Introduction

Background

Quick reactions to customers’ needs, i.e. customized production, has been a common aim of the forest industries in Finland during the past decade. At first, it was thought to be suitable only for small and medium-sized industries, but nowadays large corporations have also developed their processes to make them increasingly customer-oriented. Major development projects have been launched recently, for instance by Metsäteho, the research and development unit of the Finnish Forest Industries Federation (Metsäteho, 1997). Customer-orientation involves not only production, but also timber procurement. Researchers in the field of timber procurement have raised questions as to the appropriateness of traditional approaches in organizing customized timber procurement. Simulation has been found to be a suitable research method for studying the distribution of timber flows. In this context, the first simulation model addressing the subject of quality-oriented timber supply was introduced by Tolvanen-Sikanen et al. (1995). Their model contained a large number of educated guesses because of the lack of earlier research knowledge on the subject. The theoretical model introduced in the study was stochastic and dynamic with discrete-event characteristics.

Summary

Research on customer-oriented timber procurement has basically consisted of the modelling of the separate elements of procurement chains, especially of the machinery used. In the present study, the procurement process is modelled by using the discrete-event simulation technique, including formulation of the characteristics of marked stands, the purchasing process, timber harvesting, and transportation. The model is supposed to be an artificial timber procurement environment for both research and education purposes. The initial theoretical model is developed further on the basis of empirical data. The model developed was found to function properly in the testing environment. The functioning of stand and tree generators was particularly convincing.

Discrete event simulation model for purchasing of marked stands, timber harvesting and transportation

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Introduction

Background

Quick reactions to customers’ needs, i.e. customized production, has been a common aim of the forest industries in Finland during the past decade. At first, it was thought to be suitable only for small and medium-sized industries, but nowadays large corporations have also developed their processes to make them increasingly customer-oriented. Major development projects have been launched recently, for instance by Metsäteho, the research and development unit of the Finnish Forest Industries Federation (Metsäteho, 1997). Customer-orientation involves not only production, but also timber procurement. Researchers in the field of timber procurement have raised questions as to the appropriateness of traditional approaches in organizing customized timber procurement. Simulation has been found to be a suitable research method for studying the distribution of timber flows. In this context, the first simulation model addressing the subject of quality-oriented timber supply was introduced by Tolvanen-Sikanen et al. (1995). Their model contained a large number of educated guesses because of the lack of earlier research knowledge on the subject. The theoretical model introduced in the study was stochastic and dynamic with discrete-event characteristics.

The more advanced version of the model introduced in the present study includes a simulation interval of 1 s and the operator can choose steps of 1 min, 1 h or a workshift of 8 h. In the model,
the main steps of the timber procurement process (purchasing, logging, forwarding and transportation) are interconnected by the attributes affecting them (Figure 1). According to Tolvanen-Sikanen et al. (1995), the proportion of good-quality logs in a stand, the buyer's awareness of marked stands, and the buyer's ability to pay for timber, influenced the quality distribution of logs procured by the firm in question. It was found that in the model by Tolvanen-Sikanen et al. (1995), timber harvesting, the generators producing stands entering the market, and especially the timber purchasing transaction, needed further development most of all.

Willingness to sell and buyer's awareness

Tolvanen-Sikanen et al. (1995) presented two theories essential for decision-making in the timber procurement process; willingness to sell, and buyer's awareness. Willingness to sell in this context depicts the NIPF (non-industrial, private forest owner) timber seller's attitude towards timber-buying companies. When the decision is made subject to imperfect information, as is usually the case with timber sales transactions, not all timber-buying companies are in the same initial position as regards the attitudes of NIPFs (Sikanen, 1998a).

Before a buyer can direct any purchase actions to markets, the buyer has to know the target. For example, in the context of industrial purchasing theory, one essential step in the purchasing process is the search for alternatives (Möller, 1981). The concept of buyer's awareness refers to the probability of the buyer knowing (being aware) of the existence of a specific marked stand. When modelling the competition of several buyers, it is unrealistic to assume that their knowledge of all marked stands would be perfect.

The aim of the study

The main aim was to improve certain elements of the simulation model developed by Tolvanen-Sikanen et al. (1995). The shortcomings in the said model needing to be improved were as follows:

1. Stands were selected for the markets from a database in order of descending quality. Marked stands were gathered from the databases of the Pohjois-Karjala Federation of Local Forest Management Associations and controlling these stands (e.g. in order to change the distribution of certain stand characteristics) was difficult. The structure of marked stands has to be such that it lends itself to being readily altered when studying variable timber-procurement circumstances.

2. The distance to the marked stands and the enterprise type were assumed to influence the buyer's awareness of marked stands. A function based on real data, instead of educated
guesses, had to be inserted into the model and the interaction with willingness to sell had to be evaluated.

(3) The final decision to sell timber is made not only on the basis of monetary principles. The function producing the probability of willingness to sell timber to different kinds of buyers had to be modelled according to real data.

(4) Harvesting of the stand was not included in the initial simulation model (Tolvanen-Sikanen et al., 1995). In the customized timber-procurement process, the harvesting, and especially ‘cross-cutting to value and demand’ approach is so essential that it cannot be separated from the procurement process.

By means of developing the initial theoretical model, it is possible to create an artificial timber procurement environment where, for example, different kinds of organizational solutions, and competition situations can be tested. The model is also supposed to be suitable for education purposes. It can be used as an enterprise game in the training of timber procurement specialists.

Modelling solutions

Process of constructing the simulation model

In the context of the general process of the simulation project (Figure 2), this study falls within the iterative phase. The first ‘round’ of iteration was made by Tolvanen-Sikanen et al. (1995) and further data collection was carried out by Sikanen (1998a, b).

