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A Silvicultural Decision Support System to Compare Forest Management Scenarios for Larch Stands on a Multicriteria Basis.

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1. Introduction

In forest resource planning choosing a silvicultural scenario is becoming a complex problem especially due to the multiplicity of goals and wide-ranging criteria that forest managers have to consider in any decision making process (Diaz-Balteiro & Romero, 2008; Kangas & Kangas, 2005; Maness & Farrell, 2004). For a long time, research focussed on growth modelling aimed at describing stand evolution through the construction of growth models for even or uneven-aged stands. These tools are useful for predicting and analysing stand evolution over time but they are not designed to compare and help to select appropriate silvicultural scenarios.

With reference to that, DSS (Decision Support System) is a computer application typically designed to address the multi-faceted nature of management questions. Every decision can affect criteria of various kinds like: environmental issues (e.g., biodiversity conservation, carbon sequestration,..), economic issues (e.g., timber, wood quality, source of energy, ..) or social issues (e.g,. recreation, employment,..). Considering the increasing complexity of new challenges in forestry such systems are very useful in a wide range of fields, especially in sustainable natural resource management, business planning, transportation, timber harvest scheduling, … (Gordon et al., 2004 ; Reynolds, 2005).

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

This SDSS has been developed to predict the influence of silvicultural alternatives on larch stand evolution and help forest managers choose scenarios according to preset goals. It is made of three interconnected 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 using a Multi-Criteria Decision-Making – MCDM approach (Pauwels et al., 2007).

Financial, technico-economic and ecological or environmental indicators are calculated in order to characterize wood production both qualitatively and quantitatively at the stand level. 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 even-aged larch stands
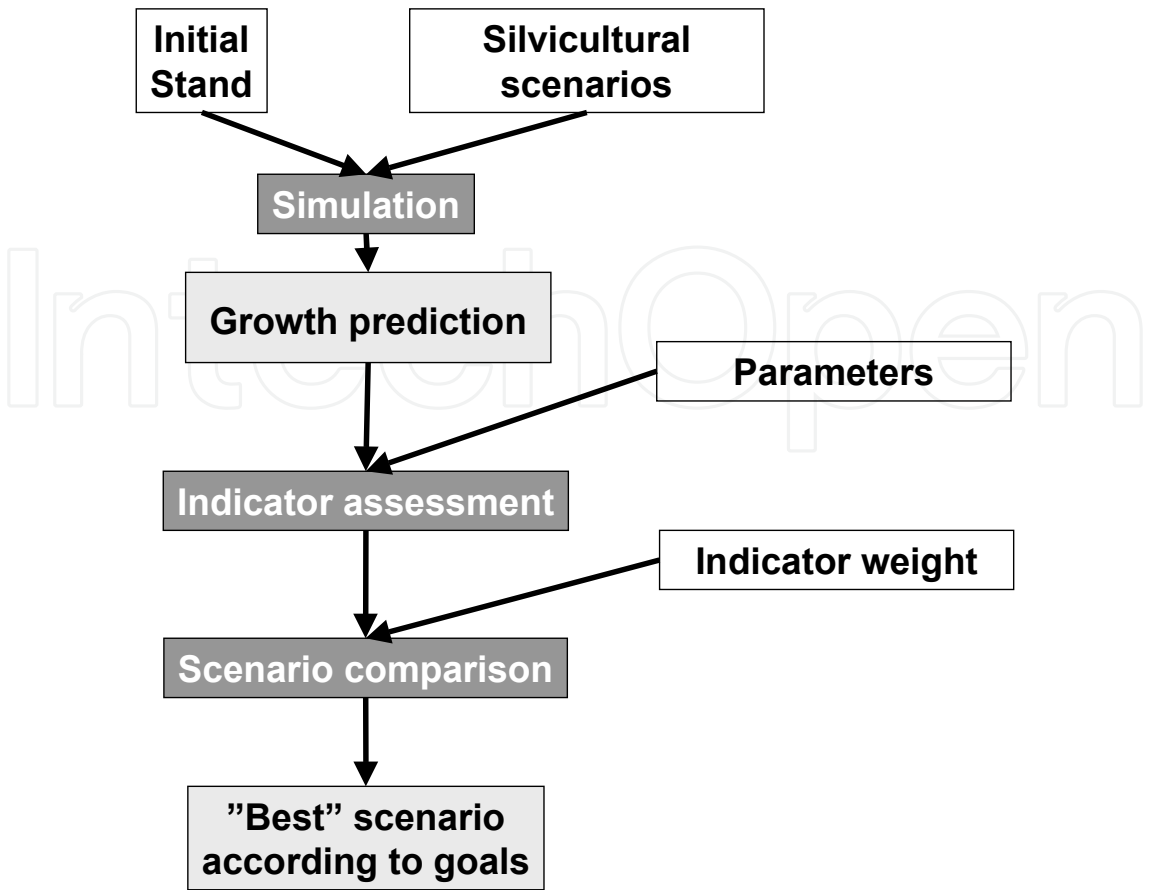
Fig. 1. General architecture of the silvicultural decision support system "MGC_larch".

