Linking growth modelling to timber quality assessment for Norway spruce

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Abstract

The aim of this paper is to propose a consistent framework for analyzing the influence of silviculture, site quality and, to some extent, genetics on the wood production of Norway spruce from both a quantitative and a qualitative point of view. Tree and stand volume, stem taper, wood basic density, proportion of juvenile wood as well as knottiness are considered as the result of growth processes.

Two complementary applications are presented. (1) An average-tree growth model which is built of several interrelated processes: site quality has an effect on height growth and hence on all other tree and stand characteristics; crown development is driven by height growth and controlled by stand density; stand basal area increment is predicted from empirical rules; tree basal area increment is then distributed along the stem. (2) A model that aims at assessing timber quality of a standing tree from usual inventory measurements such as tree age, height and diameter at breast height: growth equations are used to reconstruct the past growth of a tree and to predict its current internal structure, namely ring distribution. Both models are linked to allometric equations that estimate the characteristics of branchiness, to densitometric models that predict wood basic density from ring distribution and to a software that simulates the grading of any board located in a stem whose morphology is known in detail.

The aim of these models is not to make precise quantitative predictions but to show how different pieces of knowledge of silviculturists, forest biometricians and wood scientists may be brought together in simulation software in order to help forest managers and wood industrialists to make decisions. This framework could be extended to other fast-growing coniferous species.

Keywords: Wood quality; Growth and yield; Modelling; Forest inventory; Picea abies

1. Introduction

For a long time growth and yield studies have focused on the prediction of global stand and tree attributes — namely stand dominant height, basal area and volume or tree diameter at breast height (DBH) — as a function of age, stand density and site quality (Clutter et al., 1983). These studies have led to the construction of various types of model such as yield tables or tree distance-independent models (Houllier et al., 1991a). The connections of these models with wood quality were often limited: the only useful information that they provided about wood products were related to the size of the trees (for the mean and dominant trees with stand models or for every tree in the stand with tree models (Vannière, 1984; Lemoine, 1991)) and in some cases...
to their taper through stem profile equations (e.g. see Newnham, 1992).

More recently, the need for management tools that integrate both growth and wood quality information led to a new generation of more detailed models (Mitchell et al., 1989; Vaissäinen et al., 1989; Leban et al., 1991; Briggs, 1992; Cown, 1992; Houllier et al., 1993) which have mostly been developed for fast growing coniferous plantations (e.g. Douglas fir in North America and France, radiata pine in New Zealand, Scots pine in Finland). These models operate at the tree level but may be either average tree models, distance-independent or distance-dependent tree models. Some are based on ecophysiological processes, others on more conventional empirical approaches, but they all include several aspects that are directly connected to wood quality:

1) The crown is now often considered as a compartment of the model (e.g. through crown ratio), its development and recession are determined by tree-to-tree interactions and its size is used as a predictor of the future stem growth (e.g. Mitchell, 1975; Ottorini, 1991); in other studies, the crown is not included in the model but its characteristics (e.g. height to the lowest live branch) are predicted from usual tree measurements such as age, DBH and total height (e.g. Dyer and Burkhardt, 1987; Colin and Houllier, 1992).

2) Several authors have shown that tree branchiness — that is the number, the vertical position, the size, the insertion angle and the status of the branches — can be predicted from usual tree measurements such as age, DBH and total height and from height-over-age growth curves (e.g. Remphrey and Powell, 1984; Colin and Houllier, 1991, 1992; Maguire et al., 1994).

3) Since the vertical variation of the ring area can be predicted by using the position of the crown, the vertical profile of the stem (i.e. its taper) can be explicitly modelled as the result of the accumulation of annual wood increment (e.g. Arney, 1974; Mitchell, 1975; Ottorini, 1991; Cluzeau, 1992; Colin et al., 1992).

4) All these aspects are related to the internal structure of the stem, namely to knottiness and to ring distribution (i.e. ring age and ring width). Ring distribution is hence often considered as a good predictor of some important wood basic properties like location of juvenile wood (Polge, 1964; Olesen, 1977), wood density (Olesen, 1976; Josza et al., 1989; Mazet et al., 1989; Cot, 1991), grain angle (e.g. Keller et al., 1974), machining ability (e.g. Triboulot et al., 1991). These basic properties combined with wood defects like knots have themselves a strong influence on factors that determine the quality of endproducts, namely shrinkages (e.g. Mazet and Nepveu, 1991), mechanical strength (Leban and de Reboul, 1988; Goy, 1992a) or visual aspect (e.g. Centre Technique du Bois et de l'Ameublement (CTBA), 1986).