Stand generator

One of the main problems encountered in describing the Finnish timber procurement environment was that we did not have accurate scientific descriptions of the stand to be logged or its parameters. The first attempts to provide a
mathematical description of these properties were made in the present study. The aim was to construct a generator providing theoretical stands due to be logged with the properties typically found in Pohjois-Karjala. The parameters selected to describe these stands were cutting method (clear cutting or thinning), area, length of strip roads, mean forest-haulage distance, and timber volume per 100 m of strip road. Also, mean diameter at breast height, basal area, mean height and basal area distribution were modelled by tree species. From the viewpoint of timber purchasing, more significant parameters such as timber volumes and timber assortment volumes were then calculated using these parameters. Some of the stand data were needed when simulating the functioning of logging machinery.

A database comprising 376 real-life logging stands was used when modelling the distribution of the stands according to their thinning and clear-cutting portions. Twenty-one per cent of the stands in the database were pure thinning stands, 45 per cent pure clear-cutting stands, and the rest were homogeneous stands including elements of both. These proportions may vary regionally and from year to year, and they should be determined again when a simulation model is used in new surroundings. The stands were modelled so that they all had two elements: a thinning part and a clear-cutting part. A stand involving purely clear cutting was given a thinning area of zero and likewise in the case of stands involving purely thinning. The frequency distributions by area of these stands complied quite well with the Weibull distribution, but the parameters in thinning stands, clear-cutting stands, and stands including both, differed from each other (Table 1). The general cumulative function of the tree-parameter Weibull distribution for a random variable \(X\) is

\[
F(x) = 1 - \exp\left[-\left(\frac{x - a}{b}\right)^c\right]
\]

where \(a\) = location parameter, \(b\) = scale parameter and \(c\) = shape parameter.

When modelling the areas of stands logged in terms of thinning/clear cutting, the simplified Weibull function was used; parameter \(a\) (minimum value of depicted variable) was supposed to be zero. Also, the minimum and maximum constraints defined in the empirical database were used in addition to Weibull distribution’s parameters. Clear-cutting stands occupied between 0.2 and 5.5 ha, thinnings between 0.6 and 34.6 ha, and stands including both between 1.1 and 39.0 ha. In the case of stands including both types of logging, the share of the clear cutting was defined by the following equation. It was not used directly, but random variety was added by means of standard deviation (0.21) so that the proportion \(T_c/T_{tot}\) was forced to be within the range 0.013–0.837, which was measured from the database.

\[
\frac{T_c}{T_{tot}} = 0.6176 - 0.1514*\text{LN}(T_{tot})
\]

where \(T_c\) = area of clear cutting part in stand and \(T_{tot}\) = total area of stand logged.

Stand age was defined randomly so that it was assumed to be uniformly distributed; in the case of thinnings between 30 and 90 years and in the case of clear cuttings between 90 and 120 years. Mean stand diameter and mean stand height were defined on the basis of stand age. Modelling these parameters was done using a database comprising 807 stands and random variety was added on the basis of standard deviation. Models for mean stand diameter and mean stand height are presented in Table 2. In the present study, three tree species were included in the modelling: Scots pine (Pinus sylvestris), Norway spruce (Picea abies) and birch (Betula pendula and Betula pubescens). Pine, spruce and birch are used as abbreviations subsequently in this text.

<table>
<thead>
<tr>
<th>Logging method</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clear cutting</td>
<td>0</td>
<td>1.81191</td>
<td>1.47281</td>
<td>0.2</td>
<td>5.5</td>
</tr>
<tr>
<td>Thinning</td>
<td>0</td>
<td>5.80941</td>
<td>1.47368</td>
<td>0.6</td>
<td>34.6</td>
</tr>
<tr>
<td>Stand with both types</td>
<td>0</td>
<td>6.80658</td>
<td>1.11459</td>
<td>1.1</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 1: The parameters for the Weibull distributions depicting areas of thinning, clear cutting, and of stands including both.
that we have no previous studies on basal area per ha between stands to be logged because so far this parameter has not been of interest in forestry. It is easy to measure in the field, but still studies describing even its theoretical distribution are lacking. Thus, 'educated guesses' had to be made in the present study. A database concerning the basal areas in a wide variety of stands was in use, but the basal areas of logging stands may be distributed a little differently.

The basal area in clear-cutting stands and parts of stands was approximated by means of a very simple method. Every case of stand age of at least 90 years or mean stand diameter of at least 29 cm was selected from the database as the first step. These limits happen to be roughly the requirement for clear cutting in Finnish forestry. Stand basal area was then examined by stand age and mean stand diameter. There was no statistically significant correlation between basal area and these parameters in clear cuttings. The reason for that was supposed to be the result from different thinning treatments and regeneration methods used. Consequently the distribution of the basal area was examined and found to be fairly close to a normal distribution. Thus, it was easy to describe the basal area in clear cuttings; the mean value of 23.5 m²/ha with a random variation resulting in a standard deviation of 6.38 m²/ha was then used.

In the case of the thinnings, modelling of basal area was more complex. As a matter of fact, there were two basal areas to be described; total stand basal area and retention stand basal area. This time, every stand age between 30 and 90 years and stand mean diameter <29 cm was selected from the database. Besides these requirements, thinning models also had to be included; in Finnish forestry, forest owners are not allowed to thin unless the stand fulfils certain criteria. Thinning instructions are generally expressed so that a specific mean stand height and stand basal area have to be achieved before thinning can be performed. The final thinning model used was the average of the models for different tree species. The model of the most typical site type was used for each tree species. Because the models were expressed in graphic form, the function was constructed to describe the aforementioned mean thinning model (Figure 3). Thereby every stand fulfilling the thinning requirements and the aforementioned age and mean diameter requirements was selected for modelling of the basal area.

\[
G = 25.7 - \frac{1}{\exp(-4.277356 + 0.19160*H)}
\]

where \(G\) = required stand basal area before thinning, m²/ha and \(H\) = stand dominant height.