[European larch (<u>Larix decidua</u> Mill.), Japanese larch (<u>Larix kaempferi</u> (Lamb.) Carr.) and hybrid larch (<u>Larix eurolepis</u> 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 several generalized silvicultural alternatives being either intuitive or already 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 (Pauwels & Rondeux, 2000). This study can be used both for research purposes and for practical forest planning especially for use at the scale of an individual property. It is based on a very large database and a knowledge-based system from which indicators have been calculated.

2. Materials and methods

2.1 General decision system approach

The SDSS is based on a structure made of two main components. The first one consists in the building of a growth model used to simulate the development of a stand in response to different silvicultural treatments or "scenarios". The resulting data describing the evolution of the trees are recorded in a database which the second component uses to assess several indicators expressing different goals to be achieved by the applied silvicultural 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

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input of data as well as managing successively growth simulations, indicator assessment, scenarios comparison and results display (Figure 1).

The main body of the data required was obtained from permanent growth plots and trees measured at different occasions. The data sets consisted of selected stands and trees for whom numbers and types of collected data vary according to the modelling objectives, growth modelling being clearly at the heart of the SDSS.

2.2 Growth modelling

Several regression equations have been built to fit the observations collected in 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 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 Pauwels (2003), Pauwels et al. (1999), Pauwels et al. (2002b). Only the main results are however presented in this paper.

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

A selection based on different aspects was then considered about the variables: easily available, high biological expression, consistent signs of the estimates.

The four sub-models organized consistently were dealing with dominant height and age (site curves), self-thinning, girth growth and volume estimation (Figure 2).
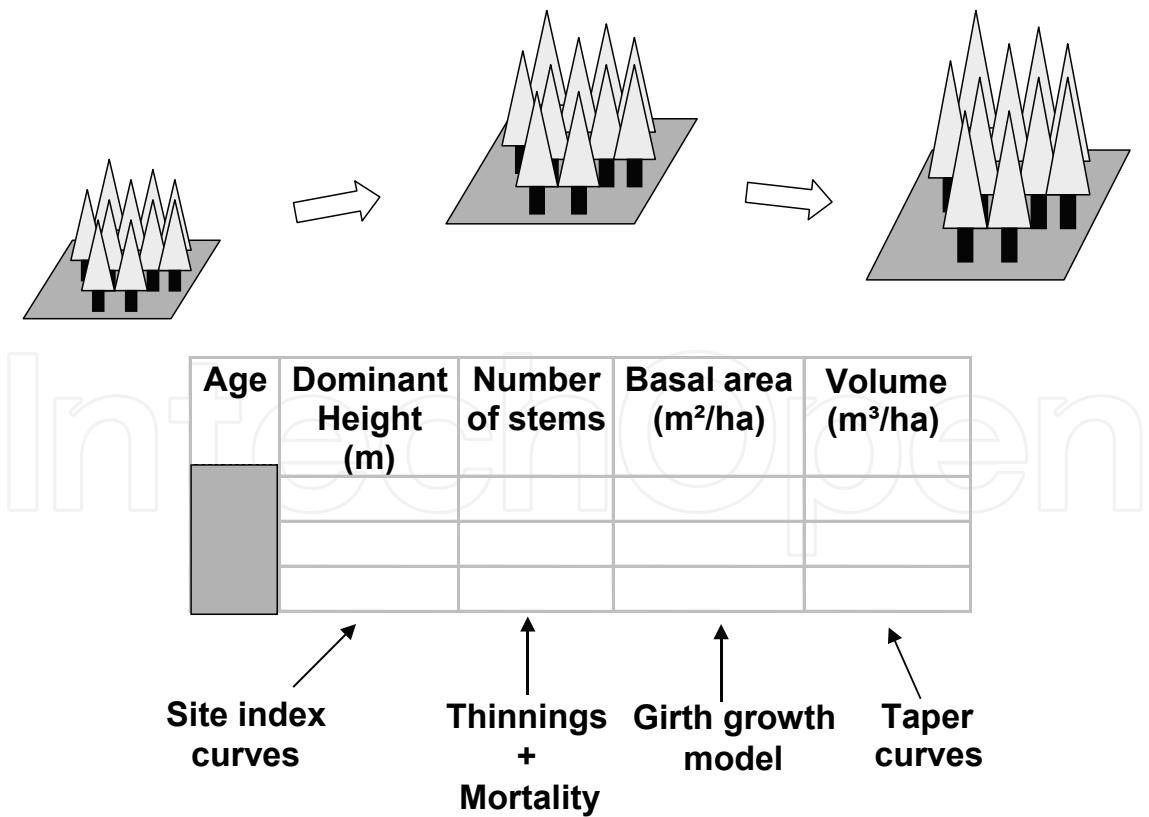

