted briefly by Nelson *et al.* (1991) in a discussion on the differences in net present values in their models. They note that a more constrained problem may reduce the timing choices of the algorithm used, leading to a decrease in the feasible region and thus lowering the optimal objective function value. However, as models are disaggregated at lower levels, the additional flexibility implied by this may lead to a higher objective function value than that obtained from the aggregated strategic-level model. This has been noted by some authors of articles referred to by Bare (1996). Thus, it could be argued that the consideration of more criteria and spatial and temporal disaggregation are related in that they affect the degree to which models are constrained. More criteria obviously constrain a model, whereas disaggregation introduces more variables and thus relaxes the model. This could explain the counteracting effects on the objective function value noted by Nelson *et al.* (1991) and Bare (1996).

Disaggregation can be either spatial or temporal. The spatial case has been the main issue of many studies, and different approaches to managing the discrepancies are discussed above under the heading spatial discrepancies. In the temporal case, it is unclear whether the discrepancies are to be regarded as problematic or merely a consequence of the model structures used in hierarchal modeling. The same may probably be said about the criteria-induced discrepancies. None of the articles referred to in the previous text focus explicitly on temporal disaggregation or the consideration of more or other criteria as a main problem.

A monolithic approach is likely to address these issues because all information is available to both planning levels at all times. A top-down approach will not address these issues. Ways of managing the problems of additional constraint in this setting include the provision of more silvicultural alternatives and/or a surplus of stands to schedule (Davis and Martell, 1993) at the tactical level. Relaxation of target levels to be attained (Weintraub *et al.*, 1986; Weintraub and Cholaky, 1991;

Davis and Martell, 1993) may also provide the ability to attain a high objective in spite of constraints. On the other hand, if the constraints are viewed as goals, discrepancies with respect to these are likely to occur. The creation of several tactical plans, and building the strategic plan from these in a pure (Davis and Liu, 1991; Kurttila *et al.*, 2001) or combined top-down bottom-up (Nelson *et al.*, 1991) process also provides the ability to attain a high objective in spite of constraints. The bottom-up approaches that build harvest levels using lower-level information in a simulation procedure (e.g., Yoshimoto *et al.*, 1994; Baskent and Jordan, 1991) should provide no discrepancies, since, when the simulation stops, the result in case is the strategic. On the other hand, a study of Boston and Bettinger (2001) indicated that heuristic approaches may benefit from top-down guidance.

A review of some approaches to an integrated forest planning

The field of hierarchical planning is very heterogeneous with respect to the focus of the articles/models presented. Applications to company, government and nonindustrial private forests can be found, and there are national aspects that further reinforce the perceived diversity. For example, the time horizons and temporal resolutions used vary considerably. In addition, there are articles explicitly dealing with strategic and tactical-level models, whereas others deal with the tactical-level models only, given a preceding strategic output. Given this heterogeneousity, as noted above, one way to generally classify the integrated planning approaches is according to the information flow into monolithic, top-down or bottom-up approaches. Several approaches to integrated planning have been tested and reported along these lines in the literature, as could be noted from the preceding paragraphs, and some of this work is briefly outlined in the following literature summary. Given the diversity and large amount of literature, the summary cannot claim to be comprehensive. Rather, it should be viewed as a compilation of some central work in the field reflecting the three approaches outlined above.

Monolithic approaches

An early attempt to integrate silvicultural and transportation activities was presented by Weintraub and Navon (1976). The mixed integer monolithic model is strata-based, and further subdivided into access zones which are defined by the nodes in the road network. Time is aggregated into 10-year periods. The exact time horizons used are not reported. Instead, the authors note that the road network and budget constraints are taken into account for the few first decades only, whereas silvicultural constraints are taken into account for a longer period. Transportation can take place on a priori defined routes, and parts of the road network not constructed need to be constructed if a route is to pass through. Construction or upgrading to different standards is not incorporated into the model, even though ways of dealing with this problem are presented. The objective is NPV maximization. Results from a small case study on nine management units showed that, compared with sequential harvest scheduling followed by road planning, the integrated model yielded a 7 percent higher NPV, of which 6 percent was attributable to reduced road building costs.

McNaughton *et al.* (1998) used a monolithic mixed integer approach. Temporal resolution is one year, using a six-year tactical time horizon and a 30-year strategic time horizon. The model used stands during the tactical part of the time horizon and strata during the strategic part. NPV maximization subject to constraints concerning adjacency and road building were implemented. The model structure and the solution process are tightly knit. Column generation and constraint branching were used to speed up the solution process. The model was tested on a 7365 ha area.

Top-down approaches

The description below is divided into two-level approaches (strategic and tactical) that describe both strategic and tactical-level models, and one-level approaches (tactical) that describe only the lower-level model, operating on data that is assumed to be given by a preceding strategic-level process.