The stand basal area inside the thinning stands appeared to have a very strong linear correlation with stand age and mean diameter. In the case of the linear regression, both of these were statistically significant as regressors (significance value < 0.0005 defined by \(t\) test). The model as a whole was also statistically significant (significance value < 0.0005) and the standard error of the estimate was 3.6 m²/ha. The stand mean diameter used in this model was the mean diameter of the dominant trees (100 ha⁻¹). A and \(d\) may have multicollinearity, because \(d\) was initially measured by \(A\). But because of random variety of \(d\), it is reasonable to take it into account in the model.

\[
G = 14.085 + 0.07976*A + 0.343*d
\]

where \(G\) = stand basal area (m²/ha), \(A\) = stand age (years) and \(d\) = stand mean diameter at breast height (cm).

Table 2: Models generating mean stand diameter and mean stand height by tree species

<table>
<thead>
<tr>
<th>Species</th>
<th>Parameter</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine and birch</td>
<td>(\ln(d_{13})) 2.255 + 0.0097 *A 0.2281</td>
<td>(\ln(h)) 16.8791 - 41.3091 * LN(d_{13}) + 28.7381 * LN(d_{13})^2 23.7384</td>
</tr>
<tr>
<td>Spruce</td>
<td>(\ln(d_{13})) 2.337 + 0.0071 *A 0.2926</td>
<td>(\ln(h)) 248.7863 - 173.7307 * LN(d_{13}) + 49.3544 * LN(d_{13})^2 30.1685</td>
</tr>
</tbody>
</table>

Explanation of the variable codes: \(d_{13}\) = mean diameter at breast height (cm); \(h\) = mean height (dm); \(A\) = stand age (years); \(s^2\) = standard deviation of model.
required before thinning. Thus the same function that was earlier determined to depict these thinning boundaries was now used to determine the retention stand’s basal areas. Because the simplified thinning model was constructed based on the thinning models for the poorest site types, the retention stand basal area was measured to be only 5 m²/ha smaller than the value of the thinning model.

One simplification in this study was that the volume proportions of the various tree species were made to be the same as their basal area proportions. In practice, this is not very often the case, but the difference is so small that it does not lead to distortion in the system developed for the purpose of simulating timber procurement. Eronen (1997) studied the volume proportions of tree species and suggested that they follow a Beta distribution. However, the problem with these results was that Eronen had measured the distributions for each tree species but he had not studied any of the interactions between the tree species. The Beta distribution is quite useful in studies like this, but its problem is that it does not have an analytical cumulative function.

\[ f(x) = c(x - x_{\text{min}})^\alpha(x_{\text{max}} - x)\beta \]

where \( x_{\text{min}} \) and \( x_{\text{max}} \) define the lower and upper limits of the distribution, \( c \) = scale parameter fixing the total accumulation to be one, and \( \alpha \) and \( \beta \) are the parameters of the distribution.

In the present study, the database for studying the proportions of tree species comprised 609 stands. Two variables were selected to determine these proportions; the proportionate volume of birch and the proportionate volume of spruce per volume of spruce plus the volume of pine \( \left( \frac{V_{\text{spruce}}}{V_{\text{spruce}} + V_{\text{pine}}} \right) \). The distributions of both of these variables followed the Beta distribution quite well. As the Beta distribution has no analytical cumulative function, it was necessary to use a stepwise numerical method. One hundredth part from zero to one was selected to be the length of the step and the starting point was at 0.05 when randomly determining the proportions of the tree species. The parameters for the Beta distributions are presented in Table 3. Cases where the proportion of some tree species was zero had to be noted as well; these are somewhat special cases as they do not fit in with theoretical distributions. The probability that the proportion of birch was zero was about 0.1 and the probability that the parameter \( \frac{V_{\text{spruce}}}{V_{\text{spruce}} + V_{\text{pine}}} \) was zero was about 0.05.

One of the main features of this study was the attempt to describe the lack of knowledge.
involved in timber procurement: when buying stands, people lack exact knowledge of their quality composition. In Finland, relascope (angle-count) tables are in common usage in estimating the total timber volumes of stands. The variables that determine these volumes (m³/ha) are dominant height (m) and basal area (m²/ha). In this study, the relascope tables were converted into numerical form. The resultant modelling was quite successful; error variances were quite constant and the simple coefficient of determination was over 98 per cent in every model (Table 4). Stand dominant height was assumed to be 2 m more than the stand mean height, as has been presented by Nyyssönen (1983).

There are a number of studies endeavouring to develop methods and models for estimating the percentages of different timber assortments in forest stands (Rikkonen, 1970, 1972; Kilkki and Siitonen, 1975; Virkki, 1976; Mielikäinen, 1980; Vuokila and Väliaho, 1980; Nyyssönen and Ojansuu, 1982; Oikarinen, 1983; Oikarinen, 1983). None of the models developed precise yield results because the percentages of the various timber assortments depend on the cutting instructions applied and the models themselves have been developed to comply with a certain set of instructions. Nowadays, many timber procurement companies have their own cutting instructions and consequently there is a tremendous need for methods capable of taking into consideration such company-specific instructions.

However, these existing rough methods for estimating the percentages of timber assortments are widely used in Finnish forest planning and consequently the said models were included in the simulation model developed in the present study. In the case of pine, the models by Virkki (1976) were used because they are based on volume tables developed at the Finnish Forest Research Institute and practical forest inventories make use of these tables. Models based on volume tables were not found for spruce and birch, and so models presented by Kilkkki and Siitonen (1975) were used. Models describing advance estimation of timber assortments are presented in Table 5.

