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RULE BASED MODELING OF THINNING REGIMES FOR A DISTANCE DEPENDENT SINGLE TREE GROWTH SIMULATOR BY IMPLEMENTING A FUZZY LOGIC CONTROLLER

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ABSTRACT

A thinning model is designed that can be implemented into distance dependent single tree growth simulators. The most central module of this thinning model is a fuzzy logic controller which consists of a merely simple rule base with no more than seven rules. The only input variables are a relative tree diameter and a distance dependent competition index, the output variable prepares the thinning decision of a single tree. The rule base is designed using formally defined thinning instructions, empirical data from experimental plots and simulation results. The evaluation of the rule base is maintained by applying the max-prod-inference, the defuzzification of the resulting thinning decision follows the center of gravity method. The thinning model is validated using independent data from experimental plots. The rule based apporach to model thinning regimes can be extended on sophisticated thinning instructions for mixed species stands.

1 INTRODUCTION

Stand growth simulators are models which are used to reproduce growth of trees and stands. The tree position-dependent growth model SILVA (Pretzsch 1992, 1993, 1995) describes and explains single tree growth in dependance on its spatial competition. This competitive stress, which a single tree endures, can for example respond from shading and the struggle for limited resources. The growth of single trees in respect to height and diameter and changes in crown dimensions can be aggregated to give information about stand dynamics. From an economic point of view the most important parameters about the development of the stand are stand volume, stand basal area, stem number, mean height, mean diameter, height and diameter distributions, assortment and financial yield. From an ecological point of view relevant stand parameters are for example in addition species mixture and horizontal tree distribution (segregation and aggregation), species diversity, proportions of dead wood and stand leaf area. Modeling tree growth intends to give exact growth prognosis of these stand parameters. Such a growth model should be capable of being applied to uneven aged mixed species stands as well as for even aged pure stands, it should be possible to deal with changes in the growth conditions (different sites, climate change) and to response on very different strategies of stand treatment (especially thinning).

The most important tree and stand growth determining variables are site conditions as well as stand structure and the spatial growth constellations of single trees respectively (Fig. 1). For modeling site dependent height and diameter development of Norway Spruce and European Beech a site model has already been designed that can be implemented into the growth simulator SILVA 2 (Pretzsch and Kahn, 1995). To generate initial stand structures Pretzsch

(1993) developed the model Strugen, which can establish a horizontal tree distribution out of verbally defined stand descriptions as they are used to forest practitioneers. The basic principle of Strugen is an inhomogenous Poisson-process, which is controlled bya set of macro- and micro-structure determining filter functions.

Stand structure changes over space and time. Tree age dependent changes are caused by growth processes, and beneath that wind, storm and insects take influence on stand structure. In economically treated forests especially thinning impacts modify stand structure and the feedback mechnisms between tree growth and spatial growth constellation. To complete the growth simulator SILVA in that respect a thinning module is designed that can be implemented into distance dependent single tree models. The basic conceptual ideas and methodical aspects of this thinning module are explained in the following chapters.

2 CONCEPTUAL IDEAS AND MODELING APPROACH

Considering the process of thinning, as it can be observed under practical conditions, under the aspect of decision theory, three main implications can be identified. The first is, that thinning is heavily normative, secondly it is intrinsic fuzzy and thirdly it is a multi criteria problem. The normative character of thinning is obvious, because thinning regimes are often defined in rules, as it is for example documented in the old instructions of the German Association of Forest Research Institutes from the year 1902 (Assmann, 1970). The necessity to represent thinning instructions in formally defined rules responds to the fact that human decision making seems to be very ill structured in the context of thinning practice. The intrinsic fuzzy character of thinning is at first based on the thinning instructions themself (with an extraordinary normative fuzziness). Secondly, in relation to that, the intrinsic fuzziness follows the fact, that the removal of single trees is justified under subjective categories. Intrinsic fuzziness means, that it is not common to use crisp metric criteria, like stem diameter, tree height or crown diameter to justify the removal ("the tree has to be removed, because it is much thinner than its neighbouring trees" and not "the tree has to be removed, because its diameter is with 23.7 cm exactly 4.5 cm lower than that of its next neighbour, which stands 2.1 m off"). Often used subjective criteria are for example tree quality, vitality, the tree's competitive stress or tree dimensions in relation to its neighbours. And it is rarely sufficient to use only one indicator to justify a tree's urgency for thinning. It is easy to see that the thinning decision has much in common with a multi criteria problem.

To deal with these handicaps a rule based thinning model is designed which evaluates the urgency for thinning of single trees. A rule based approach shall lead to a flexible thinning module, that is capable of dealing with uncertain, imprecise knowledge and that forest practioneers feel to be plausible. In addition it shall give exact results in simulation prognosis, adapting to the special features of distance dependent single tree growth simulators. It must also be possible to parameterize and to test the model with data from long term observation experimental plots. A first approach seems to be suitable by modeling a heavy thinning from below for to elaborate the methodical background in respect to rule based models. A next step should be the extension on thinning problems in mixed species stands. In the meanwhile both steps are realized. The core of the thinning algorithm is a fuzzy logic controller (Zimmermann, 1991).

For the thinning from below two criteria are used: a competition index from Pretzsch (1995) and the relative thickness of the tree. An example of a rule is: "IF the thickness of the tree is low AND its competitive stress is high THEN its urgency for thinning is high".

3 THE FUZZY LOGIC CONTROLLER

3.1 General Remarks

Following Zimmermann (1991) expert systems and fuzzy logic controllers (FLC) have surely one characteristic in common: both shall model human experience and human decision making. While expert systems have been widely applied to non-technical problems (for example in medicin, but in forest science too (Hempel and Wätzig, 1995)), FLC have usually been designed to control technical processes. In the meanwhile FLC have also been applied successfully to non-technical situations, and the characteristic of fuzzy systems as universal approximators of real functions is a well known fact since about 5 years ago. In this context of function approximation fuzzy systems have, with only a few basic asymptions, much in common with neural nets. Indeed they can be structurally equivalent (Kecman and Pfreiffer, 1994).

A fuzzy logic controller consists in general of an often merely simple knowledge or rule base (with 5 to 7, but up to several 100 rules), an inference machine to evaluate the rules (and the rule base resp.) and of mechanisms which perform the fuzzification of the input data and the defuzzification of the output data. Here in the context of growth simulation the controlled process is the act of thinning. In the next paragraphs it is shown how the FLC works and how it is used for modeling thinning regimes.

