Algorithms and software solution of thinning models for SIBYLA growth simulator

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ABSTRACT: The paper deals with a proposal for a thinning model for the growth simulator SIBYLA. The model is based on an analytical-causal modeling approach. Some partial theorems are tested on experimental data from thinning sample plots. The model is composed of the following components: the model of bio-sociological tree status, the model for score of existence, the model for type of selection, the model for amount of thinning, and the aggregated model of the thinning concept. The appropriate combination of type and amount of thinning allows the user to perform the following thinning concepts: thinning from below, thinning from above, neutral thinning, crop tree thinning, target diameter thinning, target frequency (equilibrium) curve thinning, clear cutting, and thinning by list (interactive thinning). A software solution of the algorithms, and an example of different thinning concepts for selected forest stands is presented at the end of the paper along with a discussion about the advantages and disadvantages of the thinning model compared to the SILVA 2.2 model.

Keywords: tree growth models; thinning engine; thinning concepts; forest modeling

Tree growth models are implemented in forestry and ecology. They provide the advantage of an individual tree modeling approach. Flexible reactions to very complicated phenomena are possible, for example, the relationship between tree mortality and competition. If we want to implement these models into current forestry practice as a tool for decision support, we must integrate thinning algorithms into the models. Automatic selection of thinning trees by specification of thinning concept, thinning amount, and thinning interval is assumption for an execution of different thinning strategies and selection of optimal one. A lot of models exist in Europe (SILVA, BWIN, PROGNAUS, MOSES, STAND, DRYMOS, CORKFITS) and each of them includes some thinning tool. Thinning concepts are modeled by different approaches. Some models use algorithms based on empirical data analysis, for example, the logistic model by Ledermann (2002). Several models are established in an analytical way, for example, the fuzzy model by Kahn (1995). Other models are based on knowledge and heuristic principles, for example, the expert system ThiCon (Daume, Robertson 2000). The models can be deterministic or stochastic.

The model SIBYLA (Fabrika 2003a) was developed during the period 2001–2004. The development has been supported by the Europe Committee as a part of the 5th Framework Program of the European Union. The model is built on SILVA modeling principles (Pretzsch 2001). An new software solution has been created. The growth simulator SILVA 2.2 includes a comprehensive tool for thinning concepts (Kahn 1995), but this tool is not direct applicable to Slovakian conditions. The thinning model of SILVA 2.2 does not consider tree quality. Tree quality is usually estimated in Slovakian forest inventories and seems to be very important. Also, some specific thinning concepts are not included in the SILVA 2.2 model. Therefore, we have decided to develop our own thinning engine. The thinning engine is built from a combination of new algorithms and existing algorithms and approaches (Assmann 1961; Halaj 1985; Halaj et al. 1986; Johann 1982; Kahn 1995; Konšel 1931; Korpeľ et al. 1991; Liocurt 1898; Meyer 1952; Pretzsch 2001; Remiš et al. 1988; Reynolds 1999; Schädelin 1942; Štefančík 1974, 1977, 1984). The model is created in an analytical way and some parts of it are tested on experimental data set. Experimental data comes from thinning experiments of the Department of Forest Management and Geodesy in Zvolen and the Forest Research Institute in Zvolen. The model is composed from the following components: a model of bio-sociological tree status, a model for score of existence, a model for type of selection, a model for amount of thinning and an aggregated model of the thinning concept. This paper presents algorithms of the thinning models. The model has been developed in frame of individual research by the authors and has been co-supported by foundation of Alexander von Humboldt in the years 2004–2005.

METHODOLOGY

Model of bio-sociological tree status

Bio-sociological tree status plays an important role in some thinning concepts, for example, for selection of thinning trees in thinning from below and thinning from above or for selection of crop trees. A simplified classification scale by Konšel (1931) has been used:

1 – dominant trees,
2 – co-dominant trees,
3 – intermediate trees,
4 – overshadow trees.

Classification algorithms (BIOSOC model, Fig. 1) are based on tree heights and modeling of tree crown parameters. First, the dominant height of the plot ($h_{95\%}$) is calculated. The dominant height is the limit between dominant and co-dominant trees. Utilization of dominant height has arisen by investigation on thinning research plots. Then, the height to the base of the crown ($\overline{ch}$) and the length of the light part of the crown ($\overline{l}_L$) are calculated for the dominant height by

$$\overline{ch} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{m}\left[\left(\frac{d_{ij}^{2} \cdot h_{ij}}{100}\right) \cdot ch\,(95\%)_i\right]}{\sum_{i=1}^{k}\sum_{j=1}^{m}\left(\frac{d_{ij}^{2} \cdot h_{ij}}{100}\right)} \quad (1)$$

$$\overline{l}_L = \frac{\sum_{i=1}^{k}\sum_{j=1}^{m}\left[\left(\frac{d_{ij}^{2} \cdot h_{ij}}{100}\right) \cdot \overline{l}_L\,(95\%)_i\right]}{\sum_{i=1}^{k}\sum_{j=1}^{m}\left(\frac{d_{ij}^{2} \cdot h_{ij}}{100}\right)} \quad (2)$$

where: d_{ij}, h_{ij} – diameters and heights of trees,
k – number of tree species,
m – number of trees for corresponding tree species,
$ch(95\%)_i$, $l_L(95\%)_i$ – height to the base of the crown and length of light part of the crown for trees of dominant height.

The heights to the base of the crown and lengths of the light part of the crown are calculated by Pretzsch (2001). The classification of the trees into scale is performed by the rule

$$\text{BIOSOC} = \begin{cases} h_i \geq h_{95\%} \Rightarrow 1 \\ (h_i < h_{95\%}) \wedge (h_i \geq (h_{95\%} - \overline{l}_L)) \Rightarrow 2 \\ (h_i < (h_{95\%} - \overline{l}_L)) \wedge (h_i \geq \overline{ch}) \Rightarrow 3 \\ h_i \geq \overline{ch} \Rightarrow 4 \end{cases} \quad (3)$$

Model for score of existence

Usually, a selection of individual trees is a component of the thinning concept. Properties of the trees are obviously used for the selection. The selection can be made within different groups of the trees, for example, trees with identical bio-sociological status