In this general context of tighter connections between growth and wood quality modelling, the scope of this paper is to report on a project that aims to develop joint tree growth and wood quality models for Norway spruce in France. The second section of the paper reviews the general framework of the project. The third section presents the average tree growth model that has been elaborated and gives an overview of how branchiness is predicted. Section 4 provides two illustrations: (1) two different silvicultural schedules are simulated and their outputs are compared; (2) combining forest inventory data and growth equations provides a basis for the non-destructive assessment of timber quality of standing trees. The last section is dedicated to some general comments about the reliability of our approach and its applicability in an operational context and/or to other species.

2. Aims of the project

The origins of the project lie in the importance of the Norway spruce resource in France, in the changes of silvicultural conditions during the past decades and in the consequent changes of wood quality. Norway spruce dominated stands cover about 723 000 ha (5.4% of French forest area). The total volume of standing Norway spruce trees is about 127 million m^3 (7.2% of the total growing stock) and the current volume increment amounts to 5.74 million m^3 year^-1 (8.3% of the current annual increment; Houllier et al., 1991b; Fig. 1). Most of this resource comes from stands planted since 1949 as a result of a national policy (Revue Forettrie Francaise, 1987).

Consequences of this situation are the following: (1) this resource is still quite young; (2) a lot of stands are installed on former agricultural land with a shift from mountainous areas toward hill and plain regions and from low-site quality toward higher-site quality (Ottorini, 1984); (3) the traditional silviculture based on
natural regeneration or on dense plantations (Décourt, 1971) has been progressively replaced by new practices with a lower initial stand density and fewer but more intensive thinnings that should be combined with artificial pruning (Guitton and Riou-Nivert, 1987; Riou-Nivert and Laden, 1991); (4) the wood basic properties have also changed (Nepveu et al., 1988).

In 1989, it was therefore decided to start a project with the explicit goal of modelling the influence of site quality and of silvicultural regime on individual tree growth, on stand yield and on wood quality of Norway spruce. The general framework of the project is given in Fig. 2: it consists in a package of submodels that range from primary growth factors (namely site, stand density and genetics) to the quality of sawn boards. It is however clear that this chain does not exhaustively describe the relationships that may exist between growth and wood quality. For example: the impact of climatic variations or of pests on growth was not taken into account; similarly, some aspects of wood quality such as rootrot were deliberately omitted; also, end-products other than boards as well as the interaction with machining ability were not included.

3. Growth and yield model

A simple average tree growth model was elaborated for Norway spruce pure even-aged stands in northeastern France (Houllier and Leban, 1991). This model is based on fairly restrictive assumptions about the homogeneity of the stands:

(1) All the trees are the same size, so that a stand may be characterized by its age (A), its number of stems per hectare (N), its basal area (G) and the size of its average tree: its height (H), diameter at breast height (DBH), basal area (g) and the length of the part of the crown which is free from any mechanical contact with neighbour trees (LFC).

(2) The trees are regularly scattered within the stand and the development of their crown is symmetrical around the vertical axis.

(3) Thinnings are neutral (i.e. the size of thinned trees is the same as the size of the remaining trees) and do not disturb the regularity of the spatial distribution of the trees.

As represented in Fig. 3, the model comprises several interrelated processes, namely height growth, crown development, stand basal area increment, tree basal
area growth along the stem and branchiness, that are described below.

3.1. Height growth

Site quality and genetic origin have an effect on height growth and hence on all other tree characteristics. We applied the usual site index system and the guide curve method (Clutter et al., 1983) to model height-over-age growth curves from national forest survey data. The Chapman–Richards equation was derived in this way (Lorieux, 1990):

\[ H(A) = p_1 \left[ 1 - \exp\left( - p_2 \cdot A \right) \right] \]

where \( H \) is height (m), \( A \) is age (year), \( p_1 \) is asymptotic maximum height-site index (m), \( p_2 = 0.02385 \), and \( p_3 = 1.455 \).

3.2. Silvicultural regime

In the context of our restrictive assumptions, silviculture is simply characterized by the successive values of the number of stems per hectare, \( N(A) \), meaning that we cannot simulate and compare different types of thinnings (e.g. thinnings from below vs systematic thinnings). In order to facilitate the assessment of site effects, we chose to define \( N \) as a function of height instead of age.

