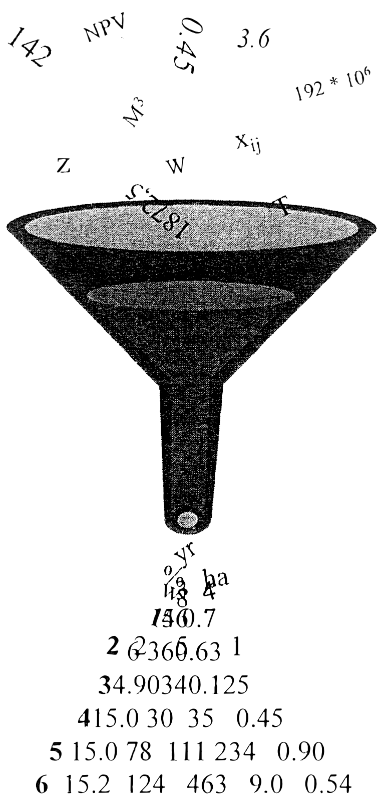
A sequential approach in mathematical programming to include spatial aspects of biodiversity in long range forest management planning



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PREFACE

This report is written as a final thesis within the scope of my study forestry at the Agricultural University of Wageningen, The Netherlands. For this I have done my research at the Swedish University of Agricultural Sciences; at the department of Forest Resource Management and Geomatics in Umeå. The possibility for this was offered by a Erasmus scholarship provided for a period of six months.

The aim of going to Umeå for writing this thesis was in the first place the excellent reputation of the department for their knowledge about mathematical programming. Next to that was going abroad for a longer period a good opportunity to improve my English and in this case to practice the basics of Swedish. During this period I got the feeling that I was ready to finish my study and find a job.

I like to express my gratitude in the first place to Professor Ljusk Ola Eriksson, my supervisor. His enthusiasm, aid and expertise have been essential for me to keep motivated and make of this study what I expected it to be.

I like to thank Tomas Lämås for the data he provided me and for his critical remarks on the research. And my thanks are for Solveig Berg Lejon and Kjell Lagerqvist for their support with managing the computer. Little by little I got some insight in the, for me, black box of the computer science. Anders Petersson made the maps in the report. Thanks!

In the Netherlands I like to thank Bram Filius of the Forestry Department.

Finally I express my most warm thanks to my family and friends for being always there when I needed them and their efforts to overcome the 2000 km that were between us.

For me, my Swedish period will always be inextricable bound up with my grandmother. She suffered a severe disease and died during this period. It has been her wish for me to do this study.

Michiel van Kerkvoorde

SUMMARY

In the discussion about forest management the maintenance of biodiversity is coming more and more to the fore. Like 120 other countries, Sweden committed itself to a sustainable use of forests at the convention of Rio de Janeiro. Sweden has a long tradition of forest management focusing on woodproduction. This implies that almost all the forest land is managed and that the area of natural forests is very small. The maintenance of biodiversity should therefor not be limited to reserved areas but it should be incorporated into the management of the total forest area. There is a need for improved methods to balance the economic and ecological benefits of forest management. In this study I designed an algorithm for mathematical programming that includes the determination of a contiguous area of old forest into a long range forest management plan that strives for the sustainable production of wood as well as the maintenance of biodiversity.

The boreal forests of Sweden were characterised by two main disturbance patterns. In dry and mesic forests, fires determined the structure of the forest. This resulted in large scale pattern where Scots pine and broad-leaved trees dominated. In the wetter forests, dominated by Norway spruce, small scale disturbances like windthrow brought about a heterogeneous forest structure with a long continuity. With the management of the forests for woodproduction, some characteristic features disappeared. The amount of old-growth forests, deciduous trees and coarse woody debris decreased significantly and large scale clearcuts resulted in a loss of retained trees, characteristic for an area after forest fire. Especially these features are of importance for the maintenance of biodiversity. Rare and sensitive species are largely dependent on structures determined by natural disturbance patterns.

The objective function in the long range forest management plan is a maximisation of the Net Present Value of the woodproduction. To ensure a sustainable supply of wood in the future this objective function is bounded by even flow and ending stock constraints. For the maintenance of biodiversity, constraints are implemented as well. These constraints stem from the assumption that the biodiversity benefits by the establishment of certain features abundant in natural forests and scarce in managed forests. Special attention is paid to a certain contiguous area of old forest. This is a conversion of the current attention for spatial aspects in biodiversity. A contiguous area of old forest ensures a core area without any edge effects. Many red-listed species depend on this.

In natural resource management, Linear Programming (LP) is most common among the mathematical programming techniques. It gives an optimal solution and is efficient. The model described above can largely be solved with LP. The constraint on the contiguous area of old forest will however cause problems. The way this constraint is formulated is known as a Quadratic Assignment Problem (QAP). This kind of problem is hard to solve and LP is not suitable. Other exact solution methods like the Branch and Bound method can only solve very small problems. Heuristics are a good alternative. Although they do not guarantee an optimal solution, they are able to solve large problems in an acceptable amount of time. Simulated Annealing (SA) is a heuristic method that gives high quality solutions because it has the ability to overcome local optima and convergence to a high value. I have designed a sequential approach. Herein the strong points of both methods are united. First the QAP is solved using SA. After that, the rest of the problem is solved by LP. This part is bounded by the outcome of the SA. In the objective function for the SA, next to a measure for the contiguous area of forest, the Net Present Value is added. A weightfactor determines the relative importance of these two elements in relation to each other. With this the SA solution will fit as effective as possible into the final solution for the whole problem, that is at the least costs.

The algorithm is tested on validity, reliability and efficiency. Validity relates to the question if the algorithm does what it is perceived to do. The test revealed some points that need extra at-

tention. The determination of the parameters for the so called cooling down of the SA is somewhat troublesome and needs to be regarded from case to case. Focusing strongly on either the contiguous area or the NPV in the SA-objective function gives results that are poor in relation to the results of an objective function wherein the two are balanced. The inclusion of the NPV in the SA-objective function does make the SA-solution effective in terms of the final outcome. In general the performance of the algorithm is as expected. The algorithm turned out to be very reliable, that means that a repetition gives about the same value all the time. For a sample forest of sixteen stands with more than 900 possible management regimes the algorithm could produce a solution within a minute, indicating that it is efficient.

In a case study the sequential approach algorithm is applied on the Brattåker area, near Umeå in Northern Sweden. The Simulated Annealing created contiguous old forest areas. The results are some more or less contiguous areas of between 100 and 150 hectares. The outcome is limited by the actual situation in the area. Not all forest can be old in fifty years. Next to that the algorithm shows a preference for small stands, causing a large part of the area, a part consisting of large stands, to be without old forest. The costs for contiguous old forest are relatively small compared to non contiguous old forest. The Simulated Annealing algorithm has the capability to form contiguous old forest in an efficient way. If the contiguous old forest is worth the additional costs, compared to non contiguous old forest, is a question for the decision makers. The Linear Programming produces a long range forest management plan. In this plan the features of importance for biodiversity are all established. With this it is assumed that biodiversity is maintained the coming fifty years. The sustainable provision of wood is guaranteed for this period. But this is at the expanse of the further future because the age structure is severely distorted. The main reason for this seems to be the combination of interest rate, initial age structure and the requirement for old forest. The used interest rate caused a strong preference for a present income to a future income. Because of that, and the initial age structure, the cut volume in the first period is extraordinary high, which has its effects on the age structure after 50 years. The requirement for old forest is in conflict with the age structure, which might cause problems for the provision of old forest after the planning horizon of 50 years.

The main conclusion is that the algorithm can give good results. It shows some of the possibilities to link a heuristic method with Linear Programming. An improvement could be the use of a shape index for the formation of contiguous old forest. It became clear that the situation and parameters in a case study have a major influence. The interest rate and an already unbalanced age structure limited the possibilities to test the algorithm. To generate data that is of use in the decision making process the algorithm needs more refinement. The site characteristics should be taken into account and a situation should be created that will ensure the sustainable provision of wood and biodiversity also after the planning horizon.

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1. INTRODUCTION

1.1 General view on the problem

One of the main tasks of nature conservation is to maintain biological diversity. On a global scale there is an immense need of conservation work directed towards biodiversity, which includes finding methods and systems for evaluating entire ecosystems, designing reserves, adapting natural resource management, etc..

In the Nordic countries the situation is quite positive. One reason is that the ecosystems are fairly young. They have developed after the last glaciation period, and consequently species diversity is relatively low. Another reason for optimism is the fact that during the last few years there has been a breakthrough in understanding the biodiversity problems in forest ecosystems among the foresters responsible for the development of the economically and ecologically important forest resources. This trend is backed up by political decisions, and there is an obvious development towards cooperation between biologists and foresters in solving the biodiversity problems in the Fennoscandian forests.

There are however many threatened species. Forestry activities influence the forest habitats in many ways. Most of the area in Sweden (65%) is covered by forests. As most of the forests are used for woodproduction (about 95%), it is no wonder that the majority of all threatened species live in managed forest habitats: about 45 - 55% (Sjöberg and Lennartsson, 1995).

Swedish forestry has been governed by production oriented forest policies since the beginning of this century. Almost all land has, as a consequence, been used for production of saw timber and pulp wood and the proportion of natural forests is only a few percentage points. This forest management has changed the structures and functions in the forest ecosystems, which has negatively affected a large number of organisms. Exclusive of sub-alpine forests, about 0.5% of the productive Swedish forest land is protected.

These circumstances, increasing ecological awareness, popular environmental concern, pressure from non-governmental organizations, as well as the fact that Sweden has committed itself to maintaining biodiversity, have brought about a new Swedish forest policy, aiming at more than just timber production. The policy may be illustrated by the first paragraph of the recently adopted Forestry Act which states that:

> *'The forest is a National resource. It shall be managed in such a way as to provide a sustainable yield and at the same time maintain biodiversity.'*

To fulfill the commitment to maintain biodiversity it is necessary to modify forest management. In Sweden, contrary to many other countries like Canada and Russia, a forest policy aiming at maintaining biodiversity must focus on the managed forests. Among other things, this strategy is determined by the fact that almost all forests have been intensively managed; there is a shortage of natural forests suitable for reserves (Lämås and Fries, 1995). The maintenance of biodiversity becomes an integral part in the forest management, planning and daily forestry activities.

Since the environmental aspects in forestry have come more to the fore, the confrontations, but also the dialog and joint research projects between biologists and foresters have intensified. The result has been an increased interest in the improvement of the prevailing methods and development of new forestry methods to meet the present-day demands of maintaining biological diversity in the forests (Sjöberg and Lennartsson, 1995). There is a need for efficient planning procedures (Skogsindustrierna, 1994).

In the decision making process the conservation effects must be weighted against the economic costs: the ecology and economy must be balanced (AssiDomän, 1995; Hunter, 1990). Mathematical programming can form a useful and efficient means to support the decision making.

1.2 Objective of the research and research questions

Definition of the problem

How can a forest management, that is meant to optimize the long term sustainability of woodproduction and maintenance of biodiversity, efficiently be generated by means of mathematical programming?

Objective of the research

To develop an algorithm for the generation of a long range forest management plan wherein the goals for a sustainable production of forest products as well as the maintenance of biological diversity are reached.

Research questions

In order to act consistently and effectively, it is necessary to define the results which one wishes to achieve - that is to formulate goals. A major part of the results in forest management becomes visible in the distant future. Long-term forecasts of the outcome of different options of action are therefor a natural component of strategic management planning.

The primary goal of such forecasts is to define the limits of possible yield, not to predict the future. The other natural part of strategic forest management planning is to access the value in economic terms of the possible outcomes.

A timber assessment is a means of linking activities and expected results in forest management. Such an assessment involves systematically investigating the consequences of a large number of different options of managing a forest, then evaluating the results in reference to a clearly specified evaluation norm (Jonsson *et al.*, 1993). This evaluation norm is a derivative of the goals.

The phrase above, together with the objective of the research, forms the base for the formulation of the research questions. The research questions form the guidelines along which the research should be performed. They are all connected to the objective of the research and will be answered throughout the report and in short in the conclusion.

1. What is the long term objective of the forest management?
2. Which aspects are related to biodiversity in boreal Swedish forests?
3. Which different strategies are possible to reach the goal for the maintenance of biodiversity?
4. How can the requirements for a sustainable woodproduction and the maintenance of biodiversity be translated into model parameters?
5. What stand treatment alternatives are possible and how will they be generated?
6. What algorithm can efficiently generate a desired forest management?
7. How can the algorithm be tested on efficiency, validity and reliability?
8. How can the treatment alternatives optimally be allocated to the forest divisions?
9. How does the algorithm perform in a case study?
10. How does the solution react on changing circumstances?
11. How is the solution translated to the forest management practices?

1.3 Demarcation of the subject

A model is always a simplification of reality. The solutions generated by the algorithm described in this report can never replace the decisions of a real forest manager. They will be, at best, a useful tool to support these decisions. The algorithm can supply information that is hard to generate without the use of a mathematical model.

Because of a limitation in both time and data available on the short term, a demarcation of the problem is necessary.

The focus in this report is clearly on the development of a useful algorithm. The direct applicability of the outcome in a real forest management situation is of secondary interest. Nevertheless I make an attempt to copy the 'real situation' in the model as far as time, methods and data allow me.

This technique oriented approach implies that special attention is paid to the testing of validity, reliability and efficiency. These aspects are only tested in relation to itself and not in relation towards other methods.

For the application in a case study, a special area will be utilized, namely the forest area of Brattåker, 60 km northwest of Umeå. The area is regarded as a representative example of a Swedish boreal forest. Forests in the South of Sweden are not considered. The ecology, history and management of these forests show large differences with the boreal forests in the North.

In chapter three I give a translation of requirements for the maintenance of biodiversity and a sustainable woodproduction into model parameters. Hereto I make assumptions about the relations between a forest management and the consequent effects on biodiversity. These assumptions are validated by the literature study in chapter two.

Other functions of the forest, like scenic beauty and recreation, are not taken into account. In some cases this might be unrealistic. In the case of most northern Swedish forests, the remote location and abundance of the forests takes away the need for this.

1.4 Structure of the report

After the general introduction to the problem, given above, in chapter two I will go into more detail about the matter of biodiversity in Swedish boreal forests. Of importance are the requisites to maintain or improve biodiversity in a forest environment and the different forestry management strategies that strive for the maintenance of biodiversity. Next to general characteristics of the forest, I pay attention to spatial elements related to biodiversity. This chapter is based on a small literature study.

Chapter three deals with the model that forms the translation of the general problem into mathematical terms. When possible, the model is supported by a review of the options for such a translation mentioned in the literature.

In chapter four the problem solving technique is the main subject. I will discuss the algorithm I developed to solve the problem and the techniques used in this algorithm. In chapter five the algorithm is tested. Therefor a small fictive forest is used. The algorithm is modified according to the outcome of the tests. The final algorithm is the basis for chapter six. Here it is applied in a case study, where the practical performance is the main subject. I will shortly discuss what implementation of the results in the forest management implies.

The last chapter, seven, is devoted to the conclusion. I will give a comprehensive and critical review on the quality of the algorithm and the results. Also the usefulness of implementation of the forest management plan is discussed. Finally some initiatives for further research are given.

2. MANAGING FOR BIODIVERSITY IN SWEDISH FORESTS

2.1 Biodiversity and sustainability

Two terms encountered very frequently in this report are biodiversity and sustainability. Together they form the base of the objective in the long range management plan. It is outside the scope of this study to go into detail with them. Nevertheless a brief discussion seems useful. Next to a definition, and short description I will place them in a practical context.

Biodiversity

Biological diversity (or in short biodiversity) refers to the variety and variability among living organisms and the ecological complexes in which they occur.

It is important to view biodiversity as something more than local species richness. Managing for just high species richness often favors 'generalists' at the expense of 'specialists' (Probst and Crow, 1991). Therefor Kangas and Kuusipalo (1993) distinguish three components of biodiversity: species richness (the number of species), rarity (the abundance of species) and vulnerability (number of endangered species). Others (Burton *et al.*, 1992; Magurran, 1988) discern richness and evenness. Hereby is a situation with a species rich environment and no species dominating or suppressed the most valuable (Hunter, 1990).

To maintain biological diversity is to ensure that viable populations of all the native species of flora and fauna characteristic of the management area will be preserved (Hunter, 1990). The need to maintain biodiversity becomes more and more clear (Burton *et al.*, 1992; Probst and Crow, 1991). There is however no unanimity for the reasons why to protect biodiversity; they are manifold. Karlsson *et al.* (1995) state that the reason for the protection of animals and plants in the environment is fundamentally ethical. A species rich countryside is the birthright of future generations. Others stress the value a high biodiversity has for human beings. This value can be economic or ecological and is already realized or potential. One could think about the value for medical care, sustaining world wide productivity and maintaining ecological stability on local and global scale (Hunter, 1990; Burton et al., 1992; Probst and Crow, 1991; Ehrlich and Ehrlich, 1992).

Most important, according to Ehrlich and Ehrlich (1992), is the array of free ecosystem services, without which civilization could not persist, supplied by plants, animals and microorganisms. One could think of controlling the gaseous mix of the atmosphere and the generation and maintenance of soils.

Sustainability

Franklin (1994) defines sustainability as the maintenance of the potential for our terrestrial and aquatic ecosystems to produce the same quantity and quality of goods and services in perpetuity. He stresses that it is not necessary to take the current situation as a reference.

The concept of sustainability is applicable to both wood production and biodiversity (Franklin, 1994; Skogsindustrierna, 1994; Stora Skog, 1994). According to Skogsindustrierna (1994) a sustainable utilized forest is the basis for a complete cycle of renewable, raw materials, environmentally adapted production and a positive CO_2 balance. Aplet *et al.* (1993) applied the concept of sustainability by transforming the traditional forest management in an 'ecosystem approach'. Real sustainable forest management in their opinion is not only ecologically sound, but also economically viable and socially responsible. Sustainable development of forests is the key to both the maintenance of biological diversity and the competitiveness of the forest industry (Booth *et al.*, 1993).

Many authors tried to translate the general concept of sustainability into manageable objectives for the forestry practice. According to Skogsindustrierna (1994) this implies that the average annual increment per hectare is larger than the average annual cut per hectare and that more trees are planted than that are cut. A more production oriented approach is give by Stora Skog (1994): produce as much timber as possible and ensure the future of fauna and flora. Kuusipalo and Kangas (1994) translate sustainability into the maintenance of an even aged forest structure, which means that each age class occupies about the same fraction of the total forest area.

In the remainder of this chapter I will discuss topics related to biodiversity in the Swedish boreal forests, whereby special attention is paid to spatial aspects, since they seem to get more and more emphasis in the recent literature. The last paragraph is devoted to forest management for the maintenance of biodiversity.

2.2 Biodiversity in boreal forests in Sweden

Biodiversity in a forest is influenced by the age structure, tree species composition, vertical structure, disturbance patterns caused by wind and fire, etc., etc.. In dry and mesic forests within the boreal region, *fire* seems to have played an important role in structuring the forest stands. Actually, natural disturbances may have been so common that they prevented forests from reaching a stable state.

Forest fires and other natural disturbances created succession stages of higher complexity compared to a clear-cut area. Standing but dead trees can constitute 15-20% of the tree volume, that is 10-30 large trees per hectare. The forests were unevenly aged and had a multilayer structure. The fires to some extent also determined the tree species composition. Scots pine and deciduous trees could survive better, compared to Norwegian spruce. The animals and plants living in burned areas show adaptation to the natural disturbance patterns in which they have evolved.

The dynamics within the tree layer in forests without forest fire (these are mainly the forests on wet soils) are caused by putrefaction and other mortality factors caused by natural aging. Regeneration in such forests occurs continuously, and appears mainly in the patches generated by windthrows and on the decaying logs. Such gap disturbances are also caused by snow, ice, etc.. The resulting micro-sites are favourable for seedling establishment, which creates heterogeneous forest structures and contributes to the coexistence of coniferous and broad-leaved tree species. This also maintains high diversity of other organisms in the boreal forests, such as bryophytes.

In this type of old-growth forests, that is mature forests with long forest continuity, certain specific qualities can be defined as important for maintaining the natural biodiversity. There are standing dead trees or snags, and fallen trees or logs at different stages of decay are abundant (Sjöberg and Lennartsson, 1995).

According to Samuelsson *et al.* (1994) the three most critical elements for the long term survival of threatened forest species in Sweden are old trees, logs (preferably large ones) and snags. The lack of *coarse woody debris* is one of the most crucial factors for many threatened species of bryophytes, lichens, fungi, insects and birds. Among bryophytes and lichens a distinct sequence of species develops as the living trees die, fall and decay.

