OFSIM: A Simulation on Dynamics of Size-Class Distribution of Forest Stand

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Abstract. OFSIM (Object-oriented Forest SIMulator) is a forest stand structure simulator for management purposes, written in object-oriented programming C++. This application for modelling forest management at the stand level has potential application for exploring several kinds of management strategy and possible extension into estate modelling, which is implemented in OFSIM. The computational aspects of simulation with OFSIM has two types of object : (i) physical objects in the forest to represent an abstraction of modelling in forestry such as Pines, Thinning and abstraction in forest financial analysis; (ii) computational objects to represent the abstraction of several numerical techniques for dynamics of size-class distribution of forest structure. The material presented here, however, is a description of the simulation models, their working mechanisms and implementation. The percentile-index function for radiata pine from several forest experiments in New Zealand has been implemented in the simulation model and further model developments and their programming implementation on OFSIM have been described.

Keywords : object-oriented simulation, forest stand, size-class distribution , difference equation.

1. INTRODUCTION

There have been two distinct dominant strands in modelling forest stand dynamics; the first is a 'process' strand [e.g. Mäkelä, 1986; West, 1993], which seeks a model with meaningful parameters; the second, a 'statistics' strand [e.g. Knoebel and Bukhart, 1991; Garcia, 1983], deals with accuracy and practicality in data collections. The methods of modelling forest stands that are discussed here are of the latter strand and useful for stand management purposes. Several simulation programs for forest growth and yield modelling and management have been developed and implemented in New Zealand: (i) StandPak [NZFRI, 1993] for stand level modelling which was written in C; (ii) RMS 2020 [Allison, 1991] for estate modelling which was written in Fortran; and (iii) CNI IGM (Central North Island Initial Growth Model) written in Prolog by Mason [1992] for stand level modelling. All of these predict growth with different emphasis and application. Re-creating entirely new software such as that listed above can be costly and of unknown quality. Object-oriented analysis for forest stand simulation provides a mechanism that captures the physical and computational objects of a model. Formulation of these aims to improve the running and comprehension of systems, the complexity of which exceeds the intellectual capacity of developers [Booch, 1986]. The advantage of designing the kind of object-oriented software presented here is its versatility for a wide range of modelling applications in forest management. The simulation developed has been made as versatile as possible for stand or estate forest modelling levels, so that it is possible to implement several applications and form responses to silvicultural treatments involving risk analysis, such as stochastic modelling of wind-throw.

2. OVERVIEW OF OFSIM

OFSIM is a forest structure simulator for management purposes, using object-oriented programming in C++. OFSIM is a development and extension of object-class library software reported by Koesmarno, et al. [1994a; 1994b]. The object-oriented programming language C++ was selected for OFSIM due to the availability of a wide range of libraries or tools which can: (i) continuously keep the object modelling and C++ programming up-to-date; (ii) provide object modelling view management, including view control in the C++ construct, regular expression, proximity, layer or directory, and so on. OFSIM was developed initially for providing a library of classes; their applications and functions are developed from the recent innovative analytical tools for modelling stand structure and stand growth developed by the first author and presented in related papers. This class library is useful for the investigation of computational techniques, especially for modelling and simulating of forests at the stand level, though these other ones seem promising for further development and extension in the future. The possible interactions of OFSIM with other software such as a knowledge-base or any expert system shell, a Forest Management Information System (FMIS) or a Geographical Information System (GIS) via object linking embedding or via dynamic data exchange also encourage further development of this software.

OFSIM, a modelling shell for forest management simulation has the following objectives .
(i) Exploration of a wide range of forest stand management strategies. A forest management and simulation environment aims to assist managers and planners to explore a wide range of

management strategies such as the effect of silvicultural treatments, long range wood supply potentials or the economic advisability of supplying certain quantities of timber to existing processing plant(s) over time from single stands or from within regions. Software tools like this provide rapid prototyping of new forestry applications.
(ii) Application to several stages of growth. This modelling is based on a generalization of notional forest stands, as most management practices in an individual company or location relate to different policies. The main forms of a development like this is modelling the growth, size-class distributions and thinning treatments which may apply. Hence, this simulation environment can be regarded as a forest stand management shell.
(iii) Stochastic simulation modelling. Risk or uncertainty analysis of the events that may occur during a crop rotation, such as wind-throw and fire, should be easily implemented in the simulation software.
(iv) Application to several types of stand or forest modelling. The object-oriented paradigm can be applied to a wide range of applications in modelling monocultures, mixed species, even or uneven-aged stands and forest estate modelling that distinguishes growth at the stand and estate level, with considerable reuse of existing code.