3.2 Selection Of The Thinning Criteria

The input data for the FLC are taken out of the process, that is to be controlled. These data have to be fuzzified, evaluated by the rules und then defuzzified for to take impact on the process. In respect to the process of thinning this means that a tree has to be evaluated in respect to the thinning decision. The tree itself provides for the relevant variables. These variables are state variables, but they can change if a thinning decision has been made (for example a tree's competitor has been removed). In the context of growth simulation it is suitable to choose those variables as input data for the FLC, which are already known in the simulation process and which do not need to be calculated only for thinning, so that the expense in computation time is kept small.

The first criteria that is chosen is the diameter of the tree at breast height (dbh). The dbh is subjectively and in a vague dimension easily to determine ("a thick tree"), and in forest practice it is also easy to approximate the dbh of a certain tree in relation to others ("much thicker than its neighbours"). In addition the dbh is highly correlated to other tree dimensions, for example tree height and crown diameter, and therefore in many respects representative to characterize a trees constitution. Using the growth simulator SILVA the dbh is one of the most important dynamic variables and for every tree and for every simulation period always available and does not have to be calculated only for the thinning algorithm. To use the dbh when transforming thinning instructions into a mathematical language it is necessary to perform a transformation. This is important because thinning instructions are time invariant. A heavy thinning from below implies to remove all trees of the classes 2 to 5 and also a few trees of tree class 1 (Assmann, 1970), and there is no difference if the stand is 40, 60 or 80 years old or if the mean diameter is 20 cm, 30 cm or 40 cm. A time invariant transformation of the dbh is its cumulative relative frequency, which can be extracted from the cumulative frequency distribution of all the dbh of a stand. This provides not only for a time invariant transformation but also for a stand related quantification of the tree's diameter (a tree is not only "thick" relativ to its or stand age but also in relation to the neighbouring trees or the mean diameter of the stand). The cumulative frequency of the dbh does not need to be calculated only for thinning, because it is also used for graphical outputs like frequency distributions. In the following the abbreviations "rel. dbh" or "relative dbh" are used for the cumulative relative frequency of the dbh.

The second criteria which serves as an input variable for the FLC is the spatial growth constellation of a tree. To indicate this spatial constellation numerically the competitive stress can be chosen. The effect of competition is quantified by the competition index CCL, which has been developed by Pretzsch (1995). This competition index CCL is calculated by summing up all the pressure that competitors have on a subject tree. The competitors are identified by establishing a light cone on the subject tree, that has an opening angle of 60° and that starts at 60 % from the bottom of the subject tree. All neighbouring trees which come with their top into this light cone are identified as competitors.

The numerical stress effect (pressure) of a competitor onto the subject tree is expressed by calculating the relation between the ground cover areas of the competitors and the subject trees crown and by weighting this relation with the angle between the basis of the subject trees light cone and the connecting line from the basis of the cone to the top of the competitor. In addition there are three more competition indices calculated (Pretzsch, 1995), which include a variable that indicates symmetric and asymmetric competition effects resp., a variable that takes the directional position of a trees competition centre into account and a variable which focuses on the effects of the species mixture in the trees neighbourhood. These variables are not yet considered in the thinning algorithm.

For the CCL it is not necessary to perform any time invariant transformations, because it is already a normalized measure. The CCL is a central variable for the growth simulator SILVA 2, and therefore no additional computations are required when applying the thinning model.

The output variable of the fuzzy logic controller is the urgency for thinning, which is the urgency for a tree to be removed ("the urgency for thinning of the tree is high"). All input and output variables have to be defined as linguistic variables on the mathematical background of fuzzy set theory (Zimmermann, 1991). Every linguistic term ("high" competitive stress) is expressed as a fuzzy set (Fig. 2). The domain of the variable "urgency for thinning" is a scalar base variable which is normalized on [0,1]. The membership functions of all the fuzzy sets of the three linguistic variables are piecewise linear defined.

3.3 Mechanisms Of Inference

Before now a rule base for thinning is designed, it shall be explained, how such a rule base will be evaluated by a fuzzy logic controller. The rules shall be as follows:

premise 1:	IF	thickness of the tree (rel. dbh) is	low
premise 2:	AND	its competitive stress (CCL) is	high
conclusion:	THEN	the urgency to remove the tree is	high

The first step is now to evaluate every premise for itself as it is depicted in figure 3. Considering the first premise for an arbitrary tree with an arbitrary dbh its cumulative relative frequency of the dbh is computed. With this relative dbh the linguistic term "low" of the linguistic variable "thickness of tree" is evaluated. This leads to one scalar numerical value. The second premise has to be evaluated similarly.

The second step in evaluating the rule base is to determine the so called "degree of fulfillment" of both premises. The degrees of fulfillment of each premise are then aggregated by the fuzzy set theoretic minimum operator, and the degree of fulfillment of both premises is returned. This procedure can be extended on arbitrarily many premises. The degree of fulfillment indicates in how far the rule itself is reliable. In the example-rule that was mentioned before the conclusion is a "high urgency".

The third step in evaluating the rule base is to apply for example the max-prod-inference: that means, the membership function of the term "high" is multiplied by the degree of fulfillment of the premises (Fig. 4). Beneath the max-prod-inference there are many other fuzzy reasoning methods which shall not be discussed here (see for example Mizumoto and Zimmermann, 1983 or Nakanishi, Turksen and Sugeno, 1993). The result of this reasoning step is a modified membership function of the linguistic term that describes the conclusion.

Now it has to be realized that not only one rule for a tree is evaluated but all rules that are in the rule base. For all rules follows a more or less heavily modified membership function for the conclusion, some may be 0 when the degree of fulfillment of a premise has been 0. The question is now how all these conclusions can be combined, so that one precise judgement about the urgency for thinning of a certain tree can be concluded. Applying the max-prod-inference, and that's where the first part of the inference's name comes from, all the conclusions are aggregated by the fuzzy set theoretic maximum operator. From this follows a (maybe) mountainous function graph (Fig. 5), which is a fuzzy set that describes the conclusion. It is surely hard to find the adequate verbal expression for such a fuzzy set ("the urgency for thinning of the tree is a bit medium but more or less low"?). This fuzzy set is defuzzified by calculating its center of gravity over the domain of the conclusion. The center of gravity provides for a real valued quantification of the urgency for thinning for a certain tree. If all trees are evaluated with the rule base concerning their urgency to be removed they can be sorted by this center of gravity, which is individually for every tree. The tree with the highest center of gravity may be removed.