Two-level approaches

Eriksson (1987) used treatment indices built on strata-based long-term plan information to maintain the connection between this and the tactical stand-based plan in a top-down hierarchical setting. Strata are formed from stands based on a fuzzy clustering on stand characteristics. The planning horizon is 70 years divided into five-year periods. Maximization of NPV or harvest level, subject to nondeclining harvest constraints, was used in different cases. The membership of stands in clusters is used to calculate two of the indices. The first index is based on the primal information; share of the strata allocated to a treatment and the class membership. The second index is based on the dual information; reduced cost of the allocation of a stratum to a treatment and the class membership. The third index is similar to the second but omits part of the dual information concerning strata area and is based on stand information rather than strata ditto. The indices were used to prioritize stands over individual years of a five-year time horizon. A test case of 568 stands divided into 30 strata was used. The results of this prioritizing were compared with those from an operative linear programming (LP) model. The third stand-based index performed best in terms of similarity in stand ranking to the LP model.

Weintraub *et al.* (1986) present a top-down hierarchical approach. Strategic model spatial resolution refers to macro stands that are formed by aggregating the original stands. The strategic management alternatives are created by using a weighted aggregation process described by Zipkin (1980a,b,c). This process produces no error in aggregation if optimal weightings are used. These cannot be known a priori, and thus weights were defined proportionally to the area of stands. More problems concerning this procedure are discussed in Cea and Jofré (2000).

Variable temporal resolution is applied. One-year periods are used to reflect the importance of timing in early investments. Longer periods are used toward the end of the planning horizon. Industry investments and timber management are modeled. The structure of the tactical model is similar to that of the strategic model. Spatial resolution is individual stands, and timber management and plant production are considered as well as more detailed access constraints, etc. (The mathematical formulation of the tactical model is not explicitly presented.) A deviation of 10 percent from strategic volume targets is allowed. The model was tested on a 255 stand, 75,000 ha case area of plantation forest. The difference between original (tactical) and aggregated (strategic) problem objectives was 4 percent.

Three models are used in the top-down, bottom-up hierarchical approach in Nelson *et al.* (1991). First, a strata-based long-term (15 ten-year periods) model is solved using linear programming and a model I (Johnson and Scheurmann, 1977) formulation. NPV maximization, subject to constraints on ending inventory and even flow of volume and money, was applied. Second, an area-based plan for the first three decades, taking adjacency constraints into account, was created using Monte Carlo Integer Programming. The strata-based model NPV and volume results for the first three periods provided targets that were to be met within a 10 percent tolerance. The MCIP procedure was performed for each of the three decades in sequence, invoking adjacency routines and road building routines given the harvest plans. Third, a model similar to the first stage was constructed to evaluate the long-term effects on harvest volume and NPV of the adjacency constraints. In order to incorporate the results from the area-based second stage, so-called coordinated allocation choices (CACs) that contain the harvested area of each analysis area were formed. These CACs form additional decision variables that are bottom-up fed to the third stage, which apart from the CACs, is similar to the first stage. Constraints on the CACs and the strata, force the necessary strata area into the solution. In addition, CACs activate the associated road building cost in the objective function. The 4000 ha case study area was divided into 62 strata at level 1, and 45 harvest units and 52 road projects were used to create the CACs at level 2. Results showed that the strata-based level 1 model overestimated the total and long-term NPV (at most, 9 percent deviation for the worst CAC). Underestimation was shown for harvest volume (at most, 3 percent deviation for the worst CAC).

Weintraub and Cholaky (1991) use two models together in a combined top-down and bottom-up iterative hierarchical approach. In the strategic model, the forest is divided into zones. In the zones, stands are aggregated into “macro areas” using aggregation on stand characteristics. Time is aggregated into three periods. Road building is represented by continuous variables representing a fraction of a sequence of roads built, affecting possibly all zones. NPV maximization subject to nondeclining harvest constraints and constraints on nontimber issues such as sediment load and recreation is used. At the tactical level, stands and roads are modeled in their disaggregated form, with roads being integer variables. Time is disaggregated into 12 periods. (Note that nothing is said about the length of the periods at either level.) The harvest volume, sediment and recreation outputs from the strategic level are used as targets. Deviations from these targets in the order of 10 percent are allowed. Top-down data flow is used initially, but, to improve the consistency between the two levels, information on the tactical-level road building plans could be fed bottom-up from the tactical to the strategic level to modify the strategic ditto and begin a new iteration. This iterative process was reported to improve consistency, although the extent of improvement was not reported. Some manual elements need to be introduced in the process. Continuous road building variables at the strategic level can lead to the financing of only part of a road needed to reach an area; this is adjusted manually. A heuristic process for rounding off fractional integer variables at the tactical level is also performed manually, although an automated approach was under construction. Although not stated explicitly, bottom-up data flow appears to be a manual process. The case study area comprised six zones containing up to 14 stands aggregated into up to five macro areas. Results showed that the level 1 model underestimated the total NPV (about 3.2 percent deviation) and harvest volume (about 1.6 percent deviation).