3.3. Crown development and canopy closure

Crown shape of open-grown trees depends on genetics: we chose to represent it crudely by a cone with a fixed angle \( 2\theta \). We further assumed that crown lateral extension is driven by height growth, that it is limited by stand density as the result of inter-tree crown contacts and that this mechanical competition leads to crown recession. The height to the base of the free crown \( (HFC(A)) \) is therefore estimated as:

\[
\begin{align*}
HFC(0) &= 0 \\
HFC(A) &= \text{Max}[HFC(A-1), H(A) - \frac{100}{\tan \theta \cdot \sqrt{N(A) \cdot \pi}}]
\end{align*}
\]

where \( LFC(A) = H(A) - HFC(A) \) (in m) and \( \tan \theta = 0.3 \).

Stand canopy closure, \( CC(A) \), is then deduced from tree crown recession:

\[ CC(A) = N(A) \cdot \pi \left[ \tan \theta \cdot LFC(A) \right]^2 \]

3.4. Stand basal area increment

Stand basal area increment is predicted from empirical rules, namely Eichhorn’s rule and self-thinning law, and from the crude assumption that stand yield is proportional to canopy closure (Assmann, 1970).

The self-thinning equation was fitted by Bossuat (1990) using non-thinned plots from two experimental designs. It was then qualitatively validated with national forest survey data (Fig. 4):

\[ \log(N) = \alpha_1 - \alpha_2 \log(C_g) \]

where \( C_g \) is quadratic mean girth (in cm), \( \alpha_1 = 5.884 \), \( \alpha_2 = 1.497 \), log being the decimal logarithm. The ratio of the average basal area of dying trees vs the average basal area of all trees (before death) was also approximately estimated from the same non-thinned experimental stands (Bossuat, 1990):

\[ K_d = 0.4 \]

Following Eichhorn’s rule (1904) extended by Gehhardt (1909), an equation predicting the maximum standing basal area \( (G_{\text{max}}) \) from dominant height \( (H) \)
3.75  
3.7  
3.6  
3.5  
3.4  
3.3  
3.2  
3.1  
3.

Fig. 4. Self-thinning line derived from experimental plots by Bossuat (1990) and position of national forest survey plots in northeastern part of France (from Houllier et al., 1991b). Note: some plots are above the theoretical self-thinning line because of the small size of the inventory plots.

was subjectively adjusted from both non-thinned experimental plots and national forest survey data (Fig. 5):

\[
G_{\text{max}} = \mu_1 \cdot \ln \left( \frac{\mu_2 \cdot (H-1.3)}{\mu_1} + 1 \right)
\]

with \( \mu_1 = 25 \text{ m}^2 \text{ ha}^{-1} \) and \( \mu_2 = 10 \text{ m}^{-1} \text{ ha}^{-1} \). These equations were then differentiated and combined in the following stand basal area growth model (Houllier, 1992):

\[
\Delta G(A) = N(A) \cdot \Delta g(A)
\]

\[
= CC(A) \cdot \frac{1 - [\alpha_2 \cdot (1 - K_d)/2]}{1 - (\alpha_2/2)} \cdot \frac{\mu_1 \cdot \mu_2}{\mu_2 \cdot [H(A) - 1.3] + \mu_1} \cdot \Delta H(A)
\]

where \( \Delta G \) is the stand basal area increment while \( \Delta g \) and \( \Delta H \) are, respectively, the annual tree basal area and height increments.

3.5. Tree basal area growth

Tree basal area increment is then distributed along the stem according to Pressler's rule (Pressler, 1865; Ottorini, 1991) with the base of the free crown being the limit of the efficient part of the crown (Colin, unpublished results, 1992).

\[
\begin{cases}
\text{if } z < HFC(A): \Delta g(z, A) = \Delta g(1.3, A) \\
\text{if } z \geq HFC(A): \Delta g(z, A) = \Delta g(1.3, A) \cdot \frac{H(A) - z}{LFC(A)}
\end{cases}
\]

where \( \Delta g(z, A) \) is the basal area growth at height \( z \) and age \( A \). This model obviously underestimates cambial growth at the bottom of the tree (butt swell) and this point should be improved in the future.

