Techniques of Australian Forest Planning

Australian Forestry Council

Research Working Group No. 2[1]

Abstract: Computer modeling has been extensively adopted for Australian forest planning over the last ten years. It has been confined almost entirely to the plantations of fast-growing species for which adequate inventory, growth, and experimental data are available. Stand simulation models have replaced conventional yield tables and enabled a wide range of alternative strategies to be evaluated for each individual stand. Simulation models for entire plantations have been found invaluable for the preparation of 1- to 5-year cutting plans and for regulating the yield over 20- to 60-year periods. Many models have been constructed and found to be simple and highly cost-effective. Optimization models, using linear programming, have been constructed for yield regulation and found to give powerful insights into the interactions between the various alternatives available for all stands. However, these models are expensive and require considerable data and expertise. They are difficult to maintain, especially when staff change.

INTRODUCTION

This paper reviews Australian experience with the planning techniques used for plantations, and some even-aged natural forests, in the light of their potential usefulness to developing countries. Australia has a century of experience with industrial plantations of fast-growing exotic species, such as *Pinus radiata*, which have been planted extensively in developing countries in recent years. During the last 10 years, planning methods have been completely changed by the development of computer modeling techniques and it is to experience gained in this change that the paper is addressed.

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[1] Research Working Group No. 2--Mensuration and Management is one of several groups set up by the Australian Forestry Council. It consists on one or two planners from each of seven government forest services, as well as representatives from industry and universities. Members of the group are concerned both with developing new models and with the routine preparation of management plans based on their results.

The extent to which modeling has been adopted, and the type of models developed, in each region have been determined largely by the data required and available. Data collection in the mixed-species, mixed-age, natural hardwood forests is very difficult and has often not been warranted by the slow growth and low value of the stands; very few models have been built for these forests. By contrast, extensive inventory, growth, and experimental data have been collected for long periods in the single-species, even-aged, fast-growing, and valuable plantations. It has been found often that the available data did not cover as wide a range as was needed to enable models to examine new options for the future. In particular, existing inventory data has rarely been suitable for the construction of growth models. Wider ranges are being included in the designs of many new experiments.

Thorough testing of the models is of great importance and is generally done on a continual and long-term basis by comparing estimated yields with actual deliveries to mills. Several effects, such as errors of growth estimation or modeling thinnings, quantity of residues, degree of utilization and conversion factors, are confounded in such comparisons. However, adequate performance in the tests is essential for management acceptance of the forecasts made by the models.

SIMULATION OF GROWTH AND YIELD

The simulation of growth and yield with computer models has been a considerable advance on the use of standard yield tables because the effects of many more silvicultural and management options can be examined quickly, and because the individual conditions of each stand can be allowed for.

Each model described comprises several biometric functions, forecasting the development of various stand parameters, which are combined into a compatible system enabling the stand as a whole to be characterized. The key functions are those to forecast height and basal area or volume growth and to estimate the effects of tree breeding and alternative silvicultural options such as cultivation, fertilization, or thinning. Almost all these functions were constructed with data from repeated measurements of permanent growth plots and designed experiments and only a few from stem analysis or inventory data.

Some other functions, such as those describing stem form or volume, basal area, and height relationships, are also needed. Useful functions were often prepared initially by hand-drawn graphical analysis, and early modeling was based on computerized versions. Linear regression analysis has now almost entirely replaced graphical analysis. More advanced forms of analysis are being introduced such as nonlinear estimations and generalized least squares. As some extrapolation has almost always been necessary, the forms of the growth functions have had to be chosen very carefully.

There has been a gradual shift towards more intensive silviculture in Australia, as elsewhere in the world. The stands now being planted are expected to grow differently from those which provided the data for the growth functions currently used. The methodology needed to allow for this difference, the nature of interactions between effects (e.g., tree breeding and thinning), and the long-term upper limits to growth of stands grown under new conditions are matters requiring considerably more research.