Davis and Martell (1993) presented a strategic model and a combined strategic–tactical model used together in a top-down hierarchical manner. The strata-based strategic model uses 10-year periods; the tactical model uses one-year periods in the first 10 years and 10-year periods in the later periods. Both are solved using linear programming. After running the strategic model, the stands in the timber strata used in the first 10-year period plus additional areas are subjected to tactical planning, where considerations such as working block size and delineation, access to roads and 'vegetative diversity' are manually handled by the planners in the GIS environment. The additional area was used to provide the model with extra flexibility in selecting good working block layouts. Constraints link the working block areas to the strata-based, temporally aggregated, strategic part of the plan. Maximizing harvest volume was set as the goal, subject to constraints on the silvicultural budget, ending inventory and even flow of volume. A 90,000 ha case study area was used. The number of strata used for strategic planning was not presented, and 47 working blocks were delineated for the tactical planning phase. The results showed small differences in harvest volume (at most, about 3 percent) between the planning levels over a range of silvicultural budgets.

Cea and Jofré (2000) present a hierarchical system using a combined top-down and bottom-up iterative approach. The first-level strategic MIP handles a long-term harvest problem (NPV maximization), including industry complex building and location. Cluster analysis based on stand properties is used to create strategic macro stand management units. The time horizon is 45 years divided into three-year periods. The second level handles the tactical aspects in the first four three-year periods. The macro stands selected in the strategic plan are disaggregated to stands. Road building and upgrading and the costs of transportation in the road network are considered. The tactical level model is solved by using simulated annealing (SA) to find a solution to the road building part of the problem. Given this solution, the continuous harvesting and transportation part of the problem is solved, after which an algorithm called the secondary algorithm that utilizes the tree structures defined by the flow in the road graph is used to improve this solution. Given the solution to the tactical problem in the form of harvest costs, transportation and returns and stand properties, a new, less aggregated clustering of stands into strata is computed for the first period and used to reformulate the strategic plan in a bottom-up manner. There is no connection between the tactical problem and the following strategic decisions at runtime when the tactical problem is solved. The authors note that, once a new (bottom-up defined) strategic problem is solved, tactical information can be transmitted to the following periods. The model was tested in a case consisting of 1151 stands (36 macro stands). Results of a comparison of strategic and tactical model outputs for the first period in the form of harvested area, harvest cost and transport cost yielded 1.8, 4.6 and 2.0 percent deviations, respectively.

The following three approaches by Boston and Bettinger (2001), Kurttila *et al.* (2001) and Kurttila and Pukkala (2003) utilize top-down as well as other approaches. They are placed here to avoid separating their descriptions.

Boston and Bettinger (2001) compared a top-down and a monolithic approach for addressing harvest scheduling with adjacency and habitat constraints. The top-down approach utilizes an LP model to determine volume targets while maximizing NPV subject to no spatial constraints. The second-level model used tabu search to also incorporate the spatial constraints and the volume targets. The monolithic approach used the tabu search process to determine the harvest schedule, including the spatial constraints without exogenous volume targets. A 15-year time horizon and temporal resolution of one year was used. Spatial resolution was stands at both levels. The corporate pine plantation case study area was divided into 700 stands. The results indicate that the top-down approach yielded higher NPV than did the monolithic approach.

Top-down, bottom-up and integrated approaches to the planning of multiple private forest owner properties was tested by Kurttila *et al.* (2001). A planning horizon of 30 years divided into 10-year periods was used. Spatial resolution was stands at both levels. The landscape goal was to increase the area of old forest and growing stock, while holding goals were to maximize NPV. Goal programming methodology was used. The top-down approach ignored holding-level goals. Instead, the goal was to minimize the deviation from the landscape goals. The bottom-up approach utilized five plans for each holding and, given these, minimized the deviation from the landscape goals. The integrated approach minimized the deviations from both holding and landscape goals. A case of 39 holdings in a total 1486 stands over a 1884 ha area was used as a test case. The approaches produced quite similar results.

Kurttila and Pukkala (2003) addressed the issues of integrating the utility maximization of private forest owners with maximization of forest-level utility. Forest-level and holding-level goals were assigned different weights in the same objective function, and the problem was solved using SA. Thus, it is difficult to categorize the approach since the categorization depends on the weights. Three different weight settings were tested. The reference plan is probably best described as a bottom-up approach since it put no weight on the forest-level objectives. The integrated plans put weight on both forest-level and holding-level objectives and is probably best described as a monolithic approach. The last case put all weight on the forest level and, since individual holdings are assigned no weight, the results from the planning process are applied to them in a top-down manner. The planning period was divided into three 20-year periods and spatial resolution was stands. Six cases of 200–800 stands each were tested. The results indicated that the forest-level objectives only marginally affected the holding-level objectives.

One-level approaches

Kirby *et al.* (1986) present a general model formulation (IRPM) that incorporates harvest decisions as well as a network for stream sediment transport and road networks with upgrading options for each road segment. Traffic volume is regulated by the capacity in the road network. The spatial resolution is loosely described as “contiguous land parcels”. Nothing is explicitly mentioned about time horizons or resolution. Likewise, nothing is explicitly mentioned on how the model is related to the strategic plan. The model is a mixed integer problem, and a rounding heuristic is recommended for larger problem instances. Weintraub *et al.* (1995) devised a heuristic process (HIP) that iteratively fixed continuous variables to integer values in an IRPM model described by Kirby *et al.* (1986).

Covington *et al.*’s (1988) TEAMS system is a tactical planning system based on mixed integer programming. Stands are the spatial unit. Different versions of the model exist, dealing with different temporal resolutions and horizons. Versions utilizing 10 one-year periods and six five-year periods are reported. Stand treatment may be determined by the user, the system, or a combination. Several options for objective functions and constraints can be specified.