The amount of coarse woody debris in forests goes hand in hand with the occurrence of fires. The removal of dead wood, especially snags, is, next to the removal of vegetation (Korsnäs, 1995) the foremost reason for the decline of natural forest fires (Samuelsson *et al.*, 1994).

Therefore Fries and Lämås (1996) state that the most important restoration measures in boreal Swedish forests for promoting biodiversity are, among others, to increase the number and quality of undisturbed forests, the amount of coarse woody debris and to reintroduce fire.

They also mention increasing the proportion of *deciduous trees* in this context. Due to the demand for short fibred pulpwood, there is a shortage of deciduous trees nowadays (Skogsindustrierna, 1994). As a gross generalization, deciduous forests have a richer biota than coniferous forests (Hunter, 1990). A well-defined group of vulnerable species in Swedish forests depends on deciduous forest (Sjöberg and Lennartsson, 1995). Deciduous trees will normally be out-competed by the shade tolerant spruce before they can reach high ages. When spruces have occupied a site, only large scale disturbances as a fire or clear felling can regenerate a stand that is dominated by pioneers like deciduous trees or pines. With the suppression of fires in the current forest management the amount of deciduous trees has decreased as well. It must be arranged that stands that are rich of deciduous trees in different successional stages are always present in the landscape (Lämås and Fries, 1995).

The difference between different deciduous tree species for biodiversity is far less important than the distinction with coniferous trees (Hunter, 1990).

Like every stage in the successional sequence, *old forest* has its own range of species, which makes it important to have an area of old forest. The old forest represents however what is likely to be the most biological diverse portion of the sequence (Hunter, 1990). In a forest clear-cut with a rotation period of about 100 years, few, if any, of the species depending on old forest will survive a certain forest stand without being given particular attention. It will be even more evident when considering the time needed for recolonization of a forest stand. Specialized species will disappear after every clear-cut rotation period (Sjöberg and Lennartsson, 1995). A differentiation of age classes on a stand level favors a vertical structure, providing a range of different niches. Herbs and shrubs contribute to a vertical structure as well (Hunter, 1990).

When speaking about the importance of age of forests as a the reason for changes in fauna and flora, among others, the following aspects should be taken into account:

- the age of single trees influences species which are dependent on tree dimension and bark structure, and species living on dead wood of long-living tree species, such as oak and pine.

- the age of the forest stand influences species with weak dispersal capacity or species which are dependent on the late successional stages (Sjöberg and Lennartsson, 1995).

2.3 The question of spatial aspects

In the biodiversity discussion, scale is an important aspect. The spatial and temporal scales with respect to habitat area requirements are different for species belonging to different taxa (for example soil organisms, plants, beetles, birds, large mammalian predators) (Sjöberg and Lennartsson, 1995). Dividing large and continuous tracts of natural land habitat into smaller habitats surrounded by altered or disturbed areas - called habitat fragmentation - is a major concern relating to biological diversity (Probst and Crow, 1991). Some species can live in a variety of habitats, some require a diverse habitat and some a fairly uniform habitat (Hunter, 1990).

Species of different size will certainly react differently to the fragmented landscape. Their distribution or dispersal patterns may not coincide with the borders of landscape elements. Further, each species has a characteristic response to landscape patterns (Sjöberg and Lennartsson, 1995). Small stand may be more appropriate for some species, large ones may favor some other species (Oliver, 1992).

Many problems of spatial and temporal scale in conservation relate to disturbance. The area affected by a disturbance (patch size) is of primary consideration in studies of disturbance ecology, and determines the grain of a landscape. Small disturbances such as individual tree falls create a fine-grained pattern, whereas large disturbances create a coarse-grained pattern. Different types of organisms certainly perceive a landscape grain quite differently. Most landscapes are characterized by overlaying fine and coarse-grained patterns, which reflect the diverse history of disturbances. Therefore, no single scale of observation will provide full understanding.

Depending on the scale of the disturbance, two main types can be separated in the Northern Swedish situation:

- large-scale disturbance patterns caused by forest fires, which create forest with marked succession stages;
- small-scale disturbance patterns caused by, for example, wind, which create forests with long continuity and internal stand dynamics (Sjöberg and Lennartsson, 1995).

Another spatial aspect related to biodiversity concerns edges. The most important edges are those where two ecosystems come together. Many species use edges, but only few depend on them. Especially game animals and birds of prey take advantage of edges (Hunter, 1990). A natural forest controlled by forest fire shows irregular edges in a mosaic like landscape. Edges among small scale clear-cut areas provide the possibility for natural regeneration (Korsnäs, 1995).

Especially specialists, species dependent on a specific habitat, are sensible for ‘edge’ effects. They have an interest in a certain core habitat free of edges. This is shown in figure 2.1.

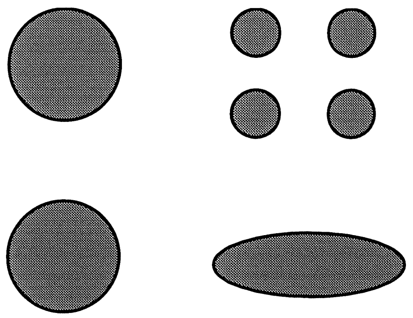

Figure 2.1 Edge effects on habitats
Source: Hunter, 1990

1. A single large habitat is preferable to several small habitats.
2. By making habitats as circular as possible, dispersal within the area will be enhanced and the negative effects of edges will be minimized.

According to Oliver (1992) the solution for the maintenance of biodiversity lies at a landscape level, in stead of at a stand level - where the appropriate, dynamic balance of stands in diverse structures can maintain habitats for a diversity of plants and animals.

The awareness of the importance of scale for the management of biodiversity asks for an ecological landscape planning: a long term plan on a large scale. Hereby areas with a special value are mapped out, for instance because of the occurrence of sensitive species or ecosystems. They should be tied in a stable network in the landscape (Korsnäs, 1995). Such ecosystem management on a large scale deals for instance with:

- merits of investment in corridors;
- intensity of edges;
- dispersion or aggregation of management activities in time and space (Franklin, 1994).

In general forest diversity on a large scale is greatest if the landscape is covered by stands of many sizes, ages and species composition (Hunter, 1990). Thus, use of a broad spectrum of spatial and temporal scales is recommended. A variety of structures across the landscape is good for biodiversity, high quality timber and rural community productivity (Oliver, 1992).

2.4 Forest management strategies in relation to biodiversity

The features of forests related to biodiversity in Swedish forests are discussed in 2.2. In 2.3 I mentioned, more in general, the importance of spatial aspects. A traditional forest management does not provide a guarantee for the maintenance of these aspects. A special forest management, not just focusing on woodproduction, has to be applied.

On the extreme sides there seem to be two strategies to maintain biodiversity in forests. On one hand a large forest area can be set aside as a reserve while the rest of the forest is managed for woodproduction only. On the other hand the whole forest area could be managed for both woodproduction and biodiversity (Oliver, 1992).

The need for a certain reserved area is clear. Not all species can live in managed forests (Skogsindustrierna, 1994). In Swedish conditions, the most threatened species (at least 80% of them) demand substrata typical of natural forests but occurring very rarely in exploited stands: 30% demand dead wood, 25% old trees, 35% unexposed soil, 70% are sensitive to light exposure, etc. (Sjöberg and Lennartsson, 1995).

In this context Ecological Landscape Planning (ELP) is a useful concept. ELP is an instrument for preserving the biodiversity of forests. The main objective is to develop management plans that on a landscape level lead to desired forest states. The main motive, preserving biodiversity, is reached by preserving and strengthening the qualities of the landscape. Three principles of planning are discerned:

- the forestry is planned on basis of structures and processes of the natural landscape. On different biotopes different successions are developed and the silvicultural systems are adapted to these successions;
- the forestry is planned with the existing forest state as a base, with key habitats and other domains with special characteristics included. These habitats are treated with special management and connected with corridors where it is suitable. Around the key habitats and corridors strengthening zones are established, in which the management is modified to avoid edge effects;
- according to the third principle greater consideration of the cultural landscape is taken. Knowledge about previous times cultivation of the ground is a key for understanding how the landscape has changed and with that the requirements of different species (Törnquist, 1995).

The term key habitats, mentioned above, refers to places where red listed species exist or can exist. Key habitats have a high conservation value and should therefor always have some kind of protected status. Examples are mixed conifer and broadleaf natural woodland after fire and spruce swamp (Karlsson *et al.*, 1995). A certain forest area is needed to protect areas that are too vulnerable to be managed, like forest along water courses (Skogsindustrierna, 1994; Korsnäs, 1995).

But in the Swedish situation it is not sufficient to set aside a certain area as a reserve. Because of previous management there is a shortage of natural forests suitable for reserves and reserves would in any case be isolated and dispersal possibilities for organisms through 'a hostile matrix' would be uncertain (Fries and Lämås, 1995). This implies that also outside reserves efforts must be made to maintain biodiversity: an active management over the entire area is required (Probst and Crow, 1991). This is a line of action supported by many authors. Oliver (1992) states that as more forests and other areas are excluded from management, the remaining forests are being harvested more heavily, which he perceives as a negative situation. The most efficient strategy must be to preserve as much as possible of original forests, and to imitate the dynamics, structure and function of the natural ecosystems in a given region of managed forests (Sjöberg and Lennartsson, 1995). The combination of reserves and modified forest management is, except for biological and ecological reasons, considered to be the most efficient solution (Fries and Lämås, 1995). And according to Karlsson *et al.* (1995) key habitats are not a safeguard for the survival of species. Surrounding forest land needs to be considered as well.

The situation described above is in accordance with the new forest policy in Sweden (see also chapter 1), and independent of land-owner category and geographic distribution. It requires an integrated combination of unmanaged nature reserves and key habitats, improvement of present forestry methods, introduction of new forestry methods, and consideration given to fauna and flora in all forestry activities (Sjöberg and Lennartsson, 1995).

The line of action suggested by a group of experts was to limit the portion of reserved area and to modify the management of the remaining forest land. Modification should aim at mimicking natural processes and build in natural structures into the production forest; for instance self thinning, tree species mixture and dead trees (Lämås and Fries, 1995).

When discussing how forestry activities in managed forests could be combined with maintaining biodiversity, consensus is emerging among foresters and biologists that one way is to try to reflect the natural disturbance patterns as much as possible when using the clear-cut method. A strongly modified clear-cutting method could be a reasonable substitute for natural disturbance by forest fire in forests, which were frequently exposed to large-scale disturbances in earlier times (Sjöberg and Lennartsson, 1995). The result is the same as after a forest fire: a felled area with irregular edges, individual trees and a lot of dead wood (Korsnäs, 1995). The trees that are left behind can be useful as seed trees (Skogsindustrierna, 1995). Enough wood must be left in the logged areas to secure the natural processes and to supply hole-trees, snags and logs in the future succession stages, as a large proportion of the threatened species is confined to such substrata. It has been estimated that up to 10 % of the wood has to be left after clear-cutting to sustainably maintain biological values. Deciduous trees must be saved to a much larger extent than at present in logging operations in coniferous forests and in the resulting successional stages. The clear-cut areas must be considerable smaller to allow migration and recolonization from surrounding stands (Sjöberg and Lennartsson, 1995). A strongly modified clear-cutting on dry sites is more resembling the natural processes than any selection system, and will therefore better enhance red-listed species. In the pine forest type, natural animal and plant diversity is probably enhanced if a portion of large pines will be retained at final harvest and the amount of coarse woody debris is increased. On the mesic deciduous or spruce dominated sites, an increase of the amounts of old, dying or dead deciduous trees will be beneficial for many red-listed species confined to this forest type. Favoring deciduous trees is urgent since they are out-competed by spruce and more or less routinely thinned out for decades (Fries and Lämås, 1996).

In accordance with strongly modified clear-cutting, site adapted forestry is recommended. Herein harvest and regeneration are seen as one package. Each site will have his own action. This approach favors both woodproduction and biodiversity (Assi Domän, 1995). Many authors write in this context about the mimicking or copying of natural processes and recreation of original forest features (Skogsindustrierna, 1994; Korsnäs, 1995; Karlsson *et al.*, 1995). One could think of regeneration (natural or artificial) with species that would naturally occur on a site and broad-leaved regrowth after a felling that may be left to develop naturally so that habitats similar to regrowth after fire may develop over time (Karlsson *et al.*, 1995).

3. PROBLEM SPECIFICATION IN A MODEL

3.1 The use of a model

In a planning process, some form of model is often required. Planning is largely a matter of construction and analysis of realistic models of reality. To be able to analyze a problem that in reality is very complex, it is necessary to simplify. In a model only the portions of reality relevant to the problem are described. To make meaningful analysis possible, this model must depict all components of reality that are important to the problem, as well as their interaction (Jonsson *et al.*, 1993).

The general form of a model for mathematical programming consists of equations. These equations are a representation of the goal of the decision maker and the possible activities he can undertake to reach that goal. For each activity one or more parameters indicate to which extent the activity contributes to reaching the goal. Next to that additional requirements can be implemented in the model. These requirements can stem from the goals of the decision maker or from physical conditions. Parameters will give the influence of each activity on these requirements.

In the previous chapters the goal of the forest management plan and an overview of the aspects related to the maintenance of biodiversity in Swedish boreal forests. These data are used in this chapter to describe the model of the problem.

3.2 A model for mathematical programming

The model described below is largely based on a general model I as it is labeled by Johnson and Scheurman (1977). A basic feature of a model I structure is that an activity refers to a complete set of actions that can occur on a particular land area (stand) over the entire planning horizon. These activities have two parts: (1) a sequence of regeneration harvests throughout the planing horizon and (2) an associated cultural treatment regime. An advantage of a model I structure, contrary to for instance a model II[1], is that you can locate particular stands through the time. This is an important feature since the spatial relationships seem to be important in the planning for biodiversity. Spatiality is inextricably connected to location.

The stress in this chapter is on formulation of an abstract model. The determination of parameters and other figures is discussed in 6.3, where a case study is considered.

3.2.1 The objective function

The objective function consists of a simple maximization of the Net Present Value of all the stands over the entire planning horizon.

$$\text{Max} \sum_{i=1}^{N} \sum_{j=1}^{Mi} D_{ij} x_{ij} \qquad (1)$$

x_{ij} = hectares of stand i, assigned to management regime j, ($x_{ij} \geq 0$)

[1] An activity in a model II structure refers to a complete set of actions that can occur on a particular land area from the time the area is regenerated until it is regeneration harvested.

N = number of stands

Mi = number of possible management regimes for stand i

D_{ij} = Net Present Value of stand i, assigned to management j over whole planning horizon

More specific can D_{ij} be written as:

$$D_{ij} = \sum_{t=1}^{T} \frac{P_{ijt}V_{ijt} - C_{ijt}}{(1+r)^{ty}} \qquad (2)$$

T = number of time periods
P_{ijt} = unit price of harvest in period t for stand i, assigned to management regime j

V_{ijt} = volume per ha harvested in period t for stand i, assigned to management regime j

C_{ijt} = cultural treatment costs per ha in period t for stand i, assigned to management regime j

r = discount rate
y = number of years in a time period

The objective function is in any case subject to:

$$\sum_{j=1}^{Mi} x_{ij} = a_i \qquad i = 1,\ldots\ldots,N \qquad (3)$$

a_i = number of ha in stand i

With this it is assured that every area will have a management regime.

Implementation of biodiversity, which is after all an equal objective to woodproduction, in the objective function, is an option. This would result in a multi-objective programming problem (Dijkstra, 1984; Korhonen *et al*., 1992). An objective function with two parts that can not be expressed in the same unit, asks however for a weighted score. For the case of objectivity this seems to be undesirable. Such a weight is hard to determine and has a large influence on the outcome. Furthermore the measurement of biodiversity is not free of discussion and vagueness (Hunter, 1990). Kangas and Kuusipalo (1993) state that there is a lack of understandable methods for dealing with biodiversity as an objective in planning.

And next to that, each management regime must be evaluated with respect to its effect on biodiversity. To analyze the impact of different (combinations of) management regimes on the biodiversity is far beyond the objective of this study. Such data are not already available.

Therefore I prefer a single objective function, whereby the requirement to plan for biodiversity is expressed in the constraints on the woodproduction (see 3.2.3). Although question marks are placed on this approach (Lämås, 1996), I consider it effective in respect to the controllability of the model. Adding biodiversity related objectives as constraints on the woodproduction, implies that desired levels can explicitly be added. This is in accordance with for instance Thompson *et al.* (1973).

3.2.2 A model for sustainable woodproduction

The importance of a sustainable forest management is mentioned in 2.1. To ensure a sustainable production of wood, I include even flow constraints in the model. These constraints permit the harvest level in any period to vary slightly from harvest levels in adjacent periods and thus resulting in a more or less equal production for the complete planning horizon.

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i}\left((1-\alpha)V_{ijt} - V_{ijt+1}\right)x_{ij} \leq 0 \qquad t = 1,\ldots\ldots,T-1 \qquad (4)$$

$$\sum_{i=1}^{N}\sum_{j=1}^{M_i}\left((1+\beta)V_{ijt} - V_{ijt+1}\right)x_{ij} \geq 0 \qquad t = 1,\ldots\ldots,T-1 \qquad (5)$$

α, β = maximum deviation in cut volume from adjacent period

To ensure the management commitments for a sustainable woodproduction also beyond the end of the planning horizon, ending inventory constraints are added. These constraints guarantee that the stock at the end of the planning horizon at least equals the stock at the beginning of the planning horizon, hereby presuming that this situation is a safeguard for the future.

$$\sum_{i=1}^{N}\sum_{j=1}^{Mi}\left(S_{ijT} - S_{ij1}\right)x_{ij} \geq 0 \qquad (6)$$

S_{ijt} = total standing volume per ha in period t for stand i, assigned to management regime j

The model so far is partially based on: Dijkstra, (1984); Johnson and Scheurman, (1977) and Johnson and Stuart (1988).

3.2.3 A model for the maintenance of biodiversity

Using a quantitative approach to support the management of a forest for both biodiversity and woodproduction, implies that they have to made measurable. For woodproduction this is no problem as we saw above. There is a direct relation between a management regime and the impact on the woodproduction in terms of cut volume and standing volume per hectare. There is however no direct, quantifiable means to relate forest management activities to the impact they have on biodiversity. There is a lack of knowledge for evaluation of decision alternatives with respect to dimensions of biodiversity (Bos, 1994; Kuusipalo and Kangas, 1994). An indirect relation has to be applied. The value of the forest for biodiversity is expressed in terms related to management activities. This implies that I had to make assumptions on the forest characteristics that favor biodiversity. These assumptions are based on the literature study in the previous chapter.

We saw there that some forest characteristics are of special importance for biodiversity of the boreal forests in Sweden. These are mainly features that are abundant in natural forests but relatively scarce in managed forests. The most important aspects are, in random order, coarse woody debris, deciduous trees and stands and old trees and stands. An important assumption I make is that the maintenance and/or establishment of these features guarantees a maintenance of the biodiversity. AssiDomän (1995) recommends to set a goal for the percentage of hardwoods and old growth in the planning phase, to favor biodiversity.

Since the plan is made on a forest level and for the long term, the level of detail is quite low. Important features on a stand level are outside the scope of this plan. An important term like strongly modified clear-cutting, of great importance to resemble the natural disturbance pattern, is translated into the retention of a certain amount of trees after clear-cutting. This is also the insurance of a certain amount of dead wood, since the trees that are left behind get the possibility to grow old and die. For instance the retention of logs and snags is implicitly assumed and not expressed in the model. The same goes for site adapted measures, like the form of the regeneration.

The spatial elements can be implemented in many ways. As we saw before many rare species are related to old forest. The importance of a contiguous area of old forest, to form a stable core area, is evident. Because of computational efforts needed to plan for spatial relationships, discussed in greater detail later on, no other spatial aspects like fragmentation or corridors between valuable areas are implemented. A contiguous area of old forest is a choice out of more options; nevertheless it is an important one.

