Optimization of Forest Management Decision Making under Conditions of Risk

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Abstract

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It is well known that decision making problem solving in forest management involves risks from different sources. In many cases, the incorporation of risk will change the optimal decisions in different ways. Usually, stochastic optimization models are much more complicated than the corresponding deterministic ones, and greater computational efforts are required for identification of the optimal solutions. Thus, simplification of the decision making problems is often made in one way or another, the cost being deviations from reality. In this thesis, a new optimization approach has been designed for decision problems concerning harvesting under price risk, both for single species stands (paper I) and for mixed species stands (paper II). The intention with this approach has been to keep the model simple with respect to the computational burden, without imposing very restrictive assumptions on the choice of feasible decision alternatives. Optimal stocking level functions, which are modeled as functions of stand age and stumpage price, are applied to guide the thinning decisions. A reservation price function, which is formulated using stand age and standing timber stock as independent variables, and market price observations are used to determine the final harvest time. The coefficients of these functions are calculated by simulation.

Flexibility is valuable in decision making under risk. Recently, the risk of damage to forests by moose in Sweden has been widely recognized. This problem will most likely exist also in the future, since moose hunting is very popular in the country. Study of this problem is highly relevant to forestry. In Paper III, the value of flexibility for a mixed species stand is analyzed when risks in timber price and moose damage are incorporated. An adaptive optimization model has been developed to determine the initial mix of species which maximizes the expected present value. The results show that mixed-species stands of Scots pine and Norway spruce are preferable to pure Scots pine stands when the risks of moose damage and timber price are taken into account.

The efficiency of the model also depends on the optimization technique applied. Paper IV works on a hybrid heuristic algorithm, based on a genetic algorithm and a traditional non-linear optimization method: the Hooke and Jeeves method. It is shown that the performance of the hybrid algorithm is significantly better than that of the Hooke and Jeeves method, and of the Powell search method.

Keywords: Even-aged stand management, thinning, reservation price, feedback control, rotation age, adaptive harvest strategy, risk, adaptive optimization, genetic algorithm, Hooke and Jeeves method, Powell search

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Contents

Background

When a forest owner makes management decisions with the aim of maximizing his or her utility, essential information concerning both economic and biological issues must be available, e.g. prevailing timber price, current state of forest stand, prices predicted in the future, forest growth prediction, etc. Traditionally, it has often been assumed that timber prices and forest growth in the future are known with certainty. Based on these assumptions, it is not difficult to make optimal decisions on silviculture and harvesting activities with the help of modern optimization techniques and computers. However, the plans made in this way are sometimes difficult to implement since the assumptions do not match reality. Actually, neither the price of timber nor the growth of stands in the future can be predicted without error.

Risk and uncertainty are two terms often used in decision making in a stochastic environment. They have different definitions in different research areas. Many economists refer to “decision making under risk” if the distribution function is known, and “decision making under uncertainty” if it is not. These definitions are applied in this thesis.

Incorporating risks into the decision model will make the problem much more complicated since, in principle, it is necessary to evaluate every possible management action with respect to all possible future outcomes of the stochastic process. This is one of the main reasons why risks have often been excluded in formal analyses of forest management decisions. In order to include risks in the model, there must be some simplification of other issues when the computation capability is limited. Usually, this is worthwhile since the overall quality of the model is dependent on the weakest aspect of it. If the assumption of certainty is unrealistic, then is there any point in trying to make the model perfect in other respects? Of course, the complexity (computational burden) of the model is also dependent on how the model is constructed and what optimization technique is applied.

In the past few decades, there have been a large number of studies dealing with risk in forest management decisions. Adaptive optimization of the intertemporal harvest and investment decisions is an active research area. Most of the studies have dealt with harvest and investment decisions when the timber growth and/or timber prices are stochastic. Due to the nature of the problem, the most commonly used optimization technique is stochastic dynamic programming (Norstrom 1975, Risvand 1976, Lohmander 1983, 1986, 1987, 1988, Brazee and Mendelsohn 1988, Carlsson 1992, Brazee and Belte 2000). Because of the well known ‘curse of dimensions’ of dynamic programming, the models based on this technique must set some strict limitations on the feasible choice of possible decision alternatives, e.g. limitation of the number and intensity of thinnings, to reduce the computational burden. Some other optimization techniques (e.g. optimal control theory, inventory theory, nonlinear programming) can also be found in the literature and can potentially be applied to this field, as long as the segmental nature of information and decisions is recognized. However, when the model is complicated, all of these techniques will have problems similar to those of dynamic programming. Hence, for complicated forestry decision problems such as forest harvest decisions under conditions of risk, it is essential to create the model in the correct way and to apply efficient optimization techniques in order to keep it manageable with respect to computation, while at the same time avoiding too much omission of detail in the model.

