A Decision Support System for Multi-Criteria Forest Estate Planning, Integrating a Forest Growth Simulator, Fuzzy-Inference Techniques and a Heuristic Optimisation Approach

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Abstract. The extended perception of sustainable forest development (MCPFE 2000) demands the integration of multiple management functions and criteria into strategic forest enterprise planning and decision making. Decision support systems (DSS) with effective model and method components can effectively support this planning procedure. For this, DSS must integrate tree growth simulators in order to run scenario simulations of stand dynamics, to project the long-term consequences of management alternatives and to scale stand dynamic processes at different spatial and temporal levels. Furthermore, DSS must include evaluation models capable of incorporating expert information and fuzzy reasoning. DSS should also integrate appropriate optimisation algorithms to identify optimal problem solutions dependent on multiple objectives. This chapter presents a DSS approach intended to support strategic multi-criteria forest planning and management at stand and estate levels. The DSS is aimed at forest enterprise managers as well as at the forest management planning services. Technically, the DSS integrates the individual tree-growth simulator SILVA 2.2 (Pretzsch 2001) and combines it with fuzzy-inference techniques and a heuristic Tabu Search optimisation approach. The main parts of the DSS concerning the technical structure, the database, the decision space, the objective system and the evaluation system will be presented as well as the main fuzzy-inference algorithms and utility functions. The heuristic multi-criteria optimisation approach developed for the specific DSS requirements will be shown. In addition, some example results demonstrating the DSS's plausibility and sensitivity will be given. Finally, the chapter concludes with a brief discussion of the DSS approach and outlines perspectives for further research.

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11.1 Introduction

Long-term forest planning aims at the sustainable development of forests. This task is becoming increasingly difficult because the demand for sustainability applies not only to timber production, but also to multiple ecological and socio-economic silvicultural functions, for example protection of soil and ground water and the aesthetics of natural scenery, and should be integrated into management decisions. These functions can address forest resources, forest ecosystem health and vitality, biological diversity, protective functions or socio-economic forest functions (MCPFE 2000). Therefore, certain criteria must be introduced into forest planning and decision making (Sodtke et al. 2004). This extended perception of sustainability is associated with the transition from pure to mixed stands (Pretzsch et al., this Vol.). However, this process requires information that cannot be provided by the model of ideal forests or yield tables. Today, much information is available from sample plots, site classification, etc. which could be better utilised if the planning procedure was improved (Hanewinkel 2001; Spellmann et al. 2001; von Gadow 2003). Furthermore, increasing public interest in forests demands participative planning methods. Subject to the extended tasks of today, DSS (e.g. Bonczek et al. 1981) can effectively support long-term forest planning (e.g. Rauscher 1999).

DSS are interactive computer-based systems intended to help decision makers utilise data and models to identify and solve badly structured problems and make effective decisions (Bonczek et al. 1981; Zimmermann 1987; Turban 1990). According to their application purposes, DSS can integrate various model and method components, covering different tasks such as communication, data and knowledge management, numerical simulation and problem solution (scenario evaluation, optimisation) (Rauscher 1999; Power 2001). Technically, a DSS should be structured in accordance with the theory of a rational (i.e. objective-orientated) decision and therefore organised into a decision space, an objective space, a problem solution component and a dialogue component (user interface) (Laux 1982; Mag 1990; Kelling 1991; Bamberg and Coenenberg 2002). As the main tools to set up the decision space, forest growth models can be applied. These models can be utilised to run scenario simulations of stand dynamics, to project the long-term consequences of management alternatives and to scale stand dynamic processes at different spatial and temporal levels. Evaluation models are required for structuring and evaluating the results, and for conducting multi-criteria plausibility and sensitivity analyses. Combined with appropriate optimisation algorithms, optimal problem solutions for multiple objectives can be identified.

The objectives of our research work are to design and develop a DSS to assist in the strategic management planning of forest enterprises and test it by using forest inventory data. The main focus is to combine a forest growth simulator with inventory databases, geographical information systems, visualisation routines and algorithms for evaluation and optimisation (Pretzsch and Seifert 2000; Pretzsch 2003). Such a system will be useful for teaching and training as well as for practical use in long-term forest planning. To simulate characteristic indicators of forest stand dynamics, the forest growth simulator SILVA 2.2 (Pretzsch

2001) will be used running in batch mode. Management objectives based on uncertain expert knowledge and requirements specified by our practical partners (The Count's Arco-Zinneberg Forest Enterprises, Moos, Bavaria, and the Municipal Forest of Traunstein, Bavaria) will be integrated into the objective system of the DSS. For problem solution, specific evaluation algorithms and optimisation procedures have to be combined and implemented into the DSS's problem solution component. For practical application, an adequate user interface will be programmed as well as links for use with a graphical information system and visualisation routines. Finally, the DSS will be tested by using inventory data from our forest enterprise partners.

11.2 The DSS Approach

11.2.1 Fields of Application

This approach of a forestry DSS is aimed at forest enterprise managers as well as forest management planners (for example, private or state-based forest planning services). While the former need an evaluation of different management alternatives at estate level subject to multiple management objectives, the latter rely on the identification of optimal treatment strategies in specific situations (stand level). Both managers and planners are interested in long-term strategic planning (silvicultural management strategies) and less in short-term operational planning (e.g. use of machines, labour organisation). The aim is to objectify the decision making processes and to make them more understandable. For this, growth simulations based on management scenarios are as significant as instruments for enhancing the transparency of silvicultural decisions and the possibilities for public participation. This may be of interest in, for example, municipal forests or areas protected by Natura 2000 or Fauna Flora Habitat designation. From this, there is a demand in developing DSS not only able to simulate long-term scenarios but also to evaluate different management alternatives with respect to multiple criteria, to consider various spatial (stand, enterprise sub-unit, enterprise) and temporal levels, and be able to visually represent alternative results in a suitable manner. Finally, such a system also introduces forestry students – the future decision-makers – to computer-aided management planning and decision-making.

11.2.2 Data

Through several interviews (based on questionnaires) of our practical partners (G. Fischer, Municipal Forest of Traunstein, Bavaria and W.-D. Radike, The Count's Arco-Zinneberg Forest Enterprises, Moos, Bavaria), information for identifying relevant characteristics of the decision process (objectives/criteria and specific indicators), as well as for deriving functional relations between objectives and indicators, was gained. The acquired information was generally given as vague or uncertain statements. Relevant variables (objectives, indicators) were usually expressed as linguistic variables with vague or fuzzy values [e.g. 'narrow height/dbh (hg/dg) ratio' (dbh, breast height diameter; hg/dg, height/diameter of a stem representative of the whole stand); 'very poor vertical structure'; see Table 11.1]. With the use of fuzzy logic, specifications of the linguistic variables could be described by fuzzy sets (see, e.g., Zimmermann 1996). The acquired expert knowledge was transferred into rules and integrated into fuzzy inference systems (Matlab Fuzzy Toolbox, The Math Works). The gained information could also be used to define utility functions for the evaluation of management alternatives at different spatial levels.

To construct a data pool with resulting forest state characteristics (i.e. indicators for evaluating multi-criteria objective fulfilment, e.g. dbh, height of dominant trees, etc.) depending on different management alternatives and environmental situations (sites, stands) various scenario simulations were carried out with the forest growth simulator SILVA 2.2. These scenarios included sets of different mixed stands of Norway spruce and common beech, several sites according to the enterprises of our practical partners and sets of different management alternatives.