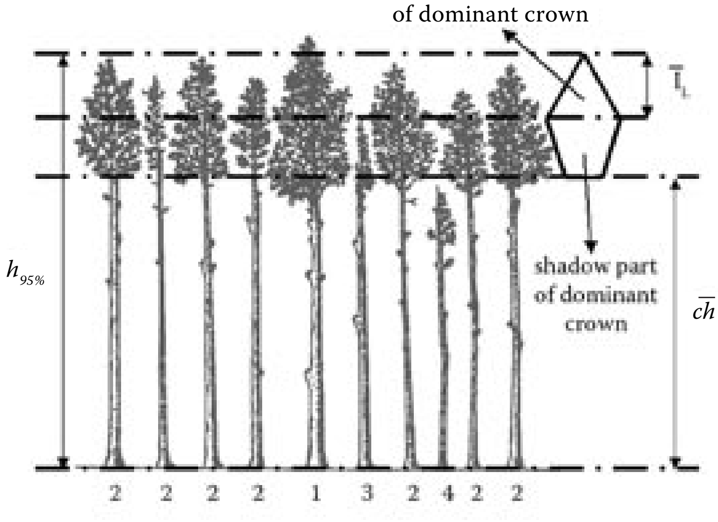


Fig. 1. BIOSOC model

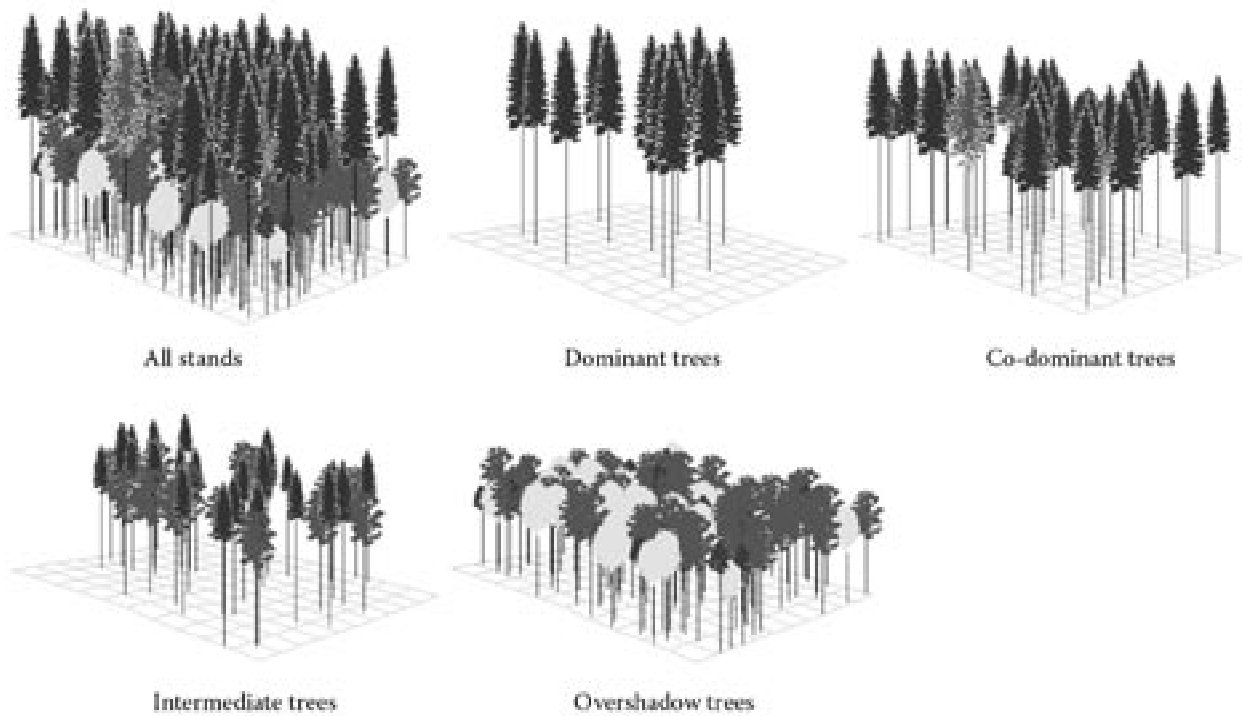


Fig. 2. Example of classification by BIOSOC model

or trees in one diameter class. The selection can be concentrated among the worst trees or the best trees. The worst trees are selected with the concepts thinning from below or thinning from above. The best trees are selected with the crop tree method. An important assumption for the selection is the specification of the selection criteria. The problem is especially complicated if we want use automatic computer algorithms. Often, the problems are solved by knowledge base systems. Production rules with fuzzy logic algorithms are frequently used. A similar approach has been used in the SILVA model (Kahn 1995), namely, thinning from below and from above. Our intention is to extend the principle for next thinning concepts and, at the same time, to integrate tree quality into decision algorithms. As a consequence, our algorithms are based on **score of existence**. Selection is managed by its value. If we concentrate on thinning trees, we remove trees with the smallest score of existence. If we concentrate on crop trees, we select trees with the biggest score of existence. The model is composed from the following axioms:

If:
– tree has low competition pressure,
– and stem quality is good,
– and tree vitality is good,
– and tree is alive,
Then
– tree has a high score of existence.

The rule is composed from four partial assumptions. The conclusion of the rule is valid only, if all assumptions are satisfied. The conjunction "*and*" is used, because the conclusion does not have justification, if the tree is dead or has marginal competition pressure from neighboring trees. Partial assumptions have been transformed into fuzzy values from 0 to 1. This means that assumptions are estimated by indicators. We used the following indicators: critical value of competition index for competition pressure, percentage of the best timber classes for tree quality, and crown surface for tree vitality. The last assumption about mortality is quantified by Boolean value: 0 (if tree is dead) or 1 (if tree is live). Conversion of the indicators to fuzzy values is achieved by fuzzy set functions. The functions have been developed in algorithm form.

Assumption 1: "*Competition pressure is low*" is modeled by

$$\boldsymbol{p}_{CCL} = \boldsymbol{e}^{-(a + b \times z_{\alpha/2})^{c}} \qquad (4)$$

Coefficients of the equation are: a = 0.903113; b = 0.257922; and c = 3.6. The critical value $z_{\alpha/2}$ for the difference between current tree competition index and mean competition index is calculated using the procedure by Pretzsch (2001). Mean competition index depends on tree volume. Graphic expression of the rule is shown in Fig. 3.

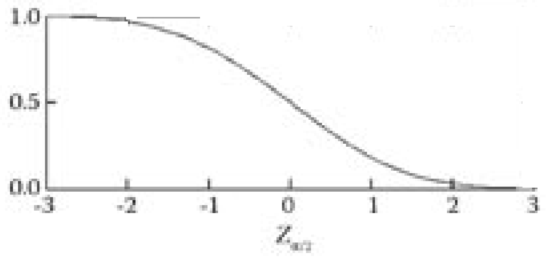


Fig. 3. Mathematical expression of assumption: Competition pressure is low

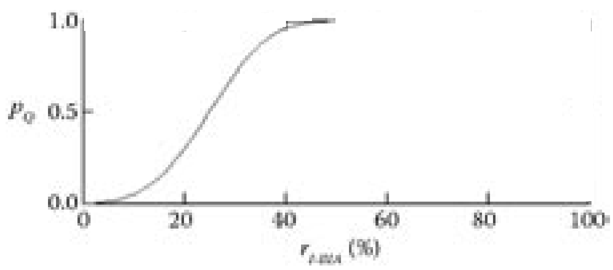


Fig. 4. Mathematical expression of assumption: Stem quality is good

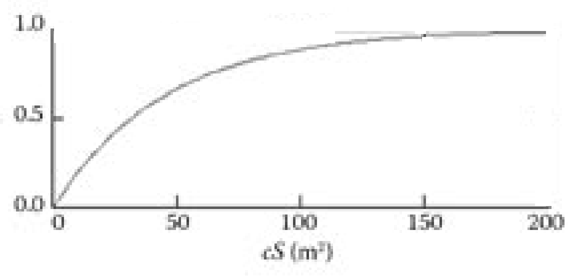


Fig. 5. Mathematical expression of assumption: Tree vitality is good (example for beech)

Assumption 2: "*Stem quality is good*" is modeled by

$$p_Q = 1 - e^{-(a + b \times r_{I-IIIA})^c} \quad (5)$$

Coefficients of the equation are: a = 0.129347; b = 0.03095064; and c = 3.6. Percentage of the best timber classes (*I+II+IIIA*) produced by the tree is calculated using models by Petráš and Nociar (1990, 1991). Graphic expression of the rule is shown in Fig. 4.