In a stochastic environment and for multi-stage decision problems, the options and flexibility have important values and meanings. The investment and harvest decisions in forestry are typical examples. Concerning the harvest decisions, forest resources naturally have flexibility, since the mature age of a forest is not as strictly defined as that for most agricultural crops. It could vary over a wide range without substantial losses in biological and economic factors. The expected economic gains of the adaptive harvest decisions based on a reservation price strategy (Lohmander,1986, 1987, Brazee, 1988) under price risk is a valuation of this flexibility. Flexibility may arise naturally or may come at an initial cost. While the flexibility of the forest harvest year is natural and free of charge, some other kinds of flexibility can only be obtained via investments. Only when the value of flexibility is higher than the cost, is the investment cost effective. In forestry, one of the most important investment decisions is selection of tree species. For a specific site, with the assumptions of certainty of timber prices and forest growth, there is often only one most suitable tree species which can maximize the utility of the forest owner, and therefore a single-species forest should be generated. In a stochastic environment, it is difficult to say which species is the best choice, since it depends on what will happen in the future. In such situations, the creation of mixed-species stands will increase the flexibility and provide options for future decisions. The values of the flexibility and options depend on the properties of the stochastic processes of timber prices and forest growth. In a given situation, it is possible to analyze the costs and benefits of the investment to increase the flexibility.

Aim of the thesis

This thesis deals with decisions of forest harvesting and investments in a stochastic environment. In particular, the aims have been:

* To develop efficient models for harvesting decisions under price risk, both for single-species stands and for mixed-species stands. The decisions of thinnings and final cutting would be adaptively optimized to the latest revealed price information.

* To assess the value of flexibility of mixed-species stands compared to single-species stands in a stochastic environment under the influence of moose damage and price risk.
* To develop and evaluate an efficient optimization technique – a hybrid heuristic algorithm based on genetic algorithm and the Hooke and Jeeves method (1961).

Risks and forest management decision making

Risks are unavoidable in forest management decision making, because of the long time scale involved. When risks are incorporated, the forest management decision making problem will be changed in many ways. Basically, there are two types of risks in forest management decision making. The first is biological risk, which is related to forest growth, and the second is economic risk, which is related to the market situation.

Biological risk

Forest management decisions usually use a growth model to predict forest growth for the whole rotation, which could last more than 100 years. However, the growth of a stand is very difficult to predict accurately, since it is subject to various risks and uncertainties. Growth models are created based on data collected in the past, and one cannot know with certainty that the situation will be the same in the future. Firstly, the climate, which is an important factor for forest growth, is impossible to predict in advance. For example, global warming will certainly affect forest growth and no one even knew the term just a few decades ago. Secondly, different kinds of damage may threaten forest growth. Recently, moose damage problems in Sweden have been reported in the media. Most of the damage is species-specific. Thirdly, degradation of site quality will change the growth of a given species on a given site. Fourthly, forest growth data that have been collected will contain errors. In addition to the four main factors mentioned above, many possible silviculture activities (e.g. fertilization, thinning, pruning, etc.) make growth predictions even more difficult.

Economic risk

The prices of forest products vary from time to time and it is very difficult to predict them with satisfactory accuracy. Similarly, management costs and interest rates also fluctuate considerably over time. The short-term variation in demand and supply is the main reason for price fluctuation. However, other factors exist which can also cause such variation. Government policy, technological improvements, the public environmental demand etc., will affect the supply and/or demand of forest products in the long run, and therefore affect the forest product prices in relatively long-term intervals (Gong, 1994).

Making decisions adaptive to the latest information on stochastic variables (e.g. prices) is a good strategy in a risky world. Obtaining the prevailing information on market-related variables is much cheaper than that of forest growth-related variables. The forest product prices, interest rates and management costs can be obtained almost without any costs (at least in Sweden), while forest growth (stand volume) can only be collected through empirical estimation, which will incur certain costs.

Forest management decision making under conditions of risk

Models of forest management decision making under risk conditions can be divided into two groups: adaptive and anticipatory models. Anticipatory models are used to derive optimal courses of action for the whole planning period in advance (Valsta 1992). Valsta (1992) developed a scenario approach for anticipatory optimization in stand management when risks of stand growth and catastrophes are considered. Anticipatory models are preferable to adaptive ones when the state of the system is not observable before a decision has to be made, and/or when feedback rules are difficult to identify.