Deciduous trees

Equation 7 guarantees that on a forest level a certain percentage of deciduous trees is established, expressed in standing volume per hectare. Some stands can contribute more than average and others less. The constraints are not valid from the beginning of the planning horizon since it takes time to adjust the forest to the requirement. An increasing parameter for the fraction of deciduous trees in the course of the time is a possibility.

$$\sum_{i=1}^{N}\sum_{j=1}^{Mi}\left(\chi S_{ijt} - L_{ijt}\right)x_{ij} \leq 0 \qquad t = t^{*},.....,T \qquad (7)$$

χ = desired percentage deciduous trees

L_{ijt} = standing volume of deciduous trees per ha in period t for stand i, assigned to management regime j

t^{*} = first time period in which constraint in valid

Total area of deciduous forest

Next to an overall percentage of deciduous trees, there is a need for a certain area of deciduous forest. In this way there is a guarantee for some stands that contain more than just a fraction of deciduous trees; they have a majority of deciduous trees. The contribution of this area to satisfying the constraint above is obviously large.

$$\sum_{i=1}^{N}\sum_{j=1}^{Mi} B_{ijt}x_{ij} - \delta A \geq 0 \qquad t = t^{*},.....,T \qquad (8)$$

δ = desired percentage of deciduous area

A = total forest area

$$B_{ijt} = \begin{cases} 1 \;\; if \dfrac{L_{ijt}}{S_{ijt}} \geq \varepsilon \\ 0 \;\; if \dfrac{L_{ijt}}{S_{ijt}} < \varepsilon \end{cases}$$

ε = defined fraction of total volume causing an area to be deciduous

Total area of old forest

This constraint guarantees a certain area that is not cut before it reaches a certain age. This age will be higher than the age at which clear-cutting is economic most profitable. The need for old trees, not necessarily old forest, is assured by equation 10.

$$\sum_{i=1}^{N}\sum_{j=1}^{Mi} O_{ijt}x_{ij} - \phi A \geq 0 \qquad t = t^{*},.....,T \tag{9}$$

ϕ = desired percentage area with old trees

$$O_{ijt} = \begin{cases} 1 \ \ if \ d_{ijt} \geq d^{*} \\ 0 \ \ if \ d_{ijt} < d^{*} \end{cases}$$

d_{ijt} = age of stand i, assigned to management regime j in period t

d^{*} = age causing an area to be old

Retention of trees

With this constraint a certain area of the clear-cut area every period is assured to have retention of trees. These trees form a contribution to the amount of old trees as well as to the need for dead wood. In this way the strongly modified clear-cutting is represented. In equation 10 the volume after clearcut should, for a certain area, at least be equal to a constant retained volume.

$$\sum_{i=1}^{N}\sum_{j=1}^{Mi} R_{ijt}\left(F_{ijt} - \varphi Z\right)x_{ij} \geq 0 \qquad t = 1,.....,T \tag{10}$$

φ = desired percentage of area with retention of trees after clear cut

$$R_{ijt} = \begin{cases} 1 \ \ if \ d_{ijt} = 0 \\ 0 \ \ if \ d_{ijt} \neq 0 \end{cases}$$

$$F_{ijt} = \begin{cases} S_{ijt} \text{ - } V_{ijt} = Z, \text{ in case of retention of trees} \\ \qquad S_{ijt} - V_{ijt} = 0, \text{otherwise} \end{cases}$$

Z = fixed retained volume per hectare after clear cut

A contiguous area of old forest

Planning for a contiguous area of old forest, as is described above, requires a constraint on the spatial layout of the forest. There are more ways to formulate this.

One way is to consider the *adjacency* of stands as a measure to express to spatial relationship between stands (e.g. Baskent and Jordan, 1995; Jones *et al.*, 1991). In a constraint this could be expressed as the minimum number of 'old' stands that should be adjacent or a minimum total area of adjacent stands that should be old. Using adjacency in this way has some limits however. In the first case the area of the stands is neglected. Since it is likely that there is a large difference in area between the stands, there is little control over the total area of old forest. Next to that is in both cases the strength of the adjacency not taken into consideration, what implies that an elongated area can give the same satisfaction as a more compact area, while the core area of the latter will be much bigger.

A second option is to use the *distance* between stands (e.g. Baskent and Jordan, 1995; Bos, 1994). This does not guarantee any adjacency. Old stands that are close to each other but not adjacent, seem to be of much lesser value (Hof and Joyce, 1993).

A third possibility is to use the *length of the common boundary* between stands (e.g. Baskent and Jordan, 1995; Li *et al.*, 1993; Romme, 1982). I will use this option in my model. The constraint has the following form:

$$\sum_{i=1}^{N}\sum_{h=1}^{N} B_{ih} x_{io} x_{ho} \geq \gamma \qquad i \neq h \tag{11}$$

$$x_{io} = \begin{cases} 1 \text{ if stand i has reached } d^{*} \text{ in period t} \\ 0, \text{ otherwise} \end{cases}$$

B_{ih} = boundary length between stand i and h

γ = total required boundary length between old stands

An advantage of this way to express the constraint on a contiguous area of old forest, is that next to adjacency (non adjacent stands have a common boundary length of zero), also a unit for the strength of the adjacency is given. Stands with a long common border will have a large positive contribution.

Next to this the boundary lengths can be used to calculate a fragmentation or aggregation index (Baskent and Jordan, 1995; Li *et al.*, 1993). Such indices can be relevant to give information about the value of an area for the biodiversity. So availability of the data about boundary length can be of importance for other applications as well.

4. PROBLEM SOLVING TECHNIQUE

4.1 Mathematical programming in natural resource management

In a planning process the decision basis consists of the alternatives available, information about the consequences of these alternatives and the preferences of the decision maker with respect to these consequences (Pukkala and Kangas, 1993).

In strategic (long term) planning the element of time plays a major role. Not only the consequences in the next few years, but also after several decades are of considerable importance. We want to use our natural resources in perpetuity. A full consumption in the presence might give the highest value (in monetary terms) but then a use in the future is not guaranteed, since the resources are not unlimited: the sustainability is violated (Jonsson *et al.*, 1993). Next to woodproduction, giving a direct financial result, other functions of the forest are more and more stressed in the forest management planning. The sustainable provision of recreation possibilities, a scenic landscape and biodiversity are of eminent importance. The society is asking for a socially and environmentally sound forest management.

Finding the best solutions in time and space in forest management problems is a complicated matter. Relatively complex models are needed to make the solutions useful. Through the years the models have become more complex and more realistic because of improved measurement techniques, advanced sampling theory and powerful computers (Jonnson *et al.*, 1993). With increasing complexity, the pressure on solution techniques to find feasible solutions has increased as well.

Linear Programming (LP) has become one of the most common analysis techniques in renewable natural resource management and planning (Hof and Joyce, 1994). A conventional LP model may incorporate two classes of objectives: (1) an overall, single dimensional optimization criterion such as profit maximization or cost minimization; (2) a set of secondary requirements imposed by the decision maker (distinct from the absolute physical constraints) such as the attainment of certain minimal production levels. LP procedures yield an optimal solution to a quantitative allocation problem only if a feasible solution exists (Field, 1973).

An example of a Linear Programming study in forest management is performed by Thompson *et al.* (1973). In this study the aim was to manage a forest for woodproduction but taking into consideration the maintenance of wildlife in the forest. The objective was to maximize the volume of wood cutted in 12 periods. This was constraint by even flow constraints as we saw them in 3.2.2 and by an upperbound on the clear-cut areas. The authors strived for a diverse pattern of small size clearcuts over the time, whereby clearcuts in hardwood forests where limited to 25 acres and in pine stands to 100 or 150 acres. With this they favored the wildlife.

As I mentioned before many decision problems in natural resource management have multiple objectives. Frequently some of these uses are in conflict, and there is no common measure that can satisfactorily evaluate all of them. Multi-objective or multi-criteria programming is in this context a useful means to generate solutions. There is a wide range of multi-objective programming methods.

One which has been extensively applied to natural resource management problems is goal programming. Goal programming is an extension of Linear Programming. Goal programming minimizes deviations from multiple goals, or objectives, subject to some constraints that are goal statements and others that are physical constraints. In contrast to physical constraints, the goal constraints are satisfied as closely as possible but need not all be met completely. This flexibility is purchased at a cost: goal programming requires the explicit quantification not only of the objectives but also of the goal levels associated with those objectives and a preference structure defining the decision makers' preferences for each objective relative to the others. The difficulty of specifying the goal levels and preference ratings in a satisfactory and objective way has surrounded goal programming with considerable controversy (Dijkstra, 1984).

An example of multi-objective programming in forestry is a study of Kuusipalo and Kangas (1993). They describe the method of Analytical Hierarchy Process. This method is applied to a forest management problem that states that biodiversity has to be promoted in an ordinary, commercial production forest area. Biodiversity is added as a decision element to a general planning hierarchy. In AHP four steps are involved: (1) the dimensions of biodiversity are defined; (2) the importance of these dimensions is determined by a pairwise comparison; (3) alternative management strategies are evaluated with respect to each factor; (4) on the basis of the first three steps, the relative priority of each management strategy with respect to biodiversity is calculated. With this the consequence of implementing a management regime on biodiversity is known; maximizing biodiversity can be added as an objective in the planning problem.

The value function of a decision maker is in reality mostly not linear. With an increase of the value of the objective function, the marginal utility received of the last unit added to objective function value decreases. Another not linear situation is the advantage of scale. Large scale operations or orders are many times relatively cheaper than small scale operations or orders. To resemble this situation in a mathematical solution technique, non linear programming can be applied. In a non linear programming problem the objective function or one or more of the constraints are non linear (Hendriks and Van Beek, 1991).

Hof and Joyce (1992) used non-linear formulations to optimize the spatial layout of cuttings accounting for a number of criteria important to wildlife. These criteria (as interpreted by Lämås, 1996) were the amount of edge, the juxtaposition of different habitat types for cover versus feeding needs, the distance between favorable habitats and the minimum size of a patch of habitat.

When indivisible elements are encountered, integer programming has to be applied. Integer programming problems are significantly more difficult, computational, then the equivalent linear programming problems (Dijkstra, 1984). Therefor non of the developed methods can guarantee an optimal solution within an acceptable computation time (Hendriks and Van Beek, 1991). A well-known integer programming method is the Branch and Bound method. The algorithm first solves an LP problem by ignoring integer restrictions. Then a new constraint, which forces the LP solution towards an integer solution, is added. This is leading to a new LP problem to be solved. The process continues till either a full integer solution is found or the solution becomes inferior to the best solution previously found or the problem is found to be infeasible with no integer solution (Yoshimoto *et al.*, 1994).

Heuristics are a good alternative to integer programming methods. Although they do not guarantee optimality, they are capable of quickly generating feasible integer solutions to complex integer problems (Nelson and Brodie, 1990).

In forestry integer programming is used for instance for the allocation of forest management actions. This allocation is restricted when a clear-cut of two adjacent harvest units should not exceed the limit on a clear-cut area. With the incorporation of such a constraint each unit should be looked upon as one, indivisible element (O'Hara *et al.*, 1989). Also in road projects, for the transportation of wood, the variables are defined as strict binary. The decision is to build a road or not. According to Nelson and Brodie (1990) the heuristic method they used, a random search algorithm, was a good alternative for integer programming methods in an area based planning problem for the generation of a harvest schedule.

4.2 A sequential approach

The model presented in chapter three contains a spatial relationship, namely the constraint on a certain contiguous area of old forest. The way this constraint is formulated is known as a Quadratic Assignment Problem (the formula contains a quadratic term) (Bos, 1993; Burkard, 1984; Connolly, 1990). QAPs belong to the so called class of NP-hard problems, which is an indication for the degree of complexity (Burkard, 1984; Aarts and Korst, 1989). And according to Burkard (1984) they belong even to the hard core of this class. In practice this implies that these problems are hard to solve, especially when they are large. Exact solution methods (for instance the Branch and Bound method) are only computationally feasible for very small problems, up to 'n' is 15 to 20 (where n is the size of the problem) (Bos, 1993; Connolly, 1990).

Heuristics seem to be a good alternative. They do not guarantee optimal solutions, but they are able to solve larger problems in reasonable amounts of computer time (Connolly, 1990). Simulated Annealing is a heuristic method that has shown good results. According to Connolly (1990) and Burkard (1984) the results of Simulated Annealing applied to QAP are promising and excellent, respectively. They both stress the extremely efficient way it can solve a problem. In a comparative study in forestry Dahlin and Sallnäs (1993) conclude that Simulated Annealing gives the best solutions, in terms of Net Present Value.

Only a small part of the problem asks for a special solution technique. Apart from the constraint on the contiguous area of old forest the model can easily be solved with Linear Programming. The most efficient and effective way to solve the problem is to make use of LP as much as possible. Therefor I designed *a sequential approach.*

The sequential approach implies the use of a heuristic method and Linear Programming (LP) in one algorithm. Those parts of the problem that can not be solved by the LP are solved by a heuristic method. Hereby the heuristic solution is determined to fit as effective as possible in the overall solution generated by the LP.

With this approach the QAP is solved first, using Simulated Annealing (SA), and after that the rest of the problem is solved with Linear Programming; the strong points of both techniques are combined. This approach, combining a heuristic and LP in one algorithm to solve one problem, seems to be quite new.

As we saw above, SA asks for some kind of objective function. For this purpose equation 11 is converted into an objective function (see 4.4). To link the two parts of the algorithm together, the Net Present Value, which is the criterion whereupon selection of management regimes in the LP is based, is included in the objective function of the SA as well. With this the SA does not just look for the best solution concerning the area of old forest, it takes the complete problem into consideration. The area of old forest will fit into the total forest management plan and is not just determined next to it.

The area of old forest, determined in the SA, is restricted by an lower and upper bound. In this way it is possible obtain the desired area of old forest and control the outcome. The same lower bound is used in the LP.

In the next sections I will discuss the two parts of the algorithm. In 4.3 and 4.4 Simulated Annealing and in 4.5 Linear Programming. At the end of the last section a figure is given that summarizes the algorithm.

4.3 Simulated Annealing

Simulated Annealing is a so called 'iterative improvement' heuristic method. Starting from a known solution a better solution for the whole problem is sought (Bos, 1994).

The underlying idea of Simulated Annealing is to view the feasible solutions of a combinatorial optimization problem (such as QAPs) as atoms of a gas. Minimizing the objective function corresponds to minimizing the total energy of a gas. In chemistry the energy is minimized by cooling down the gas and performing probabilistic state-acceptance tests. This can be remodeled for combinatorial optimization problems.

The general structure of a Simulated Annealing algorithm is based on three components: (1) a method for evaluating a solution - an objective function, (2) a scheme for perturbing the present solution, and (3) a rule for deciding whether a solution resulting from a perturbation of the last should be accepted or not (Dahlin and Sallnäs, 1993).

We start with a random chosen feasible solution and perform a random pair exchange. The new solution is accepted, if its objective function value is smaller than the previously accepted objective function value. It is also accepted with a certain probability if its objective function value is worse. The acceptance probability depends on the difference between previously accepted and momentary objective function value and on a formal parameter which decreases during the procedure. This parameter corresponds to the temperature in nature (Burkard, 1984).

According to Bos (1993) a worse objective function value is accepted if the following relationship holds:

$$x < p(DELTA)$$

in which x is a random number between 0 and 1 and $p(DELTA) = \exp(DELTA / T)$. DELTA is the difference between the objective function value of the new and the old situation. The chance that a worse configuration is accepted, is higher if T (the temperature) is higher. The algorithm starts with a high T and T is lowered during the algorithm. At each value of T is looked for new configurations. At a certain moment the system 'freezes' in a current situation. The effect of accepting some worse configuration is that it is possible to move away from a local optimum. Normal iterative improvement heuristics stop at a local optimum. With the use of Simulated Annealing this can be avoided.

Aarts and Korst (1989) have shown that the algorithm converges asymptotically. And a strong feature of the Simulated Annealing algorithm is that it finds high quality solutions, which do not strongly depend on the choice of the initial solution, that is the algorithm is effective and robust (Aarts and Korst, 1989).

4.4 Implementation of Simulated Annealing

The Simulated Annealing algorithm in this study is based on an objective function[1] that balances the boundary length between old stands and the Net Present Value (NPV).

$$MAX\sum_{i=1}^{N}\sum_{h=1}^{N}B_{ih}x_{io}x_{ho}+W\sum_{i=1}^{N}\left(NPV_{io}x_{io}+NPV_{iy}x_{iy}\right) \qquad i\neq h \qquad (12)$$

in which: $x_{io} = \begin{cases} 1 \text{ if stand i is determined to be old} \\ 0, \text{ otherwise} \end{cases}$

$x_{iy} = \begin{cases} 1 \text{ if stand i is not determined to be old} \\ 0, \text{ otherwise} \end{cases}$

B_{ij} = boundary length between stand i and stand h

N = number of stands

W =.relative weight of the NPV compared to the summed boundary length

NPV_{io} = the maximum NPV stand i can get when it is determined to be old

NPV_{iy} = the maximum NPV stand i can get (without any restriction)

The aim in the Simulated Annealing algorithm is to plan for a contiguous old area, e.g. an area of adjacent stands that are all of a certain age at a certain moment during the planning horizon (see 3.3). To get a solution that will give an acceptable (in terms of NPV) final LP value, the NPV is added in the objective function as an incentive towards a high LP-value. The influence of the NPV on the final Simulated Annealing outcome in determined by the weightfactor (W). By putting this weight to zero, the algorithm looks for the highest possible boundary length between stands that are determined to be old. This means it looks for those stands that will give the largest contiguous area of old forest. Obviously it will take as many adjacent stands as are permitted by the model parameters.

By increasing the weightfactor the algorithm takes into account the difference between the maximum NPV a stand can give and the highest possible NPV that same stand will give under the constraint that is should be old. With a weight greater than zero stands that have a big difference between the NPV_{io} and the NPV_{iy} are less likely to be selected than stands with a smaller difference. The algorithm will balance the marginal increase in boundary length by selecting a stand to the possible marginal loss in NPV by selecting that stand.

Step by step, the SA-algorithm works as follows:

The first steps are performed only once:

- all stands that can not reach the ‘old’ age at the predetermined moment in the planning horizon, are eliminated of the procedure;
- at random a number of the remaining stands is selected to be old, until the constraint for the minimum area of old forest is met;
- the objective function is calculated.

[1] Note that the goal is to maximize the objective function. In the section above, SA is discussed for the minimization of an objective function. In theory this makes no difference, the relations in 4.3 hold true in the reverse way.

The next steps are repeated in accordance with the parameters of the Simulated Annealing algorithm:

- a random stand is selected. The feature of the stand is changed (i.e. old to not-old or not-old to old);
- the upper- and lower bound on the area of old forest are checked. If they are violated the previous step is repeated;
- the objective function is adapted to the change;
- in accordance with the Simulated Annealing procedure the change is accepted if it results in a higher objective function value and with a certain chance also if it results in a lower value.
- the 'temperature' is lowered in a predetermined fashion.

The iterative process in the SA-algorithm is executed a specified number of times (M). In resemblance with Lundy and Mees (see: Connolly, 1990), this number is determined by: $M = 50(\frac{1}{2}n(n-1))$, where n is the size of the neighbourhoods, which is the number of possible changes (i.e. in this case the number of stands that can reach the 'old age').

The cooling down procedure is determined by $T_{t+1} = T_t/(1+\beta T_t)$, whereby after each change (t, t = 1,..,M) the temperature is lowered. $\beta = (T_0 - T_f)MT_0T_f$, in which T_0 is the initial temperature and T_f the final temperature at which the process is terminated (freezing). These starting and final temperatures are set as the largest and smallest downhill steps found in 10000 previously performed SA-simulations, whereby all steps, both uphill and downhill are excepted (Connolly, 1990).

Contrary to most SA studies performed (Bos, 1994; Connolly, 1990; Burkard, 1984), where two or more variables are selected and the features are exchanged, a change is determined by a selection of a *single* stand, as is shown above. This is possible because there are only two possible situations for a stand. In this way the selection procedure makes the algorithm more flexible. With a 'double change' the initial number of stands selected, would be fixed till the end. In the current way, the number of stands is only determined by the upper and lower bound on the total old area and not by the (random) starting solution.

When the Simulated Annealing process is finished, the solution is read into the LP model. This means that for the stands that are determined to be old, the management regimes that do not reach the old age at the predetermined moment in the planning horizon are eliminated. This is discussed in more detail in the next section.

4.5 A stratum based approach in Linear Programming

Using a model I structure implies that the number of activities will be relatively large (Jonhson and Scheurman, 1977). The size of a model I formulation is sensitive to the number of choices for the number of different management intensities, rotation ages and thinning regimes (Jonhson and Stuart, 1988).

In a long term plan for a large forest area, the number of stands can be large. With this a large number of management regimes (variables) has to be considered. The complexity of the problem increases more than linear with the number of variables. This will make the LP-problem cumbersome and undo the advantages of an efficient Simulated Annealing algorithm. To overcome this difficulty I made use of strata in stead of stands. A stratum is a category of land, such as pine age 45, that responds the same way to a management action, relative to the yield of interest, wherever the land occurs (Johnson and Stuart, 1988). Stands with the same characteristics are united in one stratum.

There is another reason, next to efficiency, to make use of strata in the LP. There is no accurate data for growth projections, and with that the silvicultural treatments of all the stands. This is related to the case study in chapter six.