Assumption 3: "*Tree vitality is good*" is modeled using the approach by Pretzsch (2001). Vitality depends on size of tree crown surface (*cS*) and tree species. An example for beech is presented in Fig. 5. Vitality of beech is most sensitive to crown size.

Assumption 4: "*Tree is alive*" is modeled by Boolean value (0 or 1). If the tree is dead, value is zero, otherwise value is one. Information about mortality is modeled using a mortality model by Ďurský (1997).

The resultant score of existence for an individual tree is calculated using the following equation (Reynolds 1999):

$$SCORE = MIN_p + (AVG_p - MIN_p) \times MIN_p \quad (6)$$

MIN_p means minimal value of previous four assumptions and AVG_p means their average. The result is a value between 0 and 1. A tree has a greater probability of staying in the stand after thinning if its *SCORE* is greater. Specific position has so-called **marginal score of existence**. The marginal score can be fixed at a specific value, which we can then not exceed during selection. For example, if we specify a marginal score of 0.7 and we select thinning trees, we can not choose trees with a score than 0.7. If we select crop trees, we can not select trees with a score less than 0.7. The marginal value can be used to fix tree quality before execution of selection algorithms.

Model for type of selection

The modeling of selection depends on groups or sub-groups, because trees are selected within them. In this case, a separator is established. The **separator** is a feature (characteristic) which classifies trees into groups or sub-groups. The separator can be a qualitative value, a quantitative discrete value, or a quantitative continuous value. Bio-sociological status is an example of a qualitative value used in the thinning concept from below or above. Diameter class is an example of a quantitative discrete value in the thinning concept using target frequency curve (equilibrium curve). Target diameter or clearing radius is an example of a quantitative continuous value used in the thinning concepts by target diameter and crop trees method.

With regard to **groups** and **sub-groups**, the selection is performed by the following offered approaches. The *sequential selection* classifies trees into groups and sub-groups. Then, the amount of harvesting trees is specified for all sub-groups together. Trees are selected step by step in a specified sequence of sub-groups. As mentioned previously, some sub-groups have higher priority. For example, in the thinning concept from below, trees have priority based on bio-sociological status as follows: overshadow trees → intermediate trees → co-dominant trees. We will indicate type of selection by sub-groups separated by right arrow. The *parallel selection* classifies trees into groups and sub-groups. Then, amount of harvesting trees is specified for all sub-groups together. Trees are selected simultaneously from all subgroups. For example, crop trees are selected at the same time from dominant and co-dominant trees (dominant + co-dominant). We will indicate type of selection by sub-groups separated by a plus symbol. The *serial selection* classifies trees into sub-groups. Then, the amount of harvesting trees is calculated individually for each sub-group. Selection is performed gradually with individual amounts for each sub-group. For example, the number of trees is reduced individually in diameter classes by a target frequency curve (10, 14, ..., *k*). We will indicate type of selection by sub-groups separated by comma. The *limit selection* distinguishes only one group, which is defined by a specific limit value. The selection is performed only for this group. For example, trees having a diameter bigger than the limit value are harvested in target diameter thinning or trees within a specified radius are harvested around crop trees in the crop tree method. The first example is *over-limit selection* and the second example is *under-limit selection*. We will indicate selection by upper arrow for over-limit selection and down arrow for under-limit selection, for instance $d_{max}\uparrow$ or $R_{min}\downarrow$. The examples mentioned represent *constant limit selection*. There are also possibilities for *variable limit selection*. For example, competitors are harvested which have a current distance from crop trees which is less than the marginal distance. Marginal distance is individual for each tree, depending on its A-value according to Johann (1982) and the dimensions of crop tree and competitor. We will indicate variable selection by a question mark in the upper index, in order to distinguish between constant and variable selection, for instance: $dist_{ij}\downarrow^{?}$. The *global selection* is a specific case in which we do not classify trees into any groups. Selection is performed from all trees in the stand. A typical example is degree of release for crop trees. Current A-values according to Johann (1982) are calculated for all trees in the stand. A-value depends on current distance between crop tree and competitor and their dimensions. Then, the necessary number of trees with the biggest A-values is removed. We will indicate selection with the symbol Ω.

The next important term for selection algorithms is the **selector**. The selector is a feature (characteristic), which help us to choose trees from groups or sub-groups. For example, score of existence is the most frequent selector. Trees are selected by their value in thinning from below, thinning from above, neutral thinning, crop tree method, target diameter method, and equilibrium curve method. Another example is the A-value by Johann (1982) at release of crop trees by specified number of competitors. If we apply selection by selector in decreasing order, then we call it *positive selection*. In the opposite case, we call it *negative selection*. A specific case is *total selection*, where we do not need any selector. We select all trees in the group. A typical example is harvesting all competitors around crop trees which are inside a clearing radius. In order to distinguish selections we use the following symbols:
:-) for positive selection, :-(for negative selection, and :-o for total selection (Tab. 3).

Model for amount of thinning

The algorithm for calculation of harvesting amount or specification of crop trees varies with thinning concept. We offer great scale of possibilities. If we combine type of selection with amount of thinning, we can model a lot of thinning concepts in a very flexible way.

Size of removal stand

Defining the amount of trees to be removed is one possibility to model thinning. We can use volume, basal area, or tree number for size of removal stand. The following variants are possible:

a) **Thinning percentage ($\%V_p$)** determines the relative volume to be harvested. Volume can be static or dynamic. Static volume percentage is a constant amount specified for the current period. Dynamic volume percentage is an amount that depends on age ($\bar{t}$), mean diameter (d_g), mean height (h_g), or dominant height ($h_{95\%}$). We can select an appropriate function for modeling dynamic volume. Offered functions for the SIBYLA model are in Table 1. Besides choosing a function, we must choose the type of independent value ($\bar{t}$, d_g, h_g, $h_{95\%}$) and estimate coefficients for the function. Using of regression analysis outside of the SIBYLA model is convenient. We can modify the function by additivity and multiplier:

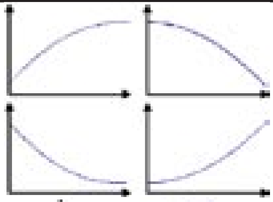
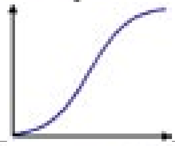
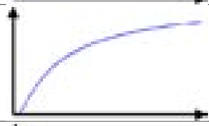
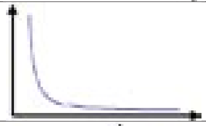
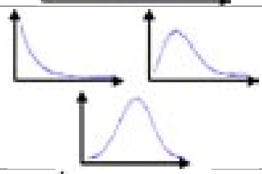
$$\%V = Additivity + f(x) \times Multiplier \qquad (7)$$

Default additivity is 0 and default multiplier is 1. We can modify these values, so the function is more flexible. Then, thinning percentage is transformed into volume of removal trees (V_p). Growing stock in cubic meters before thinning (V_Z) is utilized:

$$V_p = V_z - \frac{\%V_p}{100} \qquad (8)$$

b) **Development of remaining stand ($Y_H = f(x)$)** is expressed by curve of growing stock (V/ha); basal area (G/ha); or tree number (N/ha) based to mean

