Forest dynamics: the simulation of production and decline in Austrian forests

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The paper deals with the application of forest dynamics. Reference is made to two studies, which have been carried out at a national level. The simulations of forest decline as well as the production of exceedingly thick timber of spruce and fir provide various examples of the major problems of forest simulation and of some possible solutions. It is pointed out that the statistical analysis of empirical data is most important for modelling and it might bring about even more valuable results than the ultimate simulation itself.

Keywords: operations research, forestry, simulation, forests, decline, risk.
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Introduction

Mathematical programming and simulation are the most frequently applied techniques of Operations Research (OR) in forestry. The different kinds of programming aim at maximizing an objective function taking into account a given set of restrictions. Anyhow, in many cases there does exist a lack of information as to the structure and the dynamics of the system in question. Therefore, the optimal result of the model will not always prove to be optimal in reality, too. Whenever there is a deficiency of information, the simulation approach might offer a valuable help. In the way of simulation the response of the system to various assumptions is investigated. In fact, establishing a valid simulation model may be regarded as a first step towards mathematical programming. As to the forest system, we have got still to enhance our knowledge and understanding of its dynamics. Therefore, simulation is a most important tool of forest management and scientific research.

An important field of application of forest simulation are investigations at a national level. In the following, the special problems of such a national approach are being discussed, referring to two Austrian studies which have been carried out recently (Sekot 1989, Sekot and Flach 1992).

The first study dealt with possible effects of forest decline as regards stocking volume, current increment and potential felling. The other project investigated stock management, production and yield of exceedingly thick timber. The studies concentrated on spruce, and spruce and fir, respectively. These tree species represent about two thirds of Austria's forests and are of even greater importance in economic terms. Therefore it was justified to restrict the investigation about forest decline to spruce. The discussion about growing stock, production, marketing and use of exceedingly thick timber concerns spruce and fir only (Senitza 1990). According to the national level of investigation, those studies address mainly the bigger forest estates, the wood processing industry and forest politicians as well.

The national database

A simulation model requires at least two types of data. Basically, reliable data are necessary so as to describe the system in its present state. Furthermore information as to the dynamics of the system is needed. Austria's national forest inventory, which has been carried out permanently for 30 years, provides the database for such a purpose (e.g. Haszprunar et al. 1987). Generally, the national inventory is established as a certain type of satellite sampling, based on a regular grid of sampling units, each being composed of four individual sample plots (Forstliche Bundesversuchsanstalt 1981). Every year a subsample of about 1,100 sampling units is investigated according to a grid with a spacing of 8.7 kilometres. The individual sample plots are defined as corner points of a square. Data concerning site features or stand characters are investigated according to stratified circular plot samples. The area of an ordinary sample is 300 m^2. In case the sample plot comprises different units of investigation (e.g. more than one category of ownership or different age classes), the plot is subdivided and all stand and site features are collected separately for each unit. The smaller plot comprises just 21 m^2 and is used to investigate the trees with a diameter at breast height (bhd) of between 5.0 and 10.4 cm. The sample trees with a bhd above 10.4 cm are selected by using the relascope technique, where a counting factor of 4 is applied. Thus, the collected stand and site data are proportional to the area, whereas the features of the sample trees are weighted by the basal area. Because of those different ways of sampling, there do occur major problems in adjoining tree characteristics to certain site and stand features as needed for some special purposes.

As to forest dynamics, any simulation had to rely upon the comparison of temporary samples until recently. Each period of investigation lasted ten years. As there always do occur some changes in the guidelines for sampling from one period to the next one, those data derived from the comparison of successive sampling periods was hardly suited for modelling forest dynamics. By switching the sampling technique to permanent sampling units, the statistical validity of the information about changes was improved considerably. Since 1985 the permanent sampling plots as well as the individual sample trees are reinvestigated every five years. Changes such as fellings and increment can therefore be documented at a much higher level of accuracy than before. Thus, according to the sampling technique of the respective period of investigation, the accuracy of the data is quite different and specific problems of data-processing have to be overcome.

The basic dataset for forest simulation

Basically, there are two different ways of modelling in forest simulation. Most commonly, the growing stock is divided into age classes. In this context, the area belonging to the individual age class is an important measure. Each age-class is then described by mean characters such as stocking volume per hectare or average stand density. Such an approach was used along with the investigation of forest decline. Fig. 1 shows the age class distribution for spruce in Austria. In order to achieve this result, the estimations for the growing stock were stratified according to age classes and adjoined to the measures of the area. Furthermore, separately recorded unstocked areas of forest land due to gaps in the stands were allocated to the individual age classes proportional to their measure of area. The dynamics of the forest system then depend on the probability of transition from one age class to the next one.