For the generation of the variables the Forest Management Planning Package (FMPP) is used (Jonsson *et al.*, 1993). The FMPP is a planning system that covers the surveying of the forest, generation of growth projections as well as the generation of effective treatment options and forecasting the impact they have on the forest. The FMPP makes use of a stratum based surveying approach: two phase sampling. In the first phase a total, fast, and inexpensive description of the entire forest is made. The forest is divided into appropriate compartments. The guidance for the partitioning of the forest into compartments is whether the stand within the compartment will be simultaneously given the same silvicultural treatment. A compartment can be compared with what I use the term stand for in the report. Therefor I will use 'stand' in stead of 'compartment'.

In the second phase the stands are clustered in strata, with use of the broad description made in phase one. This stratification is based on the age and volume, as well as preservation value of the stands. Stratification based on age and volume captures the Net Present Value as well as factors of importance for thinning and final felling. Out of each stratum at least two stands are sampled. For each sample stand the FMPP generates a number of management regimes. I discuss this in section 6.3, in the case study.

Because of the relatively homogenous character of a stratum, no big mistake is made if the stands in a stratum are at random assigned to a sample stand within that same stratum.

This means that in that aspect no use is made of the data that are collected in phase one, these are quite rough. Depending on the number of sample stands in a stratum, each stratum contains several groups of stands with the same characteristics.

The Simulated Annealing makes use of this stand based information. This is inevitable since the algorithm is designed for spatial relationships whereby the stands are the decision variables.

In the Linear Programming, however, the strata based information is used. For each sample stand a number of management regimes is generated, hereby representing a group of stands. In the LP equation 3 does not contain the stand areas as right hand side but the total area of stands represented by one sample stand. For those stands that are determined to be old, new strata are generated, derived from the strata where the stands belonged to, but those management regimes (variables in the model) that do not reach the old age are deleted from the basic matrix for the new strata. And finally the LP problem is solved, bounded by the constraints as in chapter three.

The gain in efficiency because of the stratum based approach is in no way at the expense of the loss of any information. When some stands have the same features, and thus the same management regimes, the LP algorithm does not distinguish between them anyway.

With the stratum based approach the management regimes for each sample stand are afterwards assigned to the stands represented by this sample stand. This is done at random and so resulting in the same solution as a stand based approach would give.

The complete algorithm is summarized in figure 4.1.

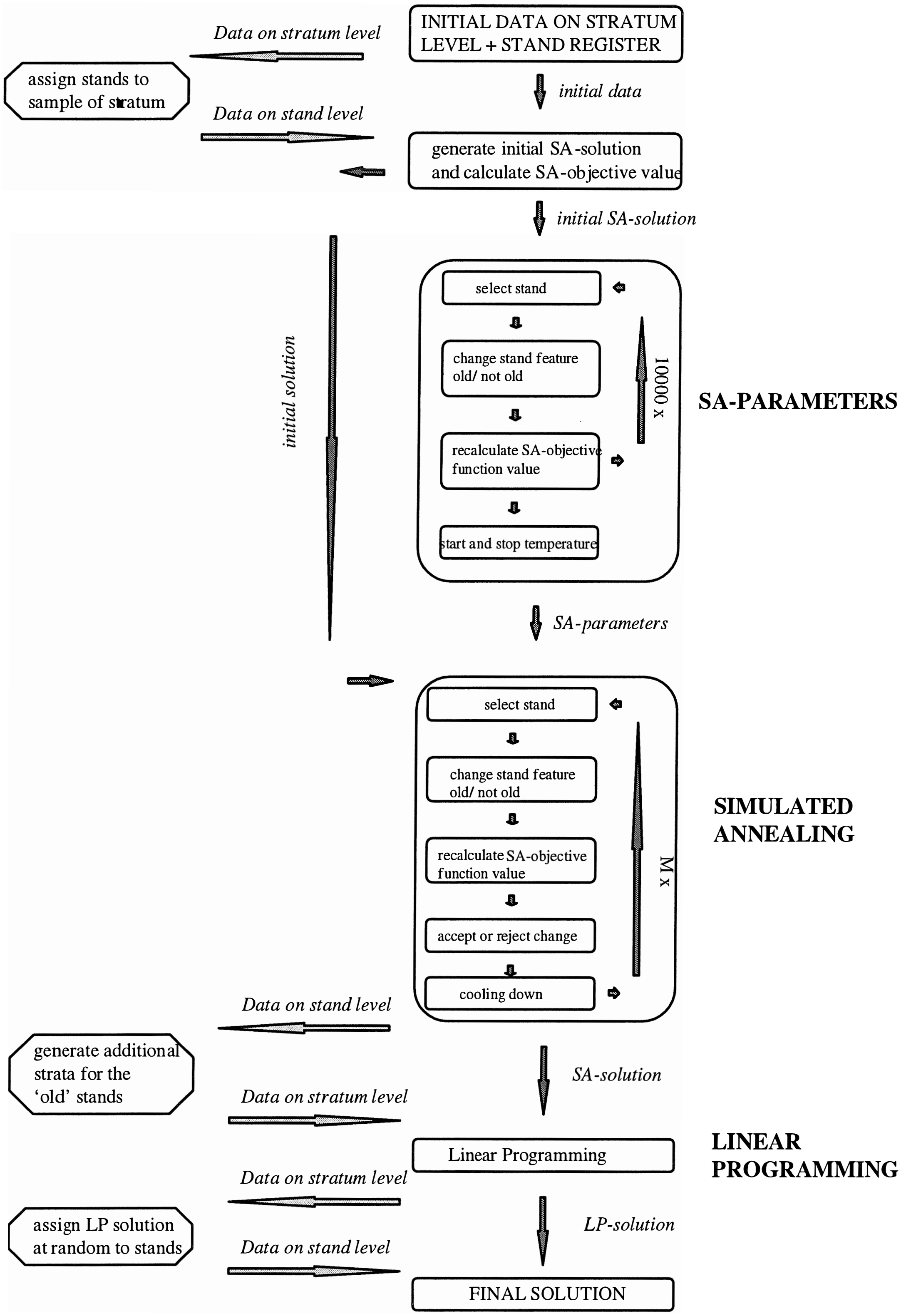

Figure 4.1 An overview of the complete algorithm

5. TESTING THE ALGORITHM

5.1 *Efficiently testing with a small sample area*

To design an algorithm that is valid, reliable and efficient, it is very time consuming to start working with a big 'real world' problem from the beginning. In my case study the area consists of 842 stands (see 6.3). This can lead to a Simulated Annealing algorithm with no less than over 17 million(!) iterations (calculated with the formula presented in 4.3).

For the design and modification of the algorithm many features have to be tested, before anything can be said about the validity and reliability. This takes an uncountable number of runs. It is obvious that 17 million iterations in each run would make the testing very cumbersome and increase the testing time unnecessarily.

Therefore I used a fictive sample forest of sixteen stands of the same size, arranged in a grid like pattern. The site characteristics and management regimes for these stands are connected to the case study in chapter six. In the Linear Programming, following the Simulated Annealing, only the even flow constraints (equation 4 and 5) were taken into account. And in stead of a stratum based approach a stand based approach is used. Except for efficiency this makes no difference. This way of testing turned out to be an efficient way to design the algorithm. For each test at least 400 runs of the algorithm are performed. The results are given in 5.2 and the conclusions in 5.3.

5.2 *Test results*

In 5.1 three aspects were mentioned upon which the test of the algorithm can be based. Reliability and validity are closely related. This relation can be shown with

$M = \alpha T + \beta + \varepsilon$. Herein is M the outcome of the algorithm, T is the real value (not known), α and β are constant and ε is a rest value. The reliability of the algorithm is determined by ε; if ε is zero, the algorithm is perceived to be reliable. The validity is determined by the constant values α and β. If α deviates from one and β from zero, one can say that the algorithm is not free from biases.

More concrete is the algorithm valid if it does what it is perceived to do. A non-valid algorithm gives a systematic error. The reliability relates to the rate in which the variability in the outcomes is caused by some form of randomness. An algorithm is reliable if a repetition of the algorithm gives results in the same order of magnitude.

In the case of the algorithm presented in chapter four, the validity has several aspects, all of them potential sources for a systematic error: 1) does the NPV in the SA objective function work as an incentive towards high LP-solutions, 2) does the algorithm react on a change in the parameters as is expected and 3) does the algorithm converse towards high solutions. The validity of Linear Programming as such is not under discussion. The algorithm is reliable when it is stable and gives solutions in the same order of magnitude all the time.

Efficiency refers to the time it takes to run the program in relation to the quality of the outcome. The question is if any sacrifices with respect to the quality of the final solution should be made to increase efficiency.

5.2.1 Validity

The most important question concerning validity for the first part, the Simulated Annealing, is whether it really weighs the increase in boundary length to the decrease in Net Present Value. When this works as expected, important progress is made with the combination of SA and LP in one algorithm. Dependent on the weight put on the Net Present Value in the objective function (equation 12) the algorithm will tend more towards a high value of the common boundary lengths or more towards a high NPV. A valid algorithm will show a higher common boundary length when the weightfactor is low and an increasing Net Present Value when the weightfactor is increased.

Testing with the 16 stands, where the SA algorithm is run 20 times for each weightfactor, gave the following results.

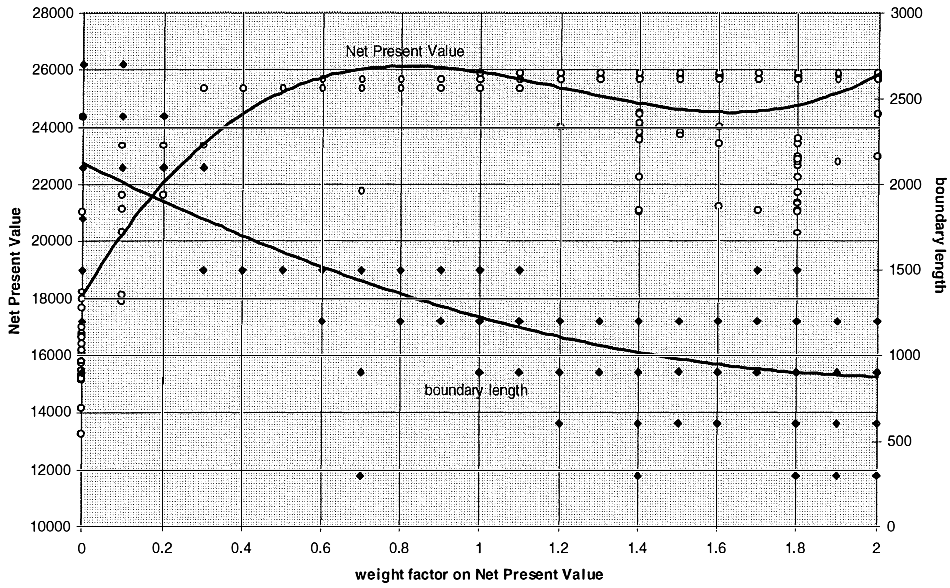

Figure 5.1 Net Present Value and boundary length as a function of the weightfactor on the Net Present Value.

What is there to see in the figure? Remarkable is the wide range of values for some of the weights, especially for the boundary length at a high weight. An explanation for this effect is that because of the small number of stands, always some stands will be adjacent. The lower bound for the area of old forest was set on 50 hectare, equal to 5 stands. Five stands out of sixteen have quite a high chance to give some adjacent stands, even if the algorithm is forced to focus on a high Net Present Value.

Another point is that at a weight of zero, which means that the Simulated Annealing objective value is determined only by the boundary length, the boundary length is sometimes remarkably low, where a high value could be expected. A close look at the data and the formulas presented in 4.3, that determine the cooling down procedure, learned that this is no indication for a poor algorithm. Because of the fixed area of stands (10 hectares for each) and consequently a fixed boundary length between two stands, the final (freezing) temperature is equal to this boundary length, since this is the smallest downhill step possible. This implies that even at the point of almost freezing, still large downhill steps are excepted. Because of the large number of different boundary lengths in a real data set, this seems to be no problem.

The decline of the Net Present Value (see trendline) at high weightfactors was a reason for further analysis. The poor values, especially at the weight of 1.4 and 1.9, turned out to be caused by a to low final temperature. The algorithm cooled down to fast in the beginning, hereby staying in a local optimum, where it could not come out anymore. It can be concluded that the cooling down procedure presented by Lundy and Mees (see 4.4) does not always give a satisfying solution.

I improved the algorithm by implementing a lower bound to the final temperature, set as a certain percentage of the starting temperature. If the final temperature for a certain weight comes below this bound, it is fixed as a certain percentage of the starting temperature, being the average of the ratios for those weights that do give a stable solution.

As is shown in the graphic below this improved the algorithm.

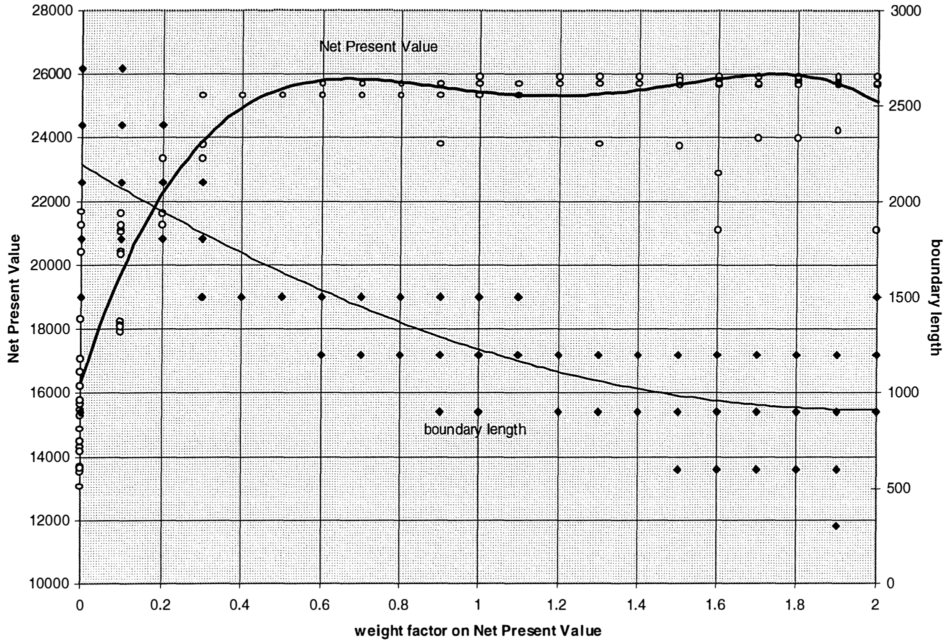

Figure 5.2 Net Present Value and boundary length as a function of the weightfactor on the Net Present Value. With an improved SA algorithm.

Improvement is made with respect to the Net Present Value at higher weights; the number of poor values is decreased significantly. The same goes for the boundary length at weights between 0.6 and 1.4.

Another aspect of validity is the question whether the Net Present Value in the SA-objective function is a real incentive for the final outcome of the Linear Programming. I showed above that a higher weight on Net Present Value in the Simulated Annealing leads to a higher Net Present Value. The question is now if this also leads to a higher LP objective function value, for which it is after all implemented.

Hereto I made the same run as above, with a changing weightfactor on the NPV. After that the SA solution is added in the Linear Programming with which the complete algorithm is finished. The relation between the Net Present Value in the SA and the LP objective function value is considered.

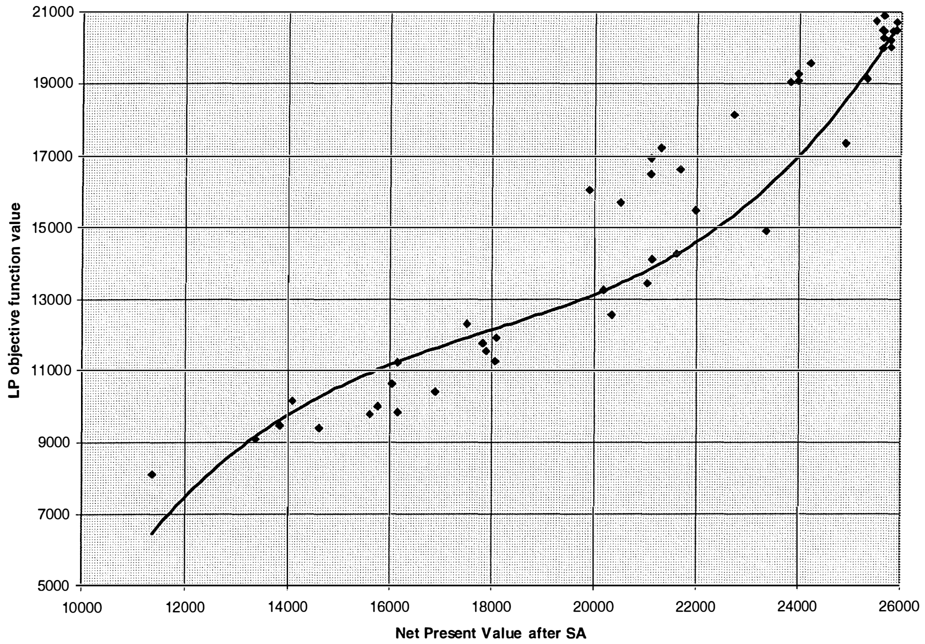

Figure 5.3 The final LP objective function value as a function of the NPV after SA.

The relation is clearly positive; the NPV in the SA-objective function is a distinct incentive towards higher LP objective function values. The LP objective function value is also expressed in terms of Net Present Value. In any case the NPV in the SA is higher than the related NPV in the Linear Programming. The reason for this is the fact that in the Simulated Annealing the *highest* possible NPVs for both 'old' and 'not old' stands are assigned. These values are however not realistic in the Linear Programming. The problem is bounded by additional constraints on even flow[1], meaning that the management regimes resulting in the highest NPV will not always give a feasible solution.

It is interesting to take a look at an other graph produced in the same test as the graph just discussed and to consider the two in relation to each other. In this graph the LP objective function value is a function of the weight factor in the Simulated Annealing.

[1] Note that in the test case only constraints on even flow are added.

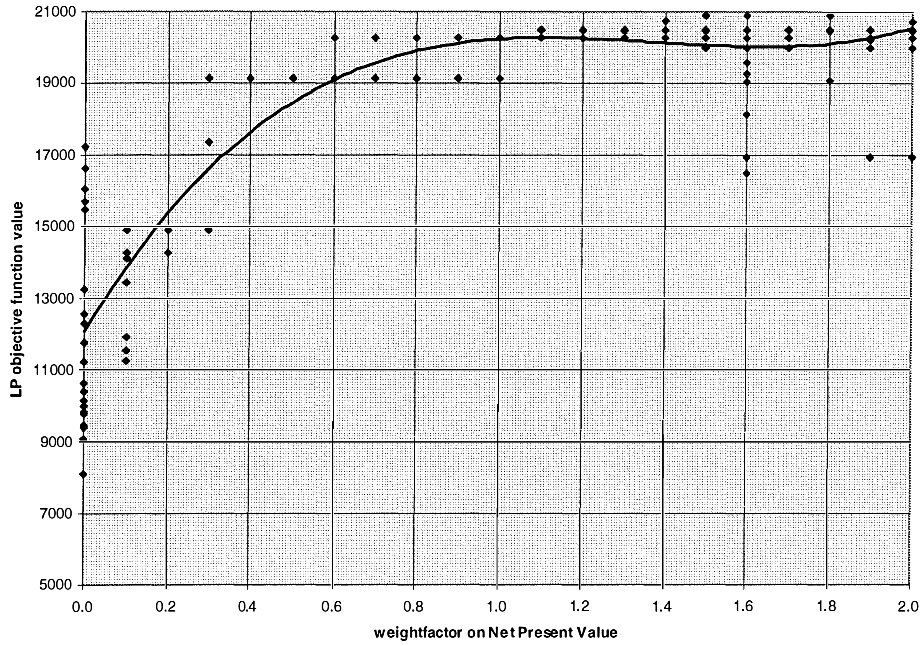

Figure 5.4 LP objective function value as a function of the weightfactor on NPV in the Simulated Annealing.

The graph is levelling of at higher weightfactors. This same effect can be seen in the upper part of figure 5.3, where the dots are clustering. The SA can not give higher NPVs. With a weightfactor of 1.1 it is already focusing enough on the NPV to give the highest values. A higher weight factor does not increase the NPV, while it might decrease the boundary length even further. The stands that should become old are only selected to satisfy the constraint on the minimum area of old forest. The contribution of the boundary lengths to the SA objective function value is marginal. This might also explain why the trendline has a small dip the end. As we saw in figure 5.1 and 5.2 the algorithm takes more or less at random stands when it plans for a high NPV. The performance is the best when the algorithm is balancing both factors in the SA-objective function.

There is quite a number of parameters that could be changed in the algorithm, to test the expected effect. One could think of the age at which a stand is considered to be old or the total area of old forest required in the SA and in the LP the evenflow parameters (α and β in equation 4 and 5) could be changed.

