OPERATIONS RESEARCH IN FOREST HARVESTING

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(Received for publication 30 July 1982)

ABSTRACT

Operations research techniques such as mathematical programming, simulation, and the development of planning systems can contribute to decision-making in forestry management. Computers have dramatically changed the possibilities and practice of data collection, storage, analysis, and presentation but the difficulty of obtaining access to them has until recently limited their use. Development of the microprocessor is extending the availability of electronic tools but costs for specialist applications are still high.

INTRODUCTION

Although operations research in forestry has its own history and traditions, it shares many of the methodologies of general operations research and its sister discipline, management science. Many believe that operations research stands at a crossroad, with the initial enthusiasm of the 1950s and 1960s now giving way to increasing disquiet about its ability to solve "real world" problems (*see* review by Dando & Sharp 1978). It seems, then, an opportune time to examine the development of operations research in the forestry field, and the rising influence of computer and electronics technology.

Operations Research

Simply stated, the objective of operations research (OR) is an improvement in the functioning of operations. A more comprehensive definition would be "the application of the methods of science to complex problems arising in the direction and management of large systems of men, machines, materials and money" (British OR Society, *in* Dando & Sharp 1978).

Operations research at its beginning was avowedly multidisciplinary (Beer 1966), employing physicists, mathematicians, statisticians, psychologists, and physiologists, often as teams to solve complex man/machine performance problems. Frederick Taylor may be thought of as one of the founders of the field with his development at the turn of the century of "scientific management" based on stopwatch study of production engineering operations. The Second World War provided a great impetus to the field with the application of scientifically trained personnel to the solution of military problems. Post-war industrial expansion and an ongoing high level of military-funded research underwrote its continuing development and by the early 1960s it had become an established discipline.

OPERATIONS RESEARCH IN FORESTRY

Palo (1971), describing his systems-oriented view of planning and management, pictured the typical forestry enterprise as being divided between a control section and a production/consumption section (Fig. 1). The production/consumption system comprises the growing of the forest and its use, the subject of management control. The control section comprises a decision system (Fig. 2) with a set of four tasks, and a supporting information system. Decision-making involves a choice between alternative courses of action but the process of finding and evaluating all the possible alternatives

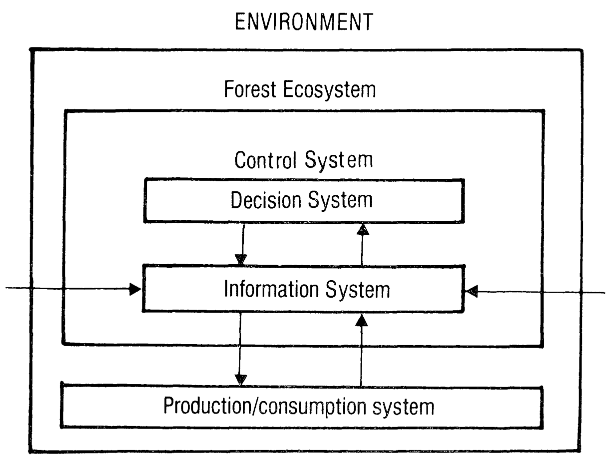

FIG. 1—Palo's frame model.

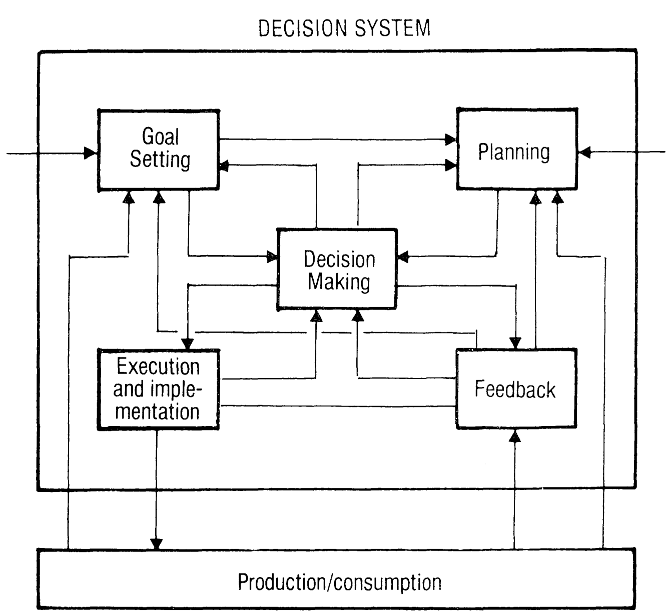

FIG. 2—Decision system of Palo's model.