One different approach, and there are many, is for example to describe the linguistic terms of the conclusion as singeltons. This leads to a computational quicker defuzzification and has some advantages in respect to an optimization of the fuzzy system (Kecman and Pfeiffer, 1994). In this context it is quite interesting to realize the interpretation of fuzzy systems (like a fuzzy logic controller) as universal approximators of real functions, similar to polynomials or Fourier transformations (Fig. 6). The search for "best" rules or optimal parameter solutions in the high parameterized space of the membership functions can be conducted for example by using evolutionary strategies (Glorennec, 1994).

3.4 Design Of The Rule Base

Beneath the "best" definition of the membership functions of the linguistic variables the design of the rule base ("which rules are the best"?) is the most sophisticated part when developing a fuzzy logic controller. Here it seems quite easy, because there can be a maximum of only 25 rules (25 combinations of the 5 verbal terms of the linguistic variable "tree thickness" and the 5 verbal terms of the linguistic variable "competitive stress") if it is accepted that there shall be no contradicting conclusions.

A first starting position how to find suitable rules are the thinning instructions themselves (Assmann, 1970). In the context of a heavy thinning from below it is known that the lower tree classes have to be removed first. These trees can be identified as those whose relative dbh is low and whose competitive stress is high. A second starting point is provided by the data from long term experimental plots: The cumulative relative frequencies of the dbh of all trees can easily be calculated, but the CCL values are still unkown. To get those CCL the data of an experimental plot, from which the stem number - diameter - distribution of the remaining and the removed trees is known, have to be treated by the growth simulator. If no tree positions are available they can be generated by Strugen (Pretzsch, 1993). The growth simulator SILVA 2 evaluates the spatial growth constellation of every tree and returns the desired CCL value (apart from the relative dbh). Then plotting the CCL against the relative dbh it gets obvious that not every rule makes sense (Fig. 7) and that several combinations of tree thickness and competitive stress do not need to be taken into account.

A third step then to get a good start with the rule base is thinning simulation. After the first two steps there exists already a set of "proto-rules". They can be applied onto real data, and it can be compared how similar the real and the simulated stem number - diameter - distribution of the removed trees are (Fig. 8). After a few simulation runs with SILVA 2 and a manual feedback onto the rule base a good prognosis behaviour of the fuzzy logic thinning controller can be achieved. The rule base consists of only seven rules.

4. THE FUZZY LOGIC CONTROLLED THINNING MODEL

4.1 The Algorithm

The thinning algorithm consists not only of the rule base and the inference engine. Very helpful is a sorting algorithm (Quicksort by Press et al., 1992) to sort the trees by the center of gravity which quantifies the evaluation of the rule base. In general this sorted list does not provide for the decision, if a tree shall be removed or not. If there is any tree with a center of gravity larger than 0 it only tells which tree should be removed first. The decision, if it really shall be removed, depends on other criteria.

There might be a limit of stem numbers per ha or stand basal area per ha as a suitable criteria for the degree of thinning. In this case here, with a special rule base designed for a heavy thinning from below, the degree of thinning is already integrated in the rule base. It is obvious that this is only the case because there are only seven rules which are carefully selected. If there were all possible 25 rules clearly defined, every tree would be evaluated with a center of gravity larger 0. Although it is possible to remove all trees in the stand with a center of gravity of the rule base larger 0 when using the "heavy thinning from below" - rule base an additional criteria (like stand basal area) can be switched on.

Assuming now that the thinning process during a simulation run with a tree position dependent single tree growth simulator is going on, the sorted list of removable trees has to be actualized after every removal. This is necessary because it can often happen, that a removed tree was a competitor to another tree. This information can for example be listed in a tree individually array with the addresses of all concerned neighbouring trees. Then for all those trees their competition index CCL has to be corrected by subtracting the CCL-proportion of the removed tree. In addition the rule base for those trees has to be evaluated again and their position in the list of removable trees might change. This procedure will be repeated until the thinning is finished, either because there is no tree left with a rule base center of gravity larger then 0 or another criteria for determining the degree of thinning set a flag.

4.2 Validation By Simulation

A validation of the fuzzy logic thinning controller is performed by simulation with the growth simulator SILVA 2. Therefore the data of the long term experimental plot Denklingen 5 with Norway Spruce are prepared for the simulation. This plot has been treated with a heavy thinning from below (degree C) since beginning of the observation period. The data come from three assessments in the stand ages 35, 55 and 104 years. The stem number - diameter - distributions as they have really been are compared to the distributions after fuzzy logic thinning (Fig. 9). The simulation results give evidence of the good estimations that can be achieved using the model to predict the diameter distribution of the thinned trees in comparison with thinning practice on experimental plots. It is remarkable in respect to the modeling approach with the fuzzy logic controller that there was only one rule base with only 7 rules that gives these results in three totaly different stand ages. This gives a first hint that the time invariant transformation of the dbh as a cumulative relative frequency was a suitable choice and that also the CCL bears such time invariant characteristics.

It is not surprising that the fuzzy logic controller works well. In technical applications fuzzy controllers are often successful because the rate, by which the rule base is evaluated and a feedback on the process is given, is very high. If the rule base is in addition dense in the critical states of the process little uncertainties do not effect too much. In the case of human decision making in thinning practice the repetition rate is also very high: each tree can be interpreted as a spatial repetition of a certain process state.

During a simulation run over many periods there would also be repetitions over time. This reveals why it does not make sense to focus on the correct or not correct removal of single trees as an optimization and validation criteria of the thinning model. More important are the good reproduction of stem number - diameter distribtutions and a reasonable horizontal distribution of tree positions before and after thinning.

4.3 Further Developments

The fuzzy logic controller promises flexibility to serve as a mechanism which is suitable to model imprecise human decision making in ill structured situations as can be observed in thinning practice. In the meanwhile the approach has been extended to crown thinning in pure stands of European Beech and to thinning in mixed stands of spruce and beech (Fig. 10). For the thinning in mixed species stands the rule base is split up into a rule set for each species. In addition the premise consists of three input variables: the variable "competitive stress" is split up into competition that results from trees of the same species and those from other species as the subject tree.