3.6. Branchiness

The characteristics of the branches are finally predicted using Colin and Houllier's static models (1991, 1992; see Fig. 6). The position of the whorls is estimated from the height-over-age growth curve (Eq. (1)). This curve is also used for deriving the length of annual shoots which itself is used to predict the number of whorl- and interwhorl-branches of each annual growth unit. The status (i.e. dead or alive) of the branches is assessed from crown recession (Eq. (2)) by assuming that the maximum survival time of a branch after mechanical contact is: \( 5 + 0.2 \cdot N_{\text{fbc}} \) (in years), where \( N_{\text{fbc}} \) is the number of growth units below the base of the free part of the crown. The vertical trend of the diameter of whorl branches and of their insertion angle is predicted from the simulated values of \( H \) and DBH and from the distance of the whorl to the apex of the stem: for living (resp. dead) branches, the equa-
4. Applications

4.1. Simulation of two different silvicultural schedules

A software called CEP that integrates the features described in previous section was developed for personal computers under Microsoft QuickBASIC environment. This program can be run by non-specialists and enables its users to simulate and compare the performance of two stands which differ by site quality and/or silvicultural regime.

Linked to SIMQUA, a ‘glass-log’ software that simulates the sawing and the grading of any board in a log whose morphology is known in detail (Leban and Duchanois, 1990), CEP provides a consistent framework for analyzing the influence of silviculture (through stand density), of site quality and, to some extent, of genetics (Colin et al., 1993) on the wood production from both a quantitative and a qualitative point of view: (1) stem taper is the consequence of ring distribution within the stem (Fig. 7(a)); (2) wood basic density (Fig. 7(b)) is also predicted from the ring distribution within the stem using any model that relates ring age and ring width to ring density (e.g. Leban and Houllier’s (1992) microdensitometric model); (3) the relative importance of juvenile wood, defined as the wood grown in the living part of the crown, is assessed from crown recession combined to ring distribution (Fig. 7(c)); (4) furthermore, SIMQUA takes the simulated characteristics of the branches and ring distribution as input data for predicting knottiness, visual aspect and grading of any board sawn within the simulated average tree (French grading rules (CTBA, 1986) and grading rules based on the knottiness area ratio (Dinwoodie, 1981) are included within SIMQUA).

As an illustration we used CEP and SIMQUA to simulate two theoretical stands that have the same site index ($\beta_i = 37$ m) and that are managed with two different silvicultural regimes (Table 1) which correspond respectively to traditional silviculture as depicted in Décourt’s (1971) yield tables and to a more modern silviculture with wider spacing at the plantation and less but more intensive thinnings.

Fig. 7 provides general information about the size, the stem taper and the internal structure of the simulated average tree for the two silvicultural schedules. As expected, CEP predicts that the average tree of the traditionally managed stand is thinner but that the shape of its stem is more cylindrical, that it contains a lower percentage of juvenile wood and that its basic density is higher.

An important feature of CEP and SIMQUA is that they provide a flexible basis for integrating further information about the relationship between growth and wood quality. Changes may occur through the replacement of submodels when they are improved or through the addition of new features that are related to stem structure. For example:

(1) Juvenile wood may be defined according to various rules — as the wood grown in the living part of the crown (see above) or as the first 5 to 20 internal rings (Zobel and Van Buijtenen, 1989), but whichever the definition, it is possible to include it into the software in order to evaluate the volume and location of juvenile wood within the stem;

(2) CEP model provides a framework for simulating the influence of artificial pruning which (i) reduces canopy closure (and subsequently changes stand basal area growth), (ii) alters the vertical distribution of the wood (and subsequently modifies stem taper) and (iii) produces a peripheral high quality clearwood zone.
Table 1
Definition of two contrasting silvicultural schedules (see Fig. 7)

<table>
<thead>
<tr>
<th>Height (m)</th>
<th>Stand density (stems ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>‘Traditional’ silviculture</td>
</tr>
<tr>
<td>0</td>
<td>4500</td>
</tr>
<tr>
<td>5</td>
<td>4200 (m)</td>
</tr>
<tr>
<td>10</td>
<td>4000 (m)</td>
</tr>
<tr>
<td>15</td>
<td>2000 (t)</td>
</tr>
<tr>
<td>20</td>
<td>1200 (t)</td>
</tr>
<tr>
<td>25</td>
<td>850 (t)</td>
</tr>
<tr>
<td>30</td>
<td>600 (t)</td>
</tr>
</tbody>
</table>

(m) natural mortality, (t) thinning.