Stand Simulation Model 1

Organisation	: A.P.M. Forests Pty. Ltd., P.O. Box 37, Morwell, Victoria 3840.
Information	: J.B. Dargavel
Forest	: 40,000 ha of **P.radiata** supplying a pulpmill and & a sawmill. There is a wide range of sites and there is very little land available for purchase economically.
Objective	: Generate alternative strategies for each stand for subsequent selection by optimisation model.
Time Span	: 25 years
Input	: Inventory plot data from existing computer system.
Method	: Functions constructed by linear regression from permanent growth plot data forecast height and basal area increments. Responses to fertiliser, weed control and tree breeding estimated from experiments. Volume yield by thinning and clear felling calculated by size and wood basic density classes.
Output	: Stand development, yield, cash flow for each of an average of 50 alternative strategies for each of 200 stands. Each strategy represents a different combination of 1. establishment method (2 alternatives) 2. thinning method (3 grades) 3. later fertilisation (Yes/No) 4. clear felling age (10 possible ages)
Application	: Provide input to plantation optimisation model.
Evaluation in Organisation	: Has enabled wide range of silvicultural options to be examined. Major difficulties are estimation of how stands will grow under combinations of alternatives that have not yet been tried. Research needed on interactions and upper limits to growth.
Assessment for Developing Countries	: Useful for generating yield tables. Tabular presentation of standard or example strategies necessary if immediate computer access not available. Accuracy depends on relevance of growth functions incorporated.
Reference	: Turner, B.J., Bednarz R.W. and Dargavel J.B. (1977). A model to generate stand strategies for intensively - managed radiata pine plantations. Australian Forestry 40 (4) : 255-67.

Stand Simulation Model 2

Organisation	: Queensland Forestry Department, 388-400 Ann Street, Brisbane, Queensland 4000.
Information	: B. Stark
Forest	: 38,000 ha of native conifers (predominantly **Auracaria cunninghamii**) and 60,000 ha of Pinus species, predominantly **P.elliottii** and **P.caribaea** but also **P.radiata**, **P.taeda** and **P.patula.**
Objective	: To calculate both short and long term yields, cash flows and standing volumes and values at any nominated time, for various management alternatives.
Time Span	: Short term up to 20 years and long term up to 60 years.
Input	: Inventory plot data and 1% dbh strip samples from existing computer system.
Method	: Functions constructed from inventory and experimental data forecast height and basal area increments and are used to calculate new diameter distributions. Currently the model requires the alternative strategies for any given stand from a measured sample, but in the future the model will generate the strategy, given certain broad guide lines. A wide range of alternative thinning strategies can be examined.
Output	: The model projects and thins the stand table in 1 cm dbh classes for each cutting unit producing estimates of basal area, predominant height, volumes and values. A very wide range of groupings or listings is available including time period options, stand conditions (basal area, predominant height, age etc.), size assortment by quality classes for the stand and thinnings, volumes and values for the stand or thinnings using current pricing, and tables of predominant height, volume and basal area information for direct comparison with the actual plots,giving a continuing check on the model predictions.
Evaluation in Organisation	: A plantation simulation is provided by aggregating the simulations of each stand. The resulting short term calculation (up to 5 years) has been very successful in organising logging and new sales.
Assessment for Developing Countries	: Possibly the basal area increment prediction method could be very useful to countries with young plantations and limited data.

Stand Simulation Model 3

Organisation : Woods & Forests Department,
P.O. Box 162, Mount Gambier, South Australia 5290.

Information : N.B. Lewis, A. Keeves and J.W. Leech.

Forest : 70,000 ha of **P.radiata** plantations, managed on an approximately 50-year rotation with up to six commercial thinnings, and with a comparatively even distribution of age classes.

Objective : To predict the yield of plantation stands of radiata pine from age 9'/2 site quality assessment to the end of rotation.

Time Span : 10 - 50 years.

Input : Permanent sample plots data - plots measured for volume every 2-3 years. Some plot trends exceed 40 years.

Method : Graphical methods using the directing curve technique.

Application : Incorporation in long term planning models for even-aged stands.