Concerning the optimzation of the parameter solutions of the membership functions of the linguistic variables and the selection of the "best" rules evolutionary strategies will be developed.

The thinning model in its contemporary implementation can already be used to conduct simulation runs to analyze the feedback mechanisms between tree increment on height and diameter and on changes in crown dimensions as well as on stand growth. Further simulations will focus on this problem to formalize the search for the "best" stand treatment and how to optimize thinning impact on stand structure respectively.

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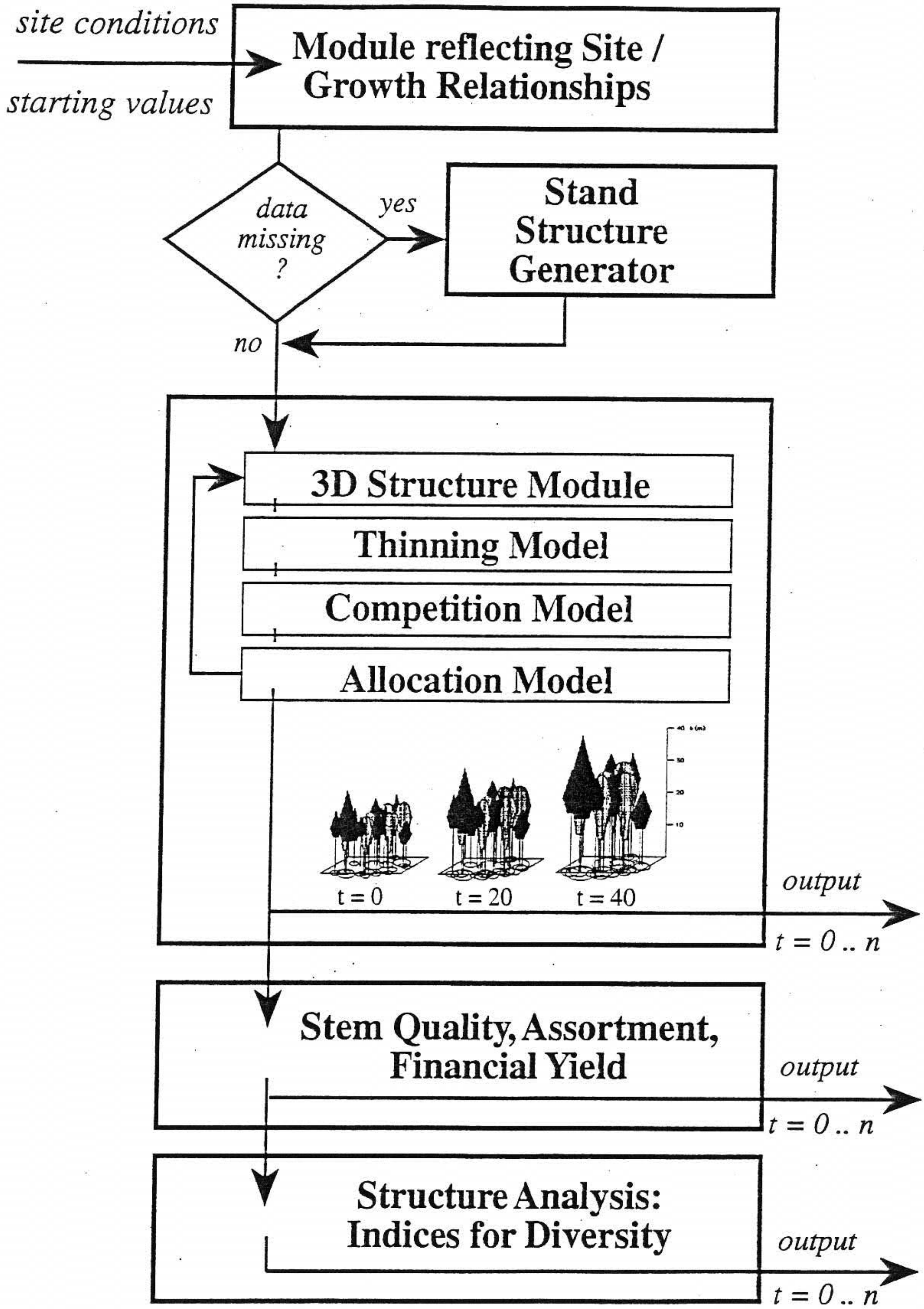


Figure 1: The main modules of the growth simulator SILVA 2 (figure by H. Pretzsch).