For DSS evaluation and validation, our practical partners supplied us with inventory data from their forest estates. These data included information about the site characteristics at district level (Bayern-Forst 1993), as well as forest planning maps with geometric information and data about tree species composition and growth characteristics (stand age, height, dbh, etc.) at stand level.

11.2.3
DSS Structure

The technical structure of the DSS 'Silva Support' is closely orientated to the theory of objective-orientated decision making (Bamberg and Coenenberg 2002; Sodtke 2003). In order to create a stand-alone software – independent of the programming software and the operating system – the DSS architecture was developed with the programming language C++ (Borland). In order to make the decision making process rational and comprehensible, the DSS integrates the following main components: an interface with the existing forest growth simulator SILVA 2.2 (Pretzsch 2001), a database for storing simulation results, a sub-system for the organisation of knowledge-based objective functions and the definition of respective objective preferences, a sub-system for multi-criteria evaluation and identification of optimal management alternatives, and a graphical user interface as a dialogue and knowledge acquisition component (Fig. 11.1). Furthermore, possibilities were created for direct and indirect linking with the GIS ArcView (ESRI) and with other visualisation systems (Pretzsch and Seifert 2000), allowing an appropriate visualisation of result and evaluation measures. A management sub-system contains algorithms for linking and running all DSS components and for processing the data input and output via the user-interface and/or data files.

Table 11.1. Management objectives and respective indicators for evaluation according to the Pan-European criteria of sustainable forest management (MCPFE 2000) and relevant to our associate forest enterprises, Municipal Forest Traunstein, Germany, and The Count's Arco-Zinneberg Forest Enterprises, Germany

Management objectives	Indicators (dynamic forest state variables)
Timber production (commercial efficiency)	Net return from timber sale
	Growing stock dynamics (balance between wood growth and removals)
	Timber assortment (quality) structure
	Rotation time
Stand stability	Tree species composition (share of deep rooters)
	Crown length/stand height ratio
	Stand height (dominant trees)
	Slenderness (h/d ratio)
Biodiversity (habitat quality, species richness)	Number of tree species
	Horizontal intermingling (index by Clark and Evans)
	Vertical structure (species profile index by Pretzsch)
	Share of dead wood (woodpecker stems, standing trees with dbh >20 cm)
Protective functions (soil, ground water protection)	Tree species composition (share of deep rooters)
	Period with continuous soil cover
	Vertical structure (species profile index by Pretzsch)
Aesthetics (recreational function)	Number of tree species
	Horizontal intermingling (index by Clark and Evans)
	Vertical structure (species profile index by Pretzsch)
	Frequency of management actions
Habitat quality for game (hunting opportunity)	Supply of area (spruce clear-cutting system)
	Share of borderlines between stands and clearance areas

With the graphical user interface (GUI), the system user is able to communicate with the DSS, to provide input data or information (such as values of decision variables, state variables or management objectives) or to export output data or information (such as indicator or utility variables). Furthermore, via the interface, the user can obtain additional or auxiliary information about the system or system status.

The growth simulator SILVA was suited for integration into the DSS because of its following properties: (1) as a distant-dependent individual tree-growth simulation model, SILVA permits simulating the development of complexity structured even and uneven-aged pure and mixed stands; (2) as defined by the parameterisation data, SILVA is reliable for most German site conditions; (3) it covers the most common German tree species; and (4) it is possible to run SILVA in a batch operation mode for enterprise simulation and external use by a DSS software (Pretzsch et al., this Vol.). Because of the growth simulator's spatial specificity, the DSS is also applicable to a wide range of forest sites in central Europe ranging from Denmark to the Swiss Alps, and particularly to site conditions found in southern Germany.

The database contains simulation results from a multitude of management scenarios generated with the growth simulator SILVA under predefined conditions (defaults). Simulation results consist of complete tree lists as well as characteristic indicators of forest state dynamics used for evaluating the objective

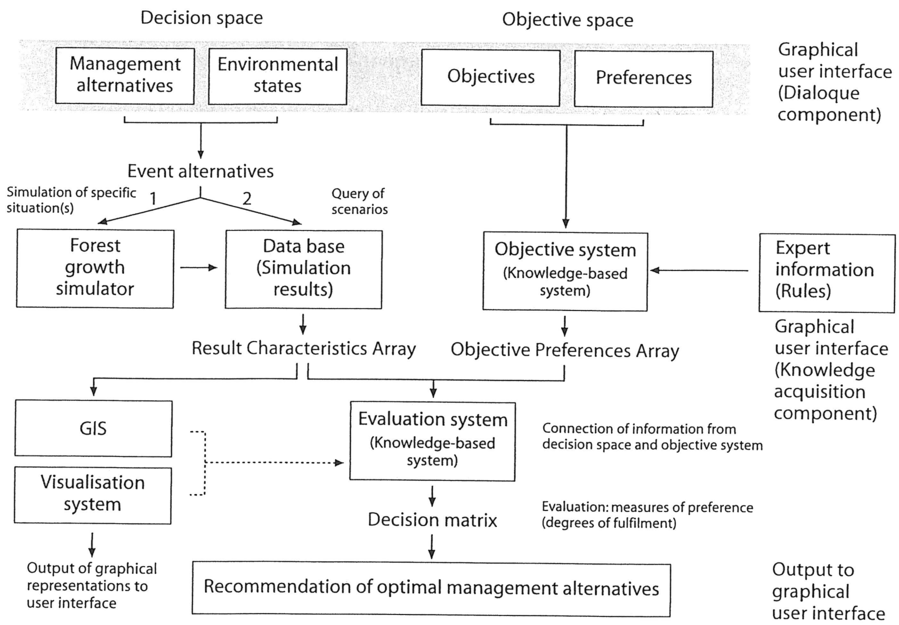


Fig. 11.1. Structural scheme of the decision support system (DSS) SILVA Support. *Boxes* represent the main DSS components. *Arrows* denote data exchange between components and the system's data input and output. For more information refer to the text

fulfilment. In the example of a 19-year-old mixed stand of Norway spruce and common beech with the management alternatives 'no thinning', 'moderate' and 'strong thinning from above', Fig. 11.2 shows the temporal dynamics of the indicators growing stock, height/diameter (hg/dg) ratio, vertical structure as expressed by the species profile index (Pretzsch et al., this Vol.) and net return from timber sales calculated from average German timber prices between 1990 and 1999. The chosen management scenarios were selected in agreement with our practical partners and address one of their main management dilemmas. In the case of no thinning, the h/d (height/diameter of an individual tree) ratio indicating stand stability evolves most unfavourably, whereas the vertical structure as an indicator of biodiversity shifts from beneficial to adverse values at the age of 34 years. Positive financial return occurs earliest with strong thinning. However, compared with the alternatives, this management technique results in lower net returns in the long run.

These simulation results can be taken from the GUI for further evaluation. Alternatively, information on site attributes and stand structure, as well as management specifications, can be supplied to the DSS by data files or via direct GUI input. Using this method, results of scenarios not yet simulated can be calculated with the growth simulator. Afterwards, the result variables (indicators) of all calculated alternatives are evaluated by the evaluation sub-system according to multiple objective preferences. These preferences result from the objective sub-system processing knowledge-based information about the management objectives (objective characteristics, weights, etc.) also specified in the GUI by the user. Finally, for each management alternative a so-called degree of fulfilment will be assigned to each management objective, plus an evaluation of the total utility as a measure of preference of an alternative.

