

A decision support system to simulate and compare silvicultural scenarios for pure even-aged larch stands

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Abstract – In sustained forest management, it is particularly useful to test the adequacy of various silvicultural scenarios, but decision-making is also becoming increasingly complex because forest managers have to simultaneously meet several different objectives in response to society demands. In order to help forest managers make appropriate choices in silvicultural systems, we propose a SDSS (Silvicultural Decision Support System) that applies to pure and even-aged larch stands (*Larix* sp.) in lowland areas where site conditions are similar to those encountered in Southern Belgium. Its main purpose is (i) to predict the influence of silvicultural treatments on stand evolution and (ii) assist forest managers in comparing different scenarios with respect to predefined goals. This SDSS consists in three modules designed to elaborate silvicultural scenarios involving (i) stand growth prediction and thinning simulation; (ii) assessment of indicators selected to define the scenarios referring to wood production, financial, technico-economic and ecological components, tree stability and wood quality; and (iii) comparison of the scenarios on the basis of the set of previously assessed indicators (multi-criteria analysis). User-friendly “MGC_Larch” software helps managers to formulate, evaluate and compare different silvicultural scenarios for larch.

Larix / silviculture / decision support system / multi-criteria analysis / Electre III

Résumé – **Système interactif d’aide à la décision pour simuler et comparer des scénarios sylvicoles pour des peuplements purs équiennes de mélèze.** Un système d’aide à la décision sylvicole (SADS) a été développé pour la sylviculture de peuplements équiennes purs de mélèzes [mélèze d’Europe (*Larix decidua* Mill.), mélèze du Japon (*Larix kaempferi* (Lamb.) Carr.), et mélèze hybride (*Larix eurolepis* Henry)] en Région wallonne (Belgique méridionale). Les objectifs de ce SAD sont : (i) de prédire l’influence de traitements sylvicoles sur l’évolution et la croissance des peuplements et (ii) de guider le choix des sylviculteurs vers un scénario répondant le mieux possible aux objectifs fixés. Ce système comporte 3 modules qui prennent respectivement en charge : (i) la simulation de la croissance en relation avec la densité de plantation initiale, le traitement sylvicole et la productivité de la station (construction de scénarios), (ii) le calcul d’un ensemble d’indicateurs caractérisant les scénarios et (iii) la comparaison par analyse multicritère des performances des scénarios en regard des indicateurs pris en considération. Les indicateurs utilisés sont de nature financière, technico-économique et écologique. Ils caractérisent la production ligneuse de manière quantitative et qualitative tout en évaluant les risques sylvicoles encourus en cas d’aléas climatiques (chablis). Le SAD est intégré dans le logiciel avec interface Windows appelé “ MGC_Larch ” (Make Good Choice for Larch).

mélèze / sylviculture / système d’aide à la décision / analyse multi-critère / Electre III

1. INTRODUCTION

Choosing a silvicultural scenario in a changing world is made difficult by the multiplicity of goals that forest managers are tasked with achieving. For a long time, research focussed on growth modelling aimed at describing stand evolution through the construction of yield tables or growth models for even or uneven-aged stands. These tools are useful for predicting stand evolution over time but they are not designed to compare and help select appropriate silvicultural scenarios.

With reference to that, DSS (Decision Support System) is a computer application typically designed to address the multifaceted nature of management questions. Considering the increasing complexity of new challenges in forestry they are very useful in a wide range of fields, especially in sustainable natural resource management, business planning, transportation, timber harvest scheduling, ... [9, 19].

The silvicultural decision support system (SDSS) we propose is an extension of this concept. It consists in the selection of a silvicultural treatment that fits the best to the objectives assigned to stands which are, in this case, larch plantations.

This SDSS has been developed to predict the influence of silvicultural treatments on *Larix* stand evolution and help forest managers choose scenarios according to preset goals. It is made of three modules designed for (i) growth prediction based on initial stand density, thinning regime and site index (scenario building), (ii) assessment of a set of indicators defining scenarios, and (iii) comparison of scenarios according to appropriate indicators (Multi-Criteria Decision-Making – MCDM approach).