Age	Dominant Height (m)	Number of stems	Basal area (m²/ha)	Volume (m³/ha)

Site index curves   Thinnings + Mortality   Girth growth model   Taper curves

Fig. 2. Organization overview of the prediction models dealing with the stand growth

Site Index curves

The first sub-model concerns site index curves which express the relationship between dominant height, conventionally the average total height of the 100 biggest trees/ha (Rondeux, 1999), and age were constructed from stem analysis data (102 dominant trees cut from inside 55 stands). We used the model IV of Duplat and Tran-Ha (Duplat & Tran-Ha, 1986) based on polymorphic techniques, which has the following formula:

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

where Hdom is the dominant height, Age is the total age (from seeds, in years) of the stand, 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 4 parameters of the models built for the three larch species are presented in Table 1.

Self-thinning model

The second sub-model was developed to quantify reduction in the number of stems per hectare, especially due to the so-called self-thinning process (Puettmann et al., 1993) occuring in the event of excessive stock growth. This model, which is used to simulate the natural mortality of trees, predicts the maximum number of potential living stems (Rondeux, 1999). A curve of the quadratic mean stand diameters for maximum number of trees per hectare fitted with a log linear regression yields the following function:

$$\log \overline{dq} = 2.81549 - 0.47277 \cdot \log Nha \qquad (2)$$

with $R^2 = 0.985$ and RMSE = 1.67 cm ,
where $\overline{dq}$ is the quadratic mean stand diameter and Nha is the number of living trees per ha

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
R² = 99.4%	R² = 99.6%	R² = 99.6%
RMSE = 0.70m	RMSE = 0.51m	RMSE = 0.53m

Table 1. Parameters of the Duplat and Tran-Ha model IV used to describe the dominant height of larch.

This equation is based on data derived from 10 fully stocked stands, and was "validated" on a sample of 268 stands (the line corresponding to the equation is located in the upper part of the scatter of points showing the relationship between $\overline{dq}$ and Nha which were calculated for all the sampled stands). Expressed in terms of stand density index, the equation has been rewritten as:

$$Nha = 10.e^{\left(\dfrac{\log \overline{d}q\text{-}2.81549}{\text{-}0.47277}\right)} \qquad (3)$$

Girth growth model

The third sub-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. The corresponding equation is written as:

$$MPGI = 6.1048 + \frac{33.325}{Gha} - 1.92103 \,.\, \ln\left(\frac{Hdom}{c} \,.\, 100\right) + 0.00046251 \,.\, H50^2 + \frac{6.9526}{Age} \qquad (4)$$

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

This tree model was built from data collected in 99 stands (sample of 2,578 trees) and was validated on a sample of 48 other stands (sample of 1,283 trees). The R^2 of this model is 0.605 and the RMSE equals 0.64 cm yr^{-1}. It is based upon explanatory variables easy to collect and results from a comparative analysis of more than 15 models using various distance independent competition indices (Adreassen & Tomter, 2003; Pauwels et al., 2002b).