It is worth noting that ‘real’ stand volumes are not known until the stands have been logged, because stand volume is formed by the volumes of single trees. Consequently, the volumes obtained by using the aforementioned models are mere estimates before logging.

In Finnish forest research, theoretical basal area diameter distributions are often based on Beta or Weibull distributions (Päivinen, 1980; Kilkki and Päivinen, 1986; Mykkänen, 1986; Siipilehto, 1988; Kilkki et al., 1989; Maltamo, 1997). The Weibull distribution was used in this study.

<table>
<thead>
<tr>
<th>Variable</th>
<th>( x_{\text{min}} )</th>
<th>( x_{\text{max}} )</th>
<th>( c )</th>
<th>Alpha</th>
<th>Beta</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of birch</td>
<td>0</td>
<td>1</td>
<td>1/1028.327</td>
<td>1.11264</td>
<td>-0.299816</td>
</tr>
<tr>
<td>Proportion spruce / (spruce + pine)</td>
<td>0</td>
<td>1</td>
<td>1/234.9357</td>
<td>-0.385579</td>
<td>-0.406872</td>
</tr>
</tbody>
</table>

**Table 4:** Models describing relascope tables for determining total stand volume (V, m³/ha) according to stand mean height (h, m) and basal area (G, m²/ha)

<table>
<thead>
<tr>
<th>Species</th>
<th>Constraint for D (mean diameter, cm)</th>
<th>M odel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine and spruce</td>
<td>d&lt;=16</td>
<td>( V = (0.91 + 0.331 \times h + 0.299 \times G)^2 )</td>
</tr>
<tr>
<td>Pine</td>
<td>d&gt;16</td>
<td>( V = (0.188 + 0.081 \times h + 0.85 \times G^{1/2})^3 )</td>
</tr>
<tr>
<td>Spruce</td>
<td>d&gt;16</td>
<td>( V = (0.023 + 0.092 \times h + 0.86 \times G^{1/2})^3 )</td>
</tr>
<tr>
<td>Birch</td>
<td>-</td>
<td>( V = (1.743 + 0.09 \times h + 0.097 \times G)^3 )</td>
</tr>
</tbody>
</table>

Explanation of the variable codes: d = mean diameter (cm); V = total volume (m³); h = mean height (m); G = basal area (m²/ha).
study because of the existence of the analytical cumulative function. The parameters were estimated using models presented by Maltamo (1997) because these are the latest available (Table 6). The said models are estimated for just two parameters because if we know two tree parameters we can calculate the rest of the parameters of the Weibull distribution by relationships:

\[
\begin{align*}
c &= \frac{\ln(-\ln(0.5))}{\ln(d_gM - a/b)} \\
b &= \frac{d_gM - a}{(-\ln(0.5))^{1/c}}
\end{align*}
\]

Simulated logging of the stands was done so that the diameter for each tree was calculated randomly from the Weibull distribution and the tree heights were calculated using the model presented by Korhonen (1991).

\[
\ln(h - 1.3) = a_0 + a_1 \frac{1}{(d + 5)} + a_2 \frac{1}{(d + 5)^2}
\]

where \( h \) = tree height (m), \( d \) = tree diameter at breast height (cm) and parameters \( a_0, a_1 \) and \( a_2 \) are as given in Table 7.

This model was not used directly, but it was weighted by a quotient; the mean stand

Table 5: Stand models describing estimation of percentage of logs (S%) and percentage of waste wood (W%) (percentage of pulpwood is 100% - S% - W% (Kilkki and Siitonen, 1975; Virkki, 1976))

<table>
<thead>
<tr>
<th>Variable</th>
<th>Species</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>S%</td>
<td>Pine</td>
<td>[130 - \exp(9.845 - 1.746 \ln(d) + 3.518 \ln(d) - 3.05^3 - 3.34 \ln(d) - 3.05^5 - 0.094 \ln(h))]</td>
</tr>
<tr>
<td>W%</td>
<td>Pine</td>
<td>[0.15 + \exp(4.605 - (7.796 + 3.189 \ln(d) + 0.4736 d_a^3 + 2.587 d_b^9 + 2.512 d_b^{25} - 37.912 d_a^{60} + 0.333 \ln(h)))]</td>
</tr>
<tr>
<td>S%</td>
<td>Spruce</td>
<td>[100 - \exp(3.228 - 0.7019 x - (0.3033 x^2 + 1.068 x + 0.9483)^{0.5} - 1.29 - 1.298 x - 0.3521 x 10^{-7}(0.2636 - x)^{10} - 0.3706 x 10^{-12}(x + 5.256)^{17}]</td>
</tr>
<tr>
<td>W%</td>
<td>Spruce</td>
<td>[\exp(-1.29 - 1.298 x - 0.1522 x 10^{-7}(0.2636 - x)^{10} - 0.1445 x 10^{-11}(x + 5.356)^{15}) + 0.3]</td>
</tr>
<tr>
<td>S%</td>
<td>Silver birch</td>
<td>[100 - \exp(2.964 - 0.8766 x - (0.138 x^2 + 0.4241 x + 0.3259)^{0.5} - 0.1515 x 10^{-4}(0.7526 - x)^{8} + 0.02994 x + 2.816)^{3}]</td>
</tr>
<tr>
<td>W%</td>
<td>Silver birch</td>
<td>[\exp(-1.199 - 1.275 x - 0.1522 x 10^{-7}(0.7526 - x)^{10} - 0.1445 x 10^{-11}(x + 5.356)^{15}) + 0.15]</td>
</tr>
</tbody>
</table>

Explanation of the variable codes: \( d \) = mean diameter at breast height (cm); \( h \) = mean height (m); \( a = \ln(d)/3.72; b = (3.72 - \ln(d))/2.44; v = \text{volume of mean tree (m}^3); x = \ln(v)\).