I will confine myself to shortly mentioning the results since they do not show anything remarkable. A negative side effect of increasing the area of old forest or the age is that unfeasibility is encountered relatively soon. An increasing age will side-track an increasing number of stands, causing the minimum area of old forest not to be reached. The same goes for increasing the minimum area of old forest at a fixed age. The number of stands in the test is on the short side.

For the feasible region the results were as expected. Increasing the age leads to a decreased boundary length and NPV in both the SA and the LP. A lower or higher weightfactor is needed respectively to plan for the same boundary length or NPV as at a lower age. Increasing the required area of old forest makes the boundary length increase and the NPV decrease.

Increasing the even flow parameters does obviously not influence the boundary length or the NPV after SA. The NPV in LP decreases as the margin for the even flow decreases, until unfeasibility follows.

The last aspect of validity I tested, is typically related to Simulated Annealing, namely the ability to overcome a local optimum and the convergence to a high final value as this is proved by Aarts and Korst (1989). This test is not meant to discuss the SA as such but whether this particular algorithm has the features it should have to work as a Simulated Annealing. Since only one run is required to test this ability, I decided to work with the final data set in stead of the sample stands. The results of such a test give a better view of the features of the algorithm.

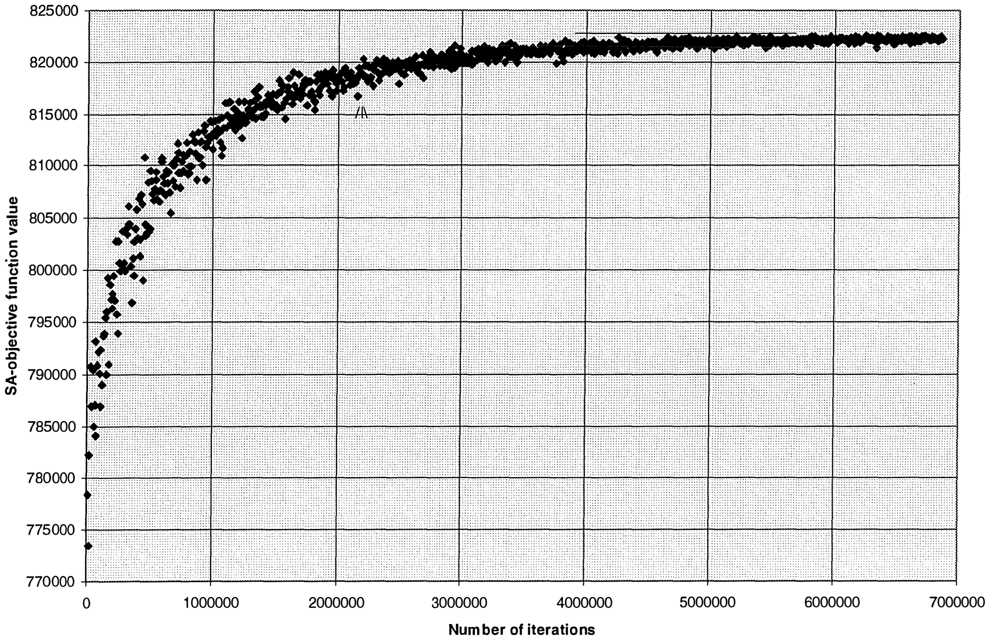

Figure 5.5 The progress of the SA-objective function value during one run with the SA algorithm.

In the first one million iterations the algorithm achieves higher values very fast. The random initial solution can be improved easily. With an increasing number of iterations, the curve levels off. It takes more effort to find a better solution and the value is coming close to its optimum. There is a clear convergence to a high final value. At a certain point no improvement is possible. The algorithm is freezing. There is no certainty about how close the objective function value at freezing is to the global optimum. I perceive it to be quite close regarding the behaviour in figure 5.5.

At the arrow one can see that the algorithm has the capability to overcome local optima. To get a high solution it is necessary to take these downhill steps as well. At the end the line is narrowing. Most downhill steps are not accepted anymore and uphill steps are not found.

I should mention that this figure is produced with some further modification of the algorithm. This is discussed in more detail in section 6.4.

5.2.2 Reliability

To test reliability I made 1000 runs with the Simulated Annealing. For certain weightfactors each run gives the same objective function value. For the weights 0.4 and 0.5 this effect can be seen in figure 5.2. They have only one point in the graph, representing 20 runs each. A more unstable outcome gives the weightfactor 0.1. For this the reliability is tested. The value of each run, presented as the maximum percentage of the highest value obtained in the 1000 runs, is used for figure 5.6.

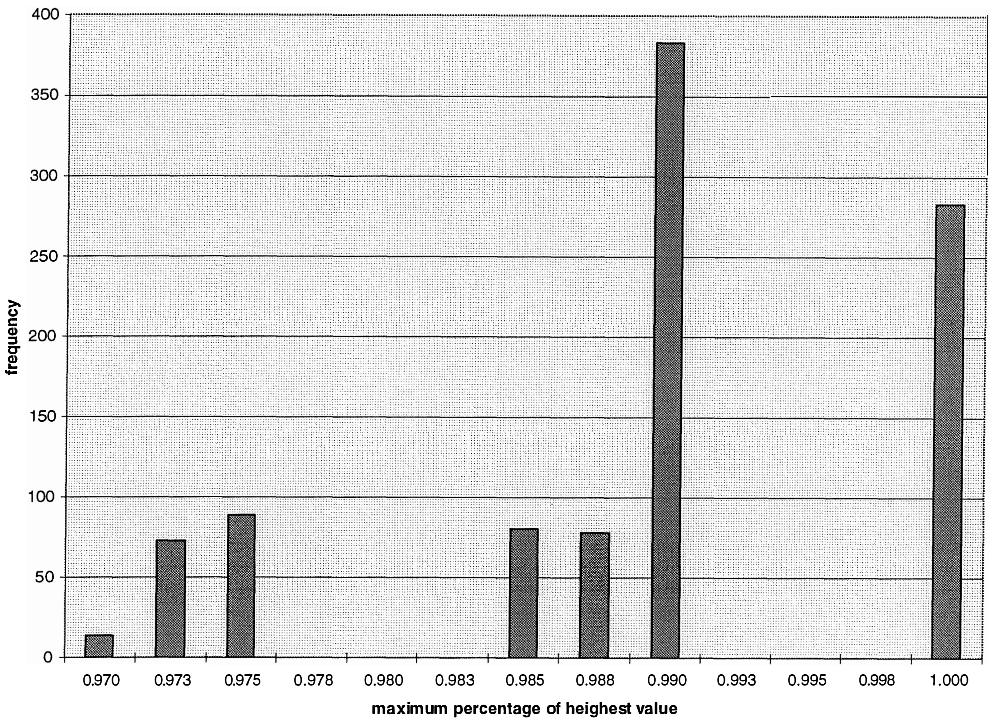

Figure 5.6 Results of 1000 runs with the Simulated Annealing, with a weightfactor of 0.1. The bar for 0.970 indicates all values equal to or less than 97% of the maximum value.

Most of the times an acceptable value is achieved, but in rare occasions the value can be poor. The highest value, this is 4559.02, is reached 283 times. A value equal to or less than 97 percent of this value is obtained 14 times. Some of these values are however much lower. The lowest value is 3923.05 (only 86 percent of the highest value).

There is no guarantee that the highest value is equal or even close to optimal value. This can only be assumed and seems reasonable taking into account the results presented in graph 5.5.

5.2.3 Efficiency

The program is written in FORTRAN 77, using a Microsoft compiler (Microsoft, 1989) for the Simulated Annealing and a Watcom compiler (Watcom IC, 1993) for the Linear Programming. The computer I used is a Pentium processor, 100Mhz. With use of a build in stopwatch, the efficiency is tested. Inefficient elements are detected and modified. I did not have to make any concessions on the quality to improve efficiency. With the test data, the algorithm takes just a couple of seconds. Here the different parts of the algorithm are united in one program (using the Microsoft compiler). For the case study four different parts are used. The first part, generation of data on a stand level has to be performed only once as long as the parameters do not change; joining it with the rest results in inefficiency. The Simulated Annealing and Linear Programming are separated because of computational limits to the size of the program. The LP program used is MINOS 5.0 (Murtagh and Saunders, 1983). The last part consists of a program assigning the LP solution to the stands. The time consumption of the LP is many times smaller than of the SA; the latter taking about 1.5 minutes for 7 million iterations, while the LP takes only a few seconds.

5.3 Lessons learned of the test

The test of the algorithm with sixteen stands is a useful and efficient way to check the algorithm on validity, reliability and efficiency. There are some important features that turned out to ask for extra attention.

The cooling down procedure presented by Lundy and Mees (Connolly, 1990), does not always give the best results. Because of a too low final temperature the algorithm cools down too fast and is not able to overcome local optima. Increasing this final temperature to a certain percentage of the starting temperature largely solves this problem.

Although most of the outcomes of the Simulated Annealing are within an acceptable range of the highest value, a poor value is possible. Therefor more than one run is desirable, before starting the Linear Programming.

When planning only for a high boundary length or focusing largely on the NPV, the algorithm does not perform as good as in the region in between. It is likely that this is no problem with the final data because of the large variety herein, contrary to the homogenous data in the test. Nevertheless precaution is required.

The combination of Simulated Annealing and Linear Programming seems to be promising. Using an objective function in the SA that weighs the boundary length to the NPV, seems to be a good option to reach a high final NPV.

The Simulated Annealing as such is able to overcome local optima and converges to high solutions in an efficient way.

Finally the size of the test seems to be rather small. A number of stands is excluded because of the fact that they can not achieve the age to be old. A somewhat larger test (for instance 25 or 30 stands) is desirable. The number of iterations needed in the SA increases more than linearly with the number of stands. The number of variables in the LP increases as well and with this more than proportional the computational efforts. An increase in the size of the test involves a loss in efficiency.

6. A CASE STUDY FOR THE BRATTÅKER AREA

6.1 Application of the algorithm in a case study

In chapter five I discussed the characteristics of the algorithm. The focus was on the technical performance. In this chapter I will present the results of an application on a real world situation. The focus is on the practical performance. For this the Brattåker area is taken into consideration. This area is a good representation of a boreal forest in Sweden. Next to that it is a study area of the department of Forest Resource Management and Geometics of the Swedish University of Agricultural Sciences. This makes it easier to get sufficient data in a short time.

In the next section I will give some general information about the Brattåker area. After that the application of the algorithm is regarded. First the data used and the parameter setting is discussed. In 6.4 I will mention the special adjustments to the algorithm stemming from this case study. The last part of the chapter is devoted to the outcome, resulting in a forest management plan, and to a sensitivity analysis.

6.2 The Brattåker area

Brattåker is an area of approximately 10000 hectares. It is situated in the boreal zone 60 km north-west of Umeå. The eastern border is formed by the Vindel River (here 150-170 m above sea level). From the river and westwards, the ground is made up by coarse glacifluvial sediments, followed by an undulating hilly terrain with mainly deep moraines, several mires in the valley bottoms and with the highest summit just above 400m. Eighty-nine percent of the area is productive forest land (site productivity >1 m^3 ha^{-1} yr^{-1}), 8% is peat land, and the remaining proportion consists of lakes and fields. In its natural state, the vegetation of the studied landscape was strongly influenced by frequent fires. Broadly, post-fire successions on drier sites were dominated by Scots pine, while on mesic sites broad-leaved trees, mainly birches and aspen were the early colonisers, succeeded by Norway spruce. On wetter sites, Norway spruce in many cases formed relatively stable stands regenerated by gap dynamics.

At present, Scots pine, Norway spruce and broad-leaved trees make up about 46, 43 and 11 percent respectively, of the standing volume in the studied landscape. About 50 percent of the productive forest land contains stands less than 60 years old and 13 percent contains stands more than 120 years old. The former are in most cases established by natural regeneration or planting after the first ever clear-felling.

The mean standing volume in Brattåker is approximately 100 m^3 ha^{-1} and the mean site productivity 3.9 m^3 ha^{-1} yr^{-1} which is close to the levels for the coastal part of the Province of Västerbotten, in which Brattåker is situated.

Seventy-two percent of the forest land is owned by forest companies, mainly MoDo Skog AB. The remaining area is owned by a about hundred non-industrial private forest owners.

Several decades of timber production have reduced the area of old forest. In addition, the remaining old forest is fragmented and there are no longer any large continuous areas of old forest (Fries and Lämås, 1995). There is however a number of species, interior habitat species, favoured by a contiguous area of old forest (Carlsson and Lämås, 1994). Furthermore, components and structures abundant in the natural forest (for example old trees and dead wood) are rare in the in the young forest, established after clear-cutting.

The rare and red listed species found in Brattåker are mostly fungi using dead wood (mainly down logs of Norway spruce) as substrate, and lichens confined to old coniferous and deciduous trees. In Brattåker, species classified as endangered in the Swedish red lists are found among insects, lichens, and fungi. Totally there are 30-50 red-listed species within the area (Fries and Lämås, 1995).

In a field inventory of natural values and key biotopes six areas were registered as valuable. One of them is a valuable creek environment. Some of the other five find their origin in a mix of Scotch pine of early generations and aspen and birch of earlier growth of deciduous trees after fire. The remaining area is full-grown spruce on wet soils free from fires. Together they make up an area of 110 hectares (Carlsson and Lämås, 1994).

In Appendix 1 a table is included, copied from a study performed by Fries and Lämås (1996). In this study the ecological and economical effects of different management regimes for the Brattåker area were analyst. The table gives an overview of the number of red-listed species in the area and the forest type and special features on which they depend. The conclusion of the authors is that a certain protected area together with a modified management on the remainder of the forest area is the best safeguard for the maintenance of biodiversity. Especially the alternative in which the landscape planning approach is studied shows promising results. The landscape planning approach is based on the key habitat - corridor model. Next to the maintenance of biodiversity, this approach gives a relatively small decrease in NPV, compared to other management alternatives, which are for example based on a large fixed preserved area (Fries and Lämås, 1996).

6.3 Input data

The Brattåker area has a stand register with 842 stands. These stands are clustered in 30 strata. The strata are represented by 63 sample stands. Each stand is associated with one of the sample stands. Some strata contain only one stand. These are the key stands (see 2.2), which means that they are of special value for the maintenance of biodiversity. These stands do not have any management activities and can be regarded as reserves. In the Simulated Annealing they are fixed as 'old' stands. In this way there is a high chance that adjacent stands are selected to be old as well and so forming a protective area around the key stands.

In the generation of the management regimes, after each clear-cutting 10 percent (recommended by Sjöberg and Lennartsson, 1995) of the trees is left behind on the area. This retention of trees is in accordance with the current forest management. Equation 10 is in this way redundant or to put it other words: φ is set on 100%, which forces us to leave trees behind after each clear felling.

For some stands an additional range of management regimes is generated. These are the so called 'deciduous friendly regimes'. Some stands with a high percentage of deciduous trees have a high potential to be of value for biodiversity. With the regular management regimes this high percentage is not guaranteed in the future. Therefor special management regimes are generated. They favour deciduous trees in the thinnings and result in a high percentage of deciduous trees. Implementing of a multitude of stand management regimes helps to create a structural and functional diversity of forest types across the landscape (Burton *et al.*, 1992). The selection of a deciduous friendly regime for a number of stands is assured by equation 8. At least 10 percent of the Brattåker area should have deciduous forest (parameter δ). A stand is considered to be deciduous if it contains at least 50 percent of deciduous trees (parameter ε). The overall contribution on forest level of deciduous trees is set on 15 percent (see Fries and Lämås, 1996). This is parameter χ in equation 7.

With this parameter setting the Linear Programming does however not give a feasible solution. Hereto the definition of deciduous forest is modified to forest with 40% deciduous trees and the desired area of deciduous forest is decreased to 5% of the total forest area.

The thinnings and clear-cuts are expressed in m^3 ha^{-1}. The percentage of deciduous trees is, as a consequence, calculated as fraction of the total standing volume, it occupies.

The planning horizon is 250 years, whereby only for the first fifty years the characteristics related to the forest management regimes are taken into consideration. The next two hundred years are used to calculate the Net Present Value. A NPV over just 50 years gives a biased picture since that period is to short to assure final felling for each management regime. Without a final felling the NPV is not a good representation of the management regime. The planning periods are 5 years; this very commonly used. The interest rate is 3%.

Fifty years is also the period after which the contiguous area of old forest should be realised. Many stands have a current age of about 70 to 80 years. The period of fifty years enables them to reach the age of 120 years, which is the age that makes a stand to be old. Hundred and twenty years is the age that Sjöberg and Lennartsson (1995) use to define an old forest. The area of old forest to be reached after fifty years (that is the ϕ in equation 9) is at least 1100 hectares. This is about one eight of the total forest area[1]. Hunter (1990) recommends an over-representation of old forest of 10 to 20 percent.

Because of the time needed to adjust the forest to certain requirements, not all constraints are valid from the beginning of the planing period. The equations 7, 8 and 9 are applied to the last 20 years, that is t^* is 7.

With the data and parameters as given in this section the LP problem consists of 31 'normal' constraints and about 100 area constraints. Of these are 63 the regular area constraints for the sample stands and dependent on the SA solution between 30 and 40 additional area constraints are added for the contiguous area of old forest. The number of variables is approximately 3200.

6.4 Modification of the algorithm for the case study

Initially the performance of the algorithm in the case study was very poor. The Simulated Annealing did not converge asymptotically to a high value, close to the global optimum. On the contrary, after looking for high values first, it finally converged to a low value.

An extensive analysis was made to find the source of these disappointing results. The outcome of the test in chapter 5 formed a useful guideline for this analysis. The cooling down procedure turned out to be a major source of error. Just like in the test the freezing temperature was to low. This resulted in a fast cooling down and freezing in a local optimum; most of the times already after 1.5 million iterations. A small modification like in the test, was not sufficient. A more rough trial and error analysis showed that the best performance is given with a final temperature 100 times higher than the smallest down hill step. Also the starting temperature had to be changed. For the best results it is half of the biggest downhill step.

These adjustments caused the algorithm to look for better solutions during the complete run. But still it did not converge to a high value. In the latter part of the search more downhill steps were taken than uphill steps. The algorithm could not find any uphill steps and because of excepting downhill steps now and then, it takes down the objective function value. By taking away the bounds on the area of old forest this problem could be overcome. Apparently all suggested uphill steps violated the bounds, while downhill steps did not do this. With this modification the results are as shown in figure 5.5, what I perceive to be a satisfying performance.

[1] The area of 10000 hectares mentioned in 6.2 includes also non forest land like lakes and pastures in the Brattåker area.

The consequence of these modifications is a loss of control on the final outcome. In the original design, the idea was to define the desired area of old forest by the upper and under bound. Given this desired area of old forest, the decision maker could, according to his preference, focus more on either the continuity of the area of old forest or on minimising the costs. With the modification, the desired area is determined by the weightfactor in the objective function. Since the solution is not limited by the bounds, each weightfactor gives another area of old forest. A direct influence on both components in the objective function is missing. To ease to analysis the objective function is changed:

$$MAX \ (1-W)\sum_{i=1}^{N}\sum_{h=1}^{N} B_{ih}x_{io}x_{ho} + W\sum_{i=1}^{N}\left(NPV_o x_{io} + NPV_y x_{iy}\right) \qquad (12a)$$

In this way the weightfactor is naturally bounded between 0 and 1; making a complete overview easier. In equation 12 it was not possible to focus for the full 100% on the NPV. For the practical application both objective functions are exchangeable.

Determination of the weightfactor is based on figure 6.1.

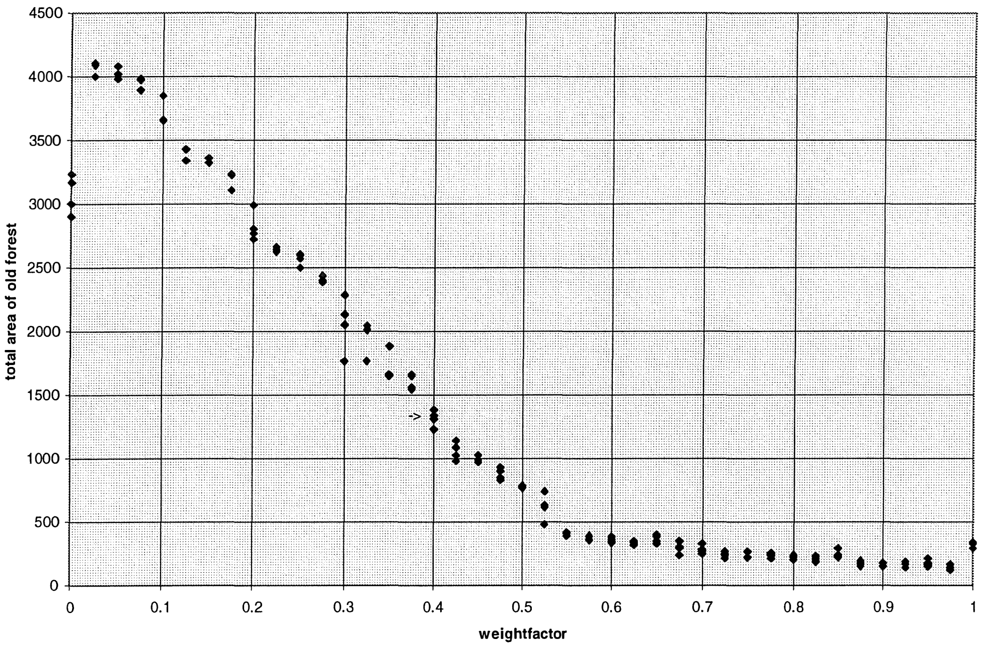

Figure 6.1 Total area of old forest as a function of the weightfactor; whereby for each weightfactor four solutions are generated.