11.2.4 Decision Space

The decision space of the DSS contains decision variables and state variables defined by specifying the range of values of the management alternatives (e.g. thinning grade) and the environmental states (e.g. site conditions, tree species composition/growth characteristics before management operations). The current DSS version integrates the following decision variables regarding intermediate thinnings and final cutting: thinning type, thinning frequency and thinning grade, as well as type and intensity of final cutting. The temporal application of these variables may be defined differently according to variable thinning schemes. Decision variables referring to stand regeneration (choice of tree species, type of regeneration) will be integrated into a future DSS version. Furthermore, a set of management constraints, such as the maximum thinning volume per hectare and period, can be defined.

The initial environmental state results from site and stand structure and is identified by a set of characteristic state variables. Site conditions are characterised by several specifications of climate and soil, such as forest growth region, precipitation, soil nutrient content, slope, exposure, etc. The properties of the initial

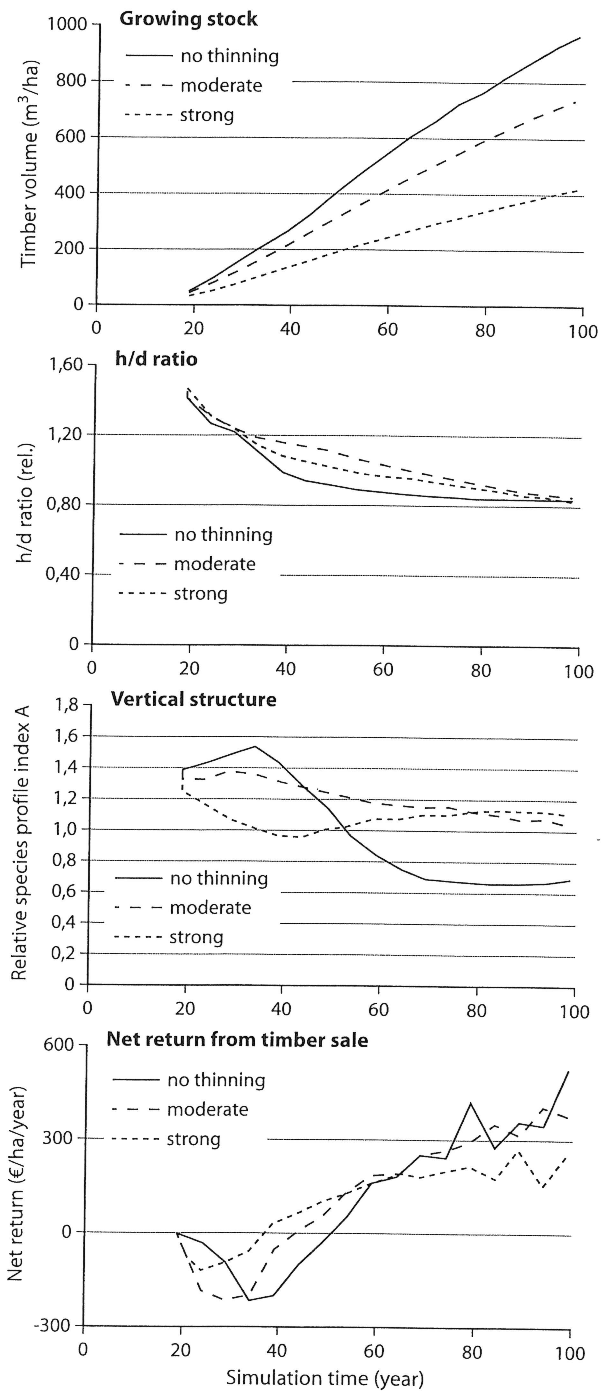


Fig. 11.2. Dynamics of characteristic indicators of forest stand dynamics simulated with the growth simulator SILVA 2.2 and used for evaluating multi-criteria objective fulfilment. In the case of a 19-year-old mixed stand of Norway spruce and common beech (80:20) with the management alternatives no thinning, moderate or strong thinning from above applied, the figure displays the temporal dynamics of growing stock, height/diameter (*hg/dg*) ratio, vertical structure as expressed by the species profile index, and net return from timber sales calculated from average German timber prices between 1990 and 1999

stand or enterprise sub-unit are denoted by tree lists or can be described by the aggregated variables tree species, stand structure, age and age structure. If information about a particular environmental state cannot be provided with certainty, each state variable can also be specified with its degree of certainty (within the interval [0, 1], where 1 = certain, 0 = totally uncertain) to be processed by fuzzy inference techniques within the evaluation sub-system.

11.2.5 Objective System

For evaluation of the management alternatives, various management objectives can be selected as well as preferences defined by the user. According to the Pan-European criteria for sustainable forest management (MCPFE 2000; see also Pretzsch et al., this Vol.) and as agreed with our practical partners, six management objectives were integrated into the objective system (Table 11.1). These objectives comprise economic as well as ecological and social aspects of forest management, which occasionally conflict. Objectives and preferences can be selected by the user from a predefined list via the DSS interface and can be assigned to the total estate, singular stands or enterprise sub-units. The objective system consists of a knowledge base representing objective contents (objective variables and their attributes = indicators), and an inference component (rule system) integrating quantitative relations (preferences) between objectives and objective variables (indicators). Indicators characterising one specific objective were also defined at the Pan-European level (MCPFE 2000). For example, forest biodiversity is characterised by indicators such as tree species diversity, vertical stand structure, share of dead wood, etc. (Table 11.1). Objective preferences refer to type, value, time and uncertainty of the indicators. If the user has stated more than one objective he/she may also specify the objective's relevance by weighting them.

The rules of the objective system were acquired from scientific literature and from interviews with our practical partners and will be supplemented by additional interviews with other experts. Such data are usually imprecise assessments characterised by linguistic terms which can be analysed as qualitative answers. Therefore, with the aid of fuzzy logic (e.g. Rommelfanger 1994; Zimmermann 1996), these variables were assigned to fuzzy sets, and the relational information between objectives and indicators (set of rules) was utilised to configure fuzzy inference systems (Matlab Fuzzy Toolbox, The Math Works; Sodtke 2003). Thus, the degree of fulfilment u_i for management objective i referring to management alternative x at stand/stratum level can be formalised by the fuzzy inference graph $\mu^Y(x)$ representing a maximum–minimum combination of the fuzzy result variable matrix μE and the fuzzy relation R (rule system) (Eq. 11.1):

$$\mathrm{u_i} = \mu^Y = \mu^E \cdot R$$

with

$$\mu^E = \begin{bmatrix} \mu_{A_1}^{E_1}(E_1(x)), \mu_{A_2}^{E_1}(E_1(x)), & \dots & \mu_{A_m}^{E_1}(E_1(x)) \\ \vdots & \ddots & \vdots \\ \mu_{A_1}^{E_n}(E_n(x)), \mu_{A_2}^{E_n}(E_n(x)), & \dots & \mu_{A_m}^{E_n}(E_n(x)) \end{bmatrix}$$

and

$$\mu_{A_k}^{E_j} = \left\{\left(e_{xst}, \mu_{\tilde{A}_k}(e_{xst})\right) \mid e \in E\right\}$$

where e_{xst} is the value of result variable E_j of management alternative x, stratum s and time t and $\mu_{A_k}^{E_j}$ is the membership function denoting the membership of values e_{xst} to the fuzzy set A_k. In the example of the management objective stand stability, Fig. 11.3 shows a scheme of a fuzzy inference system transforming crisp input information to fuzzy sets, processing them in a rule base and calculating information on the degree of objective fulfilment. The effects of changed inputs and weights may be analysed rule by rule as well as by plotting the fuzzy inference graph. Figure 11.4 displays the simulated dynamics of objective fulfilment of the management objectives timber production (commercial efficiency), stand stability and biodiversity in the example of a mixed spruce–beech stand and the management alternatives 'no thinning', 'moderate' or 'strong thinning from above'. According to the indicator variable 'net return', in the first simulation periods commercial efficiency of timber production is greatest with strong thinning. Stand stability is also best with strong thinning. With no thinning, biodiversity shifts from beneficial to adverse values in the long run; strong thinning from above shows the opposite behaviour.