3. COMPUTATIONS IN OFSIM

A technique for simulating the dynamics of size-class distributions of forest stands involves utilizing percentile-index equations to represent the nature of size-class distributions of trees at a stand level for individual treatments over time. For example, the parameters of the reverse Weibull distribution can be obtained using a percentile interval technique. The model parameters (percentile indices) presented in this section were obtained from forest experiments of radiata pine in New Zealand. The qualitative (non-quantifiable) and quantitative treatment levels have been represented by data from young stands in response to vegetation management treatments and to thinning to varying densities during the period of sigmoid growth, as explained in the next section. The segmentation of sigmoid growth equations [Koesmarno, 1994] is often very useful for the analysis and modelling such as young growth [Belli and Ek, 1988; Mason, 1992]. Transformation of distributions as a consequence of mortality or thinning that shows bias toward size-classes and the correlated distributions of height and diameter are also implemented. Log-assortments can be obtained from these distributions, so that their corresponding volumes and net revenues can be evaluated.

The implementation of the model for describing dynamics of size-class distribution and incorporation of financial analysis into OFSIM are illustrated in this section. The sketches of the classes and methods of object-oriented C++ are described, though they are now further developed or under refinements. The name of each class or object is given in italics.

Consider the percentile-index growth model of a polymorphic log-reciprocal equations with random thinning to various densities. As the prediction is for a radiata pine stand, the method must be implemented in the programme's class *Pines* as:

void *Pines*::DBH_Growth(double time, Parameter p), which denotes the contents of the following formula:

$$x(S,t) = S^{\left(\frac{25}{t}\right)^{\gamma}} \exp\left[\alpha_i\left(1 - \left(\frac{25}{t}\right)^{\gamma}\right)\right]$$

γ and α_i of the polymorphic log-reciprocal for seven levels of thinning and the percentile-index (S) were taken at stand age 25 years, x is DBH and t is time. Other numerical forms of model such as Hossfeld and the young crop model used by Belli and Ek [1988] can be applied similarly. Once the percentile-index curves were obtained, the DBH at several percentiles are used for estimation of the DBH class distribution using a percentiles algorithm which is implemented in class *PercentileInterval* e.g. void *PercentileInterval* ::PctlsAlgorithm(.....) which comprises step 1 to step 3 described below.

Generally, the Weibull and Reverse Weibull cumulative distribution functions have mirror images so that their formulations can be similarly derived. The following location (a), shape (c) and scale (b) parameter formulae utilizes percentiles (x_p) and percentile interval (Ω) techniques for their derivation.

Step 1. The location parameter [Bailey et al.,1989, Da Silva, 1986 and Knowe et al., 1992] can be approximated as:

$$a = (n^{1/3}x_{0.0} - x_{0.5})/(n^{1/3} - 1)$$

This was obtained by solving simultaneously for the minimum and 0.5 x 100th percentile observation from a sample of size n from a Weibull distribution, respectively $x_0 = \alpha + (\beta/n^{1/c})\,\Gamma_1$ and $x_{0.5} = \alpha + \beta\,[-\ln(0.5)]^{1/c}$ where the gamma function is $\Gamma_k = \int_0^\infty t^{\frac{k}{c}} e^{-t} dt$. The mirror image applies so that the reverse distribution gives:

$$a = (n^{1/3}x_{1.0} - x_{0.5})/(n^{1/3} - 1)$$

Step 2. The shape parameter [Dubey, 1967] when the location parameter is introduced for the Weibull and reverse Weibull can be expressed respectively :

$$c = \{\ln(-\ln(1-pa)) - \ln(-\ln(1-pb))\} / \{\ln(x_{pa} - a) - \ln(x_{pb} - a)\}$$
$$c = \{\ln(-\ln(1-pa)) - \ln(-\ln(1-pb))\} / \{\ln(a - x_{pa}) - \ln(a - x_{pb})\}$$

Dubey shows that the variance is minimum for the selected value of pa = 0.16730679 and pb = 0.97366352. For practical reasons, pa = 0.15 and pb = 0.95 are used in this simulation.