At the end of the simulation (at H = 30 m and A = 84 years), average tree and stand characteristics are: for traditional silviculture, DBH = 23.8 cm, total stem volume = 0.72 m³, G = 40.5 m² ha⁻¹; for modern silviculture, DBH = 40.6 cm, total stem volume = 2.06 m³, G = 34.3 m² ha⁻¹.

4.2. Assessment of timber quality of standing trees

Another application based on a similar approach was developed in order to assess the quality of existing forests either at the stand level or at a regional level (ENGREF, 1992). The precise aim of this application is to propose a non-destructive method for evaluating timber quality from inventory data and thus to complete or even, on the long-term, to replace the large but expensive sawmill recovery studies [e.g. Fahey et al., 1990].

The basic idea was to connect usual forest survey data to SIMQUA software in order to simulate the quality and the value of the products that could be obtained from standing trees. This connection was established by predicting the branching pattern and the internal stem structure of the trees that are sampled in the context of an operational forest survey: these predictions are obtained through an a posteriori reconstruction of past growth based on current inventory data which have usually the form of a list of sample trees with their age, DBH, total height, bark thickness at breast height and statistical weight (i.e. the number of stems represented by a sample tree; e.g. Inventaire Forestier National (IFN), 1985; see Table 2).

Height growth is predicted using Eq. (1) applied to individual tree (instead of stand dominant height). The past trend of annual ring width at breast height (RW(t)) is reconstructed using the following average growth equation:
Table 2
List of the trees measured by IFN in a sample plot located in the Vosges mountains (see Figs. 8 and 9 for tree number 4)

<table>
<thead>
<tr>
<th>Tree number</th>
<th>Age (years)</th>
<th>DBH (cm)</th>
<th>Height (m)</th>
<th>Bark thickness (cm)</th>
<th>Stat. weight (stems ha⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>51</td>
<td>35</td>
<td>26.00</td>
<td>0.7</td>
<td>39.3</td>
</tr>
<tr>
<td>5</td>
<td>51</td>
<td>35</td>
<td>26.00</td>
<td>0.7</td>
<td>39.3</td>
</tr>
<tr>
<td>7</td>
<td>51</td>
<td>30</td>
<td>25.50</td>
<td>0.6</td>
<td>39.3</td>
</tr>
<tr>
<td>8</td>
<td>51</td>
<td>30</td>
<td>22.00</td>
<td>0.5</td>
<td>39.3</td>
</tr>
<tr>
<td>10</td>
<td>51</td>
<td>28</td>
<td>26.00</td>
<td>0.6</td>
<td>39.3</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>26</td>
<td>25.00</td>
<td>0.6</td>
<td>39.3</td>
</tr>
<tr>
<td>9</td>
<td>51</td>
<td>26</td>
<td>25.00</td>
<td>0.6</td>
<td>39.3</td>
</tr>
<tr>
<td>11</td>
<td>51</td>
<td>26</td>
<td>24.00</td>
<td>0.8</td>
<td>39.3</td>
</tr>
<tr>
<td>6</td>
<td>51</td>
<td>23</td>
<td>21.00</td>
<td>0.5</td>
<td>39.3</td>
</tr>
<tr>
<td>12</td>
<td>51</td>
<td>22</td>
<td>21.00</td>
<td>0.5</td>
<td>88.4</td>
</tr>
<tr>
<td>13</td>
<td>51</td>
<td>22</td>
<td>22.00</td>
<td>0.5</td>
<td>88.4</td>
</tr>
<tr>
<td>18</td>
<td>51</td>
<td>22</td>
<td>21.00</td>
<td>0.5</td>
<td>88.4</td>
</tr>
<tr>
<td>15</td>
<td>51</td>
<td>18</td>
<td>19.00</td>
<td>0.4</td>
<td>88.4</td>
</tr>
<tr>
<td>17</td>
<td>51</td>
<td>18</td>
<td>20.50</td>
<td>0.4</td>
<td>88.4</td>
</tr>
<tr>
<td>14</td>
<td>51</td>
<td>15</td>
<td>13.50</td>
<td>0.5</td>
<td>88.4</td>
</tr>
<tr>
<td>15</td>
<td>51</td>
<td>14</td>
<td>16.00</td>
<td>0.4</td>
<td>88.4</td>
</tr>
</tbody>
</table>

'Stat. weight' is the number of stems per hectare represented by a sample tree according to the sampling design. Plot characteristics are: dominant height, 25.79 m; dominant diameter, 34 cm; quadratic mean diameter, 23 cm; density, 973 stems ha⁻¹; stand basal area, 40.89 m² ha⁻¹.