Compared to anticipatory models, adaptive models for optimization of the intertemporal harvest and investment decisions under risk have been studied more thoroughly. Hool (1966) developed a dynamic programming-Markov chain approach to a timber harvest problem where stand state is uncertain. Brodie and Haight (1985) applied a forward recursion dynamic programming approach to the analysis of timber harvest and a variety of silviculture investment decisions involved in even-aged stand management. Based on optimal stopping rules, Lohmander (1986, 1987) and Brazee and Mendelsohn (1988) developed the optimal reservation prices for decisions about clear-cutting when timber prices are stochastic.

Most of the studies in this field consider only final harvest age. A few studies have incorporated thinning into stochastic decision making models for even-aged stand management under price risk. Using a forward recursive dynamic programming method, Kao (1982, 1984) analyzed the optimal thinning and rotation problems under conditions of different degrees of knowledge of timber growth. Haight and Smith (1991), and also Carlsson (1992), used a stochastic dynamic programming method to optimize the thinning and final harvest of mixed-species stands. A common feature of these studies is that a few timber price levels and a relatively small number of feasible management options (stand states) are included in the decision making model, in order to keep the model numerically tractable. Teeter and Caulfield (1991) examined the thinning of loblolly pine stands in the southern United States with stochastic saw-timber price and a fixed rotation age.

Lohmander (1992) developed a two-stage adaptive optimization model for mixed-stand management with stochastic prices, where the decision was to select (at a predetermined point in time) the species to be thinned and the species to be kept in the stand until clear-cut. The numerical results showed that a mixed-species stand is economically superior to single-species stands when future timber prices are stochastic. Using a similar two-stage adaptive optimization model, Lohmander (1993) examined the value of flexible species selection options when tree growth is stochastic.

Brazee and Bulte (2000) extended the adaptive final harvest decision model to determine also the optimal time of thinning, where thinning intensity is fixed. A strategy with two reservation prices, one for thinning and the other for final harvest, was established in that study. Significant gains were observed from incorporating thinning into the adaptive decision model, even though the number of thinnings is restricted to one and thinning intensity is fixed.

Optimization techniques in forest management decision making

We have to make a decision when more than one choice is available. If the number of choices is large, it is difficult to make the decisions manually, and optimization techniques should be applied. In the past hundred years, powerful optimization techniques have been developed and many of them have been applied to forest management decisions. The emergence of operation research and computer science in the 20th century provided powerful tools for management science. Although the methods were motivated by and first used in military applications, the operations research techniques were soon applied to other research areas, such as forest management. The most frequently used operation research techniques are linear programming, dynamic programming, goal programming, mixed integer programming and the decision tree method. With these optimization techniques and modern computers, several complicated problems can easily be solved.

Many problems can be formulated as nonlinear programming problems. Such problems can be solved with a wide variety of nonlinear programming techniques (Roise, 1986). Among these, derivative free methods (e.g. Powell Search, Hooke and Jeeve, etc.) are very popular since they are easy to use and still perform well.

In the real world, there are many problems which are too complicated to be solved by the optimization techniques mentioned above, even with the help of modern computers. This is why another category of optimization techniques – heuristics – is also very popular. Typical examples are the genetic algorithm, simulated annealing, Tabu search and artificial neural networks. The common purpose of these techniques is to find near-optimal (acceptable) solutions within a reasonable solution time for complicated problems which cannot be solved by traditional techniques. There have been many successful applications of heuristic algorithms in forest management decision problem solving (Öhman and Eriksson 1998, Wikström and Eriksson 2000, Lu and Eriksson 2000).

Generally, there is no algorithm which is universally more efficient than other algorithms. However, for a given problem, it is likely that the performance of one algorithm will be superior to others (Spall 2003). Therefore, it is important to find the best algorithm for a given problem. Unfortunately, this is far from an easy task.

Summary of papers

I. Optimal Stocking Level and Harvesting with Stochastic Prices

Most of the previous studies which concern forest harvest decisions with stochastic prices focus on clear-cutting decisions without thinnings, or put strict limitations on the timing and intensity of thinnings. Using optimal stopping theory, Lohmander (1986, 1987) developed a reservation price strategy to direct the clear-cutting decision based on the most recently available market price information, and observed enormous increases in the expected net present value for this adaptive strategy compared to the Faustmann (1849) model. Brazee later did similar work (Brazee 1988). Brazee and Belte (2000) extended this strategy to include the thinning decision by adding another reservation price strategy for the thinning decision. However, in order to keep the model simple during simulation, the number of thinnings was restricted to one and the intensity of the thinning was fixed as 30%. Relaxing these restrictions will make that model impractical in terms of computation required.