Table 1. Offered mathematical functions for description of thinning amount

Multi-nominal model	$y = a_0 + a_1\,x + a_2\,x^2 + \ldots + a_6\,x^6$	
General logistic model	$y = \dfrac{a_0}{1 + a_1\,e^{(a_2 \cdot x)}}$	
Growth model by CHAPMANN and RICHARDS	$y = a_0\,(1 - e^{-a_1 \cdot x})^{a_2}$	
Growth model by KORF	$y = a_0\,e^{-a_1 \cdot x^{-a_2}}$	
Model by REINEKE	$y = a_0\,x^{a_1}$	
WEIBULL frequency function	$y = \dfrac{a_2}{a_1}\left(\dfrac{x - a_0}{a_1}\right)^{a_2 - 1} e^{-\left(\frac{x - a_0}{a_1}\right)^{a_2}}$	
MEYER frequency function	$y = a_0\,e^{-a_1 \cdot x}$	

age ($\bar{t}$), mean diameter (d_g), mean height (h_g), or dominant height ($h_{95\%}$). We must choose an appropriate function (Table 1), select dependent and independent values of the function, and specify the coefficients for the function. Amount of thinning (Y_p) is calculated from size of stand before thinning (Y_Z) using the function (*f(x)*), stand area (*P*), tree species percentage (*%R*), and stand density (*SD*):

$$Y_p = Y_Z - [Additivity + f(x) \times Multiplier] \cdot \frac{\%R}{100} \times$$
$$\times\ \mathrm{SD} \times P;\ \text{valid for } Y_p > 0 \qquad (9)$$

c) **Stand density of remaining stand (*SD*)** is fixed by model

$$SD = Additivity + f(x) \times Multiplier \qquad (10)$$

The function, coefficient, and independent values are determined by the user. Then, volume of removal stand is calculated from growing stock before thinning (V_Z) and standard growing stock from yields tables ($V_{H(RT)}$) within the formula

$$V_p = V_Z - SD \times V_{H(RT)} \frac{\%R}{100} P;\ \text{valid for } Y_p > 0 \qquad (11)$$

d) **Volume of removal stand (V_p)** is the last variant. This variant is the most simple and direct way to specify thinning amount. The variant is offered for purposes of forest updating if we know the actual amount of cuttings. This method can replace current updating methods, for example those by FABRIKA and ŠMELKO (2002).

Size of target group

A possibility is proposed for selection of crop trees. Number of crop trees is specified directly or indirectly by theoretical distance between crop trees. Then, the resulting number of crop trees (N_C) is calculated by the following variants:

a) **Number of crop trees (N_C/ha)**. Simulation plot area (*P*) and tree species percentage (*%R*) is used in formula

$$N_C = (N_C/\text{ha}) \frac{\%R}{100} P \qquad (12)$$

b) **Target distance between crop trees (a_C)**. Number of crop trees is calculated by formula

$$N_C = \frac{100}{a_C^{\,2}} \%R\,P \quad (13)$$

Clearing radius

Clearing radius is offered for harvesting competitors in the crop tree method. The principle is very simple. We determine a fixed radius around crop trees (R_{min}). Competitors inside of the radius are harvested without any reference to their dimensions, quality, or vitality.

Degree of release

This method represents another possibility for harvesting competitors in the crop tree method. The method is formulated in order to satisfy the requirements of the approach by Schädelin (1942) and Štefančík (1984) in their thinning concept. In this case, number of competitors is specified per crop tree. We harvest competitors with the biggest A-values according to Johann (1982):

$$A = \frac{H_j}{a_{ij}} \frac{d_i}{D_j} \quad (14)$$

where: H_j, D_j – height and diameter of crop tree,
d_i – diameter of competitor,
a_{ij} – distance between crop tree and competitor.

Marginal distance

Thinning amount is also modeled by Johann's approach (1982) also. However, we determine A-value instead of competitors per crop trees. Marginal distance ($dist_{ij}$) is calculated by

$$dist_{ij} = \frac{H_j}{A} \cdot \frac{d_i}{D_j} \quad (15)$$

If real distance is less than marginal distance ($a_{ij} < dist_{ij}$), then competitor is removed. Johann (1982) has defined different levels of thinning amounts (Table 2).

Target percentage

Target percentage is used in the target diameter method. We harvest a relative amount of trees ($\%d_{max}$) with diameter greater or equal to a specified target dimension d_{max}. Number of thinning trees (N_p) is calculated by

$$N_p = \frac{\%d_{max}}{100}\, n\,(d_i \geq d_{max}) \quad (16)$$

where: $n(d_i \geq d_{max})$ – number of trees with diameter greater or equal to the target diameter.

Removal curve

A removal curve expresses the amount of harvested trees in individual diameter classes. The SIBYLA model has two variants for specification of the removal curve:

a) **Geometrical series by Liocurt (1898)**. Target harvesting dimension (d_{max}) and number of trees with mentioned dimension ($n_{d\,max}$) are inputs into the model. In the first step, we calculate the mean quotient of the geometrical series by

$$q = \frac{\sum_{i=1}^{i-1} q_i}{i-1} = \frac{\sum_{i=1}^{i-1} \frac{n_i}{n_{i+1}}}{i-1} \quad (17)$$

where: n_i – numbers of trees in individual diameter classes.

We exclude extreme values of individual quotients q_i (less or qual to 1, bigger or equal to 2). Then we calculate target frequency curve (equilibrium curve) by

$$\boldsymbol{m}_i = 10^{\,[\log n_{d\max}] + (k-i)\log q} \quad (18)$$

where: m_i – target frequencies in diameter classes,
k – order for diameter class with target harvesting diameter d_{max}.

Number of trees harvested in individual diameter classes is calculated by

$$y_i = \boldsymbol{n}_i - \boldsymbol{m}_i;\ \text{valid for } y_i > 0 \quad (19)$$

b) **Regression model of frequency curve**. A theoretical frequency curve is input for the model. We can use for example Weibull function or Meyer function (Table 1):

$$m = Additivity + f(d_{1.3}) \times Multipier \quad (20)$$

The resultant removal curve is calculated by

$$y_i = n_i - m(d_i) \times h;\ \text{valid for } y_i > 0 \quad (21)$$

where: $m(d_i)$ – number of trees in diameter class,
h – size of diameter class (standard is 4 cm).

Table 2. Level of thinning amount by A-value of Johann (1982)

A-value	Level of thinning
4	extreme
5	very strong
6	strong
7	moderate
8	slight
9	very slight

Size of cutting element

This variant for calculation of thinning amount is developed mainly for stands in rotation period, but the model is also applicable to schematic or geometrical thinning. Amount of thinning is determined by cutting element (shape, size, and location). All trees inside the cutting element are harvested. We can use a circle cutting element or strip cutting element. The circle is defined by coordinates (X_{OP}, Y_{OP}) and diameters (D_1, D_2). External diameter D_1 means total size of cutting element. Internal diameter D_2 means area protected against harvesting. This is very important if we want to extend circle cutting from a previous period and we want to save new trees established by natural regeneration in a previous cutting element. If we want to cut everything inside a circle, we specify D_1 equal to 0. We calculate the distances of all trees from the middle of circle by

$$l_i = \sqrt{(x_i - X_{OP})^2 + (y_i - Y_{OP})^2} \quad (22)$$

We remove all trees where distance:

$$\frac{D_1}{2} \leq l_i \leq \frac{D_2}{2} \quad (23)$$

The strip is defined by coordinates for points on the central axis (X_{OP}, Y_{OP}) and by internal (D_1) and external (D_2) width. Internal and external widths have the same function as the circle diameters. Rotation of the strip is defined by angle α from north. We calculate the distances of all trees from the central axis by

$$l_i = \left| \frac{-\mathrm{tg}(90 - \alpha) \times x_i + y_i - [Y_{OP} - \mathrm{tg}(90 - \alpha) \times X_{OP}]}{\sqrt{[-\mathrm{tg}(90 - \alpha)]^2 + 1}} \right| \quad (24)$$

We remove all trees according to the condition in formula 23.