Evaluation in Organisation : The technique has been used successfully for over 30 years to regulate the total cut from a profitable state afforestation enterprise, keeping the cut as near sustainable maximum as possible. The model is very nearly as precise a prediction model as the best nonlinear model developed.

Assessment for Developing Countries : Advantages -
1. it is simply revised as more data becomes available.
2. being subjective, local knowledge of data relevance and accuracy can be incorporated.
3. does not need computer.
4. does not need statistical expertise.

Disadvantages -
1. precision is unknown.
2. it may be biased.

References : Lewis, N.B., Keeves, A. and Leech, J.W. (1976)
"Yield regulation in South Australian Pinus radiata plantations". Woods & Forests Bulletin 23. Adelaide.

Stand Simulation Model 4

Organisation : Woods & Forests Department,
P.O. Box 162, Mount Gambier, South Australia 5290.

Information : J.W. Leech.

Forest, Objective, Time, Input : As for Model 3.

Method : An alternative to the method used in model 3. Nonlinear regression analysis using Generalised Least Squares and optionally, Bayesian informative priors.

Output : It will be incorporated in a revision of the South Australian plantation simulation model for long term planning.

Application : Incorporation in long term planning models for even-aged stands.

Evaluation in Organisation : The algorithms used offer considerable advantages over the commonly used linear regression analysis using Ordinary Least Squares:-
1. alternative biologically sound, hypothetical models can more readily be formulated as nonlinear models than as linear models.
2. Generalised Least Squares provides a statistically sound way of utilising long term trend data.
3. Bayesian statistical methods enable thinned and unthinned plot data to be incorporated in the one analysis.

These complex techniques are necessary if a mathematical model for radiata pine is to be a superior predictor to yield tables developed by the directing curve trend technique. Further, these extensions provide a more precise prediction model that is statistically sound.

Assessment for Developing Countries : The technique used requires good long term data which could be obtained only from -
1. remeasured plots, or,
2. stem analysis.

Stand Simulation Model 4 contd.

Further the technique requires access to computing facilities and also requires a sound statistical knowledge.

Given these factors the technique offers considerable promise for yield prediction in even-aged stands.

References : Ferguson, I.S. and Leech, J.W. (1978) "Generalised Least Squares estimation of stand yield functions". Forest Science (in press).

Stand Simulation Model 5

Organisation : Tasmanian Forestry Commission, 199 Macquarrie Street, Hobart, Tasmania 7000.

Information : P.R. Lawrence.

Forest : 29,000 ha of **P.radiata** plantations managed for sawlog and pulpwood production on rather conservative thinning regimes, delayed to varying degree because of poor current market demand.

Objective : To predict thinning and clear-felling yields from stands of various ages, site indices, stocking class and thinned states. Inclusion in forest simulation model, assuming current treatment regimes.

Time Span : Up to 40 years in periods of up to 3 years.

Input : Either data from sample plots or, when used in the forest model, estimated values of mean dominant height, basal area and mean dbh obtained from age, site index and thinned state of each patch of forest recorded in the area information system.

Method : The three basic parameters predicted are mean dominant height, basal area increment and increment in mean dbh. The height/age relationship was obtained by non linear methods, the other two by linear least squares, all from permanent plots. Thinning yields and the new starting point after thinning are predicted from past records of standard treatment. Volumes are calculated from stand volume equations.

Output : Values required for the forest simulation model including mean dbh, entire stem volume and volume to four top diameter limits for either thinnings or clear-fellings.

Application : Simulation of a forest.

Evaluation in Organisation : The major limitation is that the results can only apply to stands treated in the same manner as in the past. Since new treatment regimes are being adopted, the use of these models in very limited. The major source of inaccuracy of prediction was found to be in estimating the starting points.

Assessment for Developing Countries : Few developing countries are likely to adopt the very conservative thinning regimes modelled.

Stand Simulation Model 6

"STANDSIM"

Organisation : Forests Commission, Victoria, 601 Bourke Street, Melbourne, Victoria 3001.

Information : R.B. Smith.