Volume estimation

The fourth sub-model was developed on the basis of taper functions predicting stem profile (Husch et al., 2003) 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 (Biging, 1984) using three independent variables: tree diameter, tree total height and age.

$$\hat{d}(h) = d \,.\, \left[b_1 + b_2 \,.\, \ln\left[1 - \left[1 - e^{\left(-\frac{b_1}{b_2}\right)} \right] \,.\, \left(\frac{h}{htot}\right)^{1/3} \right] \right] \qquad (5)$$

with:

$$b_1 = 1.64041 - 0.17938 \,.\, \ln\left(htot\right) - 0.02569 \,.\, \ln\left(Age\right) + 0.07317 \,.\, \ln\left(d\right)$$

$$b_2 = 0.50322 + \frac{1.6526}{Age} + 0.19668 \,.\, \ln\left(d\right) - 0.25565 \,.\, \ln\left(htot\right)$$

where $\hat{d}(h)$ is the predicted stem diameter (cm) at the height h (m), d is the diameter measured at 1.3 m above the ground level, 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 4 sub-models are then 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 a form very similar to a yield table.

All other conditions being known, stand evolution obviously depends on the manipulation of stand density values, which are affected by thinning parameters. The user defines these either by their types (high crown thinning, neutral thinning, or low thinning) and weights (intensity of removals) 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 Pauwels (2003).

2.3 Indicator assessment

The indicators are defined at stand level 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 potentialities and the knowledge necessary to describe the evolution of certain stand or tree characteristics. Nine indicators, which are presented in Table 2, are used to factor in the six following objectives for which sets of data were available: wood production, economics, technico-economics, ecology, stability facing windstorm damages and wood quality properties.

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 m^3 ha^{-1} yr^{-1}, formulated as:

$$MAVI = \frac{Vf + \sum_{j=1}^{n} Vth_j}{r} \tag{6}$$

where Vf is the stand volume (in m^3) estimated at the end of the rotation age (in years), Vth_j is the volume of living trees (in m^3) removed at thinning cycle j, 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.

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 the well-known Faustmann formula (Brazee, 2001). 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 (Leuschner, 1984). It is currently used for optimizing rotation age (Brazee, 2001) and comparing various management objectives (Buongiorno, 2001).

Since PNW is given by:

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$$\sum_{i=1}^{r} \left(R_i - C_i \right) / \left(1 + \text{rate} \right)^i \tag{7}$$

then:

$$LEV = PNW \cdot \frac{\left(1 + \text{rate} \right)^r}{\left(1 + \text{rate} \right)^r - 1} \tag{8}$$

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%). In addition to discount rate, the user has to set the stumpage prices and the costs of successive silvicultural operations (plantation, cleaning, pruning, etc.).

Goals	Indicators	Unit	Target
Production	Mean annual volume increment	m³ 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
Wood quality	Proportion of mature wood	%	Maximisation
	Ring width variation	%	Minimisation
	Modulus of elasticity	MPa	Maximisation

Table 2. Indicators used to compare silvicultural scenarios according to different predefined goals (objectives).

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 (Pauwels, 2003). The input parameters of this process are the characteristics and expected prices of the different potential stem sections which can be produced according to the uses (pulp wood, saw logs, veneer, etc.).

Ecological indicators

Two indicators are taken into account to define the general objective "ecology". The first concerns the *potential biodiversity* (diversity of ground vegetation) that might grow under the canopy, while the second describes its cover and is conventionally 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 Balandier et al.(2002b):

$$IR\left(\%\right) = e^{\left(-0.114.Gha+0.021.Age\right)}.100 \qquad (9)$$

with R²=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) for which relative irradiance has been calculated.

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 (Balandier et al., 2002a).