Modeling thinning concepts

A lot of possibilities for thinning concepts are included in the SIBYLA model: thinning from below, thinning from above, neutral thinning, crop trees method, target diameter method, equilibrium curve method, clear cutting method, and method by list. The thinning algorithm is determined by separator, type of selection, selector, and method for calculation of thinning amount. The modeling approach is summarized in Table 3.

Thinning from below

Negative parallel-sequential selection is used for this thinning method. At first, bio-sociological status and score of existence are calculated for individual trees. Bio-sociological status is the separator and separates trees into sub-groups: overshadow with intermediate trees (4 + 3) and dominant trees (2). Trees in sub-groups are arranged in ascending order by their score of existence. This means that score of existence is the selector in this thinning method. Then, we calculate thinning amount using the approach described in section *Size of removal stand*. Number of removal trees is the result of the algorithm, but growing stock or basal area of removal stand are alternative possibilities. It depends on user requirements. At a result, trees with the smallest score of existence are removed (negative selection) from sub-groups. The process of removing is parallel in sub-groups 4 + 3 and if removal amount is not sufficient, process continues sequentially in sub-group 2. Removal of thinning trees is repeated until the thinning amount is reached. We can use also marginal score of existence and fix the quality of remaining trees. In this case, we can not exceed a specified score of existence during the process of tree selection.

Thinning from above

This thinning method is modeled by an approach that is similar to the previous one. Negative parallel-sequential selection is utilized, BIOSOC value is used as separator, and score of existence is used as a selector. Amount of thinning is calculated by size of removal stand. However, different sub-groups and their order is formulated: (1 + 2) → 3. We can use also marginal score of existence in order to fix tree quality.

Neutral thinning

This method is modeled by negative parallel selection. The BIOSOC is the separator. The score of existence is the selector and can be fixed by marginal value. Thinning amount is calculated by the same procedure as in the previous methods. However, score of existence is ordered in a frame of all bio-sociological layers together (1 + 2 + 3 + 4). Then, selection is parallel in all layers at the same time. The layers have the same priority. Therefore, the thinning method is neutral.

Crop tree method

This method is modeled in two phases. We select crop trees in the first phase and competitors in the second phase. Selection of **crop trees** is done with positive parallel-sequential selection. The bio-sociological status is the separator and the score of existence is the selector. Size of selection is defined by the procedure described in the section *Size of target group*. The selection process is very similar to thinning from above, but selection is regulated in

Table 3. Modeling of thinning concepts

Thinning concept	Trees	Specification of selection: separator	selection type	selector	thinning amount
Thinning from below	removal	BIOSOC	negative parallel-sequential :-(*(4 + 3) →2*	score of existence	size of removal stand
Thinning form above	removal	BIOSOC	negative parallel-sequential :-(*(1+2)→3*	score of existence	size of removal stand
Neutral thinning	removal	BIOSOC	negative parallel :-(*1+2+3+4*	score of existence	size of removal stand
Crop tree method	crop removal	BIOSOC	positive parallel-sequential :-) *(1+2)→3*	score of existence	size of target group
		R_{min}	total constant under-limit :-o R_{min}↓	–	clearing radius
		–	positive global :-) Ω	A-value by Johann (1982)	degree of release
		$dist_{ij}$ or A-value by JOHANN (1982)	total variable under-limit :-o $dist_{ij}$↓?	–	marginal distance
Target diameter method	removal	d_{max}	negative constant over-limit :-(d_{max}↑	score of existence	target percentage
Equilibrium curve method	removal	d_i(4 cm)	negative serial :-(*2,6,...,k*	score of existence	removal curve
Clear cutting method	removal	cutting element (CE)	total constant under-limit :-o *CE*↓	–	size of cutting element
Thinning by list	selection of removal trees and crop trees is specified in external list of trees				

:-) for positive selection, :-(for negative selection, and :-o for total selection

descending order by score of existence (positive selection). This means that the best trees are selected. Sub-groups and their order are the same as in thinning from above. We can also use marginal score of existence and fix crop tree quality. Selection of **competitors** is modeled by three different alternatives. The first alternative is total constant under-limit selection. Clearing radius (R_{min}) around crop trees is defined as separator. The radius separates trees into a group inside the circle and a group outside the circle.

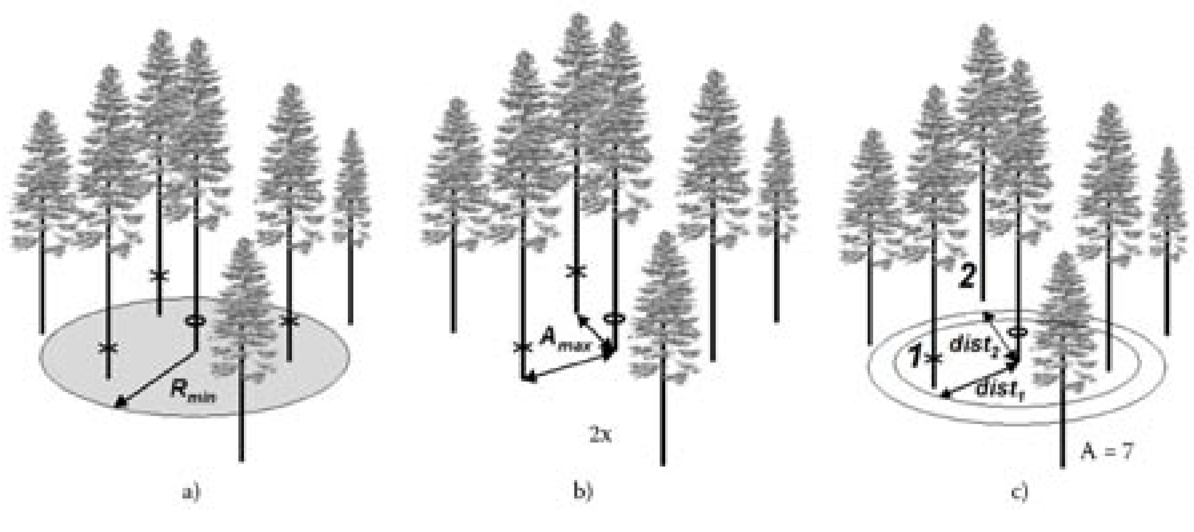


Fig. 6. Principle of selection of competitors for crop trees: a) method of clearing radius, b) method of degree of release, c) method of marginal distance

All trees inside the circle are competitors and are removed. The second alternative is positive global selection. An A-value according to JOHANN (1982) is calculated for each tree, considering all crop trees. Equation 14 is applied. The user specifies the number of competitors per crop tree and the algorithm selects this number of trees. Trees with the biggest A-value are selected. The third alternative is total variable under-limit selection. We determine thinning power by A-value (Table 2). Marginal distance (d_{ij}) is calculated for each tree, considering all crop trees. Equation 15 is applied. The marginal distance is the limit. All trees with real distance to crop trees less than marginal distance are removed.