Step 3. The scale parameter is based on solving the following f(c) and λ (percentile), respectively:

$$f(c) = \left(1 - \frac{1}{c}\right)^{\frac{1}{c}}$$

$$\lambda = \exp\left(-\left[\left(1-\frac{1}{c}\right)^{\frac{1}{c}} - \frac{\Omega_l}{b}\right]^c\right) - \exp\left(-\left[\left(1-\frac{1}{c}\right)^{\frac{1}{c}} + \frac{\Omega_u}{b}\right]^c\right)$$

The three steps described above can be used to estimate the parameters of the Weibull and Reverse Weibull distribution functions. The initial value used for solving the nonlinear equation is $\psi\, x_m\, (1-1/c)^{1/c}$ for $0.3 \le \psi \le 1.2$; where the constant ψ depends on the data set and x_m = mode.

The sequence of execution in method of percentile-index curves and the estimation of the parameter distribution involve obtaining the parameters of random thinning for the percentile-index function, void *Thinning*::RandomThinningDensity(....), generating the x_p from the percentile-index, void *Pines*::DBHGrowth(...), and then estimating the parameter, void *PercentileInterval*::PctlsAlgorithm(..). This sequence of execution can be encapsulated in the DynamicsDistr(...) of class *StandSimulation*.

Transformation of size-class distributions [Koesmarno *et al.*, 1994b] of forest stands after thinning involves a reduction of a portion of the size-class percentile distribution which can be characterised by a reduction in the size-class percentile function (rcf). The rcf can be utilized to transform the percentile (λ), so that reconstruction of the distribution after it has been reduced or augmented can be solved without re-estimating the λ and Ω from the sample. The algorithms involve fitting rcf from data and transformation of λ or Ω for reconstructing a distribution. The principle and techniques for reconstruction of a distribution which utilizes percentile intervals have shown promise for many applications. The technique demonstrates an advance on the utilization of parameter estimation using percentile interval [Koesmarno et al., 1994a] over other methods such as method of moments [Bailey and Dell, 1973; Dubey, 1967]. Although the non-linear reduction rcf may fit better than the linear rcf, however, the linear reduction [Kuru, 1992] may be useful for (i) characterizing the application due to its simplification, e.g. modelling the thinning of forest stands; and (ii) analytical solutions for size-class percentile transformation.

When the structure of the stand is reduced bias in representing either the smaller or larger tree sizes, then reconstruction of the percentile index is required. The transformation method is organized in class *Reconstruction* [Koesmarno et al., 1994b]. The thinning residual can be calculated in class *Thinning* and utilized in the method, through transformation of class reconstruction. void *Thinning*::Remain(...) involves executing the methods Transformation(..) of class *Reconstruction* and EffectsOfThinning(...) of class *Thinning*. Hence, the size-class distribution after thinning from above can be simulated using: void *StandSimulation*::DynamicsThinStructure(...) which requires execution of methods StandStructure(...) of class *StandSimulation*, Remain(...) of class *Thinning* and EstimateParameter(...) of class *PercentileInterval*.

The method can be used for obtaining log-assortments, volumes and revenues obtainable from a forest stand. Hence, several forest management strategies can be implemented in the methods above.

As money has alternative uses and a firm may well have a wealth maximization goal, so it is important to evaluate cash flows. The computation of compound interest for costs or revenues applies over the whole rotation, if the resource manager wishes to evaluate the present value of a stand, and if the expectation of the stand value and harvest time is known then the (net) present value can be obtained. If money is loaned for expenditure or maintenance of the stand in sequence and some other forest financial analysis [Clutter, *et al.*, 1983], such as effective annual rate, internal rate return, and benefit cost ratio can be utilized in the simulation.

4. SIMULATION

An example of the simulation using the methods discussed in section 3 and random thinning to varying densities using the data described by Whyte and Woollons [1991], an experiment R695 Kaingaroa forest is given. Fig. 1. shows the percentile-index curves for thinning 200, 500 and 1400 (no thinning) stems per ha and the predicted diameter at breast height over bark (DBH) size-class distribution of the reverse Weibull using OFSIM for forest stands at age 22.1 and 30 years are given respectively in Fig. 2 and Fig. 3. Fig. 2 also shows the comparison of the observational distribution and simulation results. The predicted variables at age 22.1 and 30 years which can be used as input of the algorithm for the parameter estimation of Weibull and reverse Weibull distributions in section 3 are given in Tables 1 and 2 in the appendix.