Nelson and Brodie (1990) used a random search procedure (and compared it with mixed integer programming) to solve a tactical harvest scheduling problem with adjacency constraints and road building. A 30-year planning horizon divided into three 10-year periods is considered. Volume and net revenue targets are exogenously given from the strategic plan developed using FORPLAN. No explicit linkage to the strategic plan is used. In the test case, 45 stands and 52 road projects are used.

Sessions and Sessions’ (1992) SNAP system is intended for tactical planning and takes into account road activities, harvesting system and habitat control. Spatial resolution is parcels that are delineated as part of the planning process. One to four periods, from two to 20 years in length, are used. SNAP has been further developed and Anon. (1994) reported that the number of periods had been increased from four to 30. The scheduling method is a periodwise greedy method that, given a priority queue, schedules blocks for each period until the strategic volume target is met, after which it moves on to the next period.

Jamnick and Walters (1993) used FORPLAN for modeling a strategic plan with 14 five-year periods. Maximization of the harvest volume in the first period, subject to nondeclining yield, ending inventory and budget constraints, was used. The CRYSTAL simulation algorithm was used to allocate stands to harvest blocks, given the prerequisites from the strategic plan for the first six periods. An allowed deviation in harvest timings of ±1 year was used. The model was tested on a case area of 17,458 ha and 3241 stands, divided into 57 strata for the strategic planning phase. Results from a number of runs using different parameter settings indicated that more than 80 percent of the area indicated by the strategic plan could be allocated.

Yoshimoto (1996) used mixed integer programming applied to a heavily constrained tactical problem. Road building, transportation and harvest equipment usage are among the included constraints. The time horizon was five years, and a very small test case of six stands and 18 roads was used to test the model. No explicit linkage to the strategic plan is stated.

Richards and Gunn (2000) address the tactical planning problem with a tabu search method. Harvest scheduling, road access and adjacency constraints are considered simultaneously. The road links needed to access harvest sites were constructed in response to the decisions to harvest. Road construction cost was weighted to analyze the tradeoff between road construction and productivity. Volume targets were exogenously given from the strategic plan. The model was tested on a forest area divided into 1035 stands and 135 road segments. The planning horizon was 20 years divided into four five-year periods. Further discussion on the design of the tabu search algorithm is presented in Richards and Gunn (2003).

Church *et al.* (2000b) present two models for translating strategic strata-based results from FORPLAN or SPECTRUM, to tactical area-based plans. The models are based on goal programming, where the first (BAM1) attempts to minimize the deviation of assigned area from the strategic targets and the second (BAM2) minimizes the deviation from strategic goals. Constraint sets are used to maintain the strategic plan allocation of treatments to zones when these are subdivided into subunits in the first model. No case study is presented, and nothing is mentioned about the temporal resolution. Two versions of the BAM2 model are implemented in the RELM decision support system (Church *et al.*, 2000a). These versions are intended for: 1. minimizing the area utilized in the disaggregated tactical plan, while still complying with the strategic goals; and 2. spreading activities over as much of the area as the strategic and tactical goals allow.

Bottom-up approaches

Baskent and Jordan (1991) present a simulation model. Stands are the spatial unit. The formation of harvest blocks is central and is done by taking into account the stands' relative positions and constraints on block sizes. Adjacency and road costs are also taken into account in the simulation process. The harvesting rules formed are based on these considerations, and are used to place the harvest blocks into a priority queue from which blocks are selected periodwise until the harvest level of a period is reached. Then, the process continues in the next period. If the harvest level cannot be sustained, the process is repeated using a lower level, which turns the model into a bottom-up type. In a test example, a time horizon of 80 years was used for a 72,526 ha area divided into 9640 stands.

Davis and Liu (1991) present generalized bottom-up models for integrating the planning of multiple owners. Models are formulated as integer programs where the variables are known plans for each owner. A variety of ways to manage the local and global goals is identified. Temporal resolution was 10 years, and five periods were used. A test case on 17 national forests was run, and six to 11 plans were developed for each forest, constituting the integer decision variables in the model. Budget constraints, recreation, wilderness, etc. were taken into account.

Vertinsky *et al.* (1994) present a hierarchal system using a combined top-down and bottom-up iterative approach. Their visionary paper focuses on the participatory aspects of planning and the planning process rather than mathematical methods. The system consists of a province-wide market simulation model or an LP harvest model that, via charges and subsidies, is linked to regional systems. These use LP for timber supply planning. The LP model is augmented by a forest estate simulation model in which several submodels are suggested in order to incorporate nonlinear relationships such as wildlife and recreational concerns. The results from the simulation model are evaluated by a panel of stakeholders. Stakeholder values and results from the simulation models are used to modify the coefficients in the objective function and constraints of the regional LP model. Nothing is explicitly stated about the spatial or temporal resolution or horizons used. The system was tested to evaluate the effect of cutting plans on wildlife resources in British Columbia; however, no explicit figures were presented on the effects and differences between the planning levels.