The second approach to forest simulation renounces from the information about the area. Instead of this, diameter classes are defined as units of investigation, the main characteristics for each diameter class being the total number of trees and the average tree volume. The age class distribution may thus be replaced by the distribution of stem numbers. According to the specific goal of the investigation, this approach was used for modelling the production of exceedingly thick timber. Fig. 2 shows the distribution of the growing stock according to diameter classes. Due to the high volume of the thick trees, this graph reveals quite more information about the structure, than do the curves of stem numbers. Thus, not only the total amount of volume, but also the structure of the growing stock is of great importance.

In making a decision about the level of simulation, two aspects have to be taken into account. On the one hand, any subdivision of the original database diminishes the statistical quality of the data. On the other hand, the grouping variable might be an important factor as to the dynamics of the forest. Forest decline is not very likely to depend on the category of ownership. Therefore we regarded the total of spruce in Austria. As for production and management, the structure of the growing stock gives empirical evidence for major differences between those three units distinguished by the national inventory (estates up to 200 hectares, estates bigger than 200 hectares and National Forests). For instance, the small estates have just a low share of thick timber, whereas the bigger ones and especially the National Forests typically comprise greater percentages of high diameter classes. We therefore simulated the production and harvest of exceedingly thick timber simultaneously for those categories of ownership. By choosing them as units of investigation the simulations provide more specific results. As far as there is empirical evidence for it, the respective predominant guidelines for management actions can be depicted in the model.

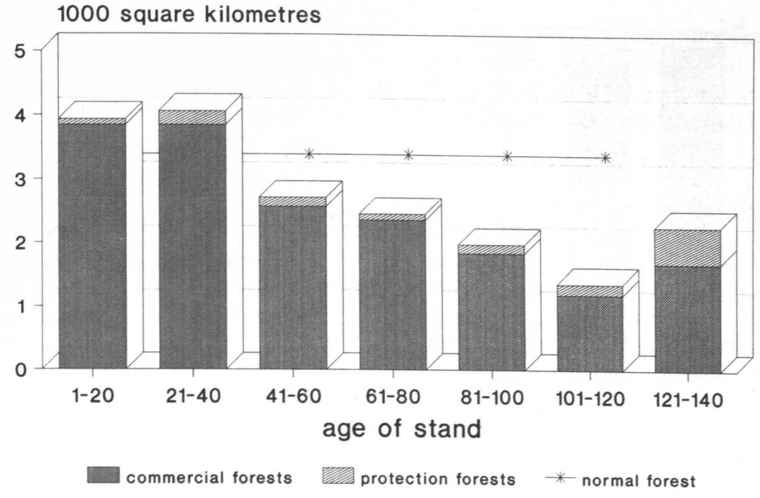

Fig. 1. Age class distribution of spruce.

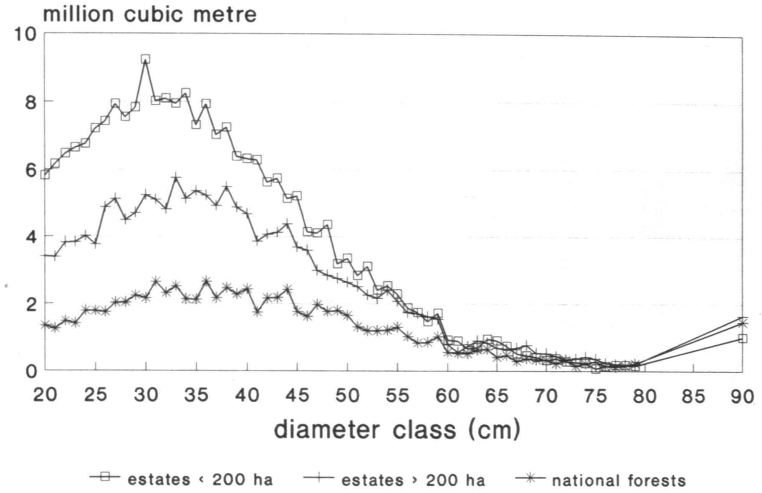

Fig. 2. Growing stock of spruce and fir.

Establishing the database for specific items

Besides such basic data about volume distribution, the purpose of the simulation usually asks

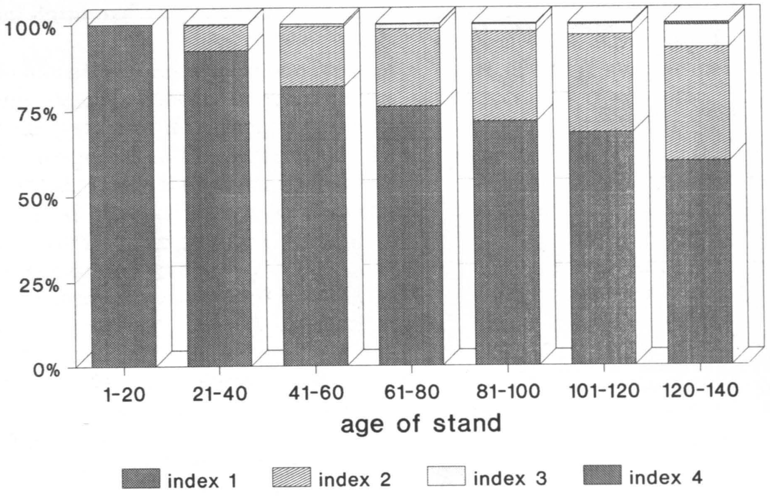

Fig. 3. Index classes for loss of foliage.