Financial, technico-economic and ecological indicators are calculated in order to characterize wood production both qualitatively and quantitatively. The SDSS is integrated into a user-friendly software package called “MGC_Larch (Make Good Choice for Larch)”. It has been developed for pure and

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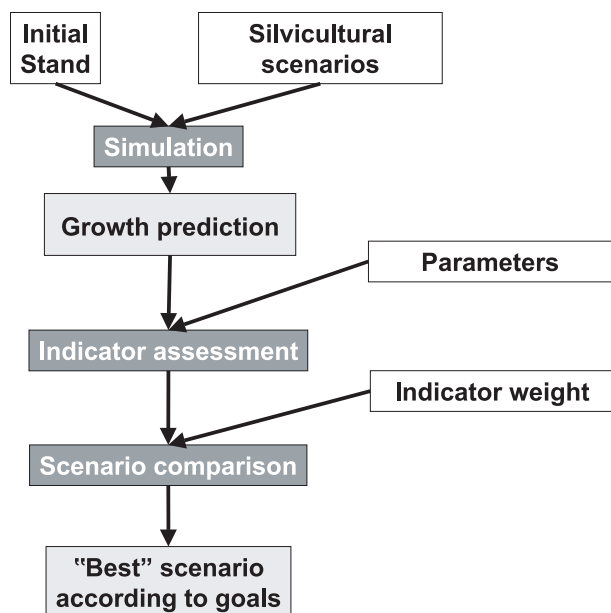


Figure 1. Architecture of the silvicultural decision support system “MGC_larch”.

even-aged larch stands (European larch (*Larix decidua* Mill.), Japanese larch (*Larix kaempferi* (Lamb.) Carr.) and hybrid larch (*Larix eurolepis* Henry)) growing in lowland areas where site conditions are similar to those in Southern Belgium.

The larch stand dynamics have been carefully designed to enhance this system, with silviculture being either intuitive or based on generalized prescriptions applied to other conifers such as spruce or Douglas fir. Furthermore, larch offers a wide range of marked or nonmarked-priced goods and ecological and financial potential in a multi-functional management context [14]. It is surprising that, to date, no specific lowland silviculture system has been defined for this species. This study can be used both for research purposes and for practical planning.

2. MATERIALS AND METHODS

2.1. Decision system strategy

The SDSS is based on an architecture comprising two main components. The first component consists in a growth model used to simulate the growth and development of a stand in response to different scenarios (silvicultural treatments). The resulting data describing the evolution of the trees subjected to these treatments are recorded in a database which the second component uses to assess a list of indicators expressing different goals to be achieved by the applied silviculture system. These indicators are then used to carry out a multi-criteria analysis of the user-defined scenarios. These two components are completed by an interface that enables the keyboard input of data as well as managing growth simulations, indicator calculations and results display (Fig. 1).

The main body of the data required was obtained from permanent plots and trees. The data sets consisted of different stands and trees

for whom numbers and types of collected data vary according to the modelling objectives covering growth, thinning and volume, as described below.

2.2. Growth modelling

Growth modelling is at the heart of the SDSS. Several regression equations have been built to fit the observations collected in pure even-aged larch stands located at low elevations (< 625 m) in Southern Belgium. Goodness-of-fit was tested by the squared correlation coefficient (R^2) and the root mean square error ($RMSE$). Four integrated sub-models organized consistently predict the change over time of the principal stand variables: average height of dominant trees, number of trees, girth and stem volume over bark. The materials and methods used to build these models are described in detail in [13, 16, 17]. Only the main results are presented in this paper.

Multiple least-square estimation was used to construct the models. We first used a stepwise regression with various combinations of variables (either plain or transformed) to expand the information on explanatory variables.

A selection based on different aspects was considered: available variables, desirable variables with a high biological expression, and variables with consistent signs of the estimates.

The four sub-models were relationship between dominant height and age, self-thinning, girth growth and volume estimation.

2.2.1. Site index curves

Site index curves expressing the relationship between dominant height (average total height of the 100 biggest trees/ha) and age were constructed from stem analysis data (102 dominant trees cut from inside 55 stands). We used model IV of Duplat and Tran-Ha [8] based on polymorphic techniques, which has the following formula:

$$H_{dom} = (a \cdot \ln(\text{Age} + 1) + b_i) \cdot \left[1 - e^{-\left(\frac{\text{Age}}{c}\right)^d} \right] + p \cdot \text{Age};$$

where H_{dom} is dominant height, Age is the age of the stand (in years), a , c , d and p are the fixed parameters of the model, and b_i is a variable parameter related to the stand site index (dominant height reached at 50 years) specific to each site curve. The parameters of the models built for the three larch species are presented in Table I.

2.2.2. Self-thinning model

The second sub-model was developed to quantify reduction in the number of stems per hectare, especially due to the self-thinning process [18]. This model, which is used to simulate the natural mortality of trees in the event of excessive stock growth, predicts the maximum number of living stems [21]. A curve of the quadratic mean stand diameters for maximum number of trees per hectare fitted with log linear regression yields the following function:

$$\log \bar{d}q = 2.81549 - 0.47277 \log N_{ha},$$

with $R^2 = 0.985$ and $RMSE = 1.67$ cm

and where $\bar{d}q$ is the quadratic mean stand diameter and N_{ha} is the number of living trees per ha (R^2 = coefficient of determination and $RMSE$ = root mean squared error).