Forest : Even aged monospecific natural stands Eucalyptus regnans, **E.delegatensis**, **E.sieberi** and approximately 75,000 ha of **P.radiata** plantations.

Objective : The future growth of a stand of any age is modelled for any period, for various sites and thinning regimes.

Time Span : Commonly 25 -40 years, with annual or 5 yearly growth cycles.

Input : Individual tree data by 10 cm size classes also rotation length, site index, thinning regimes.

Method : STANDSIM is a deterministic model which projects the development of a hectare of forest for various sites and thinning regimes, operating on individual tree data stored mainly as an array of tree diameters. In each growth cycle the trees are grown and if necessary thinned by natural mortality or cutting. Growth takes place by updating the diameters according to gross basal area increment and other functions.

Output : At the end of each growth cycle, stand data including basal area, stocking and dominant height of live trees, gross increment, net increment, mortality, and thinning information.

Application : Output from this model is used in systems for scheduling the cut from large areas of forest. It can also be used to study a range of cutting options, for example, the number and timing of thinnings, and timing of final harvest. A stochastic version of this model has been developed for studies of risk and uncertainity. [sic]

Stand Simulation Model 6 contd.

Evaluation in Organisation	: The model has been highly successful because users were involved in construction and testing.
Assessment for Developing Countries	: A simplified form of the basic growth model would be potentially useful in even-aged forest areas for which large scale industrial developments are proposed. Advantage - 1. the ability to study a whole range of thinning and clear felling options. Disadvantages - 1. the model refers to monospecific stands only, 2. model assumes fairly regular spacing, 3. no allowance for defective stands.
Reference	: Opie, J.E. 1972. STANDSIM - a general model for simulating growth of even-aged stands. Proc. 3rd Conf. Advisory Group of For. Statisticians, Section 25, IUFRO, Jouy-en-Josas, France, Sept. 1970.

SIMULATION FOR CUTTING PLANS AND YIELD REGULATION

Computer models which simulate the future yield of entire plantations, that is, all stands considered together, have become indispensable aids for preparing 1- to 5-year cutting plans and for regulating the yield over 20- to 60-year periods.

The models described in this section simulate the development of the plantations and the production of wood according to initial starting values of such things as the area and conditions of existing stands, land availability, planting rate, and the quantities of wood demanded for industrial developments. Some models include forecasts of cash flows and economic results.

For each year of the simulation, the plantation models forecast the growth of each stand using yield tables or the stand simulation models described earlier. Stands are then scheduled for cutting according to built-in decision rules and the overall yield for the year calculated.

By altering the starting values and repeating the simulations, a range of alternatives can be generated from which the planner can select the most suitable. The models are used to schedule stands for clear felling and to evaluate the timing and type of thinning operations, particularly in relation to the demand for small-diameter roundwood. In long-term planning, the models are used to evaluate alternative planting rates and investigate how proposed new industries might be supplied.

The models vary considerably in their complexity depending on the extent to which the variations in site are identified and on the nature of the decision rules used for selection. The simplest models consider only the average site and extend the areas of each age class by a standard yield table. By contrast several of the models consider each separate stand and simulate their development with stand growth and yield models imbedded within the overall plantation model.

<u>Plantation Simulation Model 1</u>

CUTTING PLAN

Organisation	:	A.P.M. Forests Pty. Ltd., P.O. Box 37, Morwell, Victoria 3840.
Information	:	J.B. Dargavel.
Forest	:	40,000 ha **P.radiata** plantations.
Objective	:	Schedule stands for cutting to supply a pulpmill and sawmill.
Time Span	:	6 months - 3 years.
Input	:	The age, basal area, height and stocking of each cutting unit, its area and suitability for summer or winter cutting.
Method	:	Includes a stand growth model. Selects stands for cutting by priority rules based on operation due, need for thinning, quality of sawlogs and volume to be met.
Output	:	Schedule of stands to be cut and volume of each product.
Application	:	Preparation of operational cutting plans.
Evaluation in Organisation	:	Comparatively cheap to develop. Easy to use and emend.
Assessment for Developing Countries	:	Cost effective. Scheduling could be done manually.
Reference	:	Dargavel J.B., and Marshall P.J. 1976. Annual cutting plans for developing plantations. Proc. IUFRO Working Group S 4.02.4 XVI World Congress. Oslo.