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 (%) during the rotation of the cover, and is estimated indirectly from irradiance (Balandier et al; 2002a) as follows:

$$Cover = [-0.63 + 0.82 . ln(IR)] . 100 \qquad (10)$$

with R² = 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.

Stand stability indicator

The "stability" objective deals with the risk of potential 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 (Riou-Nivert, 2001), and is calculated based on dominant height and mean stand diameter. Three zones have been defined (Figure 3): stable, risky and unstable. The index also takes into account thinning intensity when the stand is located in the risky zone (Pauwels, 2003).
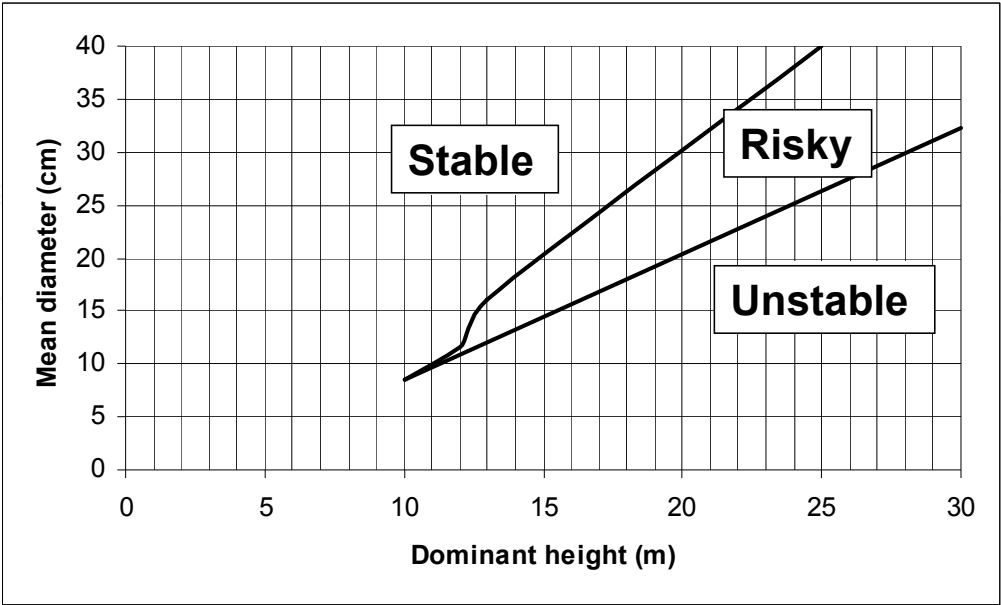

Fig. 3. Wind stability zones for even-aged coniferous stands based upon the dominant height and the mean stand diameter (Riou-Nivert, 2001).

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Wood quality indicator

Three indicators have been proposed 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 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 which are calculated for the mean tree girth of the final stand and expressed in percentage of basal area at 1.3m. Heartwood rate (*Hw*) is predicted from age, diameter at breast height (1.3 m) and species (Pauwels et al. 2002a):

$$\mathrm{Hw\%} = -51.011 + 19.513 \cdot \ln\left(\mathrm{Age}\right) + 10.637 \cdot \ln\left(\mathrm{d}\right) - 3.8548 \cdot \mathrm{ME} \tag{11}$$

with R²=0.859, RMSE=7.02% ,

where Age is the tree age (in years), d is the diameter 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 other two species (Japanese and hybrid). 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" (tree of quadratic mean diameter) of the final stand as the ratio of the standard deviation to the weighted mean of the ring width. So each ring has 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:

$$\mathrm{RWV} = \frac{\mathrm{wrstd}}{\mathrm{wmrw}} \cdot 100 \tag{12}$$

$$\mathrm{wrstd} = \sqrt{\frac{\sum\limits_{i=1}^{n}\left(\mathrm{rw}_i - \mathrm{wmrw}\right)^2}{n}} \tag{13}$$

$$\mathrm{wmrw} = \frac{\sum\limits_{i=1}^{n}\mathrm{rw}_i \cdot \mathrm{rarea}_i}{\sum\limits_{i=1}^{n}\mathrm{rarea}_i} \tag{14}$$

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 Leban & Haines (1999):

$$MOE_i = (1467 / rw_i + 7541) \cdot \left[1 - e^{\left(-0.330.rage_i\right)} \right]^{12,1} \qquad (15)$$

with R²=0.63, RMSE=2205MPa ,

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 (Pauwels, 2003). The abovementioned indicators are calculated for each scenario and the evaluations are stored in a payoff matrix.