Table 6: Regression models for the parameters of the basal area diameter Weibull distributions for pine and spruce (Maltamo, 1997)

<table>
<thead>
<tr>
<th>Tree species</th>
<th>Parameter</th>
<th>Constant</th>
<th>(\ln\left(d_gM\right))</th>
<th>(\ln(G))</th>
<th>(\ln(A))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>(\ln(a))</td>
<td>-1.9952</td>
<td>1.2302</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pine</td>
<td>(\ln(c))</td>
<td>-0.2491</td>
<td>0.3924</td>
<td>0.0057</td>
<td>-</td>
</tr>
<tr>
<td>Spruce</td>
<td>(a)</td>
<td>-1.9573</td>
<td>2.8419</td>
<td>-0.9677</td>
<td>-</td>
</tr>
<tr>
<td>Spruce</td>
<td>(\ln(b))</td>
<td>-0.3384</td>
<td>0.9126</td>
<td>0.0888</td>
<td>0.0562</td>
</tr>
</tbody>
</table>

Explanation of the variable codes: \( a, b \) and \( c \) = parameters of the Weibull distribution; \( d_gM \) = the basal area of the tree of median diameter of a certain tree species (cm); \( G \) = basal area of a certain tree species (m²); \( A \) = stand age (years).
height provided by the model for the diameter of the basal area median tree. Tree volumes were calculated using the two parameter models presented by Laasasenaho (1982). The model presented by Korhonen (1991) was as follows.

Furthermore, each tree was divided into the timber assortments obtainable from it. The models for determining the percentages of logs, pulpwood and waste wood were constructed from the log and pulpwood tables presented by Laasasenaho (1982). The constructed models are presented in Table 8.

Simulation of logging machinery required modelling of terrain class, length of strip roads and forest-haulage distance for each stand logged. Oijala and Rajamäki (1995) have estimated that 85 per cent of stands in Finland belong to terrain class 1, 10 per cent to terrain class 2, and the rest (5 per cent) to terrain class 3. The distribution of forest-haulage distance followed the Weibull distribution quite well with parameter \( a = 0 \), \( b = 223.259 \) and \( c = 1.8056 \). The minimum was 0 m and the maximum 700 m. However, the material for determining these values concerning the distribution of forest-haulage distance was quite rough and more detailed research is needed. The length of strip roads was measured using a rough method where it is assumed that the stands are quadrangular in shape and the windiness coefficient is 1.3:

\[
L = (A/0.2)^{1.3}
\]

where \( L \) = length of strip roads (100m) and \( A \) = stand area (ha).

Table 8: Models describing the percentages of timber assortments obtainable from a tree

<table>
<thead>
<tr>
<th>Species</th>
<th>Condition</th>
<th>Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pine</td>
<td>( d &lt; 17 )</td>
<td>( \ln(W%) = -1.376 + 49.209<em>1/d - 37.185</em>1/(d<em>h) - 0.0213*h - 45.674</em>(1/d)^2 )</td>
</tr>
<tr>
<td>Pine</td>
<td>( d &lt; 17 )</td>
<td>( S% = 0 )</td>
</tr>
<tr>
<td>Pine</td>
<td>( d \geq 17 )</td>
<td>( W% = 2 )</td>
</tr>
<tr>
<td>Pine</td>
<td>( d \geq 17 )</td>
<td>( \ln(S%) = 3.792 + 43.765<em>1/d - 616.258</em>(1/d)^2 + 0.01941<em>h - 0.688</em>h/d )</td>
</tr>
<tr>
<td>Spruce</td>
<td>( d \leq 21 )</td>
<td>( F% = -215.634 + 76.356*\ln(d) + 2308.062/d - 9971.461/d^2 - 96.571/h )</td>
</tr>
<tr>
<td>Spruce</td>
<td>( d \leq 21 )</td>
<td>( S% = 0 )</td>
</tr>
<tr>
<td>Spruce</td>
<td>( d \geq 16 )</td>
<td>( W% = 2 )</td>
</tr>
<tr>
<td>Spruce</td>
<td>( d &gt; 16 )</td>
<td>( \ln(W%) = 36.446 + 0.441<em>d - 31.914/d - 15.417</em>d/2 - 6.571/h )</td>
</tr>
<tr>
<td>Birch</td>
<td>( d \leq 25 )</td>
<td>( S% = 0 )</td>
</tr>
<tr>
<td>Birch</td>
<td>( d &gt; 20 )</td>
<td>( W% = 2 )</td>
</tr>
<tr>
<td>Birch</td>
<td>( \geq 63.8 )</td>
<td>( S% = 0 )</td>
</tr>
</tbody>
</table>

Explanation of the variable codes: \( d \) = diameter at breast height (cm); \( h \) = tree height (m); \( W\% \) = percentage of waste wood; \( S\% \) = percentage of logs; \( F\% \) = percentage of pulpwood.
distance distribution was studied in connection with timber sales in Pohjois-Karjala and Pohjois-Savo. The distance distribution was different for large companies and medium-large companies (Figure 4). According to Sikanen (1998b), buyer's awareness is dependent on distance as expressed in the following function:

\[ P_t = \exp \left( - \frac{s}{\beta} \right)^\gamma \]

where \( P_t \) = probability of buyer's awareness, \( s \) = distance (km), \( \beta, \gamma \) = parameters to be defined by empirical tests; for large companies \( \beta = 25 \) and \( \gamma = 4 \), for medium-large companies \( \beta = 36 \) and \( \gamma = 1.6 \).