<u>Plantation Simulation Model 2</u>

CUTTING PLAN

Organisation	:	Woods & Forests Department, P.O. Box 162, Mount Gambier, South Australia 5290.
Information	:	A. Keeves and J.W. Leech.
Forest	:	Some 70,000 ha of **P.radiata** plantations, managed on an approximately 50 year rotation with up to six commercial thinnings, and with a comparatively even distribution of age classes.
Objective	:	To predict the yield of a group of plantation stands of radiata pine in the next commercial thinning.
Time Span	:	1 - 6 years.
Input	:	Inventory data, yield prediction models, proposed thinning treatment and tree size assortment tables.
Method	:	Linear regression analysis was used to predict tree volume and increment from tree diameter, stand height, site quality and stand density for both thinnings and clear felling. Inventory data are from temporary 0.1 ha plots.
Output	:	A tabular five year cutting plan listing operations to be carried out and expected yields in a range of size assortments.
Application	:	In preparing the next 5 year cutting plan which will direct where commercial thinning and clear felling will take place to meet commitments to utilisation plants in a variety of required size and quality assortments.
Evaluation in Organisation	:	A limited test using independant data indicated the approach was satisfactory for practical use.
Assessment for Developing Countries	:	This type of model is of use when short term (1-6 year) increment is considerable and will affect planning. This is of particular importance when a fast growing plantation resource is being utilised close to its capacity.
Reference	:	Lewis, N.B., Keeves, A. and Leech, J.W. (1976) - "Yield regulation in South Australia **Pinus radiata** plantations". Woods & Forests Bulletin 23, Adelaide.

<u>Plantation Simulation Model 3</u>

CUTTING PLAN

Organisation	:	Forests Department of Western Australia, Barrack Street, Perth, Western Australia 6000.
Information	:	H. Campbell.
Forest	:	45,000 ha **P.radiata** and **P.pinaster** plantations.

Plantation Simulation Model 3 contd.

Objective	:	Development of 1 and 5 year logging plans. Planning the timing and extent of forest industry expansions.
Time Span	:	Open ended, but generally 1 or 5 years.
Input	:	Continuous inventory plot measurement data.
Method	:	Simulation of growth by a stochastic model. Thinning operations and silvicultural and marketing priorities are set interactively.
Output	:	For each year of the planning period a list of areas to be treated and volumes by assortments is produced. Also a resource summary is prepared.
Application	:	Scheduling thinning operations in pine plantations could also be used to develop strategies for input to an optimising program.
Evaluation in Organisation	:	After a slow start the model is gaining in use and acceptance in direct proportion to the degree of pressure put on the plantation resource.
Assessment for Developing Countries	:	The growth routines are specific to radiata and pinaster pine. The modifications required to adapt them to other coniferous species would probably be minimal. Extensive modifications would probably be necessary to adapt them to hardwood species.

Plantation Simulation Model 4

YIELD REGULATION (Four Models)

Organisation	:	A.P.M. Forests Pty. Ltd., P.O. Box 37, Morwell, Victoria 3840.
Information	:	J.B. Dargavel.
Forest	:	Plantations of **P.radiata, P.elliottii, E.regnans** and **E.grandis** in New South Wales, Queensland and Victoria developed to supply pulpmills.
Objective	:	Development planning. Determine if mills of given size can be supported from nominated land areas and planting rates.
Time Span	:	20 - 30 years.
Input	:	3 models assume one average site; 1 model assumes 4 different sites, models require areas of each age, standard yield table for each site, and standard costs.
Method	:	Yield table projection. Areas scheduled for clear felling to meet mill demands by nominated priority rules, mostly oldest first.
Output	:	Schedule of areas planted, thinned, felled. Times at which demands can not be met or surplus available. Condition of plantations at end of planning period.
Application	:	Development planning, particularly at initial stages of plantation development prior to industries being established.
Evaluation in Organisation	:	Simple models, easy and cheap to construct and run only require small computers. Very successful when operated in inter-active mode. Used when only limited data available i.e. before extensive inventory data base has been built up. Difficulty is that they ignore real site differences and full range of opportunities that become apparent when inventory and experimental evidence has been assessed; complex optimisation models then developed to evaluate.
Assessment for Developing Countries	:	Very high as models can be limited to the data available. Cheap and simple to construct and use. Highly cost effective.
Reference	:	J.B. Dargavel. 1969. Yield forecasting for industrial plantations. Australian Forestry 33 (3) : 153-62 gives details of an early, rather more elaborate model than is currently used.