Yoshimoto *et al.* (1994) used a heuristic bottom-up approach to address the long-term harvest scheduling problem of maximizing NPV subject to adjacency constraints and even-flow considerations. A combination of algorithms named PATH and ROHO is used. Given an even-flow level, the ROHO algorithm solves a subproblem of minimizing the deviations from this even-flow level. Even-flow levels are increased between iterations subject to certain criteria. The ROHO algorithm adopts a one period lookahead to generate solutions that are spatially feasible for at least that period. Solutions to the regional subproblems are then delivered to the PATH algorithm that solves the global problem of maximizing NPV. Thus, the method employs a bottom-up data flow. Two cases were tested. The first was the same area as in Nelson *et al.* (1991) of 109 stands of which 45 were used. The second was a 137-stand area. Temporal resolution was 10 years and time horizons from 10 to 100 years were used. Solutions were allowed to deviate 3 percent from the even-flow level. Even-flow level was specified manually and increased by a percentage as feasible solutions were found during the solution process. The results indicated that worst case fluctuations from the even-flow level were 2.93 percent and 2.07 percent for the first and second case, respectively.

Summary of papers

Paper I

In an integrated planning environment that is based on the stand as the unit of decision, the models become very large; subsequently, there is a need to reduce the size of the model. This is especially true when a monolithic approach to the problem is used. One way to reduce the model size is to aggregate time into longer periods, or aggregate small spatial units, such as stands or pixels, into strata. Studies by Williams and Yamada (1976), Eriksson (1983) and Weintraub *et al.* (1997) address the latter issue. Temporal aggregation is largely unstudied and thus the aim of paper I is to analyze the consequences of temporal aggregation in integrated and strategic planning.

The integrated models can be classified as monolithic according to the data flow-based classification scheme used above. For reference, strategic models are also used. The integrated model objectives are to maximize the net present value from harvest operations less a penalty for accessing stands. A penalty concept using binary variables is used to cluster harvest activities within the tactical part of the second level. A set of stands is assigned to a segment of the road network using GIS analysis. The segment is modeled using a binary penalty variable that is forced to take on the value of one if there is to be activity in the set of assigned stands in a period or season and for one machine system. Strategic constraints on nondeclining even-flow and ending inventory and tactical constraints on log assortment even flow are incorporated. Models are formulated using a model I (Johnsson and Scheurmann, 1977) structure and the spatial resolution is stands throughout the planning horizon. The tactical planning horizon used is five years subdivided into three seasons, whereas the strategic planning horizon is 100 years using different period lengths according to the aims of the study. Both equal and variable period lengths are used. Equal length periods range from one 95-year period to 19 five-year periods. Variable length periods are established using a second-degree polynomial, to create periods that are shorter in the close future and longer further ahead in time.

Two case study areas are used. An area in northern Sweden owned by SCA consisting of about 45,000 ha divided into 5129 stands was used to test the models at sites of lower productivity, fewer treatment schedules and larger areas. An area in southern Sweden owned by HOLMEN consisting of 5900 ha and divided into 2276 stands was used to test the models at sites of higher productivity, more treatment schedules and smaller areas. Cases using relaxed nondeclining flow and log assortment flow constraints were tested. The models were solved as linear and mixed integer programs using ILOG CPLEX 8.0.

Results are presented on NPV, harvest volume, thinning proportions, ending inventory age class structure and the set of stands to be harvested in the first three years. The results indicate that outputs from strategic and integrated plans are not particularly affected by the number of equal length strategic periods when more than five periods, i.e. about 20 year period length, are used. When modeling the strategic and integrated problems using variable-length periods, care should be taken to ensure that harvest operations late in the planning horizon get enough timing options to be adequately described. Using too few periods could lead to harvest profiles and consequently forest characteristics that differ from the more consistent solutions achievable when using equal length periods. The problems were mostly insensitive to variations in the tested tactical- as well as strategic constraints. We further conclude that the integrated model used in this study produced results similar to that of the strategic models and that the integrated models appears to have good properties in terms of solution time. Rather, computer memory seems to be the limiting factor.

Paper II

The integrated planning concept presented in paper II takes its standpoint in a practical problem facing decision makers in forestry, i.e., the clustering of harvest activities in tactical planning. These issues are currently managed manually using GIS systems (Söderholm, 2000). That is, there is no decision support system based on mathematical programming that helps managers select stands and at the same time keep track of how the previously determined strategic plan outputs are affected.

The study presents a two-level top-down approach to the integrated planning problem, focusing on the clustering of tactical harvest activities. At the first level, a stand-based strategic plan without spatial considerations is used to partition activities into a tactical and a strategic set. The tactical set is the stands that have activity during the first 10 years, and the strategic set is complementary. Partitioning serves two purposes. First, it prohibits harvests allocated to the first 10-year period by the strategic plan from being shifted out of this period during tactical planning. Second, it reduces the number of harvest operations that need to be considered during the tactical part of the integrated second level. At the second level, another stand-based model takes into account both long-term strategic and shorter-term tactical forest management decisions for the partitions. The second-level model objectives are to maximize the NPV from harvest operations less the penalty of accessing stands. The constraint sets used are similar to those in paper I.