Table I. Parameters of the Duplat and Tran-Ha model IV used to describe the dominant height of larch.

Japanese larch	European larch	Hybrid larch
$a = 7.500786$	$a = 6.418427$	$a = 4.817541$
$c = 23.238596$	$c = 12.889385$	$c = 10.544177$
$d = 1.0001$	$d = 1.0001$	$d = 1.0001$
$p = -0.016670$	$p = 0.090711$	$p = 0.275817$
$R^2 = 99.4\%$	$R^2 = 99.6\%$	$R^2 = 99.6\%$
$RMSE = 0.70$ m	$RMSE = 0.51$ m	$RMSE = 0.53$ m

This equation is based on data derived from 10 fully stocked stands, and was validated on a sample of 268 stands. Expressed in terms of stand density index, the equation is rewritten as:

$$Nha = 10 \cdot e^{\left(\frac{\log \bar{d}_g - 2.81549}{-0.47277}\right)}$$

2.2.3. Girth growth model

The third model is a distance-independent individual tree model that was developed to predict girth increment based on tree girth itself, dominant height, stand age, site index and stand basal area.

$$MPGI = 6.1048 + \frac{33.325}{Gha} - 1.92103 \cdot \ln\left(\frac{Hdom}{c} \cdot 100\right) + 0.00046251 \cdot H50^2 + \frac{6.9526}{Age};$$

where $MPGI$ is the mean periodic girth increment in cm yr^{-1} (considered at a reference height of 1.3 m above ground level), Gha is the stand basal area (in $\text{m}^2 \text{ha}^{-1}$), $Hdom$ is the dominant height of the stand (in m), c is the individual girth at 1.3 m (in cm), $H50$ is the site index of the stand (in m), and Age is the age of the stand (in years).

This model was built from data collected in 99 stands (2 578 trees) and was validated on a sample of 48 other stands (1 283 trees). The R^2 of this model is 0.605 and RMSE equals 0.64 cm yr^{-1} . It is based upon variables easy to collect and results from a comparative analysis of more than 15 models using various distance independent competition indices [16].

2.2.4. Volume estimation

The fourth sub-model was developed on the basis of taper functions (predicting stem profile) which can also give volume estimates as well as detailed information on merchantable log sizes that can be potentially produced from a tree. It is based on Biging's model [3] using two independent variables: tree diameter and tree total height.

$$\hat{d}(h) = d \cdot \left[b_1 + b_2 \cdot \ln \left[1 - \left(1 - e^{\left(-\frac{h}{b_2} \right)} \right) \cdot \left(\frac{h}{htot} \right)^{1/3} \right] \right]$$

with:

$$b_1 = 1.64041 - 0.17938 \cdot \ln(htot) - 0.02569 \cdot \ln(Age) + 0.07317 \cdot \ln(d)$$

$$b_2 = 0.50322 + \frac{1.6526}{Age} + 0.19668 \cdot \ln(d) - 0.25565 \cdot \ln(htot)$$

where $\hat{d}(h)$ is the predicted stem diameter (cm) at the height h (m), d is the diameter at 1.3 m high, $htot$ is the total height (m) of the tree, and Age is the stand age, b_1 can be interpreted as a position parameter, while b_2 is a parameter of curvature. In order to make the model usable in connexion with field data, these two parameters have been linked to tree diameter, stand age and total height. The model was developed using sets of data measured on 1 134 trees. It fits the data very acceptably ($R^2 = 0.988$ and $RMSE = 1.53$ cm).

All these four models are integrated into a simulation framework that can be used to assess the main characteristics of the stand at each cutting cycle, provided the thinning parameters are known. This estimated information is displayed in the form of a yield table.

All other conditions being known, stand evolution obviously depends on the manipulation of stand density, which is affected by thinning programmes. The user defines these either by their types and weights or by the basal area remaining after cutting, or by a specified mean annual girth increment of dominant trees. Specific algorithms have been designed to select the trees to be removed so as to meet the thinning parameters defined at stand level. These algorithms are described in [13].

2.3. Indicator assessment

The indicators are defined at stand level in order to compare various silvicultural scenarios. They cover the general scope of the main goals that forest managers seek to achieve, and are assessed based on simulated stand-level or tree-level variables. The choice of indicators is subject to limiting factors such as reproducibility, clear understanding, simulation possibilities and the knowledge necessary to describe the evolution of certain stand or tree characteristics. Nine indicators, which are presented in Table II, are used to factor in the six following objectives: wood production, economics, technico-economics, ecology, stability and wood quality.