\[
\begin{align*}
\text{if } A < \gamma_0 & : RW(A) = \gamma_1 + \gamma_2 \cdot A \\
\text{if } A \geq \gamma_0 & : RW(A) = \gamma_1 + \gamma_2 \cdot \gamma_0 + \frac{1}{\gamma_4 \gamma_5} \cdot A - \frac{1}{\gamma_4 + \gamma_5} \cdot \gamma_0
\end{align*}
\]

(9)

where RW is in meters, \( \gamma_0 = 4.5 \) years, \( \gamma_1 - 3.5 \times 10^{-3} \) m, \( \gamma_2 = \gamma_2_0 + \gamma_2_1 \cdot \text{DBH} \), \( \gamma_2_0 = 4.2 \times 10^{-5} \) m year⁻¹, \( \gamma_2_1 = 1.6 \times 10^{-3} \) year⁻¹, \( \gamma_3 = 1.1 \times 10^2 \) year⁻¹ m⁻¹, \( \gamma_4 = 22 \) m⁻¹.

This equation is then scaled so that cumulated ring width is consistent with the estimated age at breast height and the measured DBH and bark thickness (Houllier, 1993). Of course, Eq. (9) only accounts for the average trend of radial growth, but not for the variations induced by climate as well as by the past but often unknown thinnings.

Crown recession and branchiness are predicted according to Colin and Houllier's (1992) equations applied either to current or to past values of age, total height and DBH. Stem profile is modelled using the following equation that was adapted from Newnham (1992):

\[
\left\{ \begin{array}{l}
\text{if } A < \gamma_0 : RW(A) = \gamma_1 + \gamma_2 \cdot A \\
\text{if } A \geq \gamma_0 : RW(A) = \gamma_1 + \gamma_2 \cdot \gamma_0 + \frac{1}{\gamma_4 \gamma_5} \cdot A - \frac{1}{\gamma_4 + \gamma_5} \cdot \gamma_0
\end{array} \right.
\]

(9)

where \( d(z) \) is the diameter of the stem at height \( z \), \( \lambda_0 = 0.772, \lambda_0_1 = -0.00429, \lambda_1_0 = 0.355, \lambda_2_0 = 4.32, \lambda_2_1 = -0.0454, \lambda_3_0 = 39.0 \). \( H, \text{DBH} \) and \( d(z) \) are in

\[
\begin{align*}
\left\{ \begin{array}{l}
\left( \frac{H - z}{H - 1.3} \right) \cdot \left( \frac{H - 1.3}{\text{DBH}} \right) \\
\lambda_0 = \lambda_0_0 + \lambda_0_1 \cdot \left( \frac{H - 1.3}{\text{DBH}} \right) \\
\lambda_2 = \lambda_2_0 + \lambda_2_1 \cdot \left( \frac{H - 1.3}{\text{DBH}} \right)
\end{array} \right.
\end{align*}
\]

(10)

Fig. 8. Reconstruction of the past height growth and the past crown recession of a tree (tree number 4 in Table 2) and of the current internal structure of its stem. (a) Tree height growth (bold line), recession of height to the first living branch (dotted line) and of height to the first living whorl (solid line). (b) External profile of the stem and internal ring distribution within the stem. Only every four ring limit is drawn on the right half of the stem. The trace of the recession of the first living branch and of the first living whorl are also drawn on the right half of the stem.
Fig. 9. Simulated characteristics of whorl branches in a tree (tree number 4 in Table 2). (a) Number of whorl branches per growth unit. (b) Diameter of whorl branches. (c) Insertion angle of whorl branches. Dotted line figures the estimated position of the first living branch; solid line figures the estimated position of the first living whorl. Abscissa: vertical position along the stem (i.e. \( z = 0 \) for the stump; top of the tree is on the right).

5. Discussion and conclusion

Although the different submodels used in the two applications — i.e. comparison of the performance of different silvicultural regimes vs assessment of timber quality of standing trees — are nearly the same, their philosophy is quite different with respect to growth modelling. In the first application, models are used to make a priori simulations and most sources of variation can therefore be controlled (at least theoretically). In the second application, average equations are used to reconstruct a posteriori the past growth of a tree but most factors that influenced it are unknown, namely initial stand density, successive thinnings, changes of tree social status, date of pruning, etc.