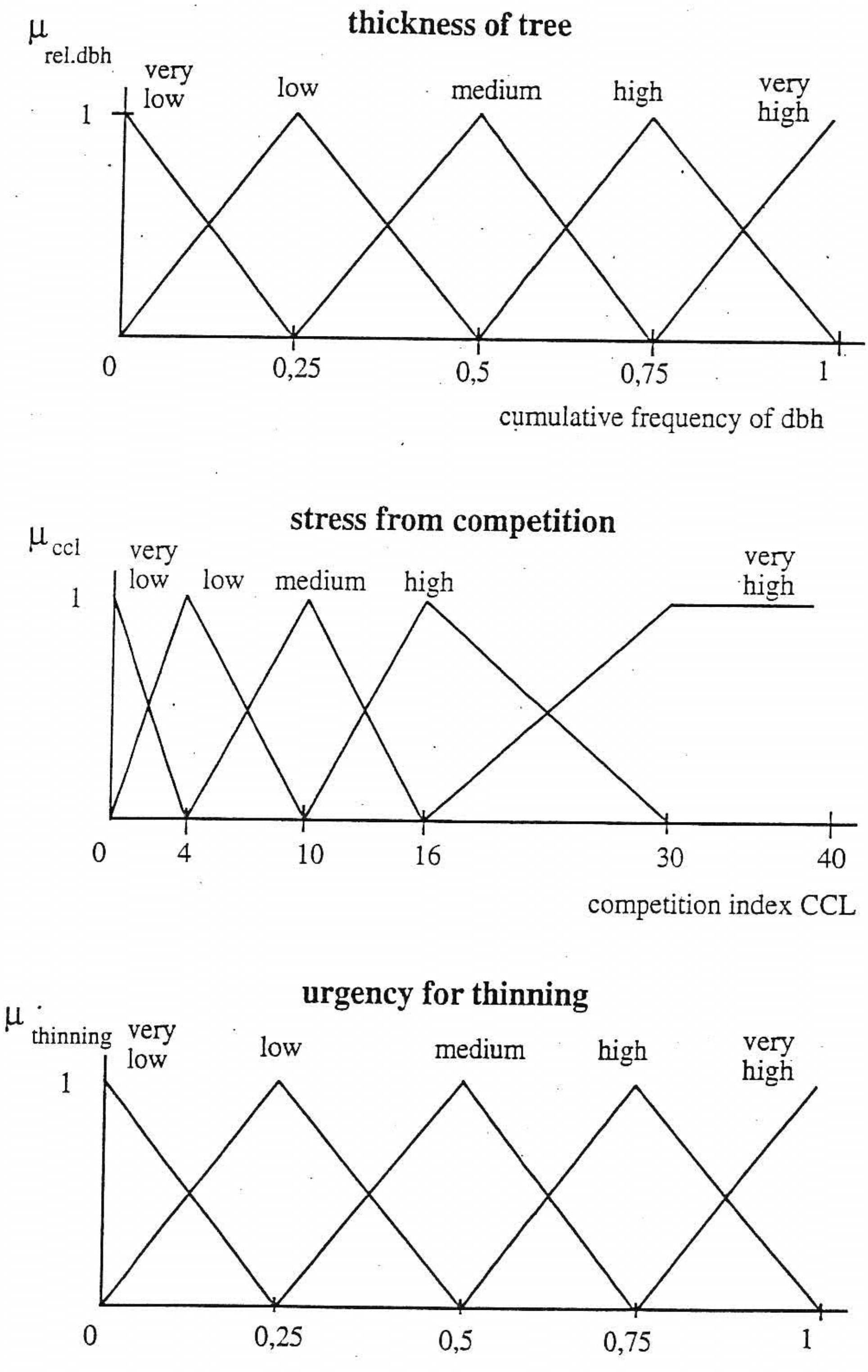
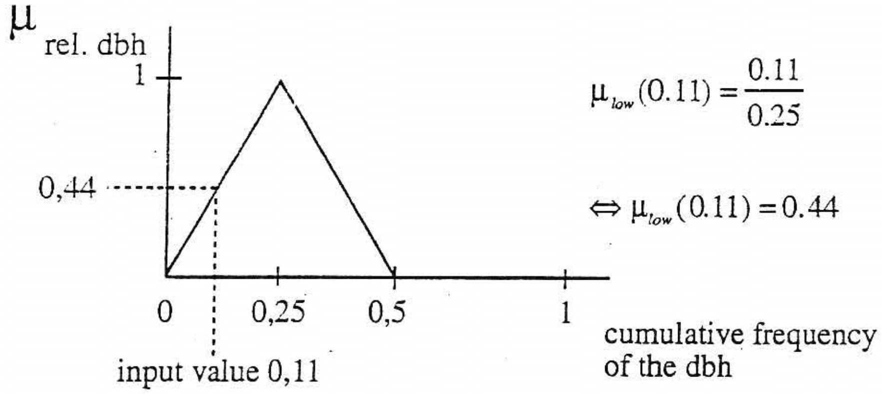


Figure 2: The input variables of the fuzzy logic controller (the relative tree diameter at breast height and the competition index CCL) as well as the output variable (the urgency for thinning) are defined as linguistic variables.

The membership function of the fuzzy set "tree thickness is low" is piecewise linear defined:

$$\mu_{low}(rel.dbh) = \begin{cases} \dfrac{rel.dbh}{0.25} & ,0 \le rel.dbh \le 0.25 \\ \dfrac{0.5 - rel.dbh}{0.25} & ,0.25 < rel.dbh \le 0.5 \\ 0 & ,(rel.dbh < 0) \text{ or } (rel.dbh > 0.5) \end{cases}$$

Degree of fulfillment of the 1. premise:



$$\mu_{low}(0.11) = \frac{0.11}{0.25}$$

$$\Leftrightarrow \mu_{low}(0.11) = 0.44$$

Degree of fulfillment of both premises:

- aggregation with the minimum operator

$$\mu_{\text{both premises}} = \min\{\mu_{\text{rel. dbh}} ; \mu_{\text{CCL}}\}$$

Figure 3: At a first step both premises are avaluated by themselves. The degree of fulfillment of both premises is then determined by applying the minimum operator.

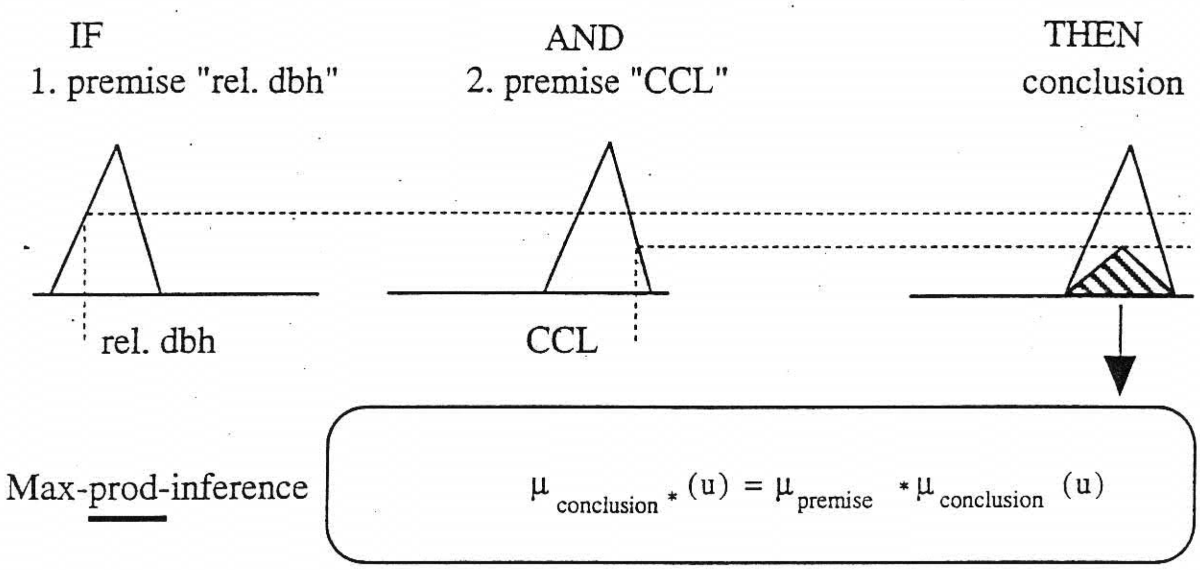


Figure 4: Max-prod-inference. The membership function of the linguistic term of the conclusion is multiplied by the degree of fulfillment of the premise.