2.3.1. Wood production indicator

The production objective only takes into account wood quantity, regardless of its quality. It can be set to meet the requirements of wood pulp industries, or simply for wood as a source of energy or a tool for carbon sequestration. The corresponding indicator is the mean annual volume increment ($MAVI$) in $\text{m}^3 \text{ha}^{-1} \text{yr}^{-1}$, formulated as:

$$MAVI = \frac{Vf + \sum_{j=1}^n Vth_j}{r};$$

where Vf is the stand volume (in m^3) at the end of the rotation (in years), Vth_j is the volume (in m^3) removed at thinning cycle j (excluding dead wood), n is the number of thinning cycles and r is the rotation age (in years). The $MAVI$ is calculated at the end of the rotation, since a silvicultural scenario is assumed to be repeated indefinitely.

2.3.2. Economics indicator

Concerning the economics objective, the forest investment decision indicator which has been adopted to match the management objectives, is the land expectation value, LEV , which corresponds to

Table II. Indicators used to compare silvicultural scenarios according to different predefined goals (objectives).

Goals	Indicators	Unit	Target	
Production	Mean annual volume increment	m ³ ha ⁻¹ yr ⁻¹	Maximisation	
Economics	Land expectation value	€/ha	Maximisation	
Technico-economics	Value of stems after bucking optimisation	€/ha	Maximisation	
Ecology:	Plant biodiversity	Biodiversity under the canopy	%	Maximisation
	Plant “bioquantity”	Plant cover under the canopy	%	Maximisation
Stability	Stand stability index	%	Maximisation	
	Proportion of mature wood	%	Maximisation	
Wood quality	Ring width variation	%	Minimisation	
	Modulus of elasticity	MPa	Maximisation	

the well-known Faustmann formula [5]. It is a special case of *PNW* (present net worth or net discounted value) which maximises the capitalized land value, factoring in all costs and revenues except land cost which is specifically excluded [11]. It is currently used for optimizing rotation age [5] and comparing various management objectives [7].

Since *PNW* is given by:

$$\sum_{i=1}^r (R_i - C_i) / (1 + rate)^i$$

then:

$$LEV = PNW \cdot \frac{(1 + rate)^i}{(1 + rate)^i - 1},$$

where R_i and C_i are the revenues and costs per hectare, i is the year in which the cash flows occur, r is the rotation (number of years in the planning period) and *rate* is the guideline discount rate. This can be chosen in the range 1 to 5% (the default value is set at 3%). The indicator can be negative if the rate is higher than the internal rate of return (*IRR*), which is the interest rate that equalizes the present value of the costs and revenues. In addition to discount rate, the user has to set the stumpage prices and the costs of successive silvicultural operations (plantation, cleaning, pruning, etc.).

2.3.3. Technico-economic indicator

The technico-economic objective deals with the evaluation of a silvicultural scenario capability to produce logs of high economic value. The corresponding indicator is derived from a bucking optimization algorithm that uses the abovementioned taper function in a dynamic programming approach [13]. The input parameters of this process are the characteristics and expected prices of the different potential stem sections which can be produced (pulp wood, saw logs, veneer, etc.).

2.3.4. Ecological indicators

Two indicators are taken into account to define the objective “ecology”. The first concerns the “potential biodiversity” (diversity of lesser vegetation) that might grow under the canopy, while the second describes its cover and is named “bioquantity” indicator. Both are based on predicted relative irradiance (*IR*, expressed as a percentage). This parameter represents the ratio between irradiance under the canopy and measured daylight irradiance.

The prediction equation for the relative irradiance is derived from [2]:

$$IR(\%) = e^{(-0.114 \cdot Gha + 0.021 \cdot Age)} \cdot 100,$$

with $R^2 = 0.932$ and $RMSE = 6.4\%$;

where *Gha* is the stand basal area per hectare (in m²) and *Age* is the stand age (in years).

This model was developed using data from 40 plots (13 stands).

The “biodiversity” indicator is defined as the proportion of rotation time (%) during which relative irradiance is within a range that can be considered as optimal for maximal species development. This range is set as 12% to 18% based on studies conducted in France and Belgium on the plant composition of larch plots presenting different densities under the same site conditions [1].