Plantation Simulation Model 5

YIELD REGULATION

Organisation	:	Woods & Forests Department, P.O. Box 162, Mount Gambier, South Australia, 5290.
Information	:	A. Keeves and J.W. Leech.
Forest	:	70,000 ha of **P.radiata** plantations, managed on an approximately 50 year rotation with up to six commercial thinnings, and with a comparatively even distribution of age classes.
Objective	:	To predict the long term yield of the resource.
Time Span	:	60 years.

Plantation Simulation Model 5 contd.

Input	:	Inventory data, yield prediction models, potential thinning regimes, information from the short-term planning model and stand size assortment table.
Method	:	Currently uses yield tables to predict the growth of a logging unit allowing for variations of site potential, but will incorporate mathematical models recently developed. Logging units are thinned according to a variety of commercial thinning regimes and potential yields are aggregated by assortments into years. Yields between years were balanced by varying the clear felling age for some logging units over the first 25 years of the planning horizon.
Output	:	Tables listing thinning and clear felling operations, areas and volumes by assortments included in each year's potential cut, and summaries by five year periods and by forests.
Application	:	Strategic planning of the long term permissible cut.
Evaluation in Organisation	:	The technique has been used successfully to determine long term cutting strategy from a limited forest resource that is now fully committed to industry. A limited range of management strategies can be evaluated, depending on the range of data used to develop the model. The model is deterministic not stochastic. These limitations have not proved significant and the accuracy of the predictions is satisfactory for long term strategic planning in an environment subject to short term change.
Assessment for Developing Countries	:	This type of model is applicable in many developing countries as it can use simple growth - yield - inventory data to estimate wood availability under a variety of management strategies.
Reference	:	Lewis, N.B., Keeves, A. and Leech, J.W. (1976) "Yield regulation in South Australia **Pinus radiata** plantation." Woods & Forests Bulletin 23, 174 pp.

<u>Plantation Simulation Model 6</u>

YIELD REGULATION

Organisation	:	Tasmanian Forestry Commission, 199 Macquarie Street, Hobart, Tasmania 7001.
Information	:	M. L. Higgs.
Forest	:	29,000 ha of plantation, predominantly **P.radiata**, supplying privately owned sawmills, pulpmills and other utilization plants.
Objective	:	To predict thinnings and clear-felling yields by various classes given specified felling age prescriptions and volume constraints.
Time Span	:	Varies depending on need, generally 15 - 30 years.
Input	:	Uniform batches of forest are classified by stand parameters including age, site index class and thinned state.
Method	:	Initially each patch is assigned thinning and clear-felling priority values based on its stand parameters. Stands are then ranked in decreasing priority order for clear-felling or thinning. Yields for stands eligible for felling are accumulated subject to volume constraints.
Output	:	Stand volume, growth, and felling yields are estimated by means of functions comprising the stand simulation model.
Application	:	Annual schedule or areas available for felling. Deficits or surpluses if volume constraints applied. Summary of growing stock at five year intervals.
Evaluation in Organisation	:	Resource level planning of sawlog and pulpwood sales.
Assessment for Developing	:	The model is good where economic considerations with respect to management have not been emphasized.
Countries	:	Represents a simple, inexpensive system with potential where optimisation involving cost criteria is not required. Disadvantages are in lack of diverse range of cutting strategies and in not having log assortment output.