is not exhaustive; often the search stops long before the optimal alternative is found (Cyert & March 1963) because of lack of time or funds. One way in which the forest operations researcher can help in decision-making is by providing more information and thus more alternatives. Another function of the researcher is to find faster methods of information retrieval, which can speed up the decision-maker's search. The process of decision-making itself is also a topic of research, as is the development of new methods of evaluation.

Hilf (Germany), Marn (Sweden), and Koroleff (Canada) were pioneers in the forestry branch of operations research, later to be known as Forest Work Science (Samset 1979). Post-war work included Samset's cutting studies (Samset *et al.* 1969) which were scientifically rigorous and recognised some of the complexity of man/machine/forest work interactions by including work physiology measures in addition to forest and environment factors. Under the influence of these and other studies, Nordic work scientists eventually rejected the widely practised use of performance rating in time study as "unscientific" and also the use of work study as a direct basis for the determination of piece-rate payments. They preferred "Comparative Work Study" (Makkonen 1954) as a tool for the scientific investigation of the effects of changes in the work method, work environment, or management situations. In other countries, however, work study remained committed to wage-rate determination and operational improvement, and to the continued use of standard industrial study techniques, including work rating.

In a report sponsored by IUFRO Division 3 on European Forest Work Study, Kopf (1976) observed that a study aimed at standardising payment across all significant logging conditions in Germany had apparently failed in predicting satisfactory rates of payment. Kopf ascribed this failure to unmeasured variations in working conditions and the resultant adoption of different work techniques, despite the measurement of over 120 parameters. He also noted the failure of the study to include social and ergonomic variables, and the statistical difficulty experienced with large parameter sets.

A study by Battelle Memorial Institute (Hamilton 1966) of 120 pulpwood logging crews in the southern United States included a social or crew-related variable, a subjectively assessed factor termed "crew agressiveness". This factor was found to be associated more closely with lower logging costs than were forest or environmental conditions.

A major study of skidding operations in Canada (Cottell *et al.* 1971) also found that forest and environmental factors did not satisfactorily explain the performance of crews. The large residual or unexplained variation was attributed to fluctuations in motivation and unmeasured changes in the physical effort required. Their study also compared different intensities of data collection, shift level production, and detailed study. Detailed study was shown to be a tool for specific circumstances while less-intensive routine data-collection provided the better basis for management control.

A follow-up to the Battelle study by the American Pulpwood Association Harvesting Research Group (since disbanded) to produce a set of production tables for logging in the southern states developed a system for the collection and analysis of data on a very large scale. Data were collected on readily measurable forest environmental and production variables and reduced to production equations by regression methods. As with previous studies, the objectives were not met because of the variation in logging methods, not captured in the data despite the large number of factors measured.

In the late 1960s and early 1970s broad-scale regression studies were carried out, the growing power to compute sometimes exceeding the capacity of researchers to design and comprehend their experiments. It was also a period in which was recognised the importance of human physiological and social factors in forestry production systems, and the complexity of the interaction between workers, forests, and machines in harvesting systems.

APPLICATION OF COMPUTERS

The use of computers has been the most significant development in the field of forest operational research in the last two decades and the development and application of new techniques have been affected by the degree of access to computer facilities. Workers in academic and research institutions have been by far the best served, often sharing facilities with users who have supported large, scientifically oriented, computer installations. Workers in industrial enterprises, however, have not usually been so well served since most computers that companies obtain for accounting functions (stock control, invoicing) are less suitable for use in operations research.

Those without access to computers have relied on calculators which, although able to perform complex calculations, are not able to store and recall data with the facility of computers. However, they have represented the only access to computation for many in industry.

Computer application in operational research has proceeded in three ways:

- Use by operational researchers in the conduct or analysis of their experiments;
- Development by operational researchers of computer tools to be used by managers as aids to planning;
- Development of computer decision-making programs to replace some aspects of management decision making.