Target diameter method

This method is modeled by negative constant over-limit selection. Target diameter and target percentage are user inputs into the model. First, selector values (score of existence) for each tree are calculated. Then, we calculate number of removal trees using equation 16. Trees are separated into two groups: trees with diameter less than target diameter and trees with diameter bigger or equal to target diameter. Trees in the second group are organized in ascending order by score of existence. At last, we remove the necessary number of trees with smallest score of existence. Marginal score of existence is rejected from the algorithm.

Equilibrium curve method

This method is modeled by negative serial selection. At first, we calculate score of existence for each tree. The score of existence is the selector. Then, we classify trees into diameter classes with size 4 cm. Diameter class is the separator. Afterwards, we calculate number of removal trees in diameter classes. We can use geometrical series (equation 18) or external function (equation 20). Trees in individual diameter classes are ranked by score of existence. We remove the necessary number of trees with the smallest score of existence in each diameter class. Marginal score of existence is rejected from the algorithm.

Clear cutting method

This method is modeled by total under-limit selection, which means that all trees with co-ordinates inside the cutting element are harvested. The user specifies the cutting element (circle or strip) using Fig. 7. Distances from the center of the cutting element are calculated for each tree. Trees, which fulfill condition 23, are removed. Minimal tree height is an additional property. We can utilize this height as a limit for cutting. If tree height is less than the mentioned height, the tree is not harvested. The limit is very important for protecting natural regeneration.

Thinning by list

The last thinning method is specific, because method is fully controlled by user. Trees are not selected by algorithm. The user specifies selection in an external list of removal and crop trees. This method is very important for updating research plots. We have repeated measurements with tree coordinates and stem and crown parameters on permanent research plots. We usually have information about removed or dead trees from previous years and sometimes have information about crop trees. We can prepare a list and execute growth prognosis. Afterwards we can compare the real situation on the plots with the situation from the prognosis. In this

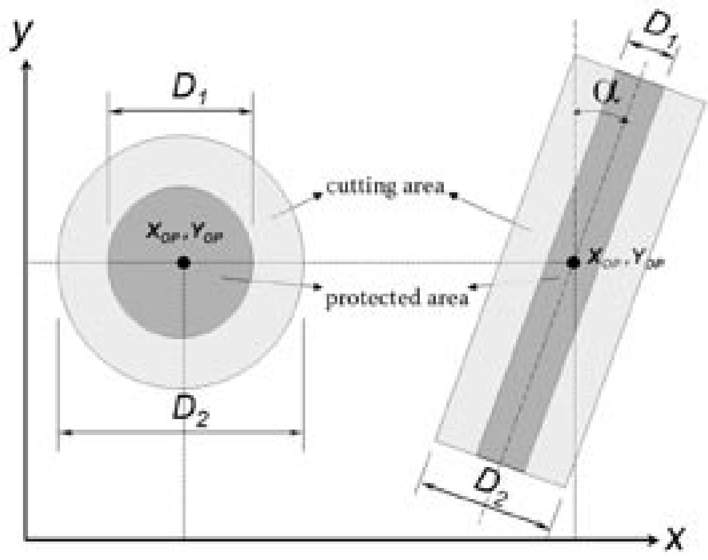
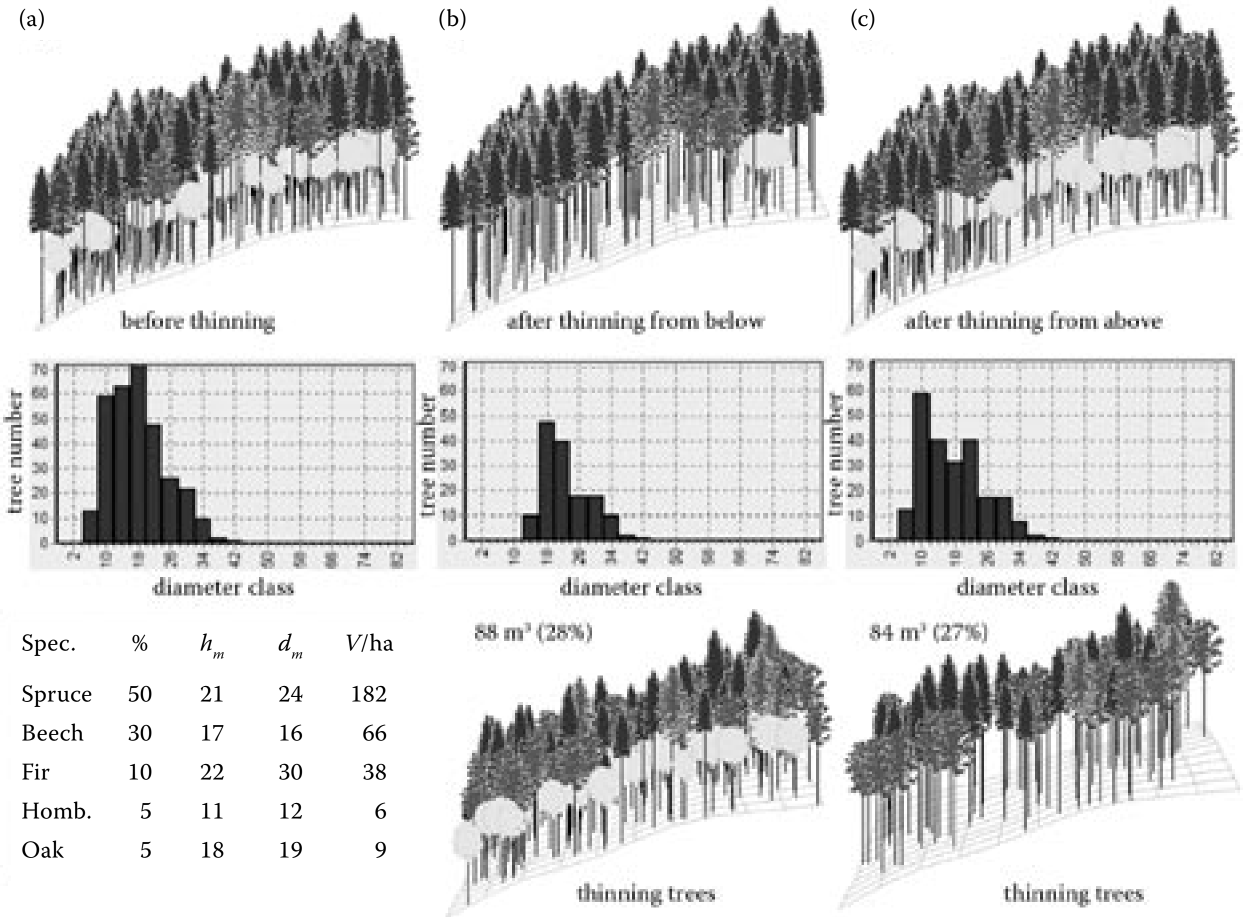


Fig. 7. Principle of clearing element description



Spec.	%	h_m	d_m	V/ha
Spruce	50	21	24	182
Beech	30	17	16	66
Fir	10	22	30	38
Homb.	5	11	12	6
Oak	5	18	19	9

Fig. 8. Example of thinning from below and thinning from above: (a) before thinning, (b) after thinning from below, (c) after thinning from above

manner we can evaluate and calibrate growth models in a very flexible way. Another example for usage is an e-learning process. Students can use virtual reality for visualization of forest stand (Fabrika 2003b) and can do interactive thinning in virtual stands. All marked trees (removal and crop trees) are saved into the list of trees. The list is used as input for the growth model SIBYLA. In this case, growth models and this thinning method can serve as a tool for training of thinning skill in forestry education.