In paper I, an integrated thinning and final harvesting strategy for even-aged stands under conditions of uncertainty in future timber prices has been developed. This strategy consists of two functions: a feedback stocking-level control function that guides the choice of thinning intensities at different ages, and a reservation price function that determines the time of final harvesting. The optimal stocking level is modelled as a function of stand age and market timber prices. The reservation price function is formulated using stand age and standing timber stock as independent variables. Instead of optimizing the clear-cutting age and the intensity and timing of thinnings directly, the problem was transferred to optimization of the few coefficients in the stocking-level control function and reservation price function. A sample stand of Scots pine (*Pinus sylvestris* L.) located in northern Sweden was used for the optimization and simulation. The values of the coefficients were estimated using a traditional nonlinear optimization technique (Powell search).

Two types of thinning and three levels of fixed cost of harvest and thinning were tested in the study. The integrated strategy is compared to a pure reservation price strategy where no thinning is allowed, and with an open-loop harvesting strategy that ignores timber price uncertainty. The results show that the integrated strategy is superior to both of the other strategies.

II. Adaptive Thinning Strategy for Mixed-Species Stand Management with Stochastic Prices

This paper extends the model presented in paper I to mixed-species stand management decisions with stochastic prices. The focus is on the principle, strategy and analysis of thinning decisions. In Sweden, thinning is very important due to the high initial forest density and long rotation. One quarter of the annual harvest comes from thinning (Anon, 1990). There are 5.28 million ha of mixed-species stands in Sweden. Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) are the dominant tree species in about two-thirds of the mixed stands (Anon, 2003). There have, however, been few studies of the thinning decisions in mixed-species stands in Sweden.

The study of Eriksson and Eriksson (1993) showed that in most cases the net present value of the sample stands could be increased by 10–44% if the stands were thinned following the optimal program, instead of the thinning schemes of the National Forestry Board. However, the models in the study were built on the assumption that timber prices are constant over time and are known with certainty.

Paper II presents an efficient and flexible approach to determining the optimal thinning strategy for mixed-species stands with stochastic timber prices. This approach aims at determining the optimal stock of each species to be maintained in the stand, conditional on the state of the stand and timber prices, whereas thinning intensity is given by the difference between the observed and the optimal stocks. The optimal stock of each species is formulated as a parametric function of stand age and stumpage prices. Different functional forms are tested and compared. The coefficients of the optimal stock-level functions are determined simultaneously with a reservation price function used to determine the clear-cutting age. Numerical results are presented for an example stand of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* L. Karst.) in northern Sweden. The results show that variations in timber prices have significant effects on the optimal timing and intensity of thinning. The adaptive thinning strategy leads to significantly higher expected present value of the stand than the optimal harvest program, which ignores price uncertainty. The simulation also shows clear differences between the two species with respect to the timing and intensity of thinning.

III. Optimal Mixed Stand Management under Risk

When a forest owner makes an investment decision, he or she has to face the risk and uncertainty in the future, since there is no way of perfectly predicting the economic and environment situation 50 or 100 years from now. It is also difficult to know what damage might occur to the forest during the long rotation period. One can only know the exact situation in the future when the ‘future’ becomes ‘now’. Obviously, the more one knows about the future situation, the better the decision that can be made. Then, can we postpone the decision to the future when we know more? Yes; a flexible investment decision will give the option of making a further decision in the future when more is known.

In forestry, the selection of species when we generate a new forest is a very important decision. Generating a mixed-species stand can create flexibility and leave an option to the future. The value of the option in this case is obvious, since one can choose the better species in the middle of the rotation according to the latest available information, to avoid the possible losses caused by changes in the market, the environment or by damage. Thus, mixed-species stands provide valuable options for sequential adaptive management.

In paper III, an adaptive optimization model has been developed which determines the initial mix of species that maximizes the expected present value. Two kinds of risk are recognized in the model. One is the price risk of different forest products, and another is moose damage risk during the earlier stage of the rotation. It has been found that the expected present value of the investment can be improved in typical forest management decision making if we select a “flexible” multi-species plantation instead of a traditional “stiff” single-species plantation. The study also analyzes the role of stem number requirements at age 20 in the Swedish Forest Act and the sensitivity of different harvesting and transportation costs. Besides the risks considered here, other kinds of species-specific damage and phenomena may occur during the life of the forest stand, which implies that there may be other reasons for preferring multi-species forests to single-species forests.