Considering this figure I have made the decision to work with the weightfactor of 0.4. This value gives an area of about 1300 hectares. With this it is coming close to the requirement of at least one eighth of the forest to be old. Moreover does this weightfactor give a stable outcome, the reliability is high[2].

It is worth noticing the abnormal values for the weightfactor zero and to a lesser degree also one. As in the test they deviate strongly from the expected values. Because these weightfactors are not used, a further analysis is not made.

[2] This pronouncement is not based on the areas of old forest produced for a weightfactor of 0.4 (they show some variation) but on the SA-objective function values.

6.5 The long range forest management plan

The base of this section is the results of the algorithm for the Brattåker area. Because of a desired area of old forest of about 1100 hectares, a weightfactor of 0.4 in the Simulated Annealing objective function is implemented. The SA produces a contiguous area of old forest in year 50, the Linear Programming a management plan that indicates how much to cut in each period, where to cut, what to cut and what the revenues are. Next to that it shows how the features of importance for biodiversity develop in the coming fifty years.

With a series of four maps of the Brattåker area I like to show the spatial aspects related to the forest management plan. On figure 6.2 the results of the Simulated Annealing are shown; this is the area of old forest after fifty years. The reserved areas are pointed out in this figure. Figure 6.3 presents the current situation. In figure 6.4 all the stands that can reach the age of 120 years at the end of the fifty years are indicated. And finally figure 6.5 gives the results of the algorithm without special attention for a contiguous area of old forest, that is the outcome of the SA is not considered in the LP and the management plan. The management regimes are assigned to the stands at random.

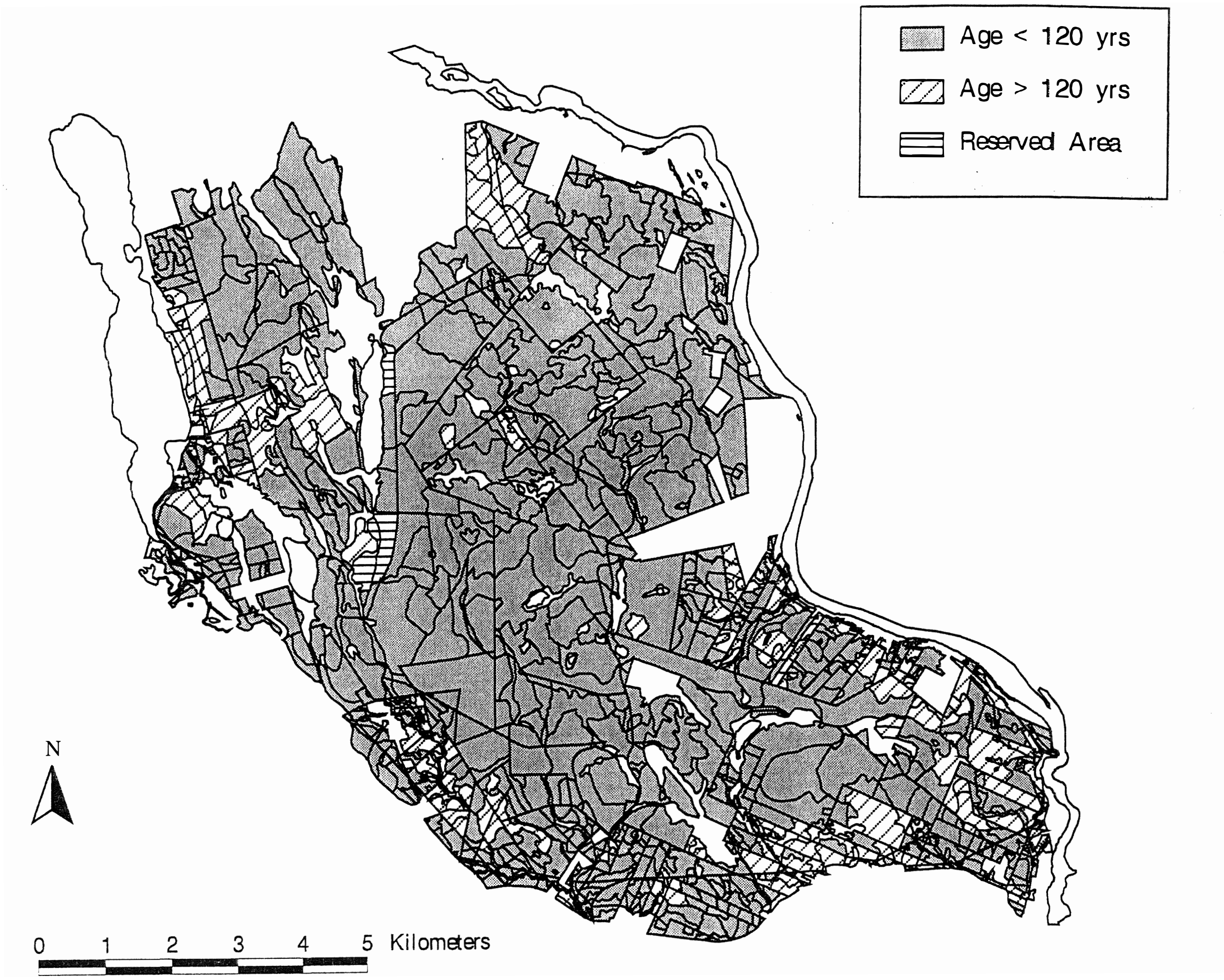

Figure 6.2 The Brattåker area after fifty years with implementation of the forest management plan.

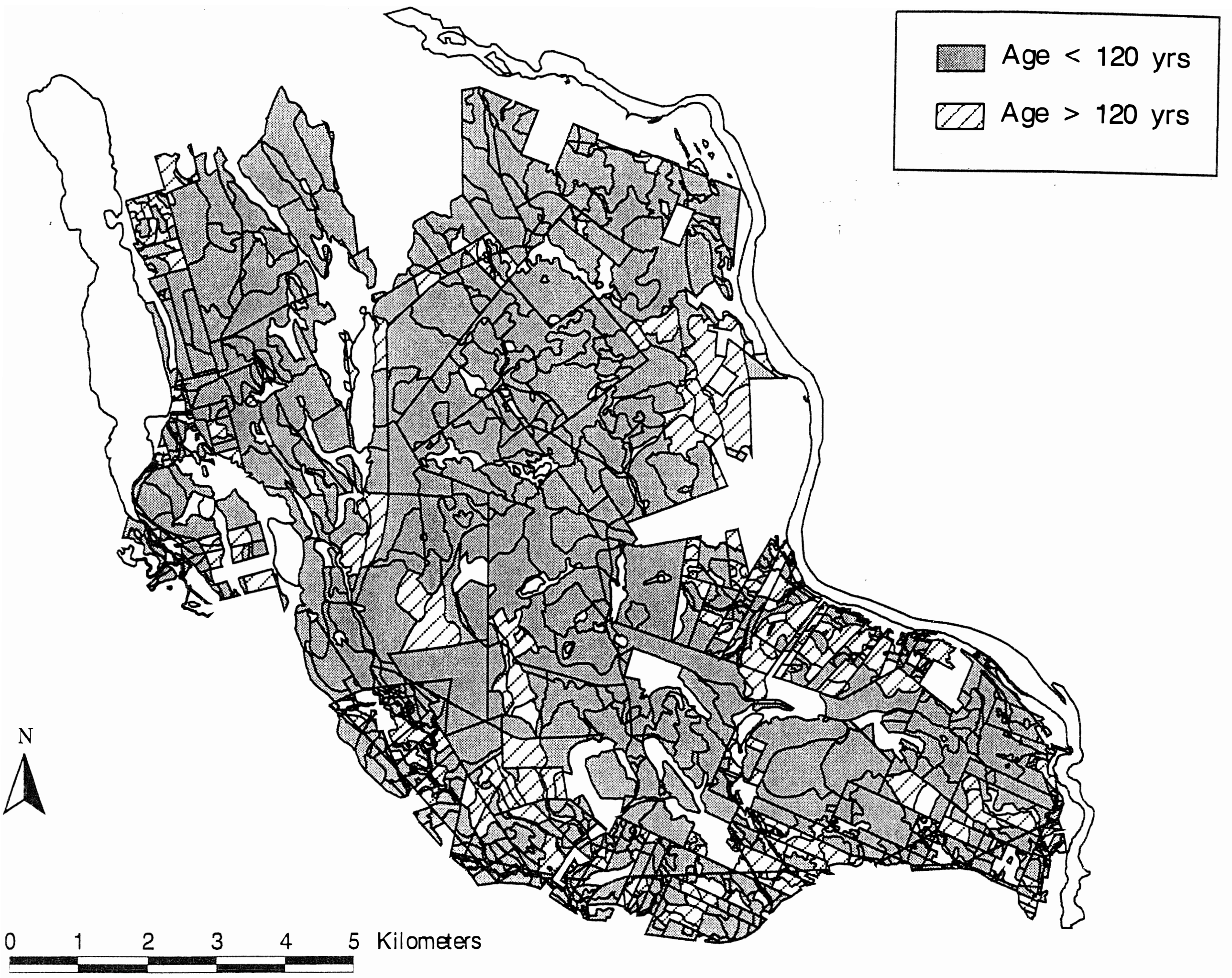

Figure 6.3 The initial situation in the Brattåker area.

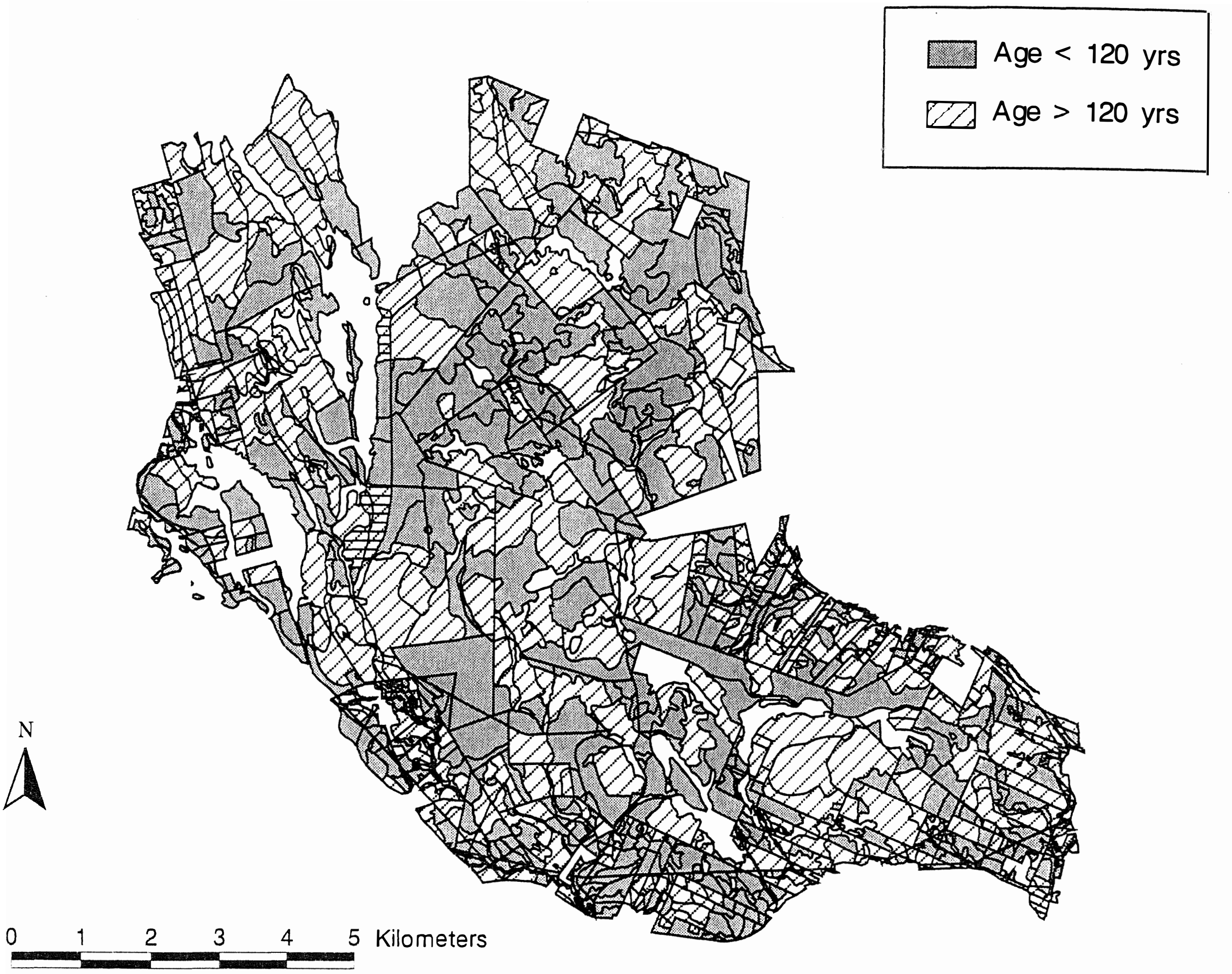

Figure 6.4 Overview of all the stands in the Brattåker area that can reach the age of 120 years within the coming 50 years.

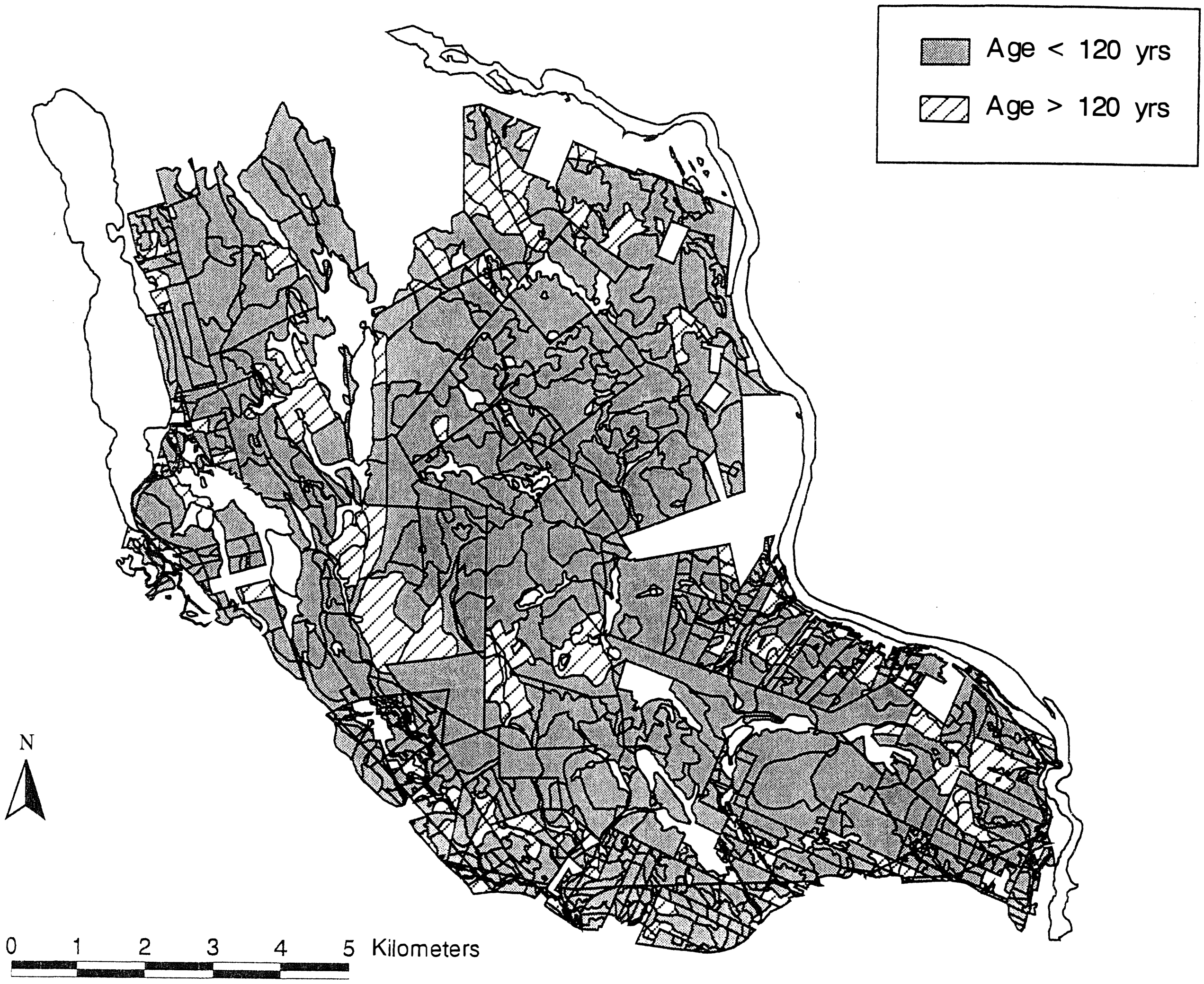

Figure 6.5 The Brattåker area in fifty years with random assignment of old forest to the stands.

The total Net Present Value of the forest management plan is SEK 192,2 * 10^6. This value is related to figure 6.2. The NPV of the plan without the constraint on the contiguous area of old forest, that is without the SA, is SEK 194,7 * 10^6. This value is related to figure 6.5. Therefore the costs of a contiguous area of old forest are 2.5 million Swedish crowns (that is 1.3 percent of the NPV), compared to a situation with about the same area of old forest, but without any requirement that it should be contiguous.

In figure 6.2 a total area of old forest of 1337 hectare is formed. The summation of the boundary length between the stands of old forest gives 54657 meters. With an at random assignment (figure 6.5) the total boundary length is 15929 meters; this figure is related to 1150 hectares of old forest. And in the initial situation the common boundary length measures 6070 meters for 595 hectares of old forest.

Figure 6.4 shows all the possible stands that can be old after 50 years. The number of large contiguous areas is limited. In the south-east one big area is significant. In the middle-west is another possibility. The rest of the Brattåker forest area shows a more or less scattered pattern, when it comes to old forest. The possibilities are clearly limited. The selection of the stands in figure 6.2, out of these stands, made by the SA, shows a preference for the small scale patterns along the edges of the area. These parts are mainly owned by small, private forest owners, while the large scale area in the middle is owned by forest company MoDo Skog AB.

There seem to be two main reasons for this preference. One is the large contribution of a large number of adjacent small stands to the SA-objective function value. Their common boundary length is many times larger as that of one or two big stands of the same total size. The second reason is the costs related to selection of big stands. Where the costs per hectare might not be higher than that of small stands, the stand related costs are much larger. This makes the selection of a big stand less likely (take in mind the rules for accepting a downhill step). It is worth mentioning that the border zone consists mainly of spruce forest on wetter sites, while the central area is formed by pine forest on the drier soils. The optimal rotation of spruce is slightly longer than of pine (about 5 to 10 years), which might make it cheaper to extend the rotation of spruce forest to 120 years compared to pine forest[3].

The preference for small stands is confirmed by looking at the selection of the stands during one run. During the run the number of selected stands increases, while the total area of old forest decreases. The average stand size is diminishing.

Compared to the initial situation (figure 6.3), there are very few stands that are old now and will still be so in 50 years. It is very costly to maintain old forest in these stands. From an economic point of view, the optimal rotation is approximately 110 years. At this age the average Net Present Value is at its maximum. The longer the stand is not cut after this age, the more it costs. The marginal revenues of the old stand are smaller than the average revenues of a possible new stand. With the course of the time this difference will become larger. Therefor stands that are old in the current situation, are more or less excluded from being old in the future.

Given the preference for small stands and the limitations caused by the pattern of actual and possible old forest, the actual outcome can be perceived to be acceptable. In the north an area of about 200 hectares is formed. On the west side another large contiguous area is created, although a real core area is lacking here. In the south east almost all the stands that can be made old, are actually old.