RESULTS AND DISCUSSION

The real stand 285A from the Forest District of the Technical University in Zvolen has been chosen for thinning model presentation. The stand belongs to forest type 410 (fresh beech stands) and stand type 22 (beech stands with spruce and fir). We have utilized stand data from forest inventory (1993) in order to reconstruct initial stand structure. The stand is 45 years old. Stand area is 8.22 ha and stand density is 0.9. The stand is situated at west aspect with slope 50%. Total growing stock is 2,474 m^3, which is 301 m^3 per ha. Spruce, fir, oak, and hornbeam exist in the stand. Tree species composition (percentage) and quantitative characteristics (mean height, mean diameter, volume per ha) are in table in Fig. 8. We have generated individual tree information (diameters, heights, quality, crown parameters, and coordinates) from forest inventory data. Methodology of Pretzsch (2001) has been applied. We generated a square plot with size 0.25 ha. After generation of the structure, the plot includes 315 m^3 per ha with mean diameter 21 cm and mean height 19 m. Total growing stock is distributed as follows: spruce 192 m^3, beech 69 m^3, fir 41 m^3, oak 7 m^3, and hornbeam 6 m^3. This means that the simulation plot is almost equal to its sample from forest inventory. Moreover, the simulation plot has been located on a digital terrain model using the methodology of Papaj (2004) and vertical tree coordinates have been derived using the methodology of Fabrika (2003b).

We have chosen thinning from below and thinning from above as a first example of thinning concepts. Thinning amount is the same in both cases. We used a standard thinning percentage from Slovakian forest management according to Halaj et al. (1986). Percentage depends on species and stand age. The

(a) (b) (c)

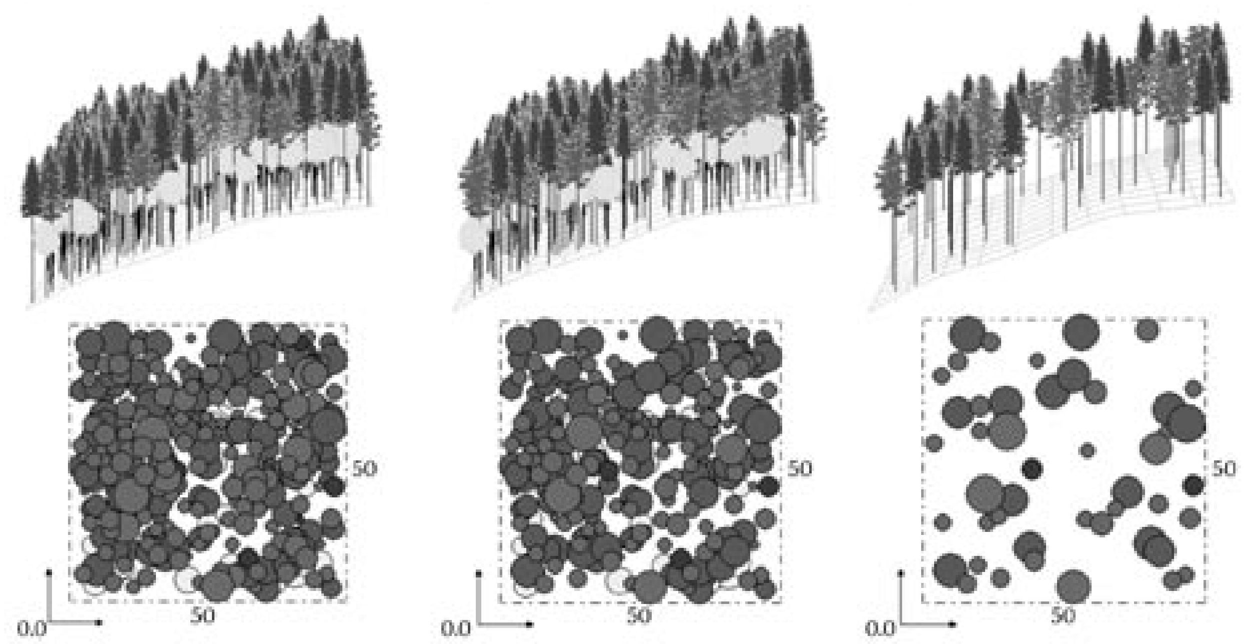


Fig. 9. Example of thinning by crop tree method: (a) before thinning, (b) after thinning, (c) only crop trees

amount is derived for thinning at intervals of one time per ten years. Generally, we removed 88 m^3 (28%) in thinning from below and 84 m^3 (27%) in thinning from above. The thinning concept results are shown in Fig. 8. The stands and their diameter distributions are shown in the picture. In addition, harvested trees are drawn separately for both thinning concepts. Frequency functions for thinning concept are left asymmetrical, low diameter classes are reduced in thinning from below, and upper diameter classes are reduced in thinning from above.

As a second example, we have applied the crop tree method. We specified 200 crop trees per ha with mean distance of approx. 7 m. We have chosen the degree of release method, with 2 competitors per crop tree. The results of the thinning method are presented in Fig. 9 and Table 4. We removed 107 m^3 per ha, or 34% of the initial growing stock. The specified number of crop trees is not satisfied, because hornbeam does not meet the criteria for crop trees. In total 4 trees in the plot have not been accepted and it is 16 trees per ha. This is the same number, which absents to 200 trees per ha.

The proposed thinning model represents a complex solution of thinning tools for the SIBYLA growth simulator. The model includes each of the important thinning concepts in Slovakia and allows very flexible combinations of thinning type, thinning volume, and thinning interval. The model is developed especially for SIBYLA software, because the SILVA software does not include all specific requirements for Slovakian conditions. The SILVA model does not consider tree quality in the thinning model. Tree quality is very important for thinning concepts in Slovakia and it is estimated in regular forest inventory measurements.

The advantages of SIBYLA thinning model compared to the SILVA model are the following:

– Period of thinning is optional, minimum one year. The SILVA model is fixed to a five-year period.
– Thinning concepts can be variable for each period and each tree species. Thinning concepts in SILVA are fixed to stand development stage (defined by dominant height) and must be the same for all tree species.
– Thinning amount is more flexible. We can use also volume and stand density, not only tree number and basal area like in SILVA. Development of the values also depends on mean diameter, mean height, and dominant height, not only on age as in SILVA.
– We can use a lot of functions: multi-nominal function, logistic function, functions by Chapmann and Richards, Korf, Reineke, Weibull, and Meyer. In the SILVA model, we can use only multi-nominal function.
– We consider tree quality and tree vitality in the thinning model by score of existence. The SILVA model does not support these parameters in thinning concepts.
– Some thinning concepts are based on bio-sociological tree status and therefore are more similar

Table 4. Results of crop tree thinning for stand 385A

Species	Crop trees		Removal trees	
	volume (m³/ha)	number per ha	volume (m³/ha)	number per ha
Spruce	43	104	72	128
Beech	18	56	10	72
Fir	15	16	22	40
Hornbeam	0	0	1	28
Oak	2	8	2	16
Total	78	184	107	284

to real thinning concepts in forestry practice. The SILVA model does not classify trees into a biosociological scale.