The so-called “bioquantity” indicator (plant biomass) is based on the composition and the extent of growth of lesser vegetation. It represents the mean value of the cover (%) during the rotation, and is estimated indirectly from irradiance [1]:

$$Cover = [-0.63 + 0.82 \cdot \ln(IR)] \cdot 100,$$

with $R^2 = 0.720$, $RMSE = 40.5\%$

Cover ranges from 0 (bare soils) to 300%, and expresses the proportion of soil covered by the vertical projection of the leaf area of understory species. It can be greater than 100% because of the different covering stages of vegetation (herbs, dwarf shrubs, ferns, mosses, etc.).

2.3.5. Stand stability indicator

The “stability” objective deals with the risk of windstorm damage. It is quantified as the proportion of time during which the stand can be considered as wind-stable according to its stability index as defined by Riou-Nivert [20], and is calculated based on dominant height and mean stand diameter. Three zones have been defined (Fig. 2): stable, risky and unstable. The index also takes into account thinning intensity when the stand is located in the risky zone [13].

2.3.6. Wood quality indicator

There are three indicators to characterize the wood quality objective: proportion of mature wood, ring width variation and modulus of elasticity. The straightness of the tree and the knots have not been

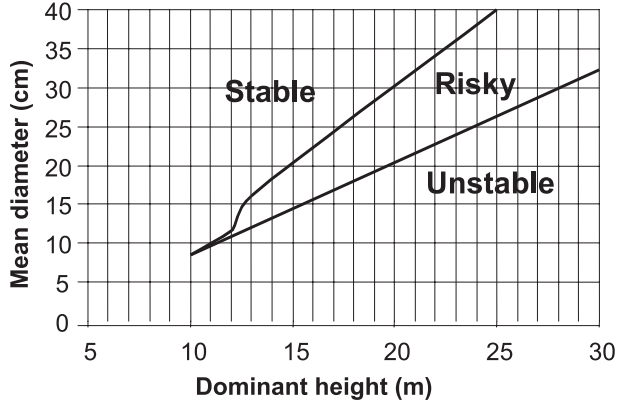


Figure 2. Wind stability zones for even-aged coniferous stands [20].

considered because there is currently no model able to predict the impact of silvicultural treatment on these characteristics, which indeed appear to be more influenced by genetic quality.

“Proportion of mature wood” (%) is the difference between heartwood rate and juvenile wood rate. It is calculated for the mean tree girth of the final stand. Heartwood rate (Hw) is predicted from age, diameter at breast height (1.3 m) and species [15]:

$$Hw = -51.011 + 19.513 \cdot \ln(\text{Age}) + 10.637 \cdot \ln(d) - 3.8548 \cdot ME,$$

with $R^2 = 0.859$, $RMSE = 7.02\%$,

where Age is the tree age (in years), d is the diameter (in cm) at breast height (1.3 m), and ME is a dummy variable that takes the value of 1 for European larches and 0 for the two other species. This model was fitted with data derived from 382 trees. Juvenile wood is defined by the 15 rings close to the pith, with ring width being estimated using the girth growth model.

The “ring width variation” (RWV %) is defined for the “average tree” (of quadratic mean) of the final stand as the ratio of the standard deviation to the weighted mean of the ring width. The aim of this weighting is to give to each ring an importance proportional to its surface in the log section. Unlike the other indicators, this indicator has to be minimized because the target is to produce rings that are as regular as possible.

It can be written as:

$$RWV = \frac{wrstd}{wmrw} \cdot 100;$$

$$wrstd = \sqrt{\frac{\sum_{i=1}^n (rw_i - wmrw)^2}{n}};$$

$$wmrw = \frac{\sum_{i=1}^n rw_i \cdot rarea_i}{\sum_{i=1}^n rarea_i};$$

where RWV is the coefficient of variation of the ring width (%), $wrstd$ is the standard deviation of weighted mean of the ring width, $wmrw$ is the weighted mean ring width, rw_i is the width of the ring i , $rarea_i$ is the ring i area and n is the total number of rings.

The “modulus of elasticity” (MOE) is estimated for the average tree of the final stand, and is derived from the MOE_i calculated for each ring according to [10]:

$$MOE_i = (1467/rw_i + 7541) \cdot \left[1 - e^{(-0.330 \cdot rage_i)}\right]^{12.1}$$

with $R^2 = 0.63$, $RMSE = 2205$ MPa;

where rw_i is the width of ring i (in mm) and $rage_i$ is the age of ring i (in years).

This model was based on 492 wood samples extracted from 18 trees. The mean MOE is calculated by weighting MOE_i on the basis of ring area [13]. The abovementioned indicators are calculated for each scenario and the evaluations are stored in a payoff matrix.