The appearance on the market of marked stands was assumed to be constant according to geographical area. Every marked stand can appear for sale at every point within the simulated area, which in the present study was 150 x 150 km in size. Buyers, too, can be located anywhere within the area.

Willingness to sell

According to Sikanen (1998a), timber sellers have varying attitudes in regard to timber-buying companies. The NIPF timber seller's age, relative proportion of forestry income, and earlier timber-trading history all influence a person's willingness to sell. A logistic regression was chosen as the model type because it directly produces the probability of an event. The model was formulated according to data used by Sikanen (1998a) by selecting cases with the highest (1) and lowest (0) possible willingness to sell, and by using these as the dependent 0/1 variable. The initial model classified 95.1 per cent of the zeros and 66.7 per cent of the ones correctly. When the model was tested on other cases (i.e. willingness-to-sell between 0 and 1), the model classified 71.9 per cent of the cases correctly. The model produced the probability of willingness to sell to small and medium-large buyers. It is assumed that the willingness to sell to large buyers is inverse so that if the probability is 0.4 in the case of small and medium-large buyers, it is 0.6 in the case of large buyers.

\[ P_w = \frac{1}{1 + e^{-\left(0.9106 - 0.03991*\text{age} - 0.2575*\text{inco} + 3.246*\text{sawtr}\right)}} \]

where \( P_w \) = willingness to sell to small and medium-large buyer companies, age = NIPF timber seller's age, inco = relative proportion (percentage) of forestry income in NIPF

![Figure 4. Purchased stands of large and medium-large companies according to the distance from the buyer's office to the stand.](image)
household, and sawtr = number of earlier transactions with SME buyers.

In the simulation process, the independent variables were produced by generators based on data presented by Sikanen (1998a).

The NIPF timber seller’s age was found to be normally distributed with the average being 50.9 years and the standard deviation being 13.51 years.

\[
\text{age} = 50.9 + 13.51 \times (\cos(2\pi x_1) \times \sqrt{-2 \ln(x_2)})
\]

The relative proportion (percentage) of forestry income in NIPF timber sellers’ households was obtained from the data used by Sikanen (1998a). The said proportion was strongly dependent on forest holding area as follows:

\[
inco = 1.008 + 0.3209 \times \text{area} - 9.739 \times 10^{-6} \times \text{area}^2 + e
\]

where inco = [0..87] percentage of forestry income in forest owners household, and area = [0..270] forest area owned by forest owner, produced with formula 'area'.

The forest area owned by NIPF timber sellers was produced by a generator based on the study by Ripatti (1994) because the data used by Sikanen (1998a) had been stratified according to area and the distribution would thus have been false (Table 9).

The forest holding area owned by NIPF timber sellers can be generated by means of a cumulative function as follows:

Forest holding area owned by NIPF timber seller:

\[
\text{area} = e^{[0.111249 - X] / -0.158657}
\]

where area = [0..270] forest area owned by forest owner and X = evenly distributed random number [0..1].

Table 9: The size distribution of forest holdings owned by NIPF timber sellers (Ripatti, 1994)

<table>
<thead>
<tr>
<th>Size class (ha)</th>
<th>Year 1992</th>
<th>Year 2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>under 5</td>
<td>35</td>
<td>37</td>
</tr>
<tr>
<td>5-19.9</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>20-49.9</td>
<td>23</td>
<td>21</td>
</tr>
<tr>
<td>50-99.9</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>over 100</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Logging machinery

Simulation of logging machinery was mainly based on the simulation model presented by Asikainen (1995). One assumption was that logging is performed by means of a single-grip harvester. This required two functions to be modelled; moving time and time required to process trees. In forest haulage by forwarder there were five elements to be modelled; loading, driving time for loading, time of driving loaded, time of driving unloaded, and unloading time. These models are presented by Kuitto et al. (1994). In the present study, the coefficients in the models for loading and unloading time were simplified using the mean values of sawlogs, long pulpwood and short pulpwood. The loading time for a conventional timber lorry was estimated by Nousiainen et al. (1993) to be composed of two elements; indirect loading time (45 min) and direct loading time (20 min). The former includes preparing for loading and fastening the load after loading, the latter means actual loading. The driving speeds were estimated by models presented by Kukko et al. (1990).

Kuitto et al. (1994) presented that the operating times of harvesters have to be multiplied by 1.917 to include delays of under 15 min. Because the operating times in the follow-up study by Kuitto et al. (1994) were 27.6 per cent greater than in the time study, the said times, too, had to be multiplied by 1.276. The corresponding coefficients for the forwarder were 1.084 and 1.224. In the present study, the costs of the different machines were entered in the system as parameters (FIM/m³). This was assumed to describe the Finnish practice: productivity and cost accounting belongs to the entrepreneur and the costs for timber procurement organizations are formed as the result of price negotiations with entrepreneurs.

Evaluation of the various parts of the model

One problem in validating the stand generator was that Finnish forest-industry companies do not usually measure the characteristics of marked stands. Instead, the results of logging are their main concern. In the first stage of the present study, the characteristics of the marked stands
(mean height, mean diameter at breast height, distribution of basal area to different diameter classes i.e. basal area diameter distribution) were modelled mainly from data that included stands without knowledge of logging. Stands that could be logged according to valid logging instructions were then selected from the data. In the second stage, some of the stand characteristics (stand area and percentages of tree species) were modelled from the database of stands including the logging results.