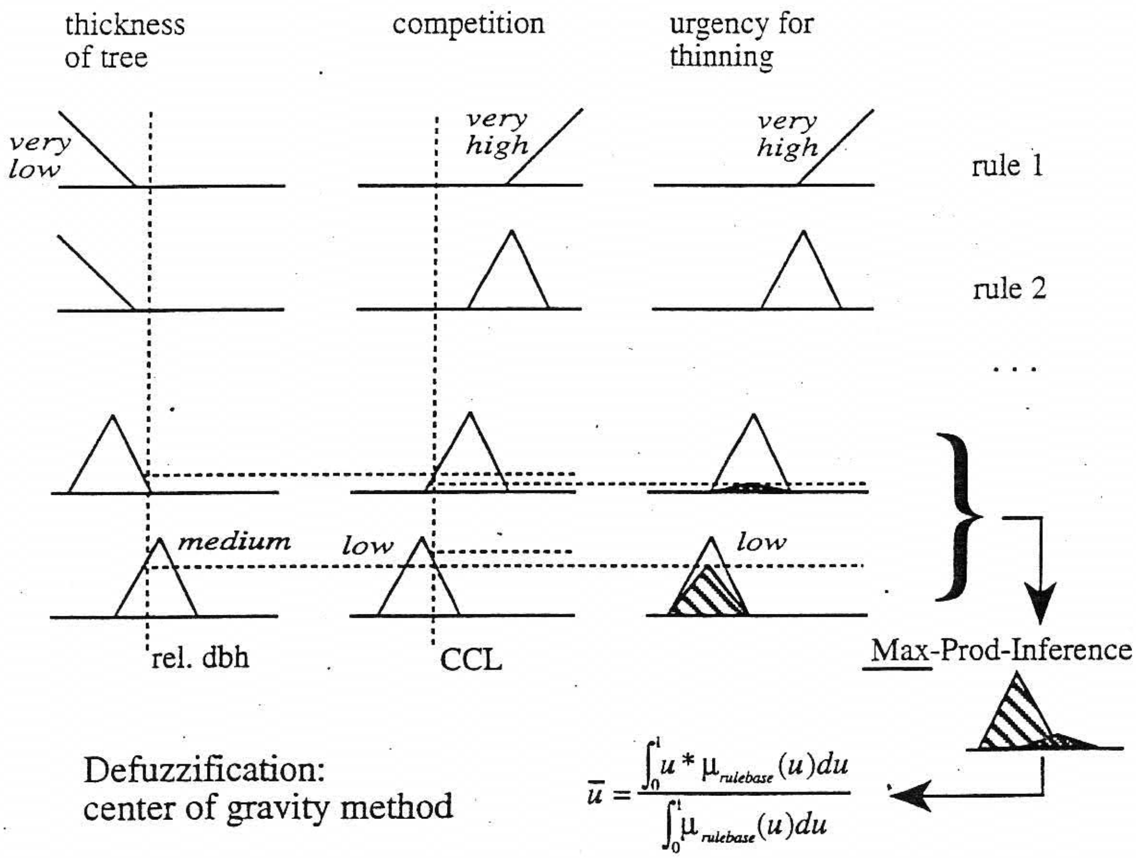
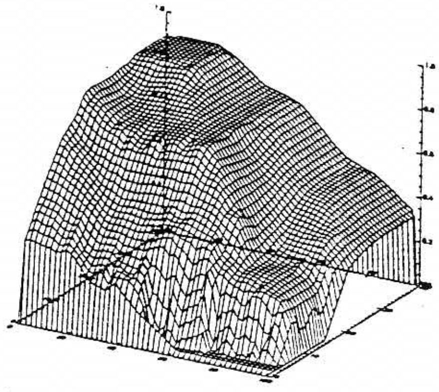


Figure 5: Evaluation of the rule base with max-prod-inference and defuzzification with the center of gravity method.

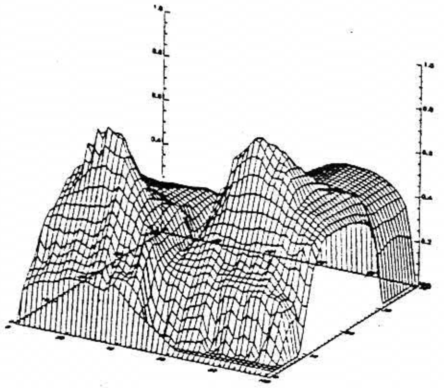
CCL (very low → very high); rel. dbh (very low → very high)

rel. dbh	1	2	3	4	5
1	2	3	4	5	5
2	1	2	3	4	5
3	1	1	3	4	4
4	1	1	2	2	3
5	1	1	1	1	2



CCL

rel. dbh	1	2	3	4	5
1	1	1	1	1	1
2	1	2	5	3	1
3	1	1	2	1	1
4	1	1	2	5	3
5	1	1	1	3	1



CCL

heavy thinning from below

rel. dbh	1	2	3	4	5
1	0	2	0	4	5
2	0	0	2	4	0
3	0	2	0	0	0
4	0	2	0	0	0
5	0	0	0	0	0

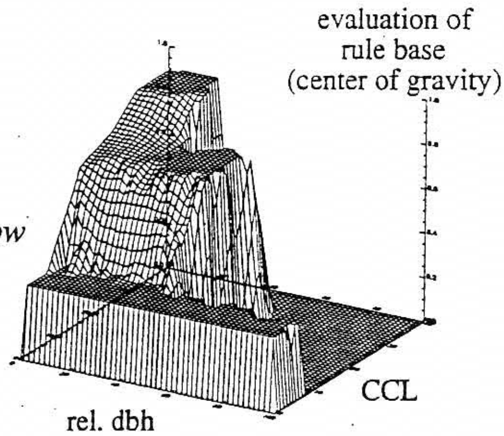


Figure 6: Fuzzy Systems are universal approximators of real functions. Abbreviations in the matrices: 1= very low, 2= low, 3= medium, 4= high, 5= very high. In the example at the bottom the rule base for a heavy thinning from below is shown in a matrix and function graph. This matrix expresses for example in the third column and the second row the rule: IF tree thickness is low AND the tree's competitive stress is medium THEN the urgency for thinning is low.