Remarkable is that the reserved stands, that are completely isolated in the initial situation, are after fifty years still not embedded in an area of old forest. However the possibilities for this are limited and the costs presumably high. For the two southern reserved stands all the possibilities are used; the northern area is lacking any adjacent stand of old forest, while there are possibilities.

An at random allocation of the old stands to the forest area, as in figure 6.5, saves the forest owner 2.5 million crowns. In figure 6.5 1150 hectares of forest are at least 120 years. Because of the at random assignment, the old forest is more spread over the whole area, in stead of being concentrated in the border zone as in figure 6.2. In this border zone most of the old forest is isolated; small stands are surrounded by younger forest. But next to that some bigger stands in the central area are selected. They tend to form some larger areas of old forest.

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[3] The fact that the optimal rotation of spruce is slightly longer than of pine might seem somewhat odd because spruce is in general growing on the better soils. This fact could be associated with the generation of the management regimes and is thus inherent to the data used.

The preference for old forest (at least one eighth of the forest area) seems to have a considerable impact on the age structure. This is shown in figure 6.6.

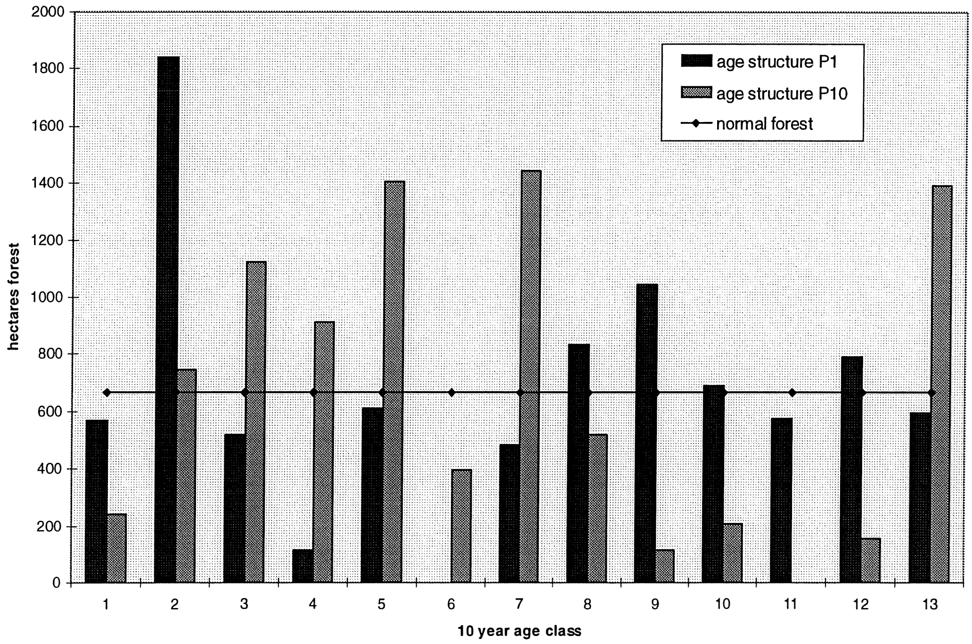

Figure 6.6 Age structure in period 1 and period 10 as a consequence of implementation of the forest management plan.

In the current situation (P1), the age structure shows a pattern close to the normal forest for many age classes, but with ups and downs for a few. The forest between 10 and 20 years occupies about 1800 hectares, more than 20% of the area and the age classes 4 and 6 have almost and completely no forest, respectively. In general one can say that the forest between 30 and 80 years, the premature forest, is poorly represented.

The age structure after fifty years makes clear that the forest management plan, with the requirement of at least 1100 hectares of old forest, is not realistic. The area of old forest is realised, but this seems to be largely at the expense of forest between 80 and 120 years. The empty state of age class 11 is inevitable. But the discrepancy between on the one hand the area of forest above 120 years and on the other hand the forest in the age classes 9, 10 and 12 is not necessary (the corresponding age classes in period one contain more forest) and not desirable. A more or less equal age class distribution is completely out of sight.

To meet the constraint on the area of old forest, forest in several age classes entering the last age class is added together. Because of this accumulation of old forest, the younger stands have to take care of the provision of wood, that is to satisfy the evenflow constraints on woodproduction. Consequently the area of mature forest decreases.

The total production of wood is represented in figure 6.7.

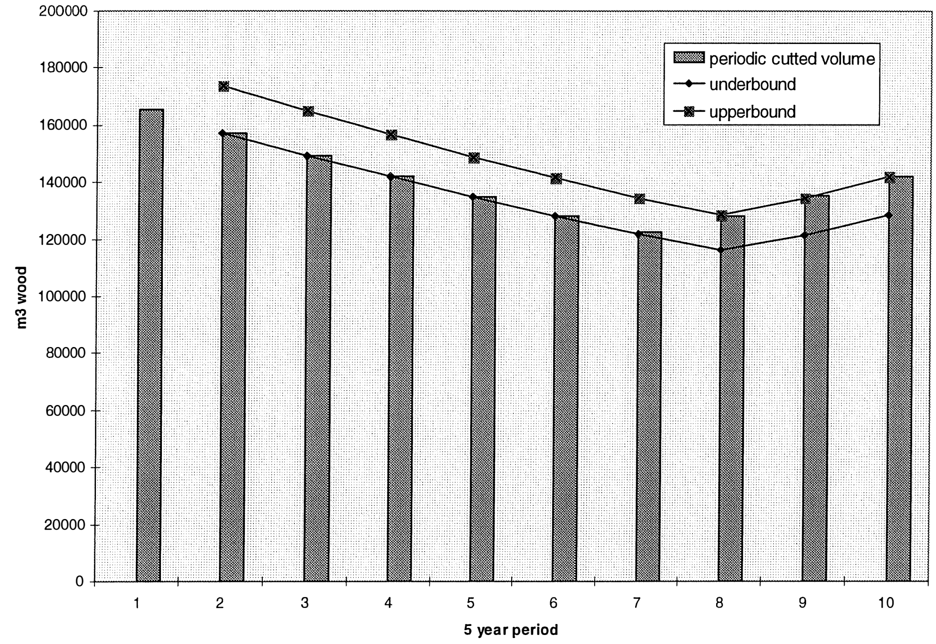

Figure 6.7 Total periodic wood production

The figure shows a stable provision of wood, whereby the levels of production in the first and last period are almost equal. The average annual cut per hectare in the coming fifty years is about 3.3 m^3. This is less than the current average annual increment of 3.9 m^3. This is, at least in part, the result of the retention of trees after each clear-cut. An important explanation of the pattern of cut in the time, that is a high initial production level, a decrease for the next seven periods and finally an upward trend, lies in the interest rate. The interest rate is an expression for the time preference of income. Low rates emphasise the present value of the farther future, high rates that of the nearer future (Duerr, 1993). An interest rate of three percent apparently causes a preference for a present income. Next to the high initial level of cut in figure 6.7, this is also visible in figure 6.6. The cut volume in period one is related to the forest of between 40 and 50 years in period ten. Age class five in period 10 represents about 1400 hectares. This implies that at least 1400 hectares are cut in period 1.

To follow the same line of reasoning further on, this situation causes some stands in period one to be cut before the age of 110, which is the optimal rotation, and this causes that the cut volume in coming periods is hard to get: the lower bound on evenflow is binding. The upward trend at the end is presumably caused by the maturing of stands initially situated in the age class 2. This class has decreased with 400 hectares in period 10, where it is entering age class 7.

The dual solution of a Linear Programming problem can give useful information with respect to the constraints. In the dual solution a so called shadow price is connected with each constraint. This shadow price indicates the marginal revenue of increasing the capacity with one unit. The shadow price of each area constraint is an estimate of the change in revenues if one land unit (hectare) from the corresponding stand type is added. For the constraints on the production level, the shadow price indicates the additional revenues of relaxing the constraint in question with one unit. For the non-binding constraints the shadow prices are obviously zero (Hendriks and Van Beek, 1991; Hoganson and Rose, 1984).

With respect to the evenflow constraints, the lower bound on the production level is binding from period 2 to 6 and the upper bound from period 8 to 10; the shadow prices are positive. The shadow prices of the first three evenflow-down constraints are as twice as high as the shadow prices of the other evenflow constraints. The costs of these constraints are higher, presumably due to the high level of initial production.

So, the unfavourable situation with respect to the age structure in period 10 might next to the need for old forest, be caused by the interest rate. The evenflow pattern as such seems to me to be as desired and is a positive aspect in the forest management plan. But in connection with the age structure, the situation is less bright.

In table 6.1 other forest characteristics coming forth of the forest management plan, for the ten planning periods are given.

Table 6.1 Characteristics of the Brattåker forest area with application of the forest management plan, for ten periods of five years.

5 year period	area old forest in ha.	area deciduous forest in ha.	area deciduous forest > 100 yr in ha.	total standing volume in $10^4 m^3$	standing deciduous volume in $10^4 m^3$	percentage deciduous trees
1	595.2	548.4	0.0	93.47	10.20	10.9
2	642.4	587.6	0.0	90.17	9.56	10.6
3	592.3	364.5	0.0	88.02	8.85	10.1
4	681.7	468.6	0.0	87.77	9.419	10.7
5	610.5	392.9	71.6	88.42	10.10	11.4
6	770.2	392.9	71.6	90.21	11.91	13.2
7	1083.0	433.0	163.5	92.75	13.91	15.0
8	1083.0	433.0	228.2	96.10	14.41	15.0
9	1083.0	433.0	228.2	98.95	14.84	15.0
10	1337.2	433.0	228.2	101.82	15.32	15.1

The general impression of table 6.1 is positive. As is stated in section 6.4 the forest needs some time for adjustment to the requirements on old forest, deciduous forest and deciduous trees. Therefor these requirements are valid from period 7 to 10. Starting the validation in period six results in unfeasibility. In the first 6 periods non of the features show a sharp decline.

With small ups and downs, the area of old forest increases from 595 hectares in period 1 to 770 hectares in period 6. In period seven the costs of the old forest are the highest. Decreasing the requirement of 1083 hectares with one unit, will yield a NPV of SEK 3000,-. In period 8 and 9 this is about half the amount. The amount of old forest in period 10 results from the outcome of the Simulated Annealing.

The costs of deciduous forest (forest with at least 40% deciduous trees) are smaller. This is not surprising because the gap between the 5% limit (433 ha) up from period 7 and the situation in the previous periods is small. The costs of 1 hectare deciduous forest are the highest in period 10: SEK 1900,- for the marginal hectare. The effect of the deciduous friendly management regimes becomes clear the in third column. The amount of mature deciduous forest increases from zero in the first four periods to 228 hectares in the last three periods. Because of thinnings of deciduous trees in premature stands the amount in mature stands is at present very small. The special attention in the deciduous friendly management regimes ensures a certain area of mature deciduous forest in the future. This kind of forest has valuable characteristics for biodiversity.

As a result of an error in the data generation, the deciduous friendly management regimes are only generated for the current stands. After regeneration only traditional management can be applied. This might be the cause of the unfeasibility with the initial requirement of 10% deciduous forest.

As mentioned before, the ending stock constraint is not binding. This can be seen in the forth column. The total inventory in period 10 is $101.82*10^4$ m^3, which is higher than the $93.47*10^4$ m^3 in period one. The high level of production in the first period finds expression in the sharp decrease in standing volume between period one and two.

The fraction of deciduous trees increases gradually to the desired fraction of 15% in period seven. In period ten a slight increase is visible; the constraint is not binding anymore.

The shadow prices related to the area constraints vary from SEK 86600,- to SEK 380,-. This difference is explained by the current state of the stand. Mature stands with a high site productivity give the highest shadow prices, while young stands with a low site productivity give the lowest values. This is not surprising because the mature stands are capable of given a high positive NPV; young stands might even have a negative NPV. The distinction between spruce and pine forest is not reflected in the shadow prices. The shadow prices for all the stands that are made old in the SA at lower or equal to the shadow prices of the connected stands that do not have the restriction. It is more profitable to expand forest with an economic optimal rotation with one hectare than old forest with an extended rotation. The opportunity costs of a stand increase as it gets older, since more money is accumulated in the stand; the standing volume is of higher value.

6.6 Sensitivity analysis

From section 6.5 it becomes clear that application of the forest management plan in the Brattåker area does not have merely positive effects. The age structure is severely distorted and with that the sustainable provision of goods and services after fifty years is not guaranteed. I suggested that the reasons are, in a random order, the constraint on the area of old forest, the initial age structure and the discount rate.

To get more insight in the issue, I have performed a sensitivity analysis with a changing requirement for old forest. The results are interesting. In figure 6.8 the age structure is displayed for a requirement of five percent old forest, and compared with the requirement for 12.5 percent old forest as in figure 6.6.

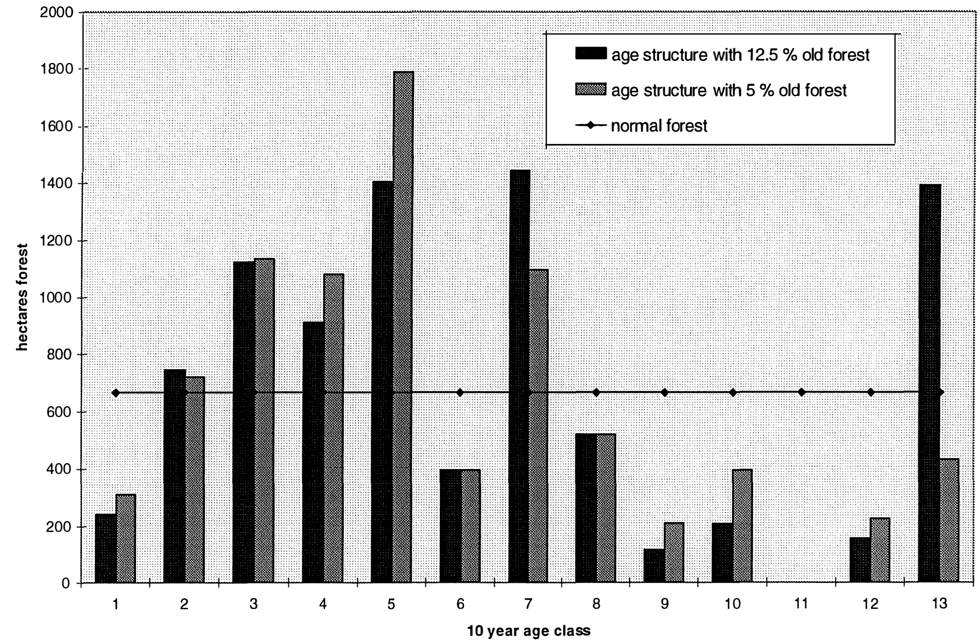

Figure 6.8 Age structure in period 10 with a requirement for 12.5 % and 5% old forest.

It is not the forest between 70 and 120 years that benefits in the first place from the decrease of old forest area, but the forest in age class five. Within the limits of the constraints, all the available forest land seems to be used to increase the cut in period one. This is due to the interest rate, causing a high preference for a present income to a future income.

The level of woodproduction in period one is even higher than in the same period in the forest management plan in section 6.5. This causes a downward trend of woodproduction in the following eight periods. The lower bound on woodproduction is binding in all these periods. And, contrary to the plan in the previous section, the constraint on ending stock is binding as well. These are all indications that the emphasis is on woodproduction in period one. The Net Present Value in this situation is SEK 198.0 $*10^6$, which is an increase of SEK 3.3 $*10^6$ compared to the initial situation with 12.5 percent old forest..

When taking away the constraint on the old forest area (that is reduce the requirement to zero), the pattern of figure 6.8 remains more or less the same. The area of old forest decreases to about 240 hectares. Sixty one hectares are reserved area; the remainder is forest with a long optimal rotation. The production in period one does not increase; this is prevented by the ending stock constraint. Forest in age class one and two benefits. The shadow price of the ending stock constraint in this situation is higher than with five percent of old forest: the costs of the ending stock constraint are higher ('more binding'). Going back to the previous section, it seems that the requirement on old forest is also an assurance of a high ending stock. The NPV without any constraint on old forest is 199.4 million Swedish crowns.[4]

On the basis of figure 6.9 the costs of the contiguous area of old forest are discussed. For this figure the situation in section 6.5 is used as a reference. The costs for a contiguous area of old forest in that situation are fixed on zero. The differences in costs for other areas of contiguous forest are computed. For this purpose varying weightfactors are used in the Simulated Annealing, going from 0.2 to 0.6. Next to this the costs of old forest are determined without the constraint that it should be contiguous. For each SA outcome, in terms of hectares of old forest, the Linear Programming is run with a constraint on the same area of old forest in period 10, but without implementation of the SA outcome.

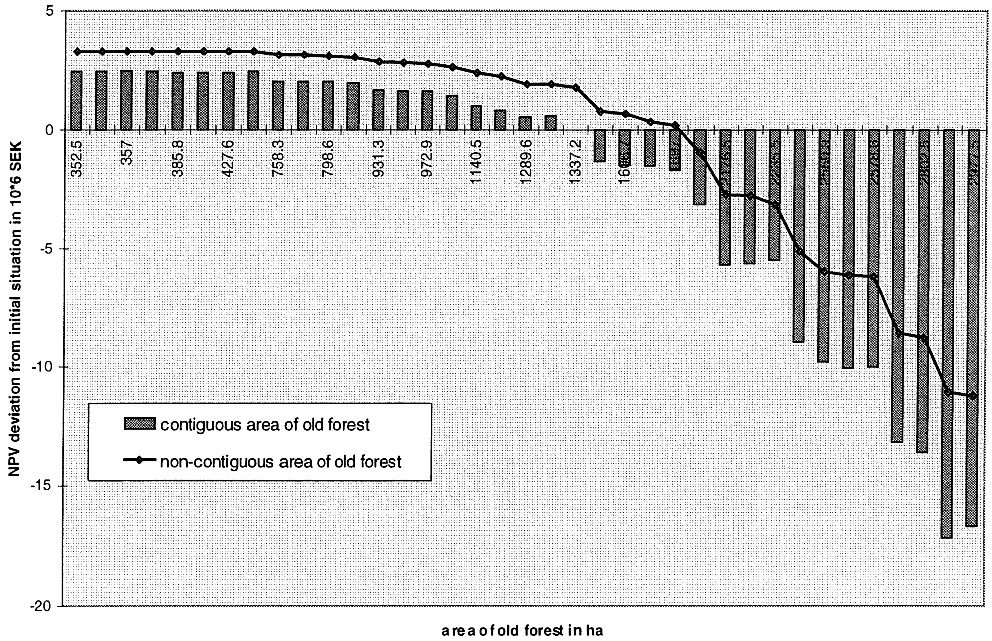

Figure 6.9 Costs of contiguous and non-contiguous areas of old forest, in relation to the situation in section 6.5

[4] Without any constraint on the woodproduction to maintain biodiversity the Net Present Value is SEK 200.5 $*10^6$.

The total revenues of the reference situation are SEK 192.2 $*10^6$. An area of 1337.2 ha of contiguous old forest is created (see figure 6.2). Without the need to make the area contiguous an additional income of SEK 1.75 million is gained. This is somewhat less than the 2.5 million mentioned before. The reason for this is that that value is obtained with the regular requirement for one eighth (1085 hectare) of old forest. Now the requirement is increased to 1337.2 ha in the last period, that is exactly the amount of old forest in the connected SA outcome. With this a true comparison is possible.

The costs of a contiguous area of old forest compared with a non-contiguous area of the same size are relatively low. Especially for small areas they are close together. The reason for this is that they are coming close to and finally reaching the maximum value. The constraint on old forest in the last period is not binding anymore. The old forest formed in previous periods guarantees a certain amount of old forest in the last period. The maximum net revenue in this situation is SEK 195.5 $*10^6$ for non contiguous old forest and approximately SEK 194.6 $*10^6$ for contiguous old forest.

When the area of old forest increases, the costs increase more than linear. This goes especially for the contiguous situation. The restrictions formed by the Simulated Annealing are getting stronger. For a larger area of the forest the choice among variables is limited to those that give forest of at least 120 years old. The distance between the costs for contiguous and non contiguous old forest increases as well. The same reasoning can be applied. When forming non contiguous old forest the Linear programming can still choose between all the management regimes available and 'make those stands old' that give the smallest loss of revenues.

When looking at the reference situation, that is 1337.2 hectare of contiguous old forest, the figure shows tat for the same money an area of almost 1700 hectares of non contiguous old forest can be created. This might be another way at looking at the 'cost of contiguous old forest'. These costs are 350 hectares of old forest.