Models describing the relative proportions (percentages) of pulpwood, waste wood and logs had to be examined because there were two different model groups; models for individual trees and models for whole stands. It appeared that there was no difference between these two model groups and empirical data when looking at the amount of waste wood. However, the models for individual trees gave excessive values for the percentage of logs. The difference between the tree models and the stand models did not depend on the size of the stand to be logged, but instead it was dependent on the tree species and type of logging (thinning or clear cutting). The differences between the model groups in thinning stands were 38.5 percentage points (pine) and 39 percentage points (spruce). The difference was due to using only diameter-based bucking. The difference was very small values, and thus it was decided that the value for birch logs in the case of thinnings is zero. In clear cuttings, the differences in measuring the percentages of logs were 14 percentage points (pine), 16 percentage points (spruce) and 19 percentage points (birch). All of these differences were subtracted from the values given by the log models for individual trees. Parts of the test runs when examining the percentages of the different timber assortments are described in Figures 5 and 6. It is noteworthy that in practical forest planning 'log deductions' are also used when estimating the volume of logs, and this deduction is rarely (or hardly ever) zero.

Test runs revealed that the volumes per ha did not agree with the empirical data. Therefore the mean logging removals (basal areas) had to be readjusted by means of test runs iteratively. In clear cuttings, the mean basal area was measured to be 20m²/ha (as compared to earlier 23.5 m²/ha) while in thinnings the retention stand's basal area was measured to be 4.5 m²/ha less than the value provided by the theoretical thinning model (as compared to earlier 5 m²/ha). The distributions of the total volumes (m³/ha) both in clear cuttings and thinnings are presented in Figures 7 and 8.

In clear-cutting stands, the distribution of the empirical data showed two peaks, and distribution of the test runs differed slightly. It was assumed that some of the clear-cutting stands in the empirical database consisted of the removal of seed trees, but because there was no absolute

![Graph](image-url)

Figure 5. An example of the differences between the tree models and stand models as regards percentages of pine logs in thinnings. In these runs, the final corrections were included in the tree models.
certainty of this, it was not possible to reduce the empirical data. However, the mean volumes of clear-cutting stands in the test runs and in the empirical database were almost the same. Also in thinning stands, the empirical database was assumed to be abnormal; thinnings of more than 100 m³/ha are very rare in practice. Cases of high thinning volumes were assumed to consist of late thinnings preceding clear cutting, but again there was no certainty of this. Some parameters of the distributions of volumes per ha are presented in Table 10. It shows that the standard deviations in

Figure 6. An example of the differences between the tree models and the stand models as regards the percentages of pine logs in clear cuttings. In these runs, the final corrections were included in the tree models.

Figure 7. The distributions of the total volume of clear-cutting stands as revealed by test runs and empirical data.
The test runs were smaller than in the empirical data. This was not felt to be a major problem, and so the main interest focused on the mean and median values. The last and the most important test runs were made using the entire stand generator. The main interest focused on the distribution of the total volume and relative proportions of the tree species. Also, no statistical methods were used with these parameters, because the empirical database used was quite narrow. Comparisons were made to make sure that parameters obtained from the test runs resembled the parameters from the empirical database and that the mean values were the same. The mean stand volume in the test runs was 483 m$^3$/ha and the median size was 390 m$^3$/ha; in the empirical database, the corresponding values were 468 m$^3$/ha and 330 m$^3$/ha. The distributions of the total stand volumes are presented in Figure 9.

**Figure 8.** The distribution of the total volumes of thinning stands as revealed by test runs and empirical data.

<table>
<thead>
<tr>
<th>Logging type</th>
<th>Database</th>
<th>Mean (m$^3$/ha)</th>
<th>Median (m$^3$/ha)</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thinning</td>
<td>Empirical</td>
<td>58</td>
<td>50</td>
<td>26</td>
</tr>
<tr>
<td>Thinning</td>
<td>Test runs</td>
<td>52</td>
<td>51</td>
<td>15</td>
</tr>
<tr>
<td>Clear cutting</td>
<td>Empirical</td>
<td>170</td>
<td>181</td>
<td>65</td>
</tr>
<tr>
<td>Clear cutting</td>
<td>Test runs</td>
<td>173</td>
<td>171</td>
<td>32</td>
</tr>
</tbody>
</table>
The relative proportions of the tree species in the test runs corresponded very well with the values of the empirical database. However, it is noteworthy that there may be some divergences between the simulations and practice, because the proportions of tree species volumes in the model are assumed to be the same as the proportions of the basal areas of the different tree species.

The testing of stand purchasing (i.e. stand generator, willingness to sell and buyer's awareness linked together) was done under the same arrangements emulating real-life situations in which Tolvanen-Sikanen et al. (1995) had tested the initial model. Product prices and stumpage prices of the sawmill and the competitors as well as the costs were real. The results of the new test drive were then compared with the results of the old run. In the new functions, the probabilities of willingness to sell and buyer's awareness were computed again for every transaction according to the functions mentioned earlier. The test showed that the improved model can steer the quality distribution of timber near to what it is in reality. Buyer A is the buyer under study and buyer B is the competitor (Table 11). The assumption was that purchase efforts are not steered to stands where the percentage of logs of I-quality of volume of pine logs is less than 25 per cent. Pricing was formulated so that when the percentage logs of I-quality logs exceeded 25 per cent, the bid for pine logs was \(1.15 \times\) average stumpage price. If the percentage was assumed to be over 30 per cent the bid was \(1.18 \times\) average stumpage price.