3. SCENARIO COMPARISON

The scenarios are compared according to indicator evaluations. The multi-criteria decision-making approach, Electre III [4, 12] is used. It ranks scenarios from best to worst. Electre III starts the comparison from the payoff matrix and uses three thresholds (Fig. 3) to take into account inaccuracy in the indicator evaluations.

The first threshold is the “indifference” threshold q . When the difference between two evaluations, $g(s_k) - g(s_i)$, is less than q , then the scenarios s_i and s_k are considered equivalent for the indicator (concordance index = 1).

The second threshold is the “strict preference” threshold p . If the difference between two evaluations $g(s_k) - g(s_i)$ is greater than p , then one scenario s_k is preferred to the other s_i (concordance index = 0). If this difference is between q and p , a slight preference is given to the scenario s_k ($0 < \text{concordance index} < 1$).

The third threshold is the “veto” threshold v , which corresponds to the limit of the difference between two evaluations beyond which the worst scenario has to be rejected, even if this scenario comes out best for all the other indicators. This rejection is called discordance. If the difference between two evaluations, $g(s_k) - g(s_i)$, is greater than v , then discordance (s_i cannot outclass s_k) equals 1. Between p and v , the discordance is represented by a value between 0 and 1. If the difference is less than p , then there is no discordance.

The method also factors in weightings assigned to each indicator according to the importance the user lends them.

Electre III compares the scenarios two-by-two. For each indicator j , a concordance index $c_j(s_i, s_k)$ is determined which compares evaluations according to the indifference and preference thresholds. Ranging between 0 and 1, it measures whether scenario s_i is at least as good as scenario s_k for the indicator.

Based on the concordance indices and the weight W_j associated to each indicator, a global concordance index, C_{ik} , is calculated:

$$C_{ik} = \frac{\sum_{j=1}^n W_j \cdot c_j(s_i, s_k)}{\sum_{j=1}^n W_j}$$

where n is the number of objectives (9 in this study).

This global concordance index quantifies the preference for scenario s_i over scenario s_k .

The next step calculates discordance indices per indicator $d_j(s_i, s_k)$ according to preference and veto thresholds. Ranging between 0 and 1, these discordance indices measure, for each evaluation, to what extent they conflict with the global preference.

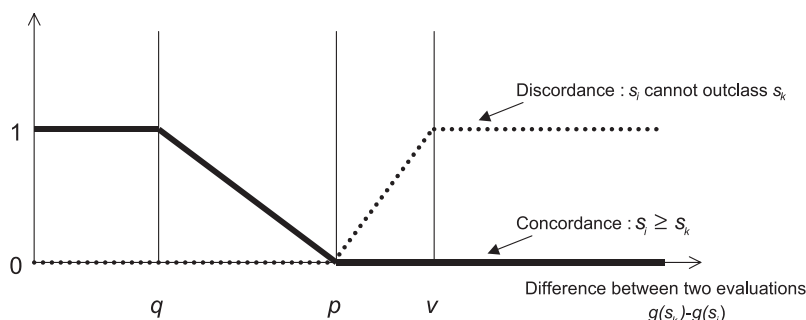


Figure 3. Thresholds used to compare scenarios in the Electre III multi-criteria method (thresholds: q = indifference threshold, p = strict preference, v = veto threshold, s_k and s_i = scenarios k and i).

Using the global concordance index C_{ik} and the discordance indices $d_j(s_i, s_k)$, this method determines a degree of credibility δ_{ik} measured by:

$$\delta_{ik} = C_{ik} \cdot \prod_{j \in \bar{F}} \frac{1 - d_j(s_i, s_k)}{1 - C_{ik}}$$

where:

$$\bar{F} = \{j | j \in F, d_j(s_i, s_j) > C_{ik}\} \text{ and } F \supset \bar{F}$$

If the discordance index is higher than the concordance index, concordance will be weakened. Ranging between 0 and 1, the degree of credibility measures the validity of the assertion “scenario s_i outclasses scenario s_k ”. A degree of credibility is calculated for each pair of coupled scenarios.

A ranking algorithm specific to Electre III uses the degrees of credibility to rank the scenarios from best to worst. Two distillations are performed. The first one, called downward distillation, extracts the best scenario compared to all the others, and so on, step by step, while the second one, called upward distillation, extracts scenarios going from the worst to the best. Analysis of the two distillations gives a final rank to each scenario, with the tested scenario of order 1 being considered the most appropriate for the goals to be achieved. This classification also indicates scenarios that outclass others, that are equivalent to others, or that cannot be readily compared with others. This latter case which corresponds to “incomparability” occurs between scenarios a and b when there is no clear evidence in favour of either a or b [6].