Plantation Simulation Model 7

YIELD REGULATION "FORSIM"

Organisation	: Forests Commission, Victoria, 601 Bourke Street, Melbourne, Victoria 3001.
Information	: R.B. Smith.
Forest	: 75,000 ha of **P.radiata** plantations.
Objective	: To predict woodflows and cash flows from a forest consisting of a set of diverse even-aged stands.
Time Span	: Up to 50 years.
Input	: Inventory plot records for each section of the forest (sections uniform in age, species, site index).
Method	: Growth simulation of plot basal area and height, and simulation of harvesting operations (thinning and clear fellings) depending on the cutting regime.
Output	: For each strategy output includes volumes (by size classes), areas and section numbers for each year, areas by age classes, growing stock volumes for nominated years, revenues and discounted revenues for each operation for each year.
Application	: Planning and scheduling the cut, testing and comparison of cutting strategies.
Evaluation in Organisation	: Highly successful although initial problems with change of staff, change of computing environment, change of measurement units. Ideal application for **P.radiata** plantations where a large number of possible cutting strategies is involved.
Assessment for Developing Countries	: The complex FORSIM package would have little potential for forests coming under management for the first time. The simplified version ASSIM may have potential as a short term growth simulator.
Reference	: Gibson, B.F., Orr R.G. and Paine D.W.M. 1971. FORSIM - a computer program for planning management of even-aged forests. Forests Commission Bulletin. Melbourne.

OPTIMIZATION FOR FOREST YIELD REGULATION

The three optimization models described in this section were designed for yield regulation. The optimization models represent a significant advance on the simulation models described earlier because they enable the full combination of the silvicultural alternatives, for each stand times the number of stands, to be explored. For example, if there are 50 alternative strategies for each of 200 stands, an optimization model finds the best set out of the 50 x 200 = 10,000 possible alternatives. The best set consists of the strategy selected for each stand, with a few stands being divided into 2 or 3 parts each with a different strategy. Thus a little over 200 alternatives out of 10,000 are selected in a single run of the model. By contrast the simulation models only allow those combinations to be evaluated that are defined in the built-in decision rules.

Two of the models are concerned with large fast-growing exotic plantations of P. radiata and one is concerned with extensive fast-growing even-aged natural stands of E.regnans and E.delegatensis. All the models evaluate various silvicultural alternatives for each stand while meeting overall constraints, such as markets or budget, for the plantation as a whole.

Each model uses a linear program for optimization formulated along the lines originally developed by Clutter (Ware and Clutter 1971) in the Type 1 model of Johnson and Scheuman's (1977) classification. Standard computer packages are used to solve the linear programs and obtain extensive marginal analysis.

The models require extensive data prepares, by a "matrix generator" program, in a form suitable for input to the standard packages. The source data consists of the yields, cash flows, etc., for each alternative strategy considered for each stand. This extensive data is generated by stand simulation models.

The optimization models have been found to be many times more expensive to develop and operate than simulation models. They require very extensive data and considerable expertise. because of this, they have been found difficult to maintain when specialist staff move. They do, however, provide very powerful insights into interactions between the alternative strategies available for different stands. Their use can best be justified when forest structure and conditions are complex and the supply/demand relationship is critical.

The optimization models were only constructed after substantial experience had been gained both with stand and plantation simulation models.