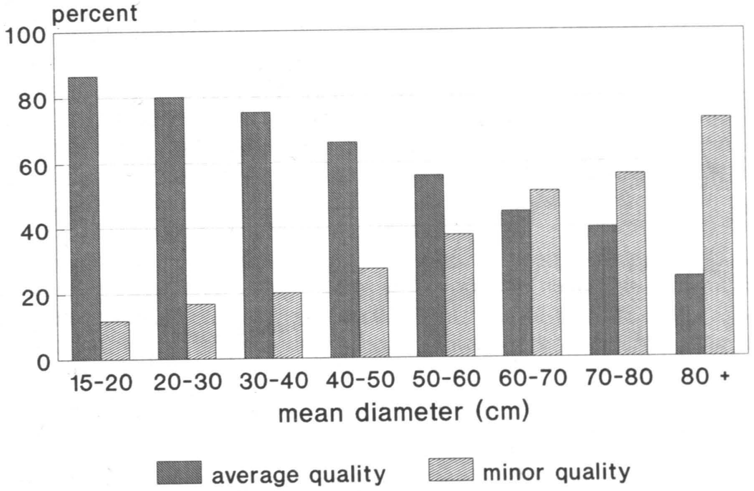

Fig. 4. Quality of timber assortments.

for further characteristics to be included in the model. As for the investigation of forest decline, the distribution of crown parameters is of vital importance (Fig. 3). Such information could not be obtained from the national inventory itself. But in 1985 a special, national monitoring system was established in order to investigate forest decline (Forstliche Bundesversuchsanstalt 1985a). We could therefore rely upon the primary data of this sample, too. Statistical analysis of the survey data revealed a highly significant correlation between the share of each index class and the age of stand. The best fitting regressions are given below (index 1 - no damage –> index 5 - dead):

$$\text{Index 1 (\%)} = 158.75952 - 19.74832 \cdot \ln(\text{age}) \quad (1)$$
$R^2 = 0.93$

$$\text{Index 2 (\%)} = -24.26588 + 11.31311 \cdot \ln(\text{age}) \quad (2)$$
$R^2 = 0.76$

$$\text{Index 3 (\%)} = \exp(-0.18556 + 0.014066 \cdot (\text{age})) \quad (3)$$
$R^2 = 0.98$

$$\text{Index 4 (\%)} = \exp(-0.40455 + 0.0065259 \cdot (\text{age})) \quad (4)$$
$R^2 = 0.86$

Including a proportional adjustment, it was thus possible to allocate fairly good estimates of the proportion of index classes to each age of stand. In this way, the simulation could be based on a complete description of crown classes derived from empirical data. This feature does not only describe the growing stock in its present state, but it is also of great importance as regards the simulation of transition.

The quality of timber assortments is another example for additional information to be used in the course of simulation (Fig. 4). This data could be derived from the national inventory only by referring to the original database for each sample tree. The trees were assorted according to a grading rule. Afterwards the quality index of the stem was related to all its respective assortments. The results confirm once more, that the data about volume are not sufficient for profound economic considerations. For instance, it is quite a remarkable result, that there is a strong, positive correlation between the diameter of the assortment and the share of minor quality. This indicates, that the problems in marketing exceedingly thick timber are not just technical ones, they are brought about by qualitative aspects as well.

We may conclude from this, that the availability as well as the reliability of specific information about the system in question is of vital importance as to the quality of the simulation model itself. Such data is needed in order to describe the state of the system properly. Otherwise the model would lack important features and therefore it might be insufficient as to the purpose of the investigation. Thus, establishing the data set is one of the most important stages of modelling.

Forest dynamics: assessing the increment

Only if the database meets all the vital requirements as to the static description of the forest system, it may be proceeded to modelling the processes underlying the dynamics of the system. Yield tables are a valuable instrument for simulating forest growth and many applications rely on them. Anyhow, it has to be kept in mind, that they themselves are just specific models. Before implementing them into a simulation model, their validity as to the system in question should be checked whenever possible. Those investigations may bring about quite astonishing results. Fig. 5 gives an example for a good fitting model. In this case, which was of some importance for our decline study, the top height of every age class could be approximated well by the curve given for one average yield class (Marschall 1986). Although the yield table fitted well for this single parameter, its use for the assessment of the increment might mislead. As shown in Fig. 6, there do exist quite significant differences as to the rate of increment between the data derived from the inventory and those of the yield table model. Especially for higher age classes, the yield table gives a severe underesti-