IV. A Hybrid Heuristic Algorithm for Harvesting Decisions in a Mixed-Species Stand under Price Risk

The model in paper II is described for solving a complicated forest harvesting decision making problem, which will optimize the decision of thinning and final cutting simultaneously under price risk for a mixed species stand of spruce and pine. Two optimal stocking level functions are used to guide the thinning decision, and a reservation price function is used to guide the final cutting. In the three functions, there are ten variables which must be optimized. The Powell search method is applied for optimization of the variables. Satisfactory results can only be obtained via a large number of repetitions with different initial guesses. One hundred price scenarios were used for the simulation, so the time for each objective function evaluation is long. Therefore, the computational burden for identification of the optimal solution is large. In addition, the optimal stock level functional forms for the two species and the reservation price functional form are somehow ‘ad hoc’, and more suitable functional forms might be found by further research, which may contain more coefficients and make the problem even more complicated because of the higher dimensionality. Thus, a more efficient optimization technique is highly desirable.

In this article, a hybrid heuristic algorithm based on a genetic algorithm and the Hooke and Jeeve algorithm is developed. The hybrid heuristic algorithm consists of two stages. In the first stage, the genetic algorithm is applied to generate initial candidate solutions, and in the second stage, the Hooke and Jeeve method is applied to find the optimal solutions using these initial solutions. Implementation of the genetic algorithm for this problem is presented, and some modifications are made to improve its performance. A local improvement strategy is applied before the selection, in order to avoid premature convergence . As a benchmark, a pure genetic algorithm, Hooke and Jeeves method and Powell search are also tested. The results show that the performance of the hybrid heuristic algorithm is the best one among all of the algorithms tested. The genetic algorithm ranks second, Hooke and Jeeves third, and the Powell search is the worst.

Conclusions

The new optimization approach, designed in this thesis for harvesting decision problems (thinning and final felling) under price risk, is efficient. Instead of determining the optimal thinning removal corresponding to each possible stand-market state (stand age, stocking level, and timber prices), one need only optimize a few coefficients of the optimal stock-level function. At the same time, the stock level, thinning removal, and timber prices can all be treated as continuous variables. With this approach, the number, time and intensity of thinning, together with the time of the final felling, can be optimized according to the latest market information available. A greater gain could be observed than that achieved with the dynamic programming approach for a similar problem in the study of Carlsson (1992).

In a stochastic environment, the value of the flexibility and options created by selecting mixed-species stands is large. Multiple species provide the option of selecting a better species by adaptive thinning based on the newest information from the markets and stand growth.

Besides moose damage and price risk, there are many other kinds of species-specific damage and phenomena that may occur during the long life of a forest stand. Together with the traditional biological theories of the advantages of mixed-species stands, we have strong reason to believe that mixed species are to be preferred in a large number of cases.

For complicated forest decision making problems, the heuristic optimization technique is a promising alternative. However, implementation of this technique is difficult and problem-specific. The hybrid heuristic algorithm developed in this thesis, based on the genetic algorithm and the Hooke and Jeeves method, is an efficient algorithm compared to the purely genetic algorithm, the Hooke and Jeeves method, and the Powell search method.

Future research

The models in Papers I and II do not include pre-commercial thinning, which is commonly practised in Swedish forestry. Since pre-commercial thinning decisions affect and at the same time are affected by the commercial thinning and final harvest decisions, the formulations should be extended to include pre-commercial thinning decisions, in order to apply the models to young stands.

Price risk is the only risk considered in Papers I and II. However, growth risk is also important and should not be neglected. Future research should extend the model to incorporate stand growth risk.

Only a few optimal stocking level functional forms were tested in the first two papers. It is clear that the efficiency of the model is highly dependent on the functional forms, and further research work is needed to find more suitable functional forms.

The models are formulated assuming risk neutrality of forest owners. Non-timber benefits are neglected. Thus, one possible extension would be to relax the assumptions, including the non-timber benefits, in the models.

In Paper III, the number of thinnings is fixed to one, the intensity of thinning is fixed to 40%, and the clear-cutting age is fixed to 80 years. While these restrictions can simplify the model with respect to computation, and satisfactory results can be obtained to explain the problem, this overlooks several details and cannot identify the real optimal solution. Future work should involve trying to remove these restrictions and to make the models more realistic.

Besides moose damage and price risk, some other species-specific forms of damage and phenomena could be included for extension of the model in Paper III.

The results obtained in Paper III are based on a specific site which, in terms of expected volume production in the case of no damage, is more favourable for Scots pine than for Norway spruce. For other site conditions, the result could be different. A possible extension of the study might be to include more site conditions (all site index combinations that are possible for pine and spruce).

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