Computers Used to Conduct or Analyse Experiments

Computer-based simulation is one of the most widely used operations research techniques because of its capacity to handle complex problems. Simulation can be used either in an experiment where the form and parameters of the model are likely to be changed, or in a package form as an aid to planning.

In simulation modelling, a mathematical or quantitative model of the behaviour of some real system is defined and implemented as a computer program. The definition of the model is more important than the computer programming as the output is useful only to the extent that the computer models "real world" behaviour. The usual difficulties with simulation lie in the limited size and complexity of models which can be practically implemented and, more importantly, with the ability of the modeller to capture all the important interactions in the specifications of the model.

Although forest harvesting systems are often simple in their sequence of production steps, the time taken to complete these steps is usually difficult to predict. "Discrete event stochastic simulation" is usually used in harvesting to study the interaction of a number of simultaneous processes, e.g., skidding and loading occurring together on a landing. The concentration of effort on machine simulation in the late 1960s and early 1970s was probably because of the great interest at the time in rapid mechanisation, coupled with the fact that it was simpler to predict mechanical than human performance.

Newnham (1967, 1970) in Canada, and Santerson & Sjunnesson (1972) and Almquist (1973) in Sweden, developed models to study the interactions of felling machines with forest types, and the interactions and interference of felling with automatic processing in tree harvesters. Peltonen (1973) in Finland developed a simulation system to cover a range of processors and harvesters to aid in the study of machines with simultaneously operating functions. The model developed by Gregersen & Johansson (1975), which simulates the performance of knucklebooms, has been used to study the effect of varying inner and outer boom length and hydraulic circuits. Such models are built and used in collaboration with machine designers and so are usually only of importance to those countries with a machine design and construction industry.

Another field of application of computers in experiments is in simulating multi-machine systems. Routhier (1974) developed a truck-fleet simulator to study the interaction of loaders, trucks, and unloaders. Newman (1975) modelled the interaction of Koehring harvesters with different forms of loading and trailer systems. The APA Harvesting Research Group in the United States developed a general-purpose harvesting system simulator as part of their Harvesting Analysis Technique (HAT) package. After the disbanding of the group, the model was released to the Virginia Polytechnic Institute where development has continued. It is probably the largest and most comprehensive of published American models (Goulet *et al.* 1979) and has been described by O'Hearn *et al.* (1976). It models felling, limbing, bucking, bunching, skidding, loading, and trucking. Recent developments of this model include the coupling of a multi-machine model to a detailed machine simulator and a tree growth simulator (Stuart 1981) to provide a more complete forest growth and harvesting simulator.

Despite these developments, simulation is not yet widely used in aiding managers of harvesting operations. Garner (1978), discussing the Routhier truck fleet simulator, noted that only three requests for information on prospective use had been received in 4 years. A study of the Goulet *et al.* (1979) review of American models reveals that all were developed by academics, students, or researchers in institutions rather than by working operations researchers.

A search of American literature by the author in 1981 revealed few published reports of the actual application of computer models to solve industrial harvesting problems. While it is probable that industrial problem solvers are not active authors, it is also likely that the complexity and variation in the forest work situation makes it difficult to model effectively. Lack of access to suitable computers is also a handicap.

Statistical packages are probably the most common form of computer use in the experiments of forest operations researchers, particularly for multiple regression. Other specific forestry uses include the development of standard packages for the data from field studies. Johansson (1971) described the development of standard package programs for the analysis of co-operative studies between companies in Sweden. The production tables project of the APA Harvesting Research Group developed a comprehensive system that included facilities for the editing and analysis of data.

Computers as Tools in Planning

Special-purpose programs have been developed to assist operations planners or managers, firstly with technical aspects of logging planning such as machine performance, and secondly with information storage and retrieval.

Cable system layout and road design programs have been among the most successful technical aids. Burke (1974), Carson (1975), Carson & Reutebuch (cited by Fjone 1979), and Young & Lemkow (1977) working in North America, and Fjone (1979) in Norway, have described their development and application. More use was made of large programmable calculators than conventional computers and substantial economic benefits were claimed; Fjone found that planning times were reduced by a factor of 12 when computer-based methods were used. Reimer (1979) obtained a reduction of 85% in office planning time with a 3% reduction in road mileage.