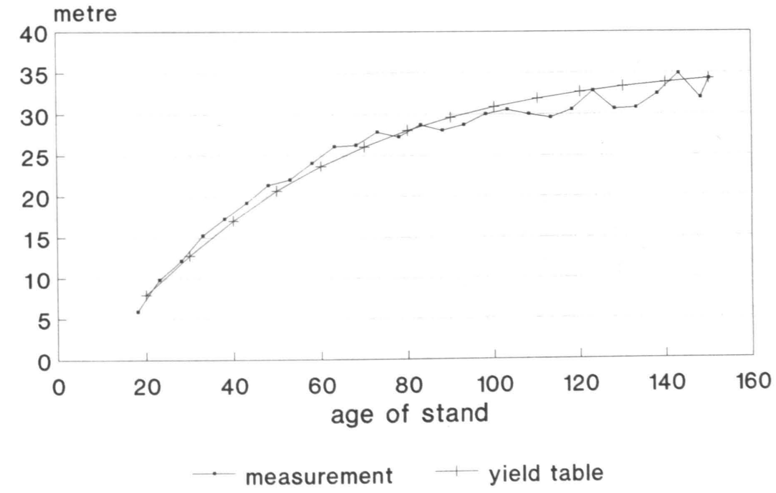

Fig. 5. Average top height of spruce.

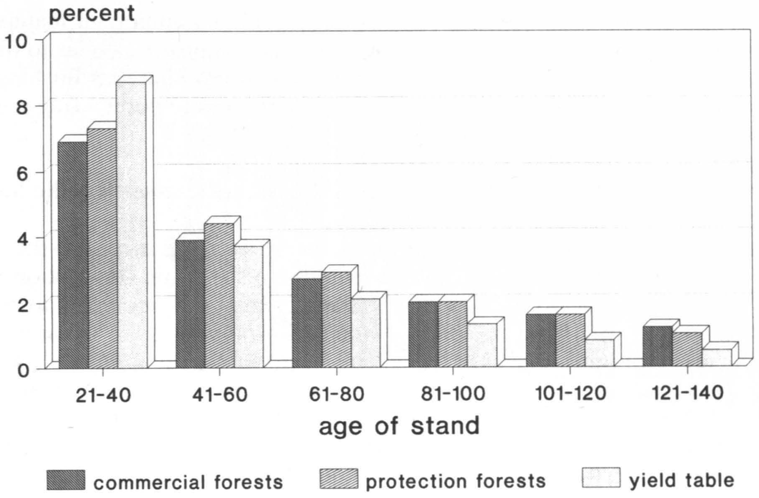

Fig. 6. Rate of increment.

mation of the current increment (Sekot 1990a). Therefore, one should always rely on a special analysis of the empirical data whenever possible.

For use in our forest decline study, the increment was to be simulated for every age class. Based on the empirical data of the increment of diameter and height, a regression equation giving the volume increment percent as a function of the age of stand was calculated. The following equation was used for calculating the increment percent (IP):

$$IP\ (\%) = 20.793397 - 4.140529 \cdot \ln(\text{age}) \qquad (5)$$
$$R^2 = 0.99$$

In the course of simulation the volume of the next period was estimated simply by applying the increment percent to the given measure of the growing stock within each age class.

In the case of our second study, not the productivity of age classes but the diameter increment of every diameter class was to be assessed. Usually, yield tables do not supply such information, as they neglect the diameter distribution and give just the data for the mean-tree. In order to describe the increment properly, some special analysis had to be carried out. This was possible by referring to the complete data set of the national inventory. As every sample tree has been remeasured after five years, various increment functions could be calculated. As revealed by a large number of such regression analyses, the documented site features do not contribute remarkably to the fitting of the increment functions. For the purpose of the simulation it was intended to estimate the increment as a function of the mean biometrical data of each diameter class. Finally, the increment of volume was calculated in two steps. In the first step the diameter increment is derived from a linear function using just the diameter as independent variable. Applying a volume function to this new diameter, the new volume is estimated. The analysis of the sample data supplied the following regressions for the three units of investigation (BHD(2) - diameter at breast height after one period of increment; V - volume):

estates < 200 ha:

$$BHD(2) = 20.494933 + 1.004512 \cdot BHD(1) \qquad (6)$$
$$R^2 = 0.98$$
$$V = 0.102557 + 8.613537 \cdot 10^{-6} \cdot BHD^2 \qquad (7)$$
$$R^2 = 0.97$$

estates > 200 ha:

$$BHD(2) = 16.702474 + 1.001674 \cdot BHD(1) \qquad (8)$$
$$R^2 = 0.99$$
$$V = -0.07585 + 9.692238 \cdot 10^{-6} \cdot BHD^2 \qquad (9)$$
$$R^2 = 0.99$$

National Forests:

$$BHD(2) = 16.775290 + 1.001445 \cdot BHD(1) \qquad (10)$$
$$R^2 = 0.99$$
$$V = -0.06054 + 9.773839 \cdot 10^{-6} \cdot BHD^2 \qquad (11)$$
$$R^2 = 0.97$$