4. RESULTS: EXAMPLES OF SIMULATION AND SCENARIO COMPARISON

As concerns the implementation of scenarios (scenarios building and comparison, definition of indicator parameters, ...), it is performed through user-friendly interfaces, data being stored in a Microsoft Access database. In the same way, the different expected results (values of indicators associated to scenarios, scenarios comparisons, ...) are presented in the form of charts and tables, these latter being exportable to Microsoft Excel environment.

The parameters of the different models are stored in another Microsoft Access database, which enables to extend the use of this application to other species as far as the corresponding models are available for these species.

“MGC_Larch” is designed to generate and compare numerous silvicultural scenarios.

In order to illustrate the use of MGC-Larch, we present the comparison of six silvicultural scenarios (Tab. III), all being based on a 12-year-old Japanese larch stand with an initial density of 1333 stems/ha (2.5×3 m) and belonging to an average site index class (dominant height reached at 50 years: $H50 = 28$ m). Scenario 1 is characterized by moderate thinnings (25% of stems removal at each cycle), the longest rotation (84 years), and the production of a mature stand with an important growing stock ($680 \text{ m}^3 \text{ ha}^{-1}$) and big trees (mean girth = 187 cm). Scenario 2 is based upon thinnings that are more heavy than in scenario 1 (35–40% of stems removal at each cycle), a relatively short rotation (54 years) leading to a mature stand with a less important stock ($410 \text{ m}^3 \text{ ha}^{-1}$). Scenario 3 is characterized by the shortest rotation (45 years) and thinnings that are designed so as to maintain a constant and relatively low basal area after each cycle ($15 \text{ m}^3 \text{ ha}^{-1}$). The rotation of scenario 4 is fixed to 60 years. As for scenario 3, the thinnings are designed to lead to a fixed remaining stand basal area which in this case is variable from cycle to cycle and is calculated to optimize the biodiversity indicator. The particularity of scenario 5, whose rotation is fixed to 60 years, is that thinnings are calibrated so as to obtain dominant trees with a more or less constant ring width, fixed to 0.4 cm. The scenario 6 is only a variant of scenario 5, where the target ring width is fixed to 0.5 cm and the rotation is reduced from 60 to 45 years.

The indicators are calculated for each scenario according to user-defined parameters and are arranged in the payoff matrix (Tab. IV). In the first step, all indicators are weighted equally. The thresholds are set according to the observed evaluations and the estimated inaccuracy of each indicator.

The scenarios analysed by the Electre III procedure are ranked from best to worst (Fig. 4). The arrows point from better scenarios towards worse scenarios (“outclass” relation). Scenarios that are not connected by an arrow cannot be compared (“incomparability” relation). For example, Scenario 1 cannot be compared with Scenario 2. Scenario 1 is relevant for wood production, and financial and technico-economic objectives but less adequate for ecological goals. Scenario 2 leads to opposite results. Scenario 4, defined by residual basal areas that can improve the biodiversity indicator, comes out best, while Scenario 6, which refers to a girth increment of the dominant trees of 3.1 cm yr^{-1} , comes out worst.

Table III. Characteristics of the six silvicultural scenarios compared.

Scenario No.	Building mode	Cutting cycle (years)	1st thinning (years)	Rotation (years)	Final No. of stems/ha	Final mean girth (diameter) c (d) (cm)
1	Moderate thinnings (Proportion of thinned stems at each cycle = 25%)	12	12	84	170	187 (59.5)
2	Heavy thinnings (Proportion of thinned stems at each cycle = 35–40%)	6	12	54	109	181 (57.6)
3	Residual basal area (after thinning) = 15 m ² ha ⁻¹	6	15	45	122	159 (50.6)
4	Residual basal area (after thinning) chosen to improve the biodiversity indicator	6	12	60	107	184 (58.6)
5	Increment of dominant trees = 2.5 cm yr ⁻¹ (0.80 cm in diameter)	3	18	60	103	165 (52.5)
6	Increment of dominant trees = 3.1 cm yr ⁻¹ (1 cm in diameter)	3	15	45	94	151 (48.1)

Table IV. Payoff matrix characterizing the six compared scenarios.