Model I (Johnsson and Scheurmann, 1977) structure is used at both levels. Temporal resolution for the first-level model is 10 years throughout, whereas, in the second-level model, the first 10 years are disaggregated into individual years with three seasons per year. The same penalty concept using binary variables as in paper I is used to cluster harvest activities within the tactical part of the second level. A set of stands is assigned to a segment of the road network using GIS analysis. The segment is modeled using a binary penalty variable that is forced to take on the value of one if there is to be activity in the set of assigned stands in a period or season and for one machine system. A range of penalty weights was tested to investigate the effects of clustering of tactical harvest activities on the model outputs.

The approach was tested on a full-scale case. The area is the same area in northern Sweden, owned by SCA, as in paper I consisting of about 45,800 ha and divided into 5129 stands. The models were solved as mixed integer programs using ILOG CPLEX 8.0.

Results show that it is possible to use the approach to cluster harvest activities at the tactical level in a full-scale forest management scenario. Results from the case study revealed that the number of clusters created declined toward a minimum level as weights were increased. The results on NPV from harvest, harvest volume in total and in tactical periods indicate small effects of assigning different weights to clustering of harvest activities. The case results also indicate that there were only very small discrepancies between the two planning levels in terms of differences in harvest volume.

Concluding remarks

This thesis approaches two of the three discrepancies often found in hierarchical planning: spatial discrepancies, temporal discrepancies, and discrepancies due to different levels of constraint. To address the spatial discrepancy, the same spatial resolution has been used, i.e., stands. Temporal discrepancies are addressed by modeling the tactical and strategic issues simultaneously. The discrepancies due to different levels of constraint are viewed as a consequence of the model structures, as in most articles noted above.

The results of paper I provide information on what temporal resolutions could be used. The head-on approach used in paper I could produce models that are very large, and paper II provides a two-stage procedure that can reduce the number of variables and preserve the allocation of stands to the first 10 years provided by a strategic plan.

The entities by which to represent the forest is an issue in the integration of planning levels, and several of the approaches to the integrated planning problem deal with different spatial resolutions. As noted, stand-level information is used for both strategic and tactical purposes, which is an approach that has both drawbacks and benefits. On the upside is that such an approach is likely to produce a more effective connection between the planning levels, in the sense that the selection of stands for tactical planning becomes a direct consequence of the strategic plan (Ståhl *et al.*, 1994). Also on the upside is that aspects other than the traditional harvest-level calculations could be incorporated at the strategic level of planning. For instance, biodiversity-related spatial issues or methods for long-term clustering of harvest activities (Öhman and Lämås, 2000) could be employed. A downside is that the data in the stand register could be of low quality (Gustafsson *et al.*, 2000) because the data are currently acquired using subjective methods. However, developments in the field of remote sensing may yield stand-level data of higher quality and perhaps more cost effective data acquisition as well.

References

Andersson, S. 1971. Modeller för långsiktiga driftsplaner I skogsbruket. *Forskningsssstiftelsen Skogsarbeten*. *Meddelande no. 7*. Stockholm. (In Swedish.)

af Ström, I.A. 1829. *Förslag till en förbättrad skogshushållning i Sverige*. Kungliga Lantbruksakademin, Stockholm, 299pp. (In Swedish.)

Anon. 2004. *Skogsstatistisk årsbok*. Skogsstyrelsen. Jönköping. ISBN: 91-88462-61-7. (In Swedish.)

Bare, B.B. 1996. Hierarchical forest planning: Some general observations. In: Martell, D. L., Davis L.S. and Weintraub, A. (eds), *Proceedings of a workshop on hierarchical approaches to forest management in public and private organizations. Petwawa National Forestry Institute*. Information Report PI-X-124. ISBN 0-662-24108-8.

Baskent, E.Z. and Jordan, G.A. 1991. Spatial wood simulation modelling. *Forest Chronicles* 67:610–621.

Boston, K. and Bettinger, P. 2001. Development of spatially feasible forest plans: A comparison of two modelling approaches. *Silva Fenninca 35(4)*:425–435.

Camenson, D.M., Sleavin, K.E. and Greer, K.D. 1996. SPECTRUM: An analytical tool for building natural resource management models. In: Päivinien, R., Riohuvuo, L. and Siitonen, M. (eds), *Large scale forest scenario models: experiences and requirements. Proceedings of the International Seminar and Summer School*, Joensuu, Finland. EFI Proceedings No 5:133–141.

Cea, C. and Jofré, A. 2000. Linking strategic and tactical forestry planning decisions. *Annals of Operations Research 95*:131–158.

Church, R.L., Murray A.T., Figueroa, M.A. and Barber K.H. 2000a. Support system development for forest ecosystem management. *European Journal of Operations Research 121*:247–258.

Church, R.L., Murray, T.M. and Barber, K.H. 2000b. Forest planning at the tactical level. *Annals of Operations Research 95*:3–18.

Covington, W.W., Wood, D.B., Young, D.L., Dykstra, D.P. and Garrett, L.D. 1988. TEAMS: a decision support system for multi resource management. *Journal of Forestry 86(8):*25–33.