Forest dynamics: modelling forest utilization

Apart from the increment, the cut is a major factor of forest dynamics. Along with the investigation of forest decline the total cut for the next 40 years was to be estimated. According to the national level of investigation, those cuts had to be assumed somehow, the sole information for every year of the simulation being the structure of the growing stock. Therefore, the potential yield as well as the average annual cut was estimated. As shown in Fig. 7, the estimation of potential yield shared the upper boundary with another calculation, published by the Forest Research Institute (Forstliche Bundesversuchsanstalt 1985b). As to the level of cuts, it had to be taken into account, that the official reports are usually biased as to the contribution of the smaller estates. Regression analysis proved incidental fellings to be the most important parameter affecting the annual cut, being restricted to those factors, that can be predicted themselves using only the information about the growing stock as database. This investigation was based on a period of 10 years, as shown in Fig. 8. Ultimately, the

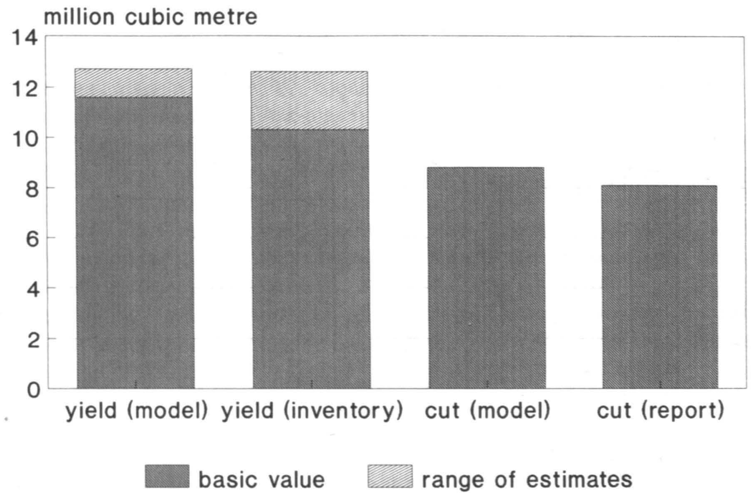

Fig. 7. Potential yield and annual cut.

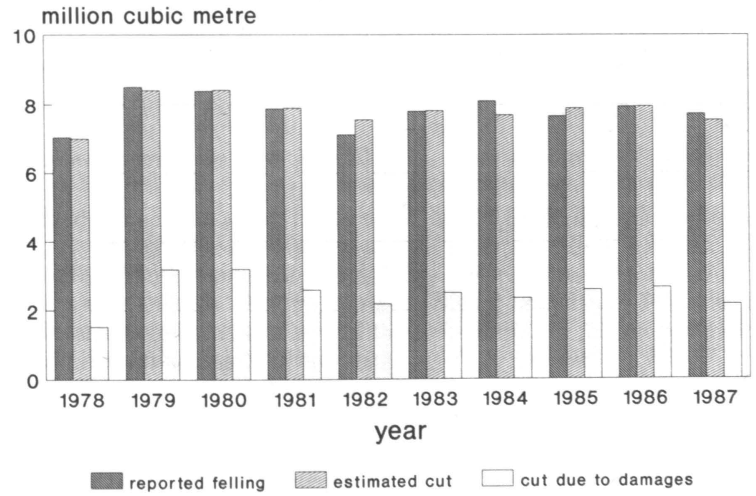

Fig. 8. Validity of the cutting module.

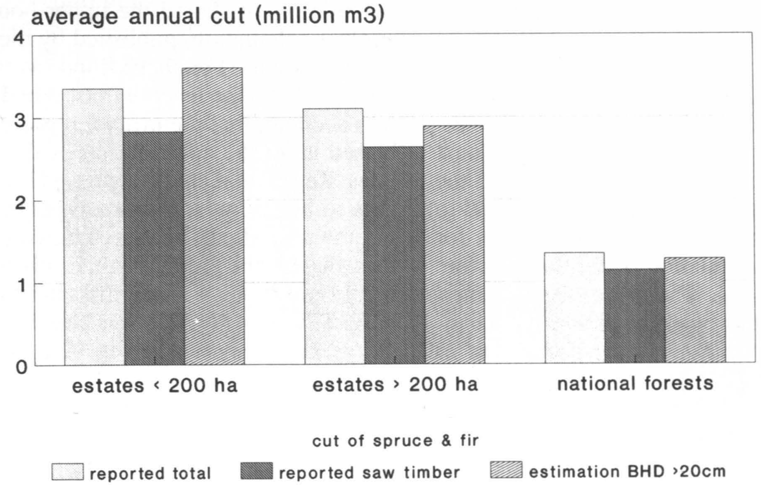

Fig. 9. Inventory based assessment of cuts.