Scenario No.	Indicators								
	$MAVI$ m ³ ha ⁻¹ yr ⁻¹	LEV €/ha	Techn-eco. €/ha	Biodiv. %	Bioqu. %	Stab. %	Mature wood %	Ring variation %	MOE MPa
1	16.9	93	101058	4	47	86	63	67	11867
2	13.1	-407	48405	31	183	100	51	45	9746
3	12.8	-907	39044	22	190	100	41	41	9289
4	14.3	-53	59214	55	158	100	55	51	10174
5	14.4	-14	56621	8	161	90	49	53	10203
6	12.7	-1248	35704	9	196	100	38	43	9244
Weights	1	1	1	1	1	1	1	1	1
Threshold q	1	200	10000	5	20	5	3	5	1000
Threshold p	2	400	20000	10	40	10	6	10	2000
Threshold v	5	1000	50000	25	100	25	15	25	5000

$MAVI$ is the mean annual volume increment, LEV is the land expectation value, MOE is the modulus of elasticity.

5. DISCUSSION

5.1. Growth simulation

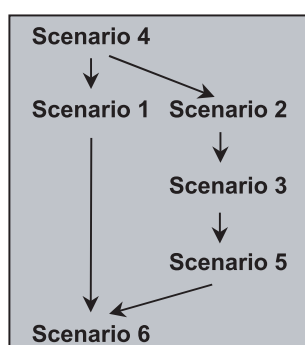
Several models have been developed to describe the growth and development of larch stands in Southern Belgium following different silvicultural scenarios. We can reasonably assume that these models could be applied to larch planted elsewhere in Western Europe at low elevation (< 600 m) as far as it would be calibrated. The “MGC_Larch” software application helps the user to interactively generate numerous silvicultural scenarios defined within a defined range of site conditions and silvicultural operations (especially thinning weightings).

5.2. Indicator assessment

The number of indicators used to compare scenarios is limited by the amount and quality of the knowledge available on larch. Knots and basal sweep, for example, have not been taken into account, even though these two factors became increasingly important in larch silviculture. Refinements to the models or other assumptions can probably be integrated in the software at a later date. However, new indicators must not compete with those already used. Nevertheless, the 9 objectives that have been defined offer a good overview of the many possible interactions between the silviculture of larch stands

Table V. Best scenario according to the main goals to be achieved.

Goal	Indicator weight	“Best” scenario	“Worst” scenario
Multiple	Same weights for all indicators	4	6
Economic	Same weights for production, economic and technico-economic indicators, null weights for the others	1	6
Ecological	Same weights for the 2 biological and the risk indicators, null weights for the others	4	1
Wood quality	Same weights for the 3 wood quality indicators, null weights for the others	2	5

**Figure 4.** Scenario classification resulting from the Electre III method (with all indicators weighted equally); the arrows point from better towards worse scenarios, scenarios that are not connected are considered as incomparable.

and how these stands achieve the goals initially defined by the forest manager.

5.3. Scenario comparison

Scenario classification can be modified by weighting each indicator according to the relative importance assigned to the expected goals. Examples are illustrated in Table V. Scenario 1, characterized by a moderate silviculture, has reached the best scores for 4 out of 7 non ecological indicators and the worst scores for the 2 ecological ones. It is thus not surprising that this scenario is placed first choice when referring to an economic goal, and the worst in the case of an ecological goal. Scenario 4 appears to be the best one for both “multiple” and “ecological” goals. This is mainly due to a more dynamic silviculture which maximizes biodiversity (abundance and nature of understorey vegetation) and reduces rotation length which is favourable to financial performance (*LEV*), and to a certain extent to volume production.

On the other side, scenario 6 which emphasizes dominant trees increment and a very short rotation (45 years) leads to the worst or nearly the worst scores for 7 out the 9 indicators, and is placed last for both multiple and economic goals.

The user can modify the parameters used to calculate the financial and technico-economic indicators (discount rate, stumpage prices, list of silvicultural operations, characteristics and prices of potential stem sections) and then test their influence in a kind of sensitivity analysis. The usefulness of pruning carefully selected trees at a higher height (e.g. 6 m) can also be evaluated. Classifications based on Electre III become

increasingly useful as the number of scenarios to be evaluated increases. However, the user must keep in mind that the final classification is still quite relative. It can thus be modified according to the scenarios compared. It is also possible to identify a non-tested scenario that could meet the predefined goals even better.

6. CONCLUSIONS

A silvicultural decision support system has been developed to predict larch stand growth according to different kinds of thinning with different weightings. This tool can also be used to rank the silvicultural scenarios generated according to the importance assigned to a range of indicators expressing the following objectives: wood production, economics, technico-economics, ecology, stability and wood quality. A weakness of this system is that some factors that ought to be taken into accounts in larch silviculture (e.g., knottiness and basal sweep) are not included among the suggested indicators due to a lack of information. However, the user-friendly “MGC_Larch” software application remains a useful tool to help forest managers choose the scenarios that will best meet their priority goals.

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