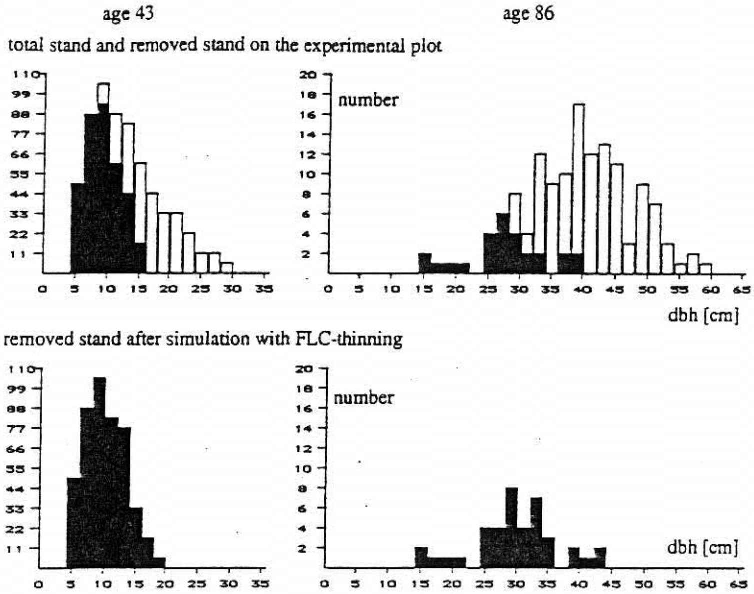


Figure 8: Simulation aided design of thinning rules with data from the experimental plot Sachsenried 67, Norway Spruce, thinning degree C. After few simulation thinnings with SILVA 2 and manual feedback onto the rule base a good prognosis behaviour of the fuzzy logic thinning controller can be achieved.

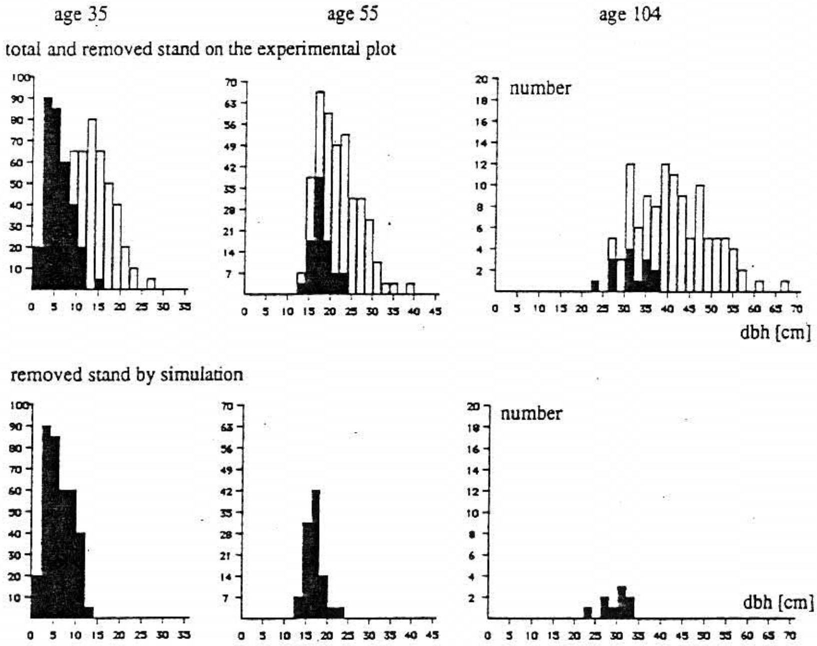
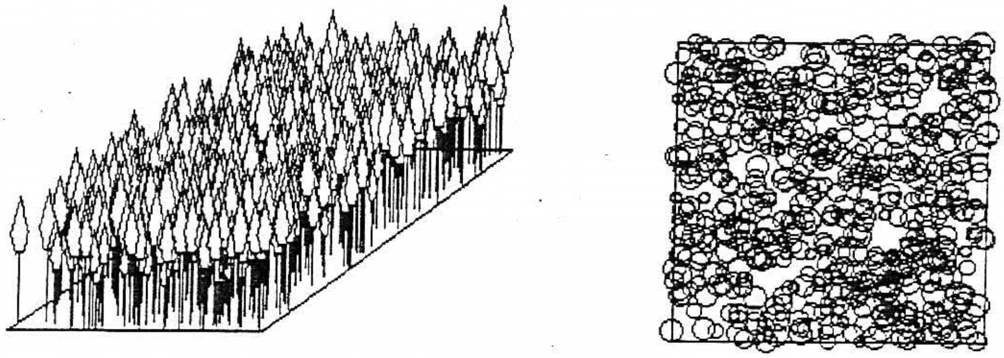


Figure 9: Validation of the thinning model with data from the experimental plot Denklingen 5, Norway Spruce, at different ages. The three upper diagramms show the stem-number-diameter-distribution as it was observed on the experimental plot. The lower diagramms show the stem-number-diameter-distribution of the removed tress after thinning with fuzzy logic controller.