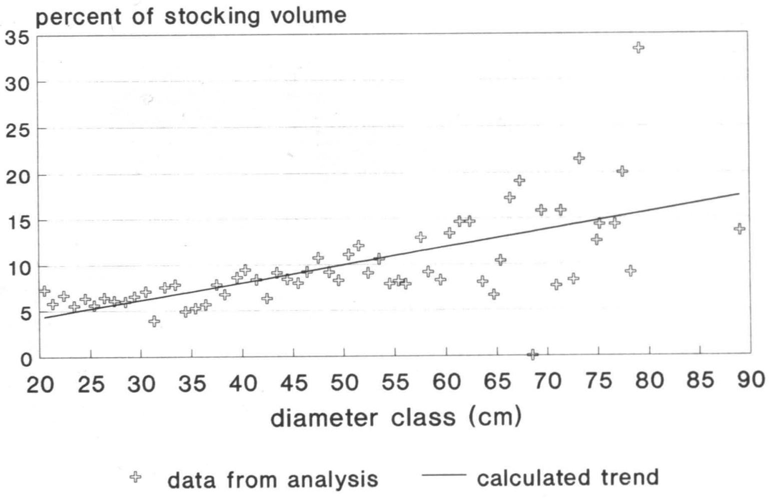

Fig. 10. Utilization percent for five years.

cutting module comprised an estimation of the incidental fellings according to the respective age class structure and a supplementary equation for assessing the total cut. The equation for the total cut of spruce runs as follows:

$$\text{cut} = 5738000 + 0.833095 \cdot (\text{incidental felling}) \quad (12)$$

An alternative approach would just assume a certain percentage of the potential yield for estimating the total cut of every year. But in such case it would not have been possible to depict the effect forest decline might exert on the total cut beyond mortality itself.

As regards our second investigation, various cutting regimes were to be investigated, the goal of the simulation being the assessment of output and growing stock of thick timber as influenced by the cutting behaviour. For the period from 1981 to 1990, the total cut of spruce and fir with a diameter exceeding 20 centimetres could be calculated from the removals of sample trees. The results of such analysis could be confirmed as shown in Fig. 9. As to the estates bigger than 200 ha and the National Forests, the value figures within the expected range given by the figures of the annual report of cuts (Bundesministerium für Land- und Forstwirtschaft 1991). Those official statistics quote only the total cut and the cut of saw timber for the tree species in question. The fellings with a diameter exceeding 20 centimetres should be less than the total cut. On the other hand, they were expected to exceed the reported cut of saw timber as those trees comprise also some pulpwood whereas the smaller ones would not give much saw timber. Even the value for the estates smaller than 200 ha corresponds with the expectation, the official statistic being known to give an underestimation.

The allocation of fellings is a major problem of forest simulation. Simple models just assume that fellings proceed from the oldest age class or the biggest diameter respectively. For special needs, such a simplification could cause a major bias. Another way of allocation gives the probability of felling for each unit of the system (age class or diameter class respectively) (Suzuki 1983, Möhring 1986). In case of our decline study the distribution of such Gentan-probabilities for all age classes had to be assumed, the lower boundary being the level of incidental fellings. At least those assumptions are consistent and should be quite realistic. The volume of thinnings up to the age of eighty years was estimated according to the extraction percentages (EP) derived from the yield table and following the equation:

$$\text{EP}\,(\%) = 92.34683 \cdot (\text{age})^{(-1.1449)} \quad (13)$$
$$R^2 = 0.99$$

Beyond the age of stand of eighty years the probability for final cutting (FC) was assumed by using the following type of equation:

$$\text{FC}\,(\%) = 1\,/\,((\text{maximum age}) - (\text{age of stand})) \cdot 100 \quad (14)$$

Along with our second investigation the allocation of the fellings to the diameter classes was based on an analytical approach. The permanent inventory provides the data for such analysis as shown in Fig. 10. According to the regression functions, a utilization percent for each diameter class can be estimated. Along with this you have got the information about the probability of transition as required for establishing the Markov-chains for the simulation. This empirical data being the reference, a set of scenarios for different levels of total cut (+10 %, +20 %) and cuts of exceedingly thick timber (+25 %, +50 %, –25 %) were calculated.

Risk analysis

Another, commonly used simplification in forest simulation is the neglect of risk. In fact, forest production is threatened by various hazards (Lohmander 1987). As to mortality, the effect can be a decrease in stand density and therefore also in productivity for all the time left till maturity. In case entire stands are affected by mortality, the effect can be depicted as a clear-cut area where a new stand is to be established. A special risk analysis based on the National Forest's annual summary of major produce supplied empirical evidence as to the influence of the age of stand on mortality (Fig. 11). Furthermore, the contribution of the different risks to total mortality is also related to the age of stand (Sekot 1990b). Whereas snow proved to be the dominant risk in young stands of spruce, older ones are threatened mainly by windfall. Nevertheless, the age of stand is not the only parameter of importance to be kept in mind when modelling the risks of production. A specially established dataset provided by the National Forests even allowed the investigation as to the relation between the stand density and the risk of windfall. For this purpose, the data of the annual summary of major produce had to be adjoined to the information of the respective stand description as recorded by the forest management. According to the diagram given in Fig. 12, there is a maximum of risk at stand density 0.7 and 0.8. In case there is sufficient information about the distribution of the stand density within the age classes, those relations ought to be included in the model.