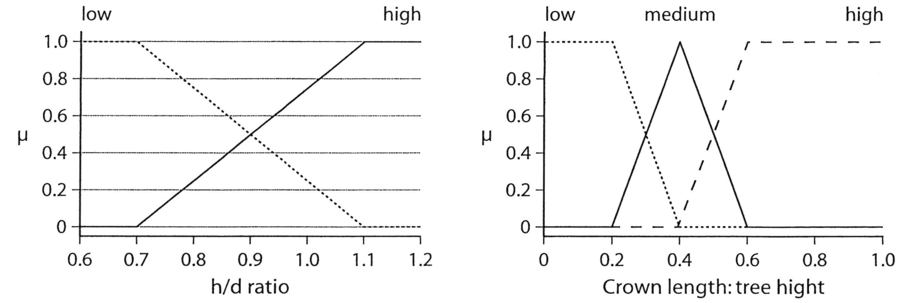
11.2.6 Evaluation

Within the evaluation sub-system, management alternatives are evaluated according to their degree of objective fulfilment. The total utility U^T for each management alternative can be determined from the user-defined objective weights a_i and the (objective-referring) partial utility $U_i(x)$ by additive utility functions (Pukkala and Miina 1997):

$$U^T(x) = \sum_{i=1}^{z} a_i \, U_i(x)$$

The total utility allows comparison of the alternatives and ranking according to their preference. If the user prefers, the DSS can alternatively offer the best management option or a set of possible alternatives sorted by objective fulfilment. The partial utility $U_i(x)$ referring to a singular objective may be represented by the weighted average of sub-utilities u_{its} per growth period t and stratum s (Eq. 11.5):

Fuzzy sets



Rule system

h/d ratio	Age	Crown length/ tree height	Objective fulfilment with share of deep rooters is low	medium	high
low	low	low	medium	medium	high
		medium	medium	medium	high
		high	medium	high	high
	high	low	low	low	medium
		medium	low	medium	medium
		high	medium	high	high
high	low	low	low	medium	medium
		medium	low	medium	medium
		high	medium	medium	medium
	high	low	low	low	low
		medium	low	low	medium
		high	low	medium	high

Fuzzy inference graph

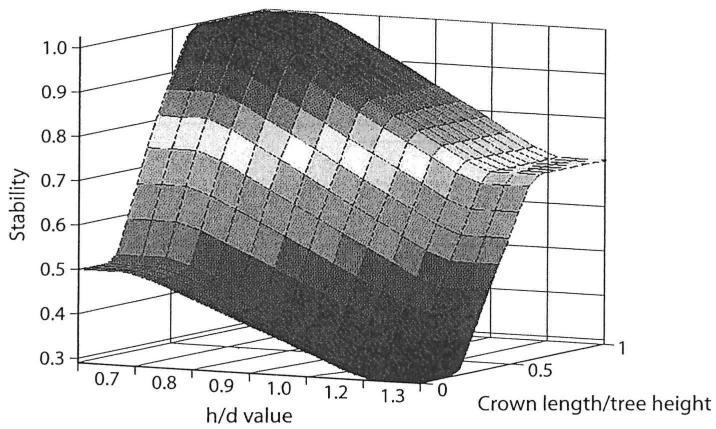


Fig. 11.3. Fuzzy inference scheme for the management objective stand stability. *Above* Fuzzy sets of input variables h/d ratio and crown length/tree height ratio. Input values are calculated with the rule system (*centre*) and result in characteristic degrees of objective fulfilment as shown by a surface plot (fuzzy inference graph, *below*).

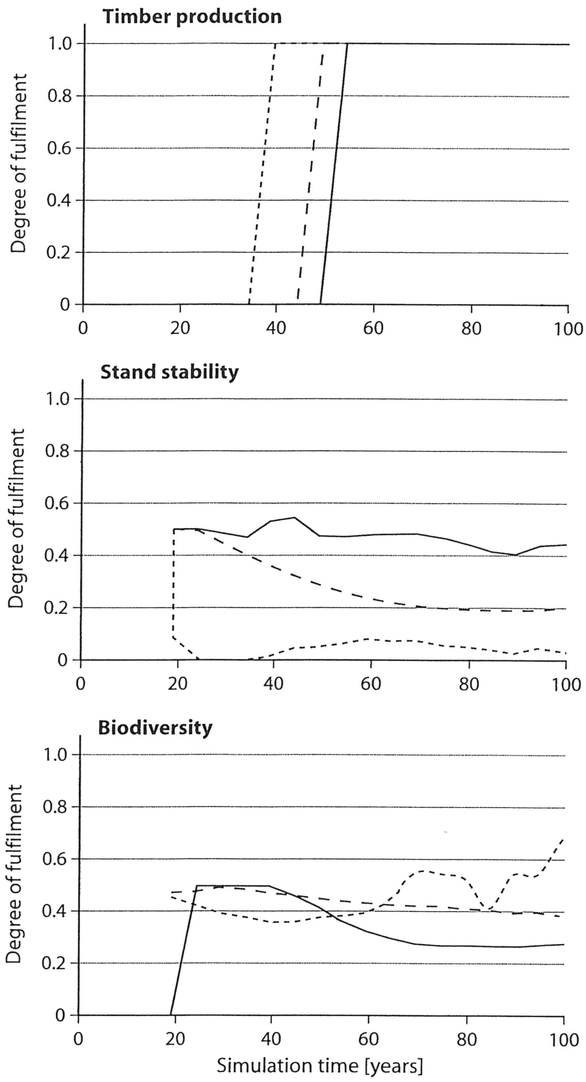


Fig. 11.4. Dynamics of objective fulfilment of the management objectives timber production (commercial efficiency), stand stability and biodiversity evaluated with DSS SILVA Support. Results refer to the example of a spruce-beech mixed stand and the management alternatives no thinning, moderate or strong thinning from above, applied as presented above (Fig. 11.2)

$$U_i(x) = \frac{1}{\sum b_t \sum c_s} \sum_{t=t_1}^{t_n} b_t \sum_{s=s_1}^{s_m} c_s \cdot u_{its}(x) \text{ with } u_{its}(x) \geq d_{is}$$

where d_{is} is the lower limit of sub-utility u_{its} (constraint), and b_t and c_s are weights.

Table 11.2 shows the results of a multi-criteria evaluation of the management alternative 'moderate thinning from above' at stratum and enterprise levels. The results are given for five different age strata of mixed stands from Norway spruce and common beech. The results also refer to the strata's spatial extension at estate level. Hence, in this example an ideal estate with equally sized strata is assumed.

Figure 11.5 presents the respective results comparing several strata differentiated by age (20–100 years) and tree species composition (pure Norway spruce and Norway spruce–common beech mixed stands), and three management alternatives (no thinning, moderate and strong thinning from above).