The aim of the present version of these two applications is not to make precise quantitative predictions but to show that, and how, the different pieces of knowledge elaborated by silviculturists, forest biometricians and wood scientists may be brought together in a simulation software. Until now these applications have mainly been used within the scientific community or for educational purposes. Before thinking of any operational application of such models (e.g. assessment of the quality of wood resources at a regional scale) there are at least two problems that have to be addressed.

The first issue concerns the evaluation of the accuracy (i.e. sign and magnitude of biases) and the precision (i.e. magnitude of the residual variances) of the final predictions that are produced by such applications. (1) The statistical properties of each submodel may be (and have been) analyzed, but it is clear that there is no tractable analytical procedure for estimating global biases and variances because the two applications contain several equations that are compounded in a non-linear fashion (growth equations, branch models, basic density models, geometric interpolation procedures, random position of the board to be sawn within the log, etc). (2) It is however possible to explore the statistical properties of these models through systematic Monte Carlo simulations based on the residual variance estimated for each submodel (see Section 5 and Fig. 9). Such procedures are also interesting because they account, at least partially, for the heterogeneity at different levels of organization: among stands, among
trees within a stand and even within trees. (3) Although growth is mostly simulated (or reconstructed) with difference equations, the risk of cumulative large errors is fairly limited because CEP equations are primarily based on integrated empirical rules that have been differentiated and because EPISA predictions are constrained by survey measurements.

The second issue concerns the level of detail that is required for operational applications. On one hand, it is clear that such software and models are much too detailed for many purposes. For example, in some cases measuring or estimating the largest branch diameter is enough for grading a log (e.g. Arlauskas and Tyabera, 1986). For a regional survey, thousands of trees are sampled and it is not realistic to imagine that the growth of each of these trees will be reconstructed and that dozens of boards will then be sawn and graded (by simulation) within each tree. On the other hand there are several aspects of our models that should be completed or improved: for example, the current description of the shape of the knot within the stem (i.e. it is conic) is likely too coarse for a precise estimation of the volume of the knots, a quantity which plays a key role in grading process.

The various submodels that are embedded in the two applications will be further developed and improved in several directions. (1) We intend to build a tree distance-independent growth model that will refine the average-tree model presented in Section 3 and that will allow the simulation of more realistic silvicultural schedules with different types of thinnings and different trees within an even-aged stand. (2) It is necessary to improve the description of crown recession: our models do not behave well in very early stages: modelling the development and the death of the small interwhorl branches will also be refined; these models will then be integrated in the applications described in Sections 4 and 5. (3) Enlarging the database that was used for elaborating and calibrating the equations would ensure a better behaviour of the equations for a wider range of stands and trees: extreme situations (young vs old trees, open vs closed stands, etc.) should therefore be sampled. (4) The exploration of how genetic variability alters the value of the parameters of the various submodels has already begun (Colin et al., 1993). (5) We also intend to add new submodels: for example a module that predicts the mechanical properties of the wood (Goy, 1992b).

As shown by Fig. 2, several important aspects for wood quality were deliberately excluded from our approach. Some were excluded because their links to tree growth are tenuous, or because it seemed impossible to model them on a deterministic basis: for instance, drought cracks (Boulet-Gercourt, 1986), rootrot due to *Fomes annosus* (Delatour, 1984) or occurrence of ramicorn branches. Others were excluded because they play only a minor role for Norway spruce: for example, reaction wood is related to tree growth and morphology (Fournier, 1989) but it does not depend directly either on ring distribution or on knottiness and it is not an important problem for spruce plantations.

It must therefore be emphasized that our approach is quite efficient for fast-growing conifers that have a strong apical control and a straight stem, but that it cannot be applied directly to species which have different architectural features — e.g. tropical pines like *Pinus kesiya* that may produce several flushes and whorls during a year (Bouillet, 1993) — or those for which wood quality factors other than knots and basic density play a key role — e.g. resin pockets, compression wood and stem shape for *Pinus pinaster* (Loup et al., 1991), tree morphology and tension wood for *Fagus sylvatica* (Chanson et al., 1992).

It is likely that considering the stem and its products as a result of dynamic biological processes — e.g. height growth, crown extension and recession, branch growth and wood accumulation — and integrating them into models and software is an efficient way (1) for understanding and ranking the relative role of the various interdependent factors that determine wood quality and (2) for providing forest managers and wood industrialists with computer tools that help them to make decisions.

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