Experimental plot Sachsenried 67, thinning degree C, Norway Spruce, age 43

Generation of the tree positions with STRUGEN



Visualization of a premise of a rule:

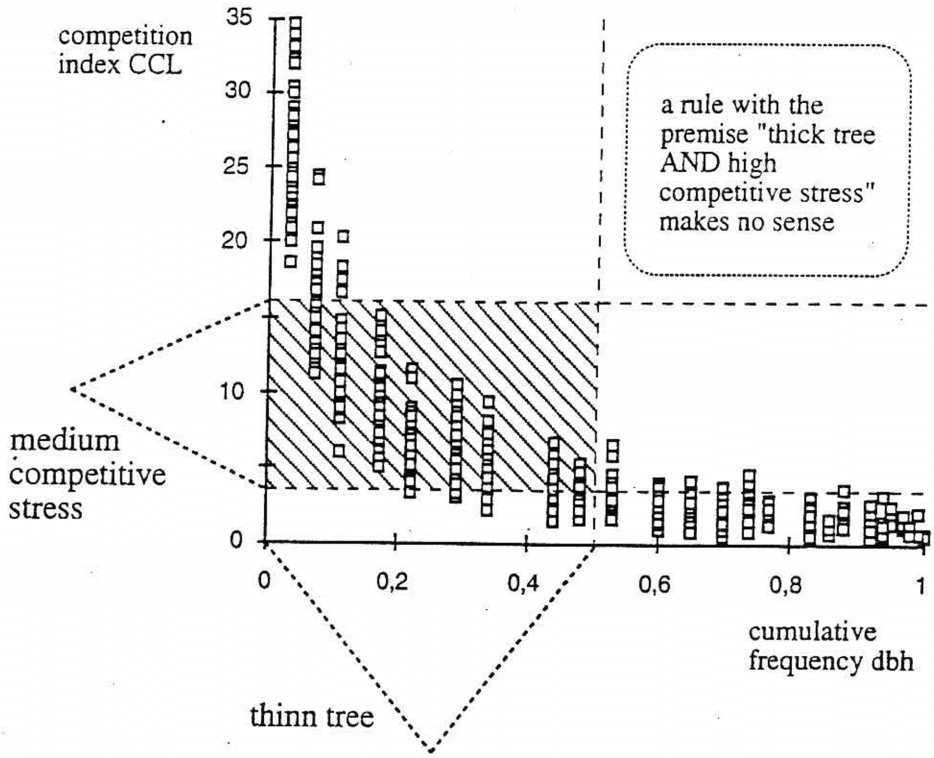


Figure 7: Using data from experimental plots as one approach to design the rule base.

Starting point of a simulation:

a mixed stand with beech and spruce

	hg	dg	N/ha	G/ha	V/ha
Spruce	23.7 m	24.0 cm	752	33.9 qm	385 cbm
Beech	21.9 m	21.0 cm	434	15.1 qm	163 cbm
Total			1186	49.0 qm	549 cbm

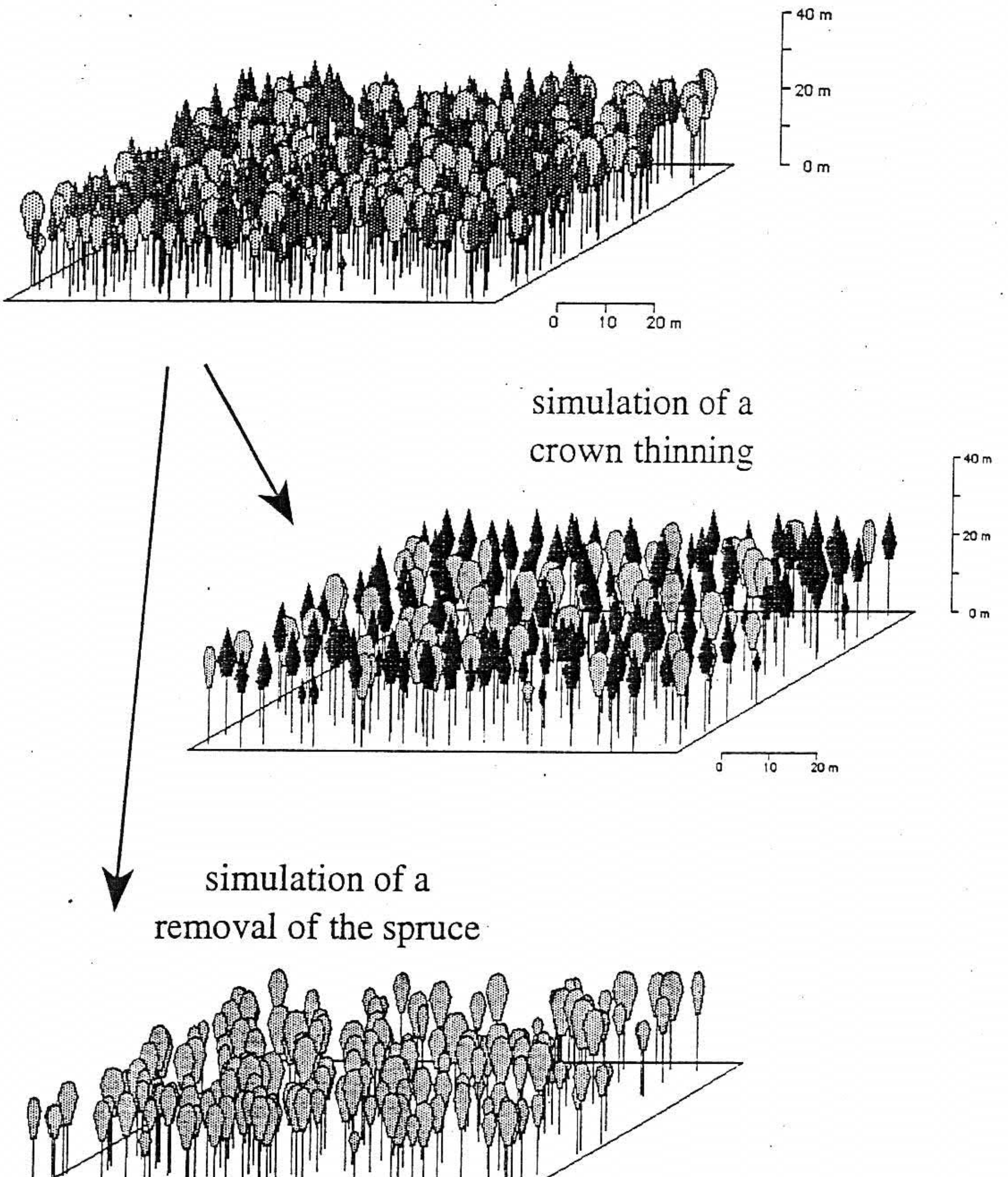


Figure 10: A prospect on analysing the effects of thinning: Growth simulations with SILVA shall reveal the feedback mechanisms between growth and stucture. The rule base of sophisticated thinning regimes consists of more than 100 rules for each tree species.