Table 11.3 displays results aggregated at estate level. The presented results refer to two different kinds of estates, one dominated by pure Norway spruce stands, the other by spruce–beech mixed stands. For both estates, and with the given objectives' weighting, highest total utilities are achieved with strong thinning. However, with pure spruce, estate differences between the management alternatives are not very large.

The DSS comprises two relevant spatial levels of silvicultural decision support: the stand level or stratum level, on the one hand, is characterised by a multi-criteria evaluation of alternative stand/stratum treatment decisions (thinning type and intensity, planting, etc.). Forest stands that are comparable according to site, tree species composition, development state and the like are combined into enterprise sub-units (strata; Durský 2000) to which the DSS will apply the same management schemes and resulting indicator values. Table 11.4 gives the criteria and characteristic values for strata definition classified by tree species composition and stand age.

The enterprise (or regional) level, on the other hand, requires an estate-orientated strategy of forest management activities relating to the spatio-temporal order of actions. To identify this strategy, an appropriate combination of stand/stra-

Table 11.2. Evaluation results of objective fulfilment at stratum level according to the objectives 'timber production', 'stand stability' and 'biodiversity' in the example of a spruce--beech mixed stand with moderate thinning from above applied and five strata of different age presented above (simulation with natural regeneration, simulation period: 30 years; see Fig. 11.5). For aggregation at estate level, the objective-referring results are weighted by the strata's spatial extension (Eq. 11.4)

Stratum (age class) (years)	Area (ha)	Objectives Timber production	Stand stability	Biodiversity
20	100	0.0	0.42	0.48
40	100	0.67	0.28	0.45
60	100	1.0	0.21	0.42
80	100	1.0	0.20	0.40
100	100	1.0	0.23	0.38
Estate result		0.73	0.27	0.43

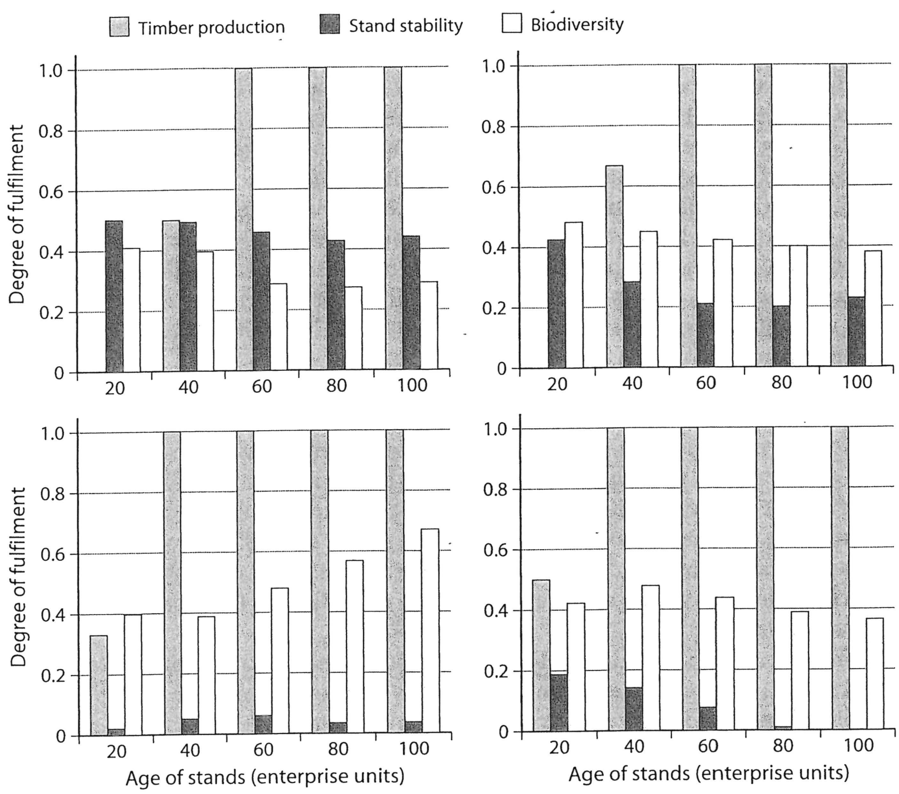


Fig. 11.5. Evaluation results of objective fulfilment regarding timber production, stand stability and biodiversity and five strata of different age (20, 40, 60, 80 and 100 years old). *Upper graphs* represent mixed strata from Norway spruce and common beech (80:20) with no thinning (*left*) and moderate thinning from above (*right*) applied (see Figs. 11.2 and 11.4). *Lower graphs* show results in the cases of a spruce-beech mixed stratum with strong thinning from above (*left*), and a pure Norway Spruce stratum with moderate thinning from above (*right*). Each simulation calculated with natural regeneration, simulation period: 30 a.

tum-level scenarios is processed at estate level. The linking of both levels of decision support is accomplished by the utility functions shown above (Eq. 11.5). Beneficial and adverse (conflicting) utilities per stratum and period may therefore 'compensate' each other in time and space. Compensations in this respect may be described as trade-offs between conflicting utilities depending on the user's preferences (weights).

Table 11.3. Evaluation results of objective fulfilment at estate level according to the objectives 'timber production', 'stand stability', and 'biodiversity' and the management alternatives no thinning, moderate thinning and strong thinning from above. Results are shown in the example of an estate consisting of five spruce–beech mixed strata of different age presented above (see Table 11.2 and Fig. 11.5), and in the example of a respective estate consisting of pure Norway spruce strata (simulation with natural regeneration, simulation period: 30 years)

	Management alternative	Objectives Timber production Weighting	Stand stability	Biodiversity	Total utility
		0.3	0.6	0.1	
Spruce–beech mixed estate	No thinning	0.70	0.47	0.33	0.52
	Moderate thinning	0.73	0.27	0.43	0.42
	Strong thinning	0.87	0.04	0.50	0.34
Pure Norway spruce estate	No thinning	0.72	0.06	0.24	0.28
	Moderate thinning	0.78	0.06	0.28	0.30
	Strong thinning	0.81	0.07	0.38	0.32

11.2.7 Optimisation

The utility functions presented above were integrated into an optimisation algorithm (heuristic Tabu Search approach). By this means, the DSS is able to identify mathematically optimal management alternatives – at stand level as well as at estate level – within a short time. Tabu Search was introduced as a heuristic optimisation algorithm to solve packing problems such as the 'knapsack or smuggler's problem' (Domschke et al. 1996). Changing a decision variable within the optimisation procedure (e.g. putting an object into or taking it out of the knapsack) sets this particular action tabu and adds it to a tabu list for a predefined time span (tabu duration). This means that this action cannot be carried out (or revised) until the number of iteration steps exceeds the tabu duration.