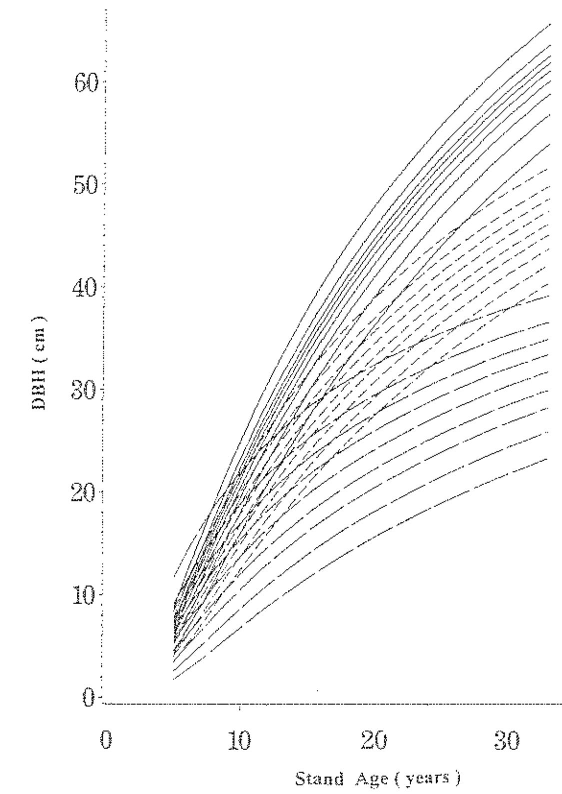

Fig. 1. Curves of indices for three treatments :
(————) random thinning to 200 stems per ha
(- - - - - - -) random thinning to 500 stems per ha
(—— —— ——) no thinning (1400 stems per ha)
with the 0.1, 0.2,..., 0.9 (x100^th^) percentiles.

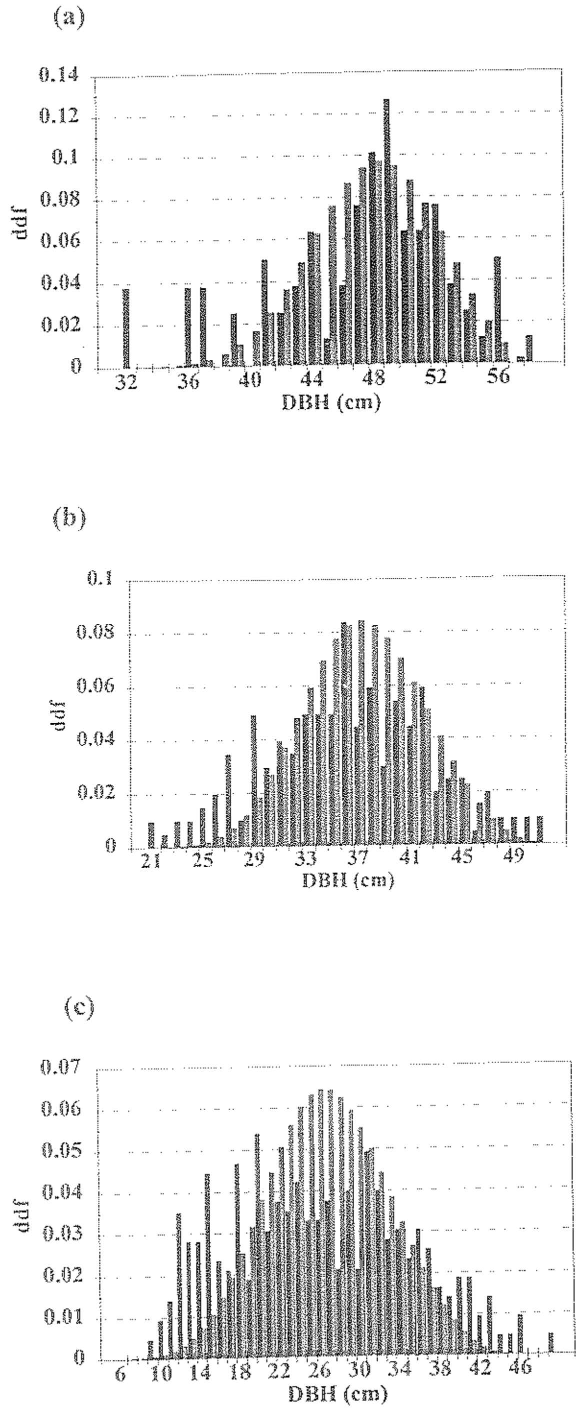

Fig. 2. Observed distribution (dark shading) and simulation results (light shading) of reverse Weibull distribution of DBH (cm) at age 22.1 years for (a) random thinning to 200 stems per ha (b) random thinning to 500 stems per ha and (c) no thinning (1400 stems per ha).