Optimisation Model 1

Organisation	:	A.P.M. Forests Pty. Ltd., P.O. Box 37, Morwell, Victoria 3840.
Information	:	J.B. Dargavel.
Forest	:	40,000 ha of **P.radiata** in Victoria supplying a pulpmill and a sawmill. There is a wide range of sites, and very little land is available for purchase economically. Some outside wood and chips are purchased.
Objective	:	Plan plantation development, and ration capital between buying land, planting and fertilisation. Also, find how much outside wood to buy, schedule thinning and clear felling and find best silvicultural regime for each stand.
Time Span	:	25 years.
Input	:	An average of 50 alternatives for each of 200 stands showing yields, cash flows and contri-bution to objectives, produced from stand model. Volumes and costs of outside wood purchase options. Many other data on conversion factors, costs etc.
Algorithm	:	Linear programming.
Output	:	Extensive reporting of: 1. silvicultural regime (planting method, fertilisation, thinning method, clear felling age) for each stand, 2. Wood purchase schedule, 3. Planting, thinning and clear felling schedules, 4. Rationing of capital between all plantation activities, 5. Forecasts of size and density distribution to mills, 6. Marginal costs of all constrained opportunities.
Evaluation in Organisation	:	Development brought all sections of organisation together. Proved to be a very powerful tool in giving insights into operation of plantation system. Very demanding in data requirements and staff time. Expensive to construct and operate. Requires ready access to large computer. Difficult to modify quickly to changing conditions.
Assessment for Developing Countries	:	Considerable data and staff time required for both construction and continued modification and maintenance of model in usable and valid condition.
Reference	:	J.B. Dargavel. 1978. A model for planning the development of industrial plantations. Australian Forestry. 41. (in press).

Optimisation Model 2

"RADHOP"

Organisation	:	Forestry Commission of N.S.W., 93 Clarence Street, Sydney, N.S.W. 2000.
Information	:	R. Wilson and M. McMullen.

Optimisation Model 2 contd.

Forest	:	100,000 ha of **P.radiata** plantations with irregular age-class distribution supplying 2 particleboard plants and numerous sawmills. One or two pulpmills are planned for the early 1980's.
Objective	:	Rationalise yield flows through time to meet market requirements.
Time Span	:	Either short term (commonly five years) or long term (commonly 35 years).
Input	:	Inventory plot data plus financial information.
Algorithm	:	Stand simulation by deterministic functions constructed from research and inventory data. Optimisation by linear programming, which selects regimes to apply to management units to maximise returns while meeting volume constraints.
Output	:	Details of regime to be applied to individual areas, size and time distribution of volume.
Application	:	Short term harvest planning, and long-term prediction of quantity of industry that can be supported at various times.
Evaluation in Organisation	:	Successfully accepted as major management aid because of demonstrated reliability. Functions continually adapted as conditions change and more data becomes available.
Assessment for Developing Countries	:	Useful for providing estimate of plantation requirements to meet markets. Operates on sample data, but requires sophisticated computing capacity. An aid also to planning industry establishment. Predictor functions are not an integral part of model, and can be altered easily. Simulation model provides much useful information and can be used alone for predicting volumes.

Optimisation Model 3
"MASH"

Organisation	:	Forests Commission Victoria, 601 Bourke Street, Melbourne, Victoria 3001.
Information	:	R.B. Smith.
Forest	:	120,000 ha of regrowth forest predominantly E.regnans and E.delegatensis principally 1939 origin.
Objective	:	To define the cutting schedule that maximises the present net worth of the wood resource, subject to woodflow constraints.
Time Span	:	Up to 100 years.
Input	:	Stand data including diameter distribution, thinning strategy, road and transport costs, royalty values, harvesting constraints.
Algorithm	:	Parametric linear programming, to maximise the present net worth subject to constraints on wood flows. MASH incorporated several features of STANDSIM.
Output	:	Optimal cutting strategy and wood flows, cash flows and present net worth associated with that strategy.
Application	:	The definition of sustainable woodflow levels, supply area and broad harvesting strategies.
Evaluation in Organisation	:	The technique has been successful in broad applications over the resource as a whole. There are problems with further application at district level because of change of staff and computing environment and intricate rules for operating the model.
Assessment for Developing Countries	:	MASH would be a useful aid in planning the management of a forest of complex structure with respect to age, density, site quality and species. Depends on good inventory and this may be a drawback. Also requires sophisticated computing system, which may be a difficulty in applying MASH to developing countries.
Reference	:	Weir, I.C.A. 1972. Planning of wood production using systems analysis. APPITA 26 (2) :107-112.

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