This procedure was applied to the problem of optimising forest management alternatives. Here, several decision variables (e.g. thinning type, thinning grade) exist which may be applied to a forest at different time periods as well as to different enterprise strata. Figure 11.6 graphically displays the Tabu Search optimisation scheme implemented in the DSS. Optimisation refers to a combination of decision variables, which may be expressed by a decision tree. In period (1) a stra-

Table 11.4. Criteria and characteristic values for stratum definition classified by stand stage and age, and share of the tree species composition. *Spr* Norway spruce; *Fir* silver fir; *Dgl* Douglas fir; *Bch* common beech; *Oak* sessile oak; *Mpl* common maple (Sycamore); *Ash* common ash; *Elm mountain elm (wych)*

Stratum	Stage	Age (years)	Tree species	Share (%)
1.1–4	Brush stage	<20/25	All species	–
2.1	Young thinning	20–40	Spr, Fir, Dgl	>80
2.2		25–45	Bch, Oak	>80
2.3		20–40	Mpl, Ash, Elm	>70
2.4		20–40	All species	–
3.1	Old thinning	40–60	Spr, Fir, Dgl	>80
3.2		45–90	Bch, Oak	>80
3.3		40–70	Mpl, Ash, Elm	>70
3.4		40–70	All species	–
4.1–4	Final cutting + regeneration	>60/90	All species	–
5.1–4	Selection forest	–	All species	–

tum's initial state may be changed by a selected thinning type and a selected thinning grade. In period (2) the stratum's resulting state again may be changed by a selected thinning type and a selected thinning grade and so on. With this procedure, the number of possible management alternatives can easily be calculated as follows (Eq. 11.6):

$$N_s = \left[\prod_{i=1}^{n} x_i \right]^p$$

where N_s is the number of possible management alternatives per stratum, x_i is the number of stages of the decision variables, n is the number of decision variables and p is the number of periods.

In case of constrained alternatives (e.g. no thinning implies no differentiation according to thinning grade), Eq. (11.6) reads as follows:

$$N_s = \left[\prod_{i=1}^{n} x_{u,i} + \prod_{j=1}^{n} x_{c,j} \right]^p$$

where $x_{u,i}$ is the number of decision variable stages with unconstrained management alternatives and $x_{c,j}$ is the number of decision variable stages with constrained management alternatives.

The optimisation algorithm proceeds as follows: first, a randomly chosen or predefined initial solution [alternative (8) in the example denoting moderate selective thinning in periods 1 and 2] is calculated with the growth simulator – or taken from a stored example in the database – and evaluated by the DSS referring to preselected objectives. Afterwards, this solution is set tabu within the tabu list for a predefined time span (tabu duration), during which this solution cannot be selected again. In iteration step (1), the solutions neighbouring the initial solution are calculated and evaluated. A neighbouring solution is characterised by changes in only one decision variable in the whole decision tree (e.g. changing the thinning grade in period 2). The alternative evaluated best [alternative (9) in Fig. 11.6] is selected as the actual solution and also set tabu in the tabu list. In iteration step (2), the solutions neighbouring the best alternative from the previous iteration step are calculated and evaluated. Neighbouring solutions are those alternatives that differ from the previous best solution only in one changed decision variable (e.g. thinning type). Again, the best alternative is selected as the actual solution and set tabu. This procedure continues until a predefined maximum number of iterations is achieved. The identified alternative with the result evaluated best within all iteration steps is taken as the optimal solution.

In the case of optimising management alternatives applied to different strata of an estate, the above procedure is extended in the following manner. For each stratum an initial solution is defined (e.g. by random selection) and set tabu. In the following iteration steps, only one decision variable in the whole estate-level decision tree can be altered. Therefore, the neighbouring solutions to a whole set of initial solutions (referring to each stratum) are calculated and evaluated at estate level. That alternative leading to the best evaluation at estate level (e.g. belonging to stratum 1) is selected as the actual solution and set tabu. The management alternatives according the other strata remain unchanged. In the next iteration step, again, the whole set of actual solutions is calculated and so on. In this case, the number of possible management alternatives is calculated as:

$$N_E = \left[\left[\prod_{i=1}^{n} x_i \right]^p \right]^s$$

or

$$N_E = \left[\left[\prod_{i=1}^{n} x_{u,i} + \prod_{j=1}^{n} x_{c,j} \right]^p \right]^s$$

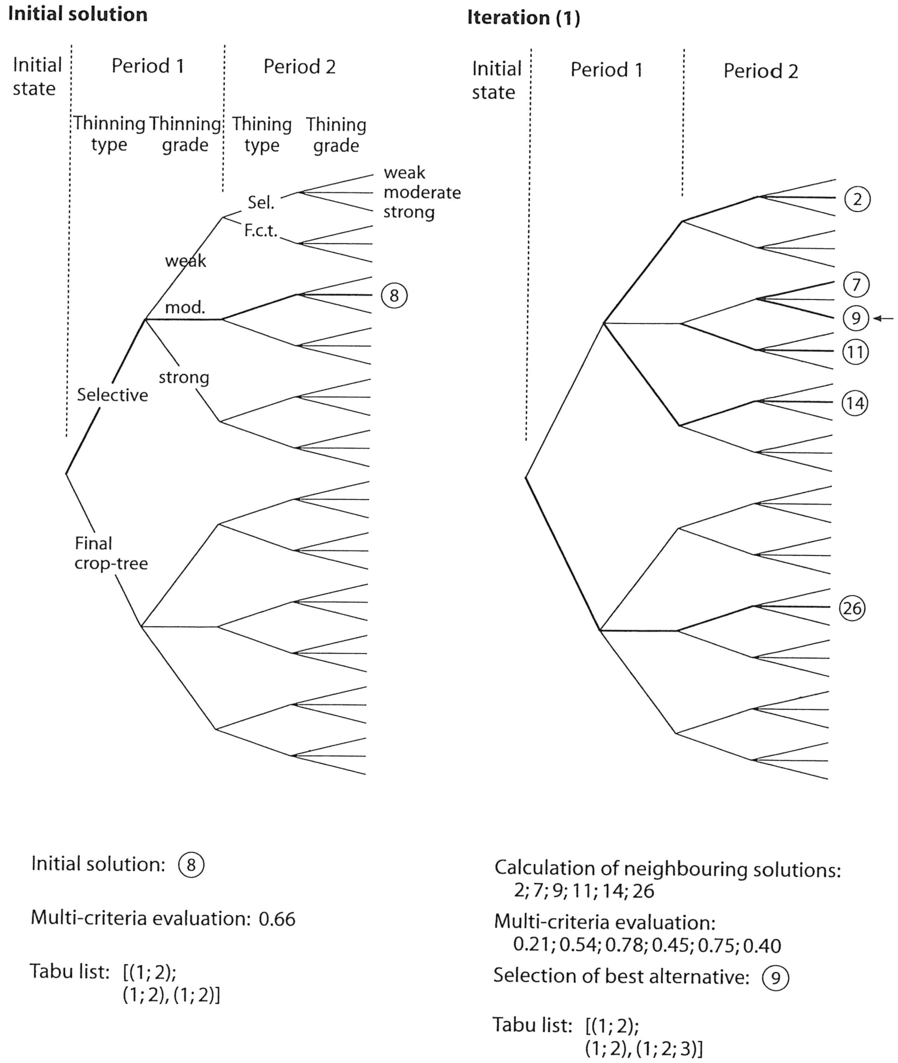
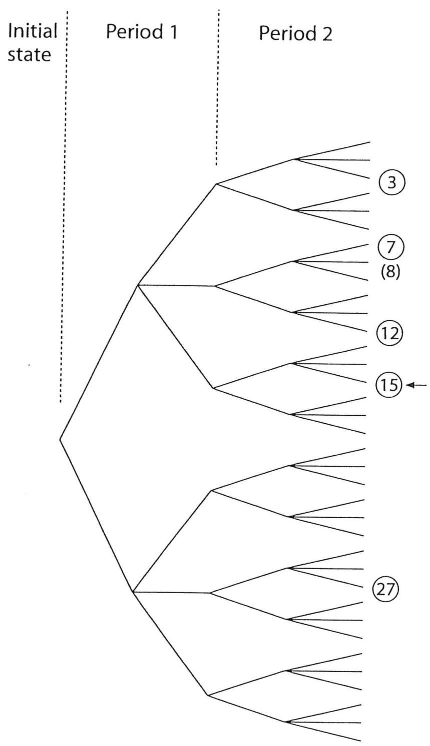