The simulated procurement target of the company was 1200 m³ of pine logs during the 1-year season. When the amount of timber on the market was 45 000 m³ (100 stands), buyer A was able to procure 342 m³ of best quality pine logs when the total amount of procured pine logs was

![Graph](image)

Figure 9. The distributions of the total stand volumes in the final test runs and empirical database.
1247 m³. In the initial model the percentage of best quality pine logs was higher than in the present study; we have to remember that those results were obtained with the model constructed according to educated guesses instead of real data. So, it is more reasonable to compare the timber procured to the general structure of forests in the operating area. The average percentage of I-quality pine logs in eastern Finland is 22.1 per cent (Tomppo, 1992). The same percentage was used also as the average level in the simulation model. If we compare that average figure to the simulated procurement, it can be said that with that kind of bid strategy, level of selling willingness and buyer's awareness, it is possible to steer the quality distribution in the desired direction. Also we can evaluate the success of the modelling by comparing the simulated procurement with the estimated real percentage of I-quality pine logs obtained by buyer A. The 30.1 per cent share was not reached, and it is very difficult to say exactly why the simulated percentage was only 27.2 per cent. The estimated ‘real’ percentage is only an estimation made by the company representatives. And, of course, buyer A’s timber procurement obviously includes elements not modelled in the study, for example, the personal negotiation abilities of the buyer personnel could be better than average.

In testing the functioning of the machines, their productivity (in terms of gross effective time, $E_{15}$) was selected to be the test parameter. In the study by Kuitto et al. (1994), machine productivity in clear-cutting conditions in southern Finland was 17.2 m³/h for harvesters and 17.2 m³/h for forwarders, and in thinning conditions 10.0 m³/h and 12.5 m³/h. In the present study, the productivity figures using the data procured by the stand generator were 19.4 m³/h and 16.0 m³/h in clear cuttings and 12.7 m³/h and 9.1 m³/h in thinning conditions. As expected, the values differed because there was no certainty about the stands generated in the present study being similar to the stands used in the study by Kuitto et al. (1994). In the simulation of timber lorries, the models were so simple that no scaling or validation of the models was required: loading time and unloading time were constant, and driving speeds unloaded and loaded were dependent solely on the driving distance.

**Discussion**

The stand generator produced in the present study should be seen as just the first stage in a theoretical approach to studying the structure of marked stands. Similar approaches are very rare in forest science where the main interest has centred around stand development. These simulation models have been widely utilized in forest planning programmes and systems (e.g.
Kolström, 1992; Pukkala, 1994). The aim in the present study was not to describe stand development, but to generate stands with enough variety to correspond to marked stands in practice. Kilkki and Siitonen (1975) constructed a simulation system for generating stands with properties resembling those encountered in the 5th National Forest Inventory. Their system was similar to the system developed in the present study, but their aim was to generate stands in general, not from the viewpoint of timber procurement.

The stand generator developed in the present study is still quite theoretical; there is no certainty that the stand structures generated are similar to marked stands in practice because the database containing stand properties was not the same as the database containing the logging results. Should interest arise towards a particular timber-purchasing environment, all of the parameters will have to be remodelled. The only thing that supports the validity of the stand generator is that stand volumes (per ha or per stand) are similar to those encountered in empirical stands. Also, adding contingency to the models was not entirely beyond reproach; although the assumption of normal distribution held true in the case of most of the variables, some were certainly distributed in some other way.

The main result that came out from generating the stands and simulating the pre-measurement of stands was that the models determining the relative proportions of the different timber mixtures are not precise enough. There are many statistical models for determining these proportions, but these models are not suitable for customer-oriented timber purchasing where the yields and requirements of individual sawlogs may vary even daily. Modelling different timber assortments more accurately needs descriptions of the taper curves of individual trees, and also a more accurate description of the functioning of cross-cutting when using harvesters. Nowadays, harvesters are equipped with quite complicated systems for the purpose of optimizing the cross-cutting of felled trees and the operator’s role is to see to it that the quality of the logs produced is appropriate.

Predicting the willingness to sell as influenced by behavioural factors would lead to better results than using demographic variables (Sikanen, 1998a). Thus, the difference between using demographic and behavioural factors is not very remarkable, the logistic regression model was constructed by demographic variables in the present study. The functions producing the demographic characteristics of forest owners was constructed using the available statistics and thus certain known changes (e.g. age of forest owners and the effect of different kinds of market segmentation) could easily be simulated.

The theory about buyer’s awareness is not indisputable. We cannot measure exactly whether some individual buyer knows the composition of a marked stand or not. In similar econometric modelling problems, the censoring technique is often used (Greene, 1993). Accordingly, the purchased stands presented here are thought to express the level of awareness. For example, approximately 5300 marked stands were sold in Pohjois-Karjala during 1996. Assuming that a buyer of a particular company was aware of about 220 stands annually (Sikanen, 1998b) and that the purchasing districts of the buyers of the same company do not overlap, that company would need 24 buyers to cover the whole of Pohjois-Karjala. The largest timber-buying company in Pohjois-Karjala had 27 buyers in 1996.

When modelling the stochastic nature of buyer’s awareness and seller’s willingness to sell, it becomes evident that still some other elements influence the distribution of the quality classes of timber obtained by the buyer. One possible issue for future research could be price elasticity of the willingness to sell, i.e. the initial selling willingness would probably increase if the bid made by a buyer is bigger than the bids of the competitors.

Moreover, simulation of logging machinery requires more knowledge of the contingency of the various work elements’ time requirements. Asikainen (1995) stated that contingency can be added by modelling randomly occurring delays. So far, there is no published research concerning the effects of the variety of different work elements’ time requirements on the accuracy of time consumption and productivity prognoses.

The final conclusion to be drawn from the present study is that the constructed simulation model is suitable for training purposes. For it to be used as a research method would require the development and specification of many models. However, the stand generator, for instance, can be
used in preliminary studies where a new system is tested prior to costly field studies. One other benefit of this simulation system is that some variables can be standardized while other variables can merely be studied.

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