3. Scenario comparison

All the scenarios are compared according to indicator evaluations. The multi-criteria decision-making approach, Electre III (Bousson, 2001; Maystre et al., 1994) is used. It ranks scenarios from best to worst. This outranking method is aimed at enabling the user to estimate the order of priority of the alternatives with the minimum of assumptions, ELECTRE as POMETHEE come in a variety of versions, suitable for different situations. Its main advantage is that it doesn't require as complete preference data as is required by AHP ("Analytic Hierarchy Process") (Saaty, 1980), however from the viewpoint of participatory planning (which was not the objective of this study) the method is hard to interpret (Kangas & Kangas, 2005). Electre III starts the comparison from the payoff matrix and uses three thresholds (Figure 4) to take into account inaccuracy in the indicator evaluations.
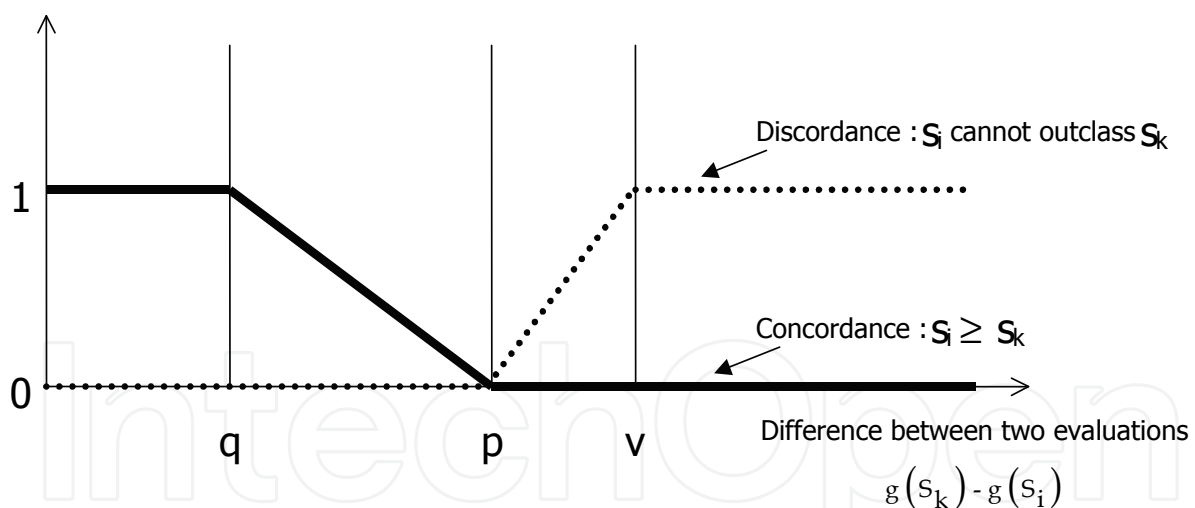

Fig. 4. Thresholds used to compare scenarios according to the Electre III multi-criteria method (thresholds : q = indifference threshold, p = strict preference, v = veto treshold, S_k and S_i = scenarios k and i)

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 < concordance index < 1).

The third threshold is the *veto* threshold v. It corresponds to the limit of the difference between two evaluations beyond which the 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 comprised 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:

$$C_{ik} = \frac{\sum\limits_{j=1}^{n} W_j \cdot c_j(s_i,s_k)}{\sum\limits_{j=1}^{n} W_j} \qquad (16)$$

where n is the number of objectives assigned (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.

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:

$$\delta_{ik} = C_{ik} \cdot \prod\limits_{j \in \overline{F}} \frac{1 - d_j(s_i, s_k)}{1 - C_{ik}} \qquad (17)$$

where:

$$\overline{F} = \left\{ j \mid j \in F, d_j(s_i, s_j) > C_{ik} \right\} \qquad \text{and} \quad F \supset \overline{F} \qquad (18)$$

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 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 (Buchanan et al., 1999).