Fig. 11.6. Tabu Search optimisation scheme within DSS SILVA Support. Figure shows a decision tree within four iteration steps by an optimisation example referring to a management recommendation for two 5-year periods, two thinning types (selective thinning, final crop-tree thinning) and three thinning grades (weak, moderate, strong). *Solid lines* in the decision tree refer to possible management alternatives within the two periods. *Bold line in left-hand picture* shows the randomly chosen initial solution [alternative (8): moderate selective thinning in periods 1 and 2]. This solution is calculated with SILVA 2.2 and evaluated by DSS referring to preselected objectives. Afterwards, this solution is set tabu within the tabu list for a predefined time span (tabu duration) of more than three iterations, during which this solution cannot be selected again. The tabu list reads as follows: 'In period (1), moderate selective thinning is set tabu (first line); in period (2) with moderate selective thinning in period (1) applied, moderate se-

Iteration (2)



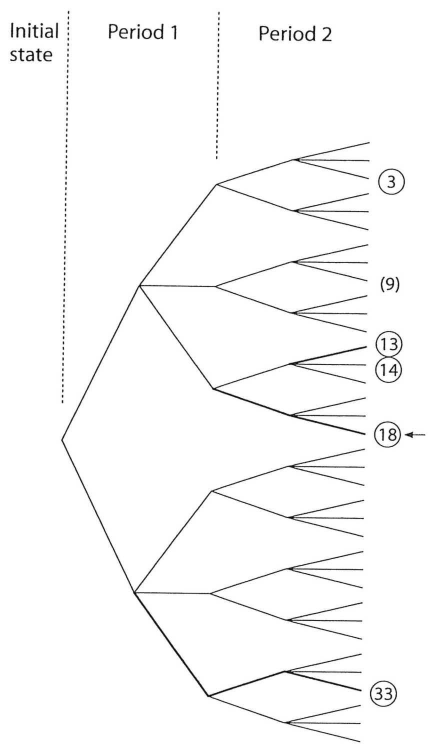
Calculation of neighbouring solutions:
3; 7; (8); 12; 15; 27

Multi-criteria evaluation:
0.25; 0.54; 0.66; 0.55; 0.81; 0.44

Selection of best alternative: 15

Tabu list: [(1; 2; 3);
(1; 2), (1; 2; 3);
(1; 3), (1; 3)]

Iteration (3)



Calculation of neighbouring solutions:
3; (9); 13; 14; 18; 33

Multi-criteria evaluation:
0.25; 0.78; 0.68; 0.75; 0.76; 0.48

Selection of best alternative: 18

Tabu list: [(1; 2; 3);
(1; 2), (1; 2; 3)]
(1; 3), (1; 3);
(1; 3), (2; 3)]

lective thinning is set tabu (second line)'. *Black bold lines* in iteration 1 denote the neighbouring solutions now to be calculated and evaluated. The alternative evaluated best (9) is selected and also set tabu afterwards. In iteration 2, the neighbouring solutions of alternative (9) are calculated and evaluated (*black bold lines*). Again, the best alternative is selected and set tabu within the tabu list. This procedure continues until the maximum number of iterations (in this example more than three iterations) is achieved. The identified alternative with the result evaluated best within all iteration steps is taken as the optimal solution where N_E is the number of possible management alternatives per estate and s is the number of strata.

The CPU time required to solve a specific problem depends on the number of decision alternatives, strata and time periods to be considered. Previously stored solutions in the database will slow down the system. If appropriate solutions can be found in the database, CPU time for optimisation may only take a few seconds. If there are no previously calculated solutions, alternatives have to be simulated by the growth simulator and evaluated by the DSS in the manner described above. In this case, CPU time may increase by several minutes or longer. This is especially true for the simulation/evaluation of young stands/strata consisting of many individual trees, the growth simulation of which is fairly time-consuming.

11.3 Demonstration

The DSS was tested with inventory data from our practical partners in order to examine the plausibility and sensitivity of the DSS results. As an example, data from The Count's Arco-Zinneberg Forest Enterprises, Germany, in the forest district of Künzing, are presented. The forest district is located on a hillside at an altitude of 345–410 m above sea level in the region 'Niederbayrisches Tertiärhügelland' (German forest growth district 09.12.09) in south-eastern Bavaria, and covers an area of 535 ha. The soils are sandy loams (medium or profound brown earths or lessivés, partially gleyic soils). The annual average temperature is 7.5 °C and the annual average precipitation is about 800 mm (Bayern-Forst 1993).

For testing the DSS, several enterprise sub-units (strata) were defined according to the criteria and characteristic values of stand age and tree species composition (a fairly even split of deciduous and coniferous trees), as given in Table 11.4. For simplification, these stands were represented as pure and mixed stands of Norway spruce and common beech. Next, various management alternatives at strata level were calculated with SILVA 2.2 and evaluated at stratum and estate levels. The evaluated management alternatives refer to a 30-year simulation period and the thinning types no thinning, thinning from above and below, selective and final crop-tree thinning, with a stepwise increased thinning grade (100, 80 and 50% of basal-area guide curve), and final linear cutting (equal cutting rates for each cutting period until a stratum is clear-cut) for older stands (>60/90 years old). Again, the management scenarios were selected in accordance with our practical partners and address their current management techniques or potential alternatives. These management alternatives were evaluated according to the management objectives of timber production, biodiversity and stand stability.

With the management objectives 'stand stability' and 'biodiversity', the resulting degrees of fulfilment show only slight differences for each alternative at stratum and estate levels. In the case of timber production there is a decreasing preference of the alternatives from weak thinning from above to heavy final crop tree thinning (Sodtke et al. 2004, not shown here). With young stands (40/45 years old), the objectives 'stand stability' and 'biodiversity' receive higher degrees of fulfilment than the objective 'timber production'. In the case of older stands