Forest decline adds another hazard to the risks of production, its primary effects being a reduction of current increment or even sudden mortality. In fact, our decline study aimed at modelling those effects, based on scenario writing according to various assumptions as regards further deterioration. As mentioned before, the present state of damages is indicated by the loss of foliage as assessed by the Austrian national survey. A special study provided a quantitative relationship between the index classes of damage and the decrease in current increment (Eckmüllner 1988). According to this study, the loss of increment is related to the crown index as shown in

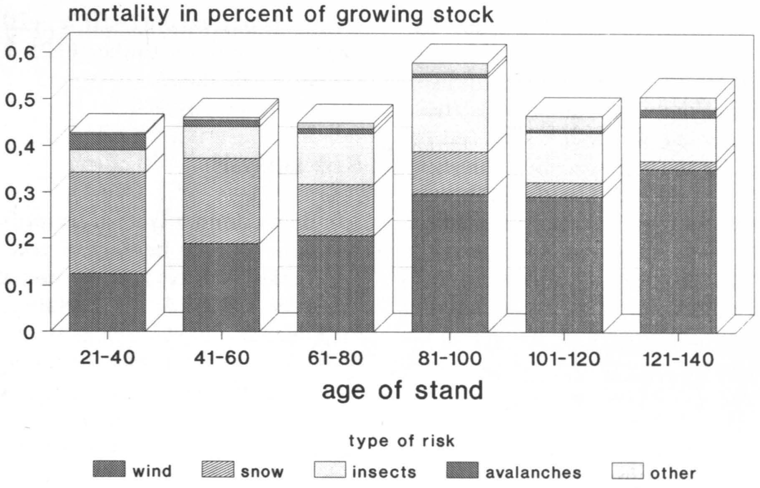

Fig. 11. Hazards of forestry production.

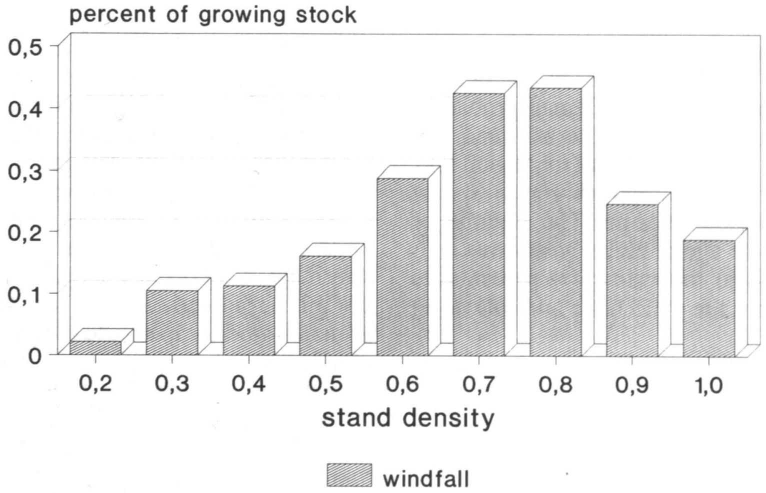

Fig. 12. Risk analysis for spruce.

Table 1. This data was sufficient to describe the present state at the beginning of the simulation period.

In order to simulate the dynamics of forest decline probabilities as to the transition of crown characteristics were to be estimated. The survey being a permanent inventory, the rates of transition as influenced by the age of stand could be calculated. Generally, three types of transition were distinguished, namely improvement, equality and deterioration. According to the limited data available, a distinction of sub-types would call in question the statistical analysis. The functions derived from this analysis are sufficient so as to set up a status quo scenario. In this case, unchanging conditions of transition are assumed. Thus, the distribution of index classes is being affected just by the time elapsing. The following equations were used so as to estimate the probability of transition be it equality (E), deterioration (D) or improvement (I) of the crown classes (1 - no damage –> 5 - dead):

Table 1. Loss of increment as indicated by defoliation index.

Crown index	Loss of increment
1	0 %
2	9 %
3	26 %
4	54 %

$$E(1) = 110.03424 - 6.16422 \cdot \ln(\text{age}) \qquad (15)$$
$R^2 = 0.41$
$$E(2) = 30.22900 + 0.17644 \cdot (\text{age}) \qquad (16)$$
$R^2 = 0.88$
$$E(3) = 12.71026 + 0.24946 \cdot (\text{age}) \qquad (17)$$
$R^2 = 0.68$
$$E(4) = \exp(1.38180 + 0.52504 \cdot \ln(\text{age})) \qquad (18)$$
$R^2 = 0.22$
$$D(1) = \exp(1.17580 + 0.38096 \cdot \ln(\text{age})) \qquad (19)$$
$R^2 = 0.45$
$$D(2) = \exp(0.65829 + 0.01021 \cdot (\text{age})) \qquad (20)$$
$R^2 = 0.88$
$$D(4) = 136.99786 - 26.10014 \cdot \ln(\text{age}) \qquad (21)$$
$R^2 = 0.51$
$$I(2) = 72.20071 - 0.25059 \cdot (\text{age}) \qquad (22)$$
$R^2 = 0.90$
$$I(3) = \exp(4.54414 - 0.0049417 \cdot (\text{age})) \qquad (23)$$
$R^2 = 0.65$