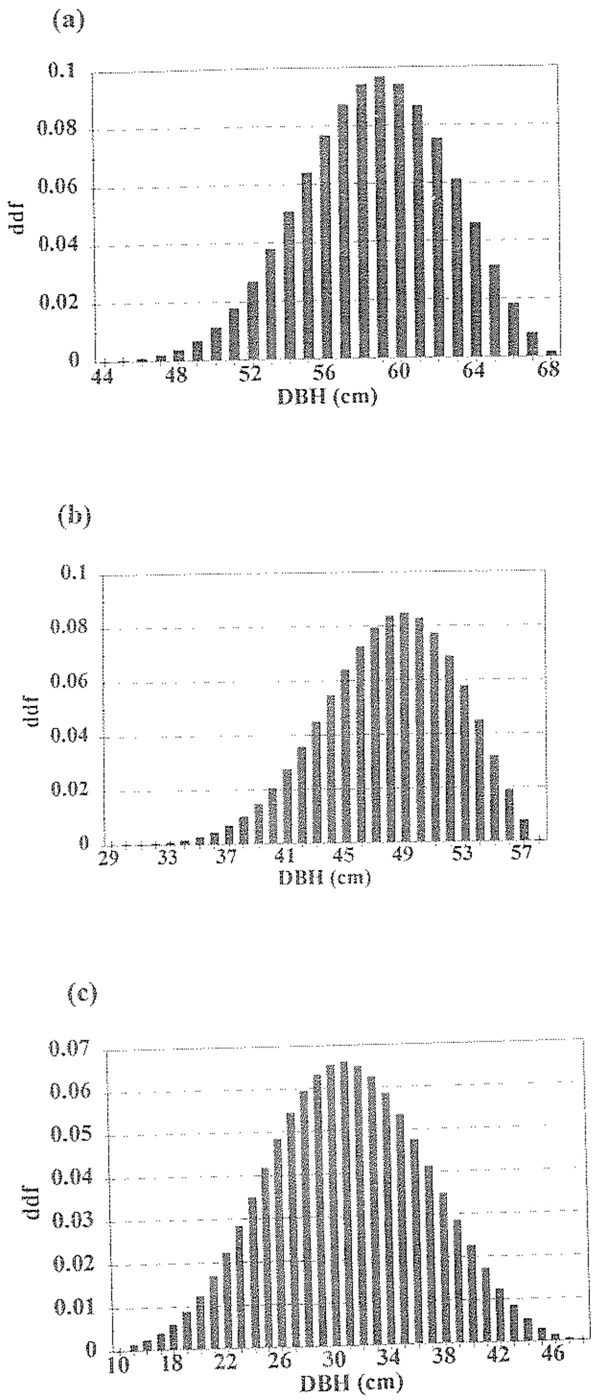

Fig. 3. Simulation results of reverse Weibull distribution of DBH (cm) at age 30 years for (a) random thinning to 200 stems per ha (b) random thinning to 500 stems per ha and (c) no thinning (1400 stems per ha).

5. CONCLUDING DISCUSSION

The computations implemented in OFSIM utilize modular data-structure programming, so that further development and application of simulation on dynamics of size-class distributions of forest structure can be practically and efficiently conducted. The computation of the simulation illustrated is based on percentile-index equations which can be constructed to represent the percentile function of the population in a stand, which is useful for constructing size-class distributions of trees at any given time. The percentile interval technique is flexible for reconstructing a distribution after thinning or mortality and for modelling the relationships between correlated size-class distributions of height and diameter. These simulation results can then be extended to obtain the volume, the log assortments, financial analysis and even combined with other software or GIS for inventory purposes. Predicting the dynamics of size-class distribution of a forest stand structure using an object-oriented approach reduces computational complexity. It is also modular and versatile for various forestry modelling applications. The models described here are based on limited data for radiata pine from several forest experiments in New Zealand. Further implementation of models using other data-bases is required for a wide-coverage of environmental and silvicultural treatments. When available, these tools will be useful for exploring a wide range of possible management strategies.

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