Dantzig, G.B. 1963. *Linear programming and extensions*. Princeton University Press, New Jersey.

Davis, L.S. and Liu, G. 1991. Integrated forest planning across multiple ownership and decision makers. *Forest Science 37(1)*:200–226.

Davis, R.G. and Martell, D.L., 1993. A decision-support system that links short-term silvicultural operating plans with long-term forest-level strategic plans. *Canadian Journal of Forest Research 23*:1078–1095.

Davis, L.S., Johnson, K.N., Bettinger, P.S. and Howard, T.E. (eds) 2000. *Forest management*. McGraw Hill. New York. 804pp. ISBN 0-07-032694-0.

Eriksson, L.O., 1983. Timber class formation by cluster analysis. *Swedish University of Agricultural Sciences, Department of Forest Technology*. *Report No. 157*. Garpenberg, Sweden.

Eriksson, L.O. 1987. Ranking stands with treatment indices. *Scandinavian Journal of Forest Research 2*:239–251.

Eriksson, L.O. and Lämås, T. 2003. Analysis and planning for multiresource sustainable forestry: The Heureka research programme at SLU. *Canadian Journal of Forest Research 33*:500–508.

Ericsson, O. and Westerling, S. 1981. Skoglig planering – Nuläge och tendenser. *Forskningsssstiftelsen Skogsarbeten. Redogörelse no. 3*. Stockholm. (In Swedish.)

Epstein, R., Morales, R., Seron, J. and Weintraub, A. 1999. Use of OR systems in the Chilean forestry industry. *Interfaces 29(1)*:7–29.

Faustmann, M. 1849. Calculation of the value which forest land and immature stands possess for forestry, *Journal of Forest Economics 1(1)*, 1995, republished with permission from Commonwealth Forestry Association. The original article “Berechnung

des Wertes welchen Waldboden sowie noch nicht haubare Holzbestände für die Waldwirtschaft besitzen", was published in Allgemeine Forst- und Jagdzeitung 15.
Fries, C., Carlsson M., Dahlin, B., Lämås, T., and Sallnäs, O. 1998. A review of conceptual landscape planning for multiobjective forestry in Sweden. *Canadian Journal of Forest Research 28*:159–167.
Fritzböger, B. and Söndergaard, P. 1995. A short history of forest uses. In: Hytonen, M. (ed.), *Multiple use forestry in the Nordic countries*. The Finnish Forest Research Institute. pp.11–42.
Gustafsson, K., Larsson, M., Källman, U. and Eriksson, L.O. 2000. Logistical Determinants for Timber Harvesting Schedule – accounting for geographical aspects in medium term forest planning. In: Sjöström, K. (ed.): *Logistics in the Forest Sector*. Proceedings of the First World Symposium on logistics in forest sector May 15–16 2000, Helsinki. IUFRO and University in Helsinki. Helsinki.
Jacobsson, J. 1986. *Optimization and data requirements – A forest management planning problem*. Section of mensuration and management, Swedish University of Agricultural Sciences. Umeå.
Jamnick, M.S. and Walters, K.R. 1993. Spatial and temporal allocation of stratum based harvest schedules. *Canadian Journal of Forest Research 23*:402-413.
Johnsson, K.N., Scheurmann, H.L. 1977. Techniques for prescribing optimal timber harvest and investment under different objectives. Discusion and synthesis. *Forest Science 18*:1-30.
Johnsson, K.N., Stuart, T. and Crimm, S.A. 1986. *FORPLAN. Version 2—an overview*. USDA Forest Service, Land Management Planning Systems Section, Washington DC.
Jonsson, B., Jacobsson, J. and Kallur, H. 1993. The Forest Management Planning Package. Theory and Application. *Studia Forestalia Suecica 189*: 56pp.
Karlsson, J. 2002. Optimization models and methods for tactical and operative harvest planning. *Thesis no. 979*, Linköping University, Linköping. ISBN 91-7373-459-4. ISSN 0280-7971.
Karlsson, J. and Rönnqvist, M. 2005. Operations research based hierarchical harvest planning in Sweden and elsewhere. In: Karlsson, J. 2005. Optimization models and methods for harvest planning and forest road upgrading. Linköping studies in science and technology. *Dissertations no. 956*. Linköping. ISBN 91-85299-72-3. ISSN 0345-7524.
Kirby, M.W. Hager, W.A. and Wong, P. 1986. Simultaneous planning of wildland management and transportation alternatives. *TIMS Studies in Management Sciences 21*:371–387.
Kurttila, M. and Pukkala, T. 2003. Combining holding-level economic goals with spatial landscape-level goals in the planning of multiple ownership forestry. *Landscape Ecology 18*:529–541.
Kurttila, M., Pukkala, T. and Kangas, J. 2001. Composing landscape level forest plans for forest areas under multiple private ownership. *Boreal Environment Research 6*:285–296.
Lönner, G. 1968. A system for short term planning of logging, storing and transportation of wood. *Forskningssstiftelsen Skogsarbeten. Bulletin no. 6*. Stockholm.
Manley, B.L. and Threadgill, J.A. 1990. Use of the FOLPI forest estate modelling system for forest management planning. In Proceedings of a IUFRO symposium. *Ministry of Forestry, FRI Bulletin 151*:112–118.
Martell, D.L., Gunn, E.A. and Weintraub, A. 1998. Forest management challenges for operational researchers. *European Journal of Operations Research 104*:1–17.
McNaughton, A., Rönnqvist, M. and Ryan, D.M. 1998. The scheduling of forest harvesting with adjacency constraints. In: *33rd Annual Conference of the ORSNZ, Online Conference Proceedings, University of Auckland, New Zealand [online]*. Available from <http://www.esc.auckland.ac.nz/Organisations/ORSNZ/conf33/papers/p75.pdf>, (020607).
Nelson, J. and Brodie, J.D. 1990. Comparison of a random search algorithm and mixed integer programming for solving area-based forest plans. *Canadian Journal of Forest Research 20*:934–942.
Nelson, J. Brodie, J.D. and Sessions, J. 1991. Integrating short term, area based logging plans with long term harvest schedules. *Forest Science 37*:101–122.