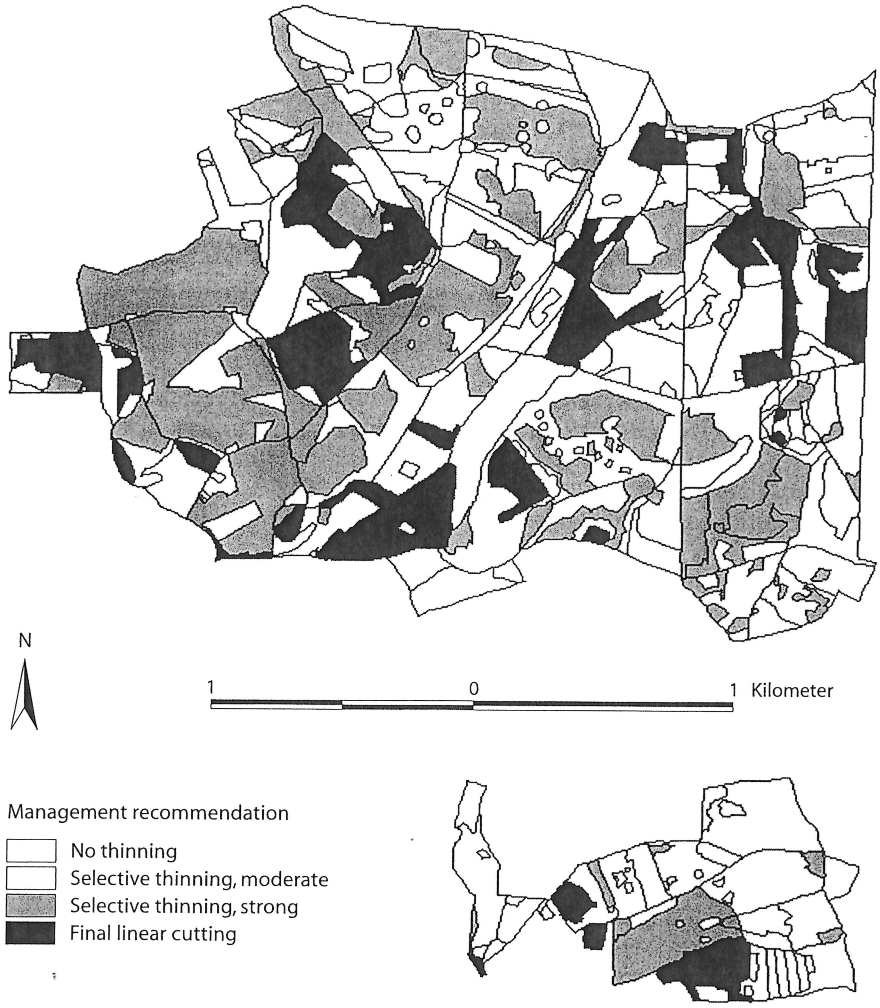


Fig. 11.7. Map of management recommendations for different management strata according to Table 11.4 and a 5-year period after forest inventorying by the example of inventory data from the forest district Kuenzing, The Count's Arco-Zinneberg Forest Enterprises, Germany

(60/90 years old), timber production is better evaluated than the other objectives. For most strata, selective thinning (moderate, strong) was found to best fulfil the desired objectives. In the case of young stands (<20/25 years old), generally no thinning, and in the case of older stands (>60/90 years old), final linear cutting were found to be optimal. Figure 11.7 shows a spatial representation of the identified optimal management for the forest district's strata.

The DSS results were considered to be reasonable and sufficiently sensitive when compared with our research results on trial plots in Bavaria. In addition, our practical partners judged the DSS results and recommendations to comply with their practical experiences in the examined forest districts. Further test runs – for example sensitivity analyses with inventory data from our practical partners – should be carried out in the future in order to search for potential anomalies and to thoroughly validate the DSS.

11.4 Discussion

DSS Silva Support represents a prototype for a decision support system in forestry. Many modifications and improvements of details seem to be possible and necessary before it can be used in practice. However, for us it was important to show the principle and the design of such a tool. In test runs and first applications implausible results will be detected and corrected in an iterative process. For example, the rule system for stand stability has to be thoroughly revised. Further research is necessary to move the system from a demo to a tool for practitioners.

The presented approach of the DSS Silva Support fulfils the general requirements of DSS by using data and models to identify and solve semi-structured problems (e.g. Bonczek et al. 1981; Zimmermann 1987). The DSS enhances strategic forest planning but – as demanded – does not replace managerial judgement (Turban 1990). The provided information can be interpreted easily (Kelling 1991). The DSS is aimed at the planning of medium- and long-term management, and therefore supports decisions concerning silviculture and forest enterprise planning. Possible users are forest planners and forest enterprise managers. By integrating and combining growth simulators with databases, evaluation and optimisation routines, and making use of GIS and visualisation routines, the approach incorporates all-important components of a 'full-service' DSS as mentioned by Rauscher (1999). It compares favourably with forest management DSS developed in North America (Mowrer et al. 1997; Rauscher 1999). Those DSS can be arranged by their spatial applicability – region, estate, project – or by the area of decision support covered, e.g. simulation of vegetation dynamics, economic analysis, disturbance simulation, visualisation, etc. (Sodtke et al. 2004). Respective DSS in central Europe (Thees and Riechsteiner 2001; Vacik and Lexer 2001; Mosandl and Felbermeier 2003) were mostly found to be in an early stage of development. Using individual-tree growth simulators is especially helpful for strata planning and enterprise simulation. Such simulators generate the most accurate solutions, using the individual-tree information provided by enterprise inventories (Pretzsch et al. 1998).

By enabling a user to fix preferences for several management objectives, the DSS allows for a multi-criteria evaluation of management alternatives. Identification of the best management alternative results from a combined procedure of evaluation and optimisation with an adjusted heuristic Tabu Search algorithm. Evaluation comprises fuzzy inferring strategies, enabling the processing of vaguely defined expert knowledge (Zimmermann 1987, 1996). Resulting utility values per management objective are aggregated to total estate utilities, serving as target functions for mathematical optimisation. Evaluation results given by the DSS help with estate-level decisions. However, the DSS does not on its own dictate an optimum strategy to the decision maker. Rather, it allows the decision maker to select the most suitable strategy from a range of alternatives.

11.5 Perspectives

Methodical testing is now complete, but the DSS prototype is not yet fully validated. Further testing with inventory data from our practical partners is currently being carried out. In the future, the presented approach will be developed and advanced, for example, in integrating more decision variables (referring to regeneration, planting, pruning, etc.) and integrating further objectives and indicator variables (economic, structural indicators, etc.). Furthermore, it is planned to convert the program into a stand-alone software – independent of the programming software and the operating system – to be used by forest managers and planners and for education purposes.

The combination of simulators, evaluation and optimisation algorithms and several visualisation systems appears to be trend-setting for decision support at estate level (Pretzsch 2003). Such integrative systems can reveal the objective criteria and preferences of decision makers, and may highlight decision pathways and possible consequences of different management alternatives in the long run. They enable participation of an interested public in the decision processes (Pretzsch 2003; Pretzsch et al., this Vol.) and allow debate over future forest management with politicians and association members, thus paving the way for strategic objective-orientated forest enterprise management.

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Hubert Hasenauer (Ed.)

Sustainable Forest Management

Growth Models for Europe

With 110 Figures, 30 in color, and 44 Tables

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Preface and Acknowledgements

Given the change in silvicultural management from being mainly clear-cut-driven to an uneven-aged mixed small-scale and/or individual tree-driven forest management system, existing yield tables will become increasingly unreliable. As a potential alternative, tree growth models have been developed in order to forecast the growth of each tree within a stand independent of tree age, species mixture and silvicultural management, allowing increased flexibility, which is necessary for modeling such managed forests.

The work presented in this book summarizes a joint effort among European tree growth modeling experts, forest policy decision-makers and forest companies to further enhance modeling theories and to investigate problem-solving methods for silvicultural decision-making. From February 2001 to January 2004, a group of 45 individuals worked within the ITM consortium (Implementing Tree Growth Models for Forest Management), an EU-funded effort to enhance and promote tree growth modeling theories within Europe. For our work, a number of tree growth models were selected. After extending the models and research gaps related to tree growth modeling theory (Chaps. 1–8), the following application examples (Chaps. 9–17) were selected by our company representatives to demonstrate the problem-solving potential:

1. Regeneration in uneven-aged mixed-species stands.
2. Timber-harvesting scenarios.
3. Incorporation of tree growth models in information systems.
4. Using tree growth models beyond the calibration area.
5. Assisting forest policy decision-makers.
6. Tree growth models as a decision support system component.
7. Optimizing cork production in southern Europe.
8. Converting even-aged pure stands into uneven-aged mixed species stands.
9. Modeling coppice forests in Greece.

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Hubert Hasenauer
November 2005

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