For the probability of deterioration from index class 3 as well as for the probability of improvement from index class 4 constants had to be used, the regression analysis being not able to prove any influence by the age of stand. Apart from the status quo scenario, each further simulation is determined by an additional, general trend of deterioration between 0.25 % and 1.0 % per year. In this context, several linear as well as periodical non-linear trends describing the dynamics of forest decline were investigated. The further modifications of the model concentrated on the following features:

- general decline of increment: linear change of the relationship between crown index on the one hand and increment on the other hand
- rate of mortality: linear increase of 0.25 % per year
- cutting behaviour: depiction of sanitary fellings by increasing the probability of cutting for index classes 3 and 4 twofold and twentyfold respectively

Results and conclusions

As to annual increment and stocking volume, the results of those forest decline scenarios do not appear to be alarming. Even according to the worst scenario, the growing stock will continue to increase for at least 20 years. The potential yield too is likely not to decrease within the next 2 decades, as indicated by Fig. 13. Those non-catastrophic scenarios would bring about a ma-

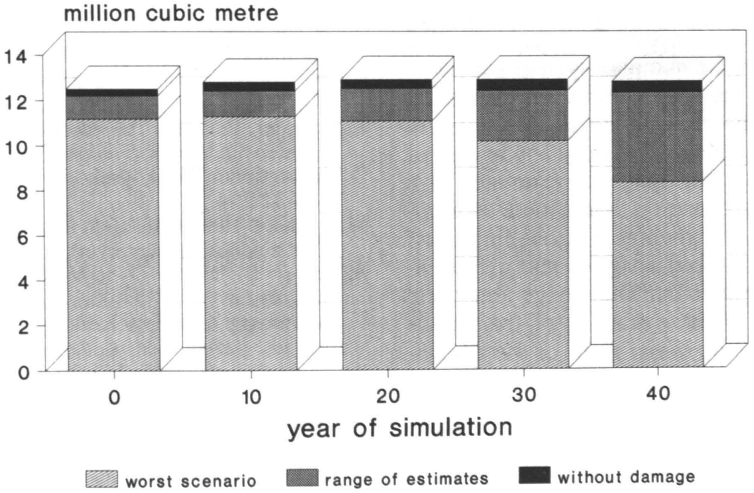

Fig. 13. Outlook on estimated potential yield.

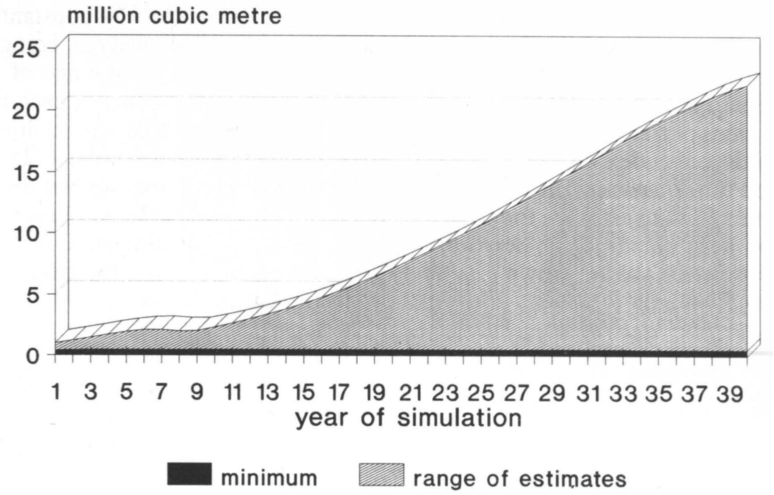

Fig. 14. Mortality due to forest decline.

jor decline only in the long run. But even if the growing stock is still increasing, at least the incidental fellings due to mortality may bring about major problems for forestry and timber trade (Fig. 14).

As to the production of exceedingly thick timber our simulations indicate, that this part of the growing stock is still going to increase considerably. Even a general increase of total cut by 20 % combined with a concentration of cuts in the higher diameter classes would result in a duplication of growing stock with more than 50 cm dbh.

Anyhow, those scenarios must not be misunderstood as forecasts at a certain level of probability. Their main function is to enhance our understanding of the complex system we are in charge of. They serve as a device for estimating the effects of any expectation as to the future conditions. For strategic decisions and in case of great uncertainty, the range of estimates is a more valuable information than a mere assumption. Moreover, the attempt of modelling itself usually triggers various analyses and investigations, which improve our knowledge about and comprehension of the dynamics of the forests often far beyond the initial goals of the simulation.

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