- Crop trees are defined in a more flexible way. We can use also target distance between crop trees as input. Also, we can specify a new selection of crop trees or we can use crop trees marked in previous thinning concepts. This means that we can emulate thinning concepts by Schädelin (1942) and Štefančík (1984). They use two categories of crop trees (expectant and target). The first category is fixed in the stand at a young age and moves to the second category only in older age.
- We offer new thinning concepts: neutral thinning, method of equilibrium curve for selection forest, clear cutting method for next artificial or natural regeneration, and thinning by list for forest updating on permanent research plots.
- The tool for interactive thinning by virtual reality (Fabrika 2003b) is built directly into the SIBYLA model. In this case, we can use the SIBYLA model directly in an e-learning process without restrictions. The SILVA model offers interactive thinning only by external tools, for example with TreeView from Seifert (1998). Reverse connection to growth simulator is applied only by external data pre-processing with user assistance.
- Dead trees are not removed in the stand automatically in thinning measures. User can decide if he wants cut them during thinning or leave them in the stand. We cut only these trees which are necessary. This approach protects forest biodiversity by saving dead wood in the stand. Sanitation thinning is liable in the stand. In this case, we must select a concept without thinning and with harvesting of dead trees.

The SIBYLA model has some disadvantages comparing to the SILVA model:

- Internal definition for degree of thinning power is not implemented in the SIBYLA model. For example, qualitative levels of thinning are defined in the SILVA model (slight, medium or strong) or thinning by optimal basal area (Assmann 1961) is offered. The user defines thinning amount in the SIBYLA model with external functions. The user must determine the type of function, independent and dependent values, and coefficients. This is flexible, but not so user friendly.
- Interval for thinning is fixed to age. The SILVA model offers size of dominant height increment as one possibility for thinning execution, for example after each 3 m of height increment.
- In conclusion, we can say that the proposed thinning models represent a considerable contribution to thinning modeling and forest prognosis in Slovakia. Because, no thinning model existed in Slovakia before, we can regard the result as very significant.

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Algoritmus a softwarové riešenie prebierkového modelu rastového simulátora SIBYLA

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ABSTRAKT: Práca sa zaoberá návrhom prebierkového modelu pre rastový simulátor SIBYLA. Model je založený na analyticko-kauzálnom prístupe, pričom niektoré čiastočné hypotézy a modely sú preverené na podklade experimentálnych údajov pochádzajúcich z prebierkových pokusov. Samotný model sa skladá z nasledujúcich modelových zložiek: modelu biosociologického postavenia stromu, modelu existenčného skóre, modelovania druhu výberu, modelovania sily zásahu a napokon agregovaného modelu druhu prebierky. Vhodnou kombináciou druhu výberu a definovania sily zásahu je možné uskutočniť nasledujúce prebierky: podúrovňová prebierka, úrovňová prebierka, neutrálna prebierka, metóda budúcich rubných stromov, metóda cieľovej hrúbky, metóda cieľovej frekvenčnej krivky, metóda obnovného prvku a prebierka podľa zoznamu (resp. interaktívna prebierka). V závere je uvedené softwarové riešenie na príklade rôznych prebierkových režimov vo vybranom lesnom poraste a sú rozobraté výhody a nevýhody modelov oproti prebierkovému modelu rastového simulátora SILVA.

Kľúčové slová: stromové rastové modely; prebierkový nástroj; prebierkový koncept; modelovanie lesa

V súčasnosti sa v lesníctve a v ekológii neustále výraznejšie presadzujú pri modelovaní rastu lesných ekosystémov stromové rastové modely. V prípade, ak chceme tieto modely zaviesť aj do oblasti bežnej lesníckej prevádzky, musia modely disponovať aj nástrojmi pre modelovanie prebierkových zásahov. Automatický výber prebierkových stromov na základe stanovenia druhu, sily a intervalu prebierky potom umožní voliť rôzne stratégie obhospodarovania lesa a podporí výber optimálneho variantu.

V rokoch 2001–2004 prebiehal na Slovensku vývoj stromového rastového simulátora SIBYLA (Fabrika 2003a), ktorý bol podporený Európskou komisiou v rámci 5. rámcového programu Európskej únie. Neskôr bol do modelu zabudovaný nový prebierkový nástroj (thinning engine). Jeho vývoj bol financovaný nadáciou Alexandra von Humboldta v rokoch 2004 a 2005 počas pôsobenia jedného z autorov na Univerzite Georga-Augusta v Göttingene. Prebierkový model je založený na analyticko-kauzálnom prístupe. Model sa skladá z nasledujúcich komponentov: modelu bio-sociologického postavenia stromu (model BIOSOC), modelu existenčného skóre stromu, modelu druhu výberu, modelu prebierkovej sily a napokon modelu druhu prebierky. Bio-sociologické postavenie stromu je modelované pomocou klasifikačného pravidla (vzťah 3). Klasifikačné pravidlo je založené na výpočte hornej výšky a na stanovení osvetlenej a zatienenej časti koruny stromu s hornou výškou (obr. 1). Existenčné skóre stromu (od 0 po 1) indikuje jeho uprednostnenie do ťažby (ak je blízke 0), alebo podporu v rámci skupiny budúcich rubných stromov (ak je blízke 1). Do modelu existenčného skóre (vzťah 6) vstupuje konkurenčný tlak stromu (obr. 3), kvalita stromu (obr. 4), vitalita stromu (obr. 5) a mortalita stromu. Výber stromov je prevádzaný prostredníctvom nasledujúcich druhov výberu: sekvenčný, paralelný, sériový, limitný a globálny. Výber sa uskutočňuje vo vnútri skupín a podskupín stromov, ktoré sú definované pomocou klasifikačného znaku (separátora), alebo sa výber prevádza v rámci celého porastu (simulačnej plochy). Výber môže byť zabezpečený negatívnym, pozitívnym alebo totálnym prístupom pomocou zvoleného výberového znaku (selektora). Sila prebierky je modelovaná pomocou nasledujúcich variantov: veľkosti podružného porastu, veľkosti cieľovej skupiny, polomeru uvolnenia, stupňa pomoci, hraničnej vzdialenosti, cieľového percenta, krivky odberu alebo veľkosti obnovného prvku. Vhodnou kombináciou druhu výberu a prebierkovej sily (tab. 3) dosiahneme realizáciu nasledujúcich prebierkových konceptov: podúrovňová prebierka, úrovňová prebierka, neutrálna prebierka, metóda budúcich rubných stromov, metóda cieľovej hrúbky, metóda cieľovej frekvenčnej krivky, metóda obnovného prvku a prebierka podľa zoznamu, resp. interaktívna prebierka.

Uvedený prebierkový model predstavuje komplexné riešenie prebierkového nástroja pre rastový simulátor SIBYLA. Zahŕňa všetky dôležité prebierkové postupy používané na Slovensku a zároveň umožňuje veľmi flexibilnú kombináciu druhu, sily a intervalu prebierkových zásahov.

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