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 6 silvicultural scenarios (Table 3), all being based on a 12-year-old Japanese larch stand with an initial

Scenario No.	Building mode	Cutting cycle (years)	1st thinning (years)	Rotation (years)	Final No. of stems/ha	Final mean girth c and diameter (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 m² 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 3. Characteristics of the 6 silvicultural scenarios compared.

density of 1,333 stems/ha (spacing: 2.5 x 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 cutting cycle), the longest rotation (84 years), and the production of a mature stand with an important growing stock (680 m³ ha⁻¹) and big trees (mean girth = 187 cm). Scenario 2 is based upon thinnings that are more heavy that in scenario 1 (35-40% of stems removal at each cutting cycle), a relatively short rotation (54 years) leading to a mature stand with a less important stock (140 m³ 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 cutting cycle (15m² 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 a 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 (Table 4). In the first step, all indicators are weighted equally. It can be shown that, when modifying the weights allocated to each indicator and/or the parameters used to calculate the indicators, the results and the position of the silvicultural scenarios are varying very little. The thresholds are set according to the observed evaluations and the estimated inaccuracy of each indicator.

Scenario No.	INDICATORS								
	MAVI (m³/ha /year)	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

Table 4. Payoff matrix characterizing the six compared scenarios

The scenarios analysed by the Electre III procedure are ranked from best to worst (Figure 5). 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, that means that 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. It can also be seen that 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.

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 stand stability 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

Table 5. Best scenario according to the main goals to be achieved.
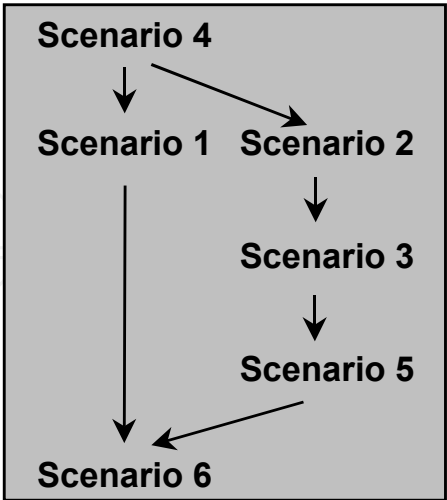
Fig. 5. Scenario classification resulting from the Electre III method with all indicators weighted equally (the arrows point from better towards worse scenarios, scenarios that are not connected are considered as incomparable).

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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. It can be reasonably assumed 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 alternative silvicultural scenarios within a defined range of site conditions and thinning regimes especially.

5.2 Indicator assessment

The number of indicators used to compare scenarios is obviously 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. Nevertheless, the 9 objectives that have been defined offer a good overview of the many possible interactions between the silviculture of larch stands and how these stands achieve the goals initially defined.

6. 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 5. 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 (based on weight of thinnings and age of 1st thinning) which maximizes biodiversity (abundance and nature of understory 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 or log lengths) 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.

7. Conclusions

A silvicultural decision support system (SDSS) 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, tree stability facing windstorm and wood quality. A weakness of this system, due to a lack of information, 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. 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. More generally the method used seems to be promising to measure forest sustainability and to evaluate its multifunctionality especially when negotiations have to be started upon.

8. Acknowledgements

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This book by In-Tech publishing helps the reader understand the power of informed decision making by covering a broad range of DSS (Decision Support Systems) applications in the fields of medical, environmental, transport and business. The expertise of the chapter writers spans an equally extensive spectrum of researchers from around the globe including universities in Canada, Mexico, Brazil and the United States, to institutes and universities in Italy, Germany, Poland, France, United Kingdom, Romania, Turkey and Ireland to as far east as Malaysia and Singapore and as far north as Finland. Decision Support Systems are not a new technology but they have evolved and developed with the ever demanding necessity to analyse a large number of options for decision makers (DM) for specific situations, where there is an increasing level of uncertainty about the problem at hand and where there is a high impact relative to the correct decisions to be made. DSS's offer decision makers a more stable solution to solving the semi-structured and unstructured problem. This is exactly what the reader will see in this book.