Öhman, K. and Lämås T. 2003. Clustering of harvest activities in multi-objective long-term forest planning. *Forest ecology and management 176*:161–171.

Sessions, J. and Sessions J.B., 1992. Post new forestry tools for tactical forest planning. *Western Wildlands Winter*:39–44.

Siitonen, M., Härkönen, K., Kilpeläinen, H. and Salminen, O. (eds) 1999. *MELA Handbook—1999 Edition*. The Finnish Forest Research Institute. 492pp [online]. Available from http://www.metla.fi/metinfo/mela/tuotteet/julkaisut-oppaat-en.htm> (040831)

Richards, E.W. and Gunn, E. 2000. A model and tabu search method to optimize stand harvest and road construction schedules. *Forest Science 46(2)*:188–203.

Stridsberg, E. 1984. Multiple use forestry in former days. In: Saastamoinen, O., Hultman, S-G., Elers, N. and Matsson, L. (eds). *Multiple use forestry in the Scandinavian countries. Proceedings of the Scandinavian Symposium held in Rovaniemi and Saariselkä, Finland, September 13–17, 1982*. Communicationes-Instisuti-Forestalis-Fenniae. No. 120:14–18.

Ståhl, G., Wilhelmsson, E. and Lämås, T. 1994. *Planering av skogsbruk – den röda tråden till grundkurs i skogsindelning*. Inst. f. biometri och skogsindelning. Sveriges Lantbruksuniversitet. Umeå. (in Swedish)

Söderholm, J. 2002. "De svenska skogsbolagens system för skoglig planering". Swedish University of Agricultural Sciences. *Department of Forest Resource Management and Geomatics. Student reports 98. M.Sc. thesis*. 47pp. Umeå. ISRN SLU-SRG-AR--98—SE. (in Swedish.)

Vertinsky, I., Brown, S., Schreier, H., Thompson, W.A. and van Kooten, G.C. 1994. A hierarchical-GIS-based decision model for forest management: The systems approach. *Interfaces 24*(4):38–53.

Weintraub, A. and Bare, B.B. 1996. New issues in forest land management from an operations research perspective. *Interfaces 26*:9–25.

Weintraub, A. and Cholaky, A. 1991. A hierarchical approach to forest planning. *Forest Science 27*:439–460.

Weintraub, A. and Davis, L. 1996. Hierarchical planning in forest resource management: Defining the dimensions of the subject area. In: Martell, D.L., Davis L.S. and Weintraub, A. (eds), Proceedings of a workshop on hierarchical approaches to forest management in public and private organizations. *Petwawa National Forestry Institute. Information Report PI-X-124*. ISBN 0-662-24108-8.

Weintraub, A. and Navon, D. 1976. A forest management planning model integrating silvicultural and transportation activities. *Management Science 22(12)*:1299–1309.

Weintraub, A., Guitart, S. and Kohn, V. 1986. Strategic planning in forest industries. *European Journal of Operations Research 24*:152–162.

Weintraub, A., Jones, G., Meacham, M., Magendzo, A., Magenzo, A. and Malchuk, D. 1995. Heuristic procedures for solving mixed integer harvest scheduling transportation models. *Canadian Journal of Forest Research 25*:1618–1626.

Weintraub, A., Saez, G. and Yadlin, M. 1997. Aggregation procedures in forest management planning using cluster analysis. *Forest Science 43(2)*:274–285.

Williams, D.H. and Yamada, M.M. 1976. A clustering technique for land management problems. *Canadian Journal of Forest Research 6*:1078–1095.

Yoshimoto A. 1996. Tactical scheduling using zero-one integer programming. *Journal of Forest Planning 2*:13–24.

Yoshimoto A. Brodie J. D. Sessions J. 1994 A new heuristic to solve spatially constrained long term harvest scheduling problems. *Forest Science 40(3)*:365–396.

Zipkin, P. 1980a. Bounds on the effect of aggregating variables in linear programs. *Operations Research 2*:403–418.

Zipkin, P. 1980b. Bounds on row aggregation in linear programs. *Operations Research 28(4)*:903–916.

Zipkin, P. 1980c. Bounds for aggregating nodes in network problems. *Mathematical Programming 19*:155–177.

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