Increasing the definition of old forest to forest of at least 140 years, clearly limits the possible solutions. The total area that can reach the age of 140 years after 10 periods is 2028 hectares (with 120 years it is 4104 hectares). To get an area of about 1100 hectares of contiguous old forest (although I doubt if it still will be contiguous), costs significantly more. In the Simulated Annealing a weightfactor of 0.075 has to be applied, to get such an area. This implies that the increase in boundary length does not compensate the loss of NPV so easy. The final LP objective function value comes to SEK 186.9 $*10^6$.

7. CONCLUSION AND DISCUSSION

In this report the technical and practical performance of an algorithm is discussed. The incentive to design this algorithm has been the growing demand for planning tools in forestry, whereby the actual objectives are translated in a forest management plan. In the current discussion about the management of Swedish forests, biodiversity plays a prominent role. The need to maintain biodiversity becomes more and more clear. The general objective in the forest management can be summarised as: 'manage the forests in such a way as to provide a sustainable production of wood and at the same time maintain biodiversity.'

In the algorithm I designed, there is special attention for the creation of a contiguous area of old forest. In the boreal forests in Sweden many threatened species (like lichens and insects) depend on old forest characteristics. Since the forest is fragmented, the need to form a contiguous area of old forest is evident.

The algorithm consists of a sequential approach. In the first part, the contiguous area of old forest is formed with use of Simulated Annealing, a heuristic method. The solution of the Simulated Annealing is taken into the second part: the Linear Programming. This Linear Programming finds the optimal solution, in terms of Net Present Value, as a combination of management regimes. This solution is restricted by constraints that ensure a sustainable woodproduction and the establishment of a series of features abundant in natural forests, but scarce in managed forests. With these features it is assumed to maintain biodiversity.

In this final chapter, I will discuss different aspects of importance in the study. In this discussion I will draw some conclusions, place question marks and commends and recommend further research. The sequence of topics in the report will largely be maintained in this chapter.

Biodiversity management

To maintain biodiversity I assumed that the (re-)establishment of certain features of the forest, of importance for rare and vulnerable species, guarantees this maintenance. These features can be achieved by implementing certain management regimes. The current scientific knowledge gives little opportunities to relate management regimes to their impact on biodiversity (in terms of evenness and richness of species). Establishing certain features is an efficient and fairly simple way to manage for biodiversity. This does not alter the fact that on a lower (stand) level, these features might be insufficient. They form a framework, in which small size measures can be taken. The translation of the requirements of rare flora and fauna species into some model parameters is a large simplification of reality. Site adapted forestry is a logical continuation on a smaller scale, a tactical level.

The model described in chapter three has some limitations. Planning for a contiguous area of old forest as addition to a more or less straight forward problem of sustainable woodproduction and maintenance of biodiversity is just one and a quite rough way to include spatiality in the model and the solution technique. The tree species and ecology of the stands are not considered. In chapter two I mentioned the distinction between dry areas, regularly subject to forest fires and the wetter areas, subject to small scale disturbances. In the algorithm this distinction is not made. The area of old forest is determined regardless of the kind of forest considered.

The desirability of the implementation of forest with an extended rotation (old forest) in the normal managed forests is not free of doubt. Hunter (1990) states that the problem with a long rotation to provide old forest habitat is that it would occupy more land than a reserve system because only a portion of the stands would be in an old stage any one time. The formation of forest reserves in Sweden is however limited (see 2.4).

When looking at the figures 6.2 and 6.3, almost no forest that is old at present, will be old in fifty years. This implies that species bounded to old forest have to move over the area. Especially for (immobile) plant species, with limited dispersal capacities, this might cause problems. A more ideal situation will be a 'moving' old forest. When at one side of the old forest a part is cut, on the other side mature forest is available to become old.

There needs to be some kind of guarantee that not all the old forest after fifty years, will be cut in year 55. As mentioned before, old forest is expensive and will be more expensive as it becomes older. The transition from one situation with old forest to another has to be taken gradually instead of stepwise.

Algorithm design

A clear positive contribution of this study is that it shows the possibilities to link a heuristic method and Linear Programming. By including the Net Present Value, which is the selection criterion in the LP, in the Simulated Annealing objective function, the SA-solution fits in the total plan. The area of old forest is determined with relatively low marginal costs.

This solution method is effective and efficient because for those parts of the problem that can be solved with the LP, it is done as such; resulting in an optimal solution in a short time. The parts that are very hard or can not at all be solved with an exact solution method, that is the Quadratic Assignment Problem, are efficiently solved with Simulated Annealing, resulting in a presumably high quality solution. Strong points of both techniques are used and combined.

The positive results achieved with SA in other studies can be confirmed. In the test in chapter five the algorithm is tested on validity, reliability and efficiency. The determination of a good cooling down procedure, resulting in an algorithm that is able to overcome local optima and converges to a near optimal value, asks a lot of effort and time. Both in the test and the application in the case study this became apparent. The parameters determined with the 'Lundy and Mees procedure' were in this case study clearly not ideal. The cause for the poor performance with these parameters is not clear. The complexity and size of the problem and the heterogeneity of the data could be a source for problems. Because of the interaction between starting and final temperature, the cooling down parameter and the number of iterations, improvement is time consuming and complex.

A main source of the problems was overcome with a strong narrowing of the cooling down interval. The final (freezing) temperature is made 100 times bigger and the starting temperature two times smaller. More or less the same conclusion is made by Connolly (1990). The best performance in different tests he did, was given with an interval going from the starting temperature $T_o = \delta_{\min} + \frac{1}{10}(\delta_{\max} - \delta_{\min})$ to the final temperature $T_f = \delta_{\min}$. Herein are $\delta_{\max}$ and $\delta_{\min}$ the biggest and smallest downhill steps in a number of previous performed swops. Instead of increasing the final temperature he decreases the starting temperature. In my study this did not have the desired effect. But the main thing, also mentioned by Burkard (1984) is that the cooling down should be performed slowly.

Instead of the random selection of stands for the improvement of a present solution, Connolly (1990) uses a selective selection criterion. This resulted in improved solutions. The selection of a single stand of which the feature is changed, as it is done in this study, is seldomly encountered.

Another modification I made in the case study, next to the adjustment of the cooling down procedure, was to take away the bounds on the area of old forest. For a reason not quite clear to me, these bounds caused the algorithm to converge to poor values. In the latter part of the search almost no uphill steps were taken and the acceptance of some downhill steps every now and then, caused the objective function value to decrease. Aarts and Korst (1989) incorporated constraints in the SA-objective function as a penalty term. In this way the algorithm might be more flexible since some violation of the constraints is admitted.

The discussion above subscribes to the conclusion of Dahlin and Sallnäs (1993): 'The results are heavily dependent on the specific situation in the study area. The structure of the area is of importance.' With the modifications I made, application of Simulated Annealing gave satisfying results, but another application might ask for other modifications and parameter setting.

In section 6.5 I mentioned the preference of the SA-algorithm for small stands. They give a higher common boundary value and consequently a higher contribution to the SA-objective function value. This might be at the expense of the selection of big stands that can form a larger contiguous area of old forest. The real influence of this shortcoming is however not known because the small stands in the case study, were also the stands that gave the lowest costs for extension of the rotation. This caused them to be preferred for more than one reason. To avoid problems with other applications it is an option to use another measure for a contiguous area. The options mentioned in section 2.2.3 are in my opinion still inferior to the one I used. A measure including both the size and shape of a patch would give the real contribution of an area to the formation of a contiguous area. In an objective function shape and size could be used with a weighted score. For the measurement of shape Baskent and Jordan (1995) mention the shape index (SI). $SI = \frac{\text{perimeter}}{2\sqrt{\text{area}(\pi)}}$.

This index represents the deviation of a patch from circularity. To form a core area, the SI should be minimised. More simple to implement would be an objective function that maximises the size and the negative perimeter of a patch.

Efficiency is a strong point of the algorithm. The Simulated Annealing with about 7 million iterations, is solved within 2 minutes; the Linear Programming in just a couple of seconds. The improved computers clearly contribute to this efficiency. Dahlin and Sallnäs mention in 1993 a computation time for a SA-algorithm of several hours.

In the discussion about the model I versus the model II formulation of a problem, one of the main objections to a model I is its inefficiency. When talking about a computation time of seconds, it seems hardly worth the effort to discuss efficiency. The stratum based approach plainly contributes to this efficiency. In the case study a maximum of 100 sample stands results in no more than 3200 variables. With a stand based approach this number could easily exceed 27000. The number of constraints in that case would increase from 130 now, to about 900. This would make the program cumbersome.

The way the validity and reliability are tested is somewhat limited. Validity is only related to itself, a real reference is lacking. Nevertheless the test was useful and necessary to design the algorithm. It supplied me with a lot of data that formed the guidelines among which improvement in the case study should be sought.

With the test on reliability the only thing that can be said is that the algorithm is capable of producing a stable outcome. About how close the values are to the global optimum, one could just guess.

The algorithm finishes with an at random assignment of the optimal management regimes for the sample stands to the stands represented by these sample stands. To fully complete the algorithm a directed assignment would be desired. Because of a lack of time I have not been able to do this. But I like to make an initiative.

- The data about the boundary length can be very useful. Many species, like predators, take profit from clear edges. The assignment can be such that clear-cuts are located adjacent to mature stands. Simulated Annealing can be a useful tool for this. By defining three age classes: young, middle and mature and a score for two adjacent age classes an objective function containing this score could be maximised. A young stand next to a mature could have a positive score and any other combination a zero or negative score (see for a similar application Bos, 1994). The boundary length is an indication for the strength of an edge.

- Limit the area of a contiguous clear-cutting. The management regimes for the sample stands could be cut into pieces of a maximum size and assigned to non-adjacent (parts of) stands, hereby spreading the clear-cuts in the time over the forest area. The discussion about this topic is however still going on. Does biodiversity benefit from a concentration of clear-cuts because fragmentation is combated or does it benefit from small size clear-cuts because of a limited disturbance and the preservation of the forest micro climate? According to Li *et al.* (1993), the cutting unit size should reflect a balance between all ecological consequences.

It might even be an option to move the allocation of old forest to the area to the end of the algorithm. In that case the Linear Programming is solved first. For those sample stands that will have an age of over 120 years, the solution is located to the concerning stands with use of Simulated Annealing. The contiguous area of old forest will be formed taking into account the LP solution. This way is cheaper, but the possibilities to form contiguous old forest are limited, which they are even in the actual situation

Finally I like to give a suggestion to improve the algorithm in the way the SA and LP are combined. Incorporation of the NPV in the Simulated Annealing turned out to be a good means to fit the SA solution in the overall solution. Another option is to use the reduced costs, in stead of the NPV, after first solving the LP. The reduced costs are the marginal costs related to each management regime. The reduced costs of the management regimes that are not used in the optimal basis are negative. Taking them in the optimal solution has a negative effect on the objective function value. The reduced costs of the activities in the optimal basis are zero. Contrary to the NPV, the reduced costs of a management regime are a measure for the extent to which an activity fits in the total solution. The effect on the satisfying the constraints and on the other activities is considered as well.

An indication for a potential good performance with reduced costs can be seen in figure 6.5. From this figure it is clear that some of the pine stands in the optimal solution are old, although the direct costs (NPV) to extend their rotation are higher than that of spruce stands. Apparently is it terms of the total plan (reduced costs) optimal to make some of the pine stands old as well.

With the use of the reduced costs the management regimes that have a positive contribution in terms of the total plan are preferred in the SA. In the algorithm this would imply that the LP has to be run preceding the SA to generate the reduced costs. The remainder of the algorithm would not change.

The algorithm in a case study

In chapter six the practical application of the algorithm in a case study is discussed. The Brattåker forest area is considered; this area is a good example of a boreal forest in the North of Sweden. The algorithm is capable of producing good solutions, that is a strategic forest management plan for 50 years. With the Simulated Annealing outcome a map is produced, showing the area of old forest after fifty years. One large contiguous area of old forest is not produced. The result is better than with a random allocation of old forest to the area, but also more costly. Three more or less contiguous areas of old forest are formed in the border zone of the area. There are several reasons for this. The possibilities are limited; not all stands have the capability to reach the age of 120 years after 50 years. And since the optimal rotation of spruce forest is closer to 120 years than the optimal rotation of pine, it is cheaper to extend the rotation of spruce to 120 years. Typically the spruce stands form a small scale pattern in the border zone of the forest area, whereas the pine forest is located in the central area. The preference for the small stands is discussed in the previous section. To include pine forest in the contiguous area of old forest, it is an option to decrease the age that makes the forest old somewhat to for instance 115 years. One could also increase the age for spruce forest. An other option is to define in the Simulated Annealing two forest types and to make sure that for both of them old forest is created. This could easily be done with a lower bound on both the old pine forest and the old spruce forest. The fact that the algorithm gives a poor performance with bounds on the area should however be taken into consideration..

The reserved stands got special attention by fixing them as old stands. This was however no guarantee that a protecting zone around those stands was formed. They are still more or less isolated.

With the Linear Programming, the forest management plan is generated. This plan causes a severe distortion of the age structure after 50 years. There are several reasons for this. The main reason seems to be the interest rate. An interest rate of 3% caused a high present income preference, which made the wood production in the first period as high as permitted (at least 16% of the area is cut at once). Stands in premature age classes were cut. Another reason is the initial age structure. Two almost empty age classes in the actual situation have their influence in the future, when they are about to be cut. They do not provide enough wood and other age classes have to be used. Since this is the case in most boreal Swedish forest, the sustainable provision of wood and old forest at the same time might be somewhat endangered in the far future. There were no clear indications that the formation of a large area of old forest had a negative influence on the age structure. Because of the 'overruling' impact of the interest rate, a real analysis was not possible.

With respect to this interest rate has been argued for years among foresters that a low rate should be applied. Such a rate favours conservation and long term planning. Some persons are even talking about a zero rate of interest for timber management. In that case a future decision has the same impact as today's decision. But this implies that forest capital has no opportunity costs and is because of that undesirable (Duerr, 1993).

I like to look into the farther future, the period after 50 years, although it is not possible to say anything with certainty. The supply of wood after 50 years seems to be in danger. Because of the restriction on the area of old forest, just a very small portion of this area can be cut. The contribution of age class 12 to the old forest is marginal and after that of class 11 is zero. These classes can add also very little to the production of wood. A careful made prediction might be that the sustainable provision of both old forest and wood is not ensured with a situation as in period ten as a starting point.

To ensure an age class distribution that is close to normal forest, the even flow constraints could be replaced by restrictions on the age class distribution. For the long term they can be preferred to even flow constraints; they create a situation with a high sustainability on the very long term. For the forest enterprise these constraints might be undesirable. To create an even age structure, the annual cut volume might vary from year to year causing an unstable pattern of income in the time. The fixed means of production like man power and machines might have an irregular occupation causing high costs.

The remainder of the forest management plan has positive aspects. The area of old forest increases to 12.5% in 30 years; in that time the area of deciduous forest (forest with at least 40% of deciduous trees) amounts 5% of the total forest area. About half of it is mature forest. And on a forest level 15% of the trees is deciduous. After each clear-cut ten percent of the trees is retained; in this way the natural disturbance pattern of forest fire is resembled.

With some caution I can conclude that these characteristics will ensure a maintenance of biodiversity in the coming fifty years, but being neither an ecologist nor a Swedish forest owner, it is not possible to make this 'hard'.

The matter will be more complicated if we incorporate ownership in the model. The current situation (figure 6.2) shows that most of the old forest is situated in the border zone of the Brattåker area. This area is owned by many small private forest owners. For some of them the allocation of old forest might mean that their complete property has an extended rotation. Compared to forest owners without any allocated old forest their burden would be disproportionately large.

The implementation of any kind of forest management is in the first place a decision of the forest owner. A plan like this can support decisions with respect to what, where and when to cut to achieve a maximum profit, within the restrictions stated by the forest owner. The plan is very rough and at best gives some aid with respect to questions about the sustainable provision of both wood and biodiversity.

As mentioned already in the introduction, the main merits of this study are supposed to be in integration of biodiversity in a forest management plan generated with mathematical programming and the design of the algorithm.

Social consequences

Implementation of the outcome of the algorithm has consequences on a social level. The most interesting question is about the costs of implementing biodiversity, old forest or contiguous old forest in the forest management.

The 'costs of biodiversity' as the total package as which it is implemented in this study is the difference between SEK 200.5 $*10^6$ and SEK 192.2 $*10^6$. The total revenues will decrease with somewhat more than 4 percent. The lost income related to the retention of trees after each clear-cut is not considered in these figures.

The special restrictions on deciduous trees and forest are relatively cheap. Implementing the constraints on these elements decreases the NPV to 199.4 $*10^6$.

The big costs seem to be embedded in the extension of the rotation for one eighth of the forest area. The NPV decreases with 4.7 million to SEK 194.6 $*10^6$. Each hectare of old forest costs about SEK 4700,-. This can also be seen in the shadow prices. The difference in shadow prices between two similar stands, whereof one is old and the other is not (that is it has an optimal rotation) is about the same amount.

To make this area of old forest contiguous, decreases the NPV to the previously mentioned amount of SEK 192.2 $*10^6$. The results are shown in figure 6.2. The limitations of this figure are mentioned before.

When we take the need for a certain area of old forest as given, the extra costs for a more or less contiguous area of old forest are limited. But above the 2000 hectares this difference is increasing. Both the costs of old and contiguous old forest increase more than linear. The cheap possibilities are exhausted and more expensive forest has to be used. This is presumably the point at which all the possible spruce forest is old and the pine forest has to be applied.

The question who is going to pay for biodiversity is a political question. Is it the responsibility of the forest owner to manage the forest a such a way as to maintain biodiversity? Or should the forest owner be compensated because he is restricted by the rules of the government? Maybe the forest owner should not be forced to maintain biodiversity, but on a voluntary base choose to do so and be rewarded by the possibility to label the wood as 'wood with heart for the nature'.

This study did not focus on future developments in the forest management. But it gave an indication that in the far future the provision of wood and old forest might be combating each other. This is due to the fact that the current age classes from 30 to 80 years show a deviation downwards. Since this is more or less the same in most of the Northern Swedish forests, it might be a case of concern.

Planning on the long term is involved with uncertainty. This uncertainty concerns the economical factors (what is the future demand and what are the production costs), social/ political factors (what requirements does society have for the forestry sector and ecological factors (how does the forest develop). Forestry is typically a matter of thinking and planning on the long term. The question is if it is useful to start working towards a situation for over 30 or 50 years, a situation one will presumably never achieve. The social and economic environment has changed by that time and will have its influence on the forest management with its goals. This asks for a dynamic forest management.

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APPENDIX

Table 1. *Number of red-listed species found in the studied landscape, divided into forest types in which they mainly occur naturally and into most important features on which they depend (Ahlen and Tjernberg 1992, Ehnström and Walden 1986, Ehnsrtöm et al. 1993, Aronsson et al. 1995). Significant natural features in respective forest type are denoted (Fries et al.* unpublished manuscript*).*

Forest type, significant feature, etc.	Vascular plants	Mosses[1]	Lichens	Fungii	Verte-brates	Everte-brates[1]	TOTAL
Spruce forest[2]							17
Continuity of old spruces[3]			4[4]	1			5
Continuity of large spruce logs (or stumps)		2[3]		7[5]		1	10
Stable hydrologic conditions	2						2
Deciduous or spruce dominated fores[6]							15
Old (or dying) deciduous trees[7]			6[8]	1	2[9]		9
Snags or logs of deciduous trees (also conifers)			2	1	1	2	6
Fire							0
Pine fores[6]							2
More than about 200 yr old pines							0
Snags and logs of large pines			2				2
Fire							0
Riparian zones	1				1	1[10]	3
Other features or threat causes	2[11]				3		5
TOTAL	5	2	14	10	7	4	42

[1]These groups have not been systematically examinated by specialists.
[2]Because of presumed low dispersal capacity for spruce forest species, the natural features denoted should have continuity at the site.
[3]Often in combination with stable microclimatic conditions.
[4]E.g. *Chaenothecopsis viridialba* and *Ramalina thrausta*
[5]E.g *Fomitopsis rosea* and *Amylosystis lapponica* (because of absence of fire these fungii are today predominantly located in the deciduous or spruce dominated forest type).
[6]Because most species in this forest type probably have relatively high dispersal capacity, it is sufficient with continuity in the landscape for the natural features denoted.
[7]In most cases aspen (*Populus tremula*).
[8]E.g the lichens *Collema curtisporum* and *C. furfuraceum.*
[9]Black woodpecker (*Dryocopus martius*), which needs large diameter aspen (or pines) for nesting, and Grey-headed Woodpecker (*Picus canus*), nesting in aspen.
[10]The mussle *Margaritifera margaritifera.*
[11]These two Grape-fern species grow at an abandoned settlement and depend on old agricultural practices as e.g. manual hay-making.

Source: Fries and Lämås (1996)

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