Simulation can be used as a computer tool where the form of the model is fixed and presented to the user as a package. Programs of this type, known as growth simulators, are based on equations predicting tree and stand growth and are used by planners to estimate future yield. Simulation is also used in the financial planning models widely used by larger companies.

Simulations of machines and machine systems can be developed as planning aids, although the programs are usually simplified and made more direct than when used as research tools. Gregersen & Jonsson (1977) developed a system in Sweden which accepts user inputs on machine costs, on productivity in different tree-diameter classes, and on travel speed, as well as on factors affecting the harvesting tasks to be performed – coupe area, standing volume, diameter distribution, terrain class, and travel distance. The program calculates total system costs and productivities (including machine imbalance problems), as well as many other statistics about the proposed operation. Results can be used by planners to set cutting sequences that maximise machine utilisation and provide the required product mix.

The use of the computer to store and retrieve information has had a big impact on the management of forest-based enterprises. Clerical procedures for storing, processing, retrieving, and presenting data have been well developed for some time, but the introduction of the computer has meant that more data could be collected, and that methods of summarising and presenting the data which had hitherto been too expensive were now feasible. In response to the need for new data management systems to take full advantage of computerisation, Holfe (1976) presented an idealised design for computer-based management information systems describing the inter-relationship between the data base, the data manipulation programs, and the model framework.

The development of computer-based management systems is not without problems. Ackoff (1967) listed common pitfalls encountered by designers of information systems, including the tendency to swamp users with an "over-abundance of irrelevant information". His proposed solution was better design and closer co-operation between users and the information system creators. Other problems have been the antipathy of individuals whose jobs were changed through the introduction of new systems, and the sheer difficulty of creating programs that worked on schedule. To help overcome these problems, computer scientists devised better programming techniques and languages ("software engineering") and systems analysts designed and implemented more reliable systems. Dargavel *et al.* (1975) described a computerised version of a forest management system now in use, noting a concern for the "management" of its development. Andersson & Mossberg (1972) described a system suitable for logging planning.

Developments in these program systems for smaller firms have been dependent on the availability of computer resources. Microcomputer systems (now available for under A$5000) and program packages for financial management now provide feasible tools for the small firm manager. These devices offer considerable scope for the future development of information systems for machine and system management.

Computers in Decision-making

The use by decision-makers of solutions produced by mathematical or other programming techniques has been dependent on the development of the computer. The main application in forest operations has been in the planning of forest cutting schedules by means of linear programming (Clutter 1968). In these systems the computer chooses an optimum set of stand treatments (thinning or clearfelling) from a large set of alternatives supplied by the user. At present, the range of problems that can be solved this way is limited. Attempts have been made to broaden programming methods to take into account a wider range of problems and variations. However, many "real world" decision problems are still not amenable to solution – either because they would take too long to solve (on our biggest computers) or because they are too complex to be programmed at all.

One alternative becoming more widely applied is heuristic programming where the computer is programmed to use rules for decision-making similar to those used by human planners when trying to solve complex problems like scheduling. Typical examples are high school timetables or hospital shift rosters where the number of possible combinations is enormous.

Few applications have been made to forestry operational problems, although Dykstra (1976) has described a system for improving the layout of cable system settings. Solutions produced by these methods are usually "good" but not "optimal" in the sense used by the operations researchers. Rules are tested by experiment before acceptance and are usually shown to have a good level of performance (in many cases almost optimal) and usually use far less computer time than comparable mathematical optimising techniques.

CURRENT ISSUES AND DEVELOPMENTS

Developments in micro-electronics are perhaps the most important technical factors promoting progress in forest operations research. Miniaturisation of circuits has led to more powerful micro-chips and there has been a massive decline in their price (Fig. 3); this has meant cheaper and more powerful computers. An increasingly important contribution of micro-electronics is in the development of tools for the collection and storage of new data. Commercially available devices range from the digital stopwatch, through electronic recording callipers, to electronic time-study systems. Wittering & Sawyer (1978) described a time-study system weighing about 9 kg, and recently advertised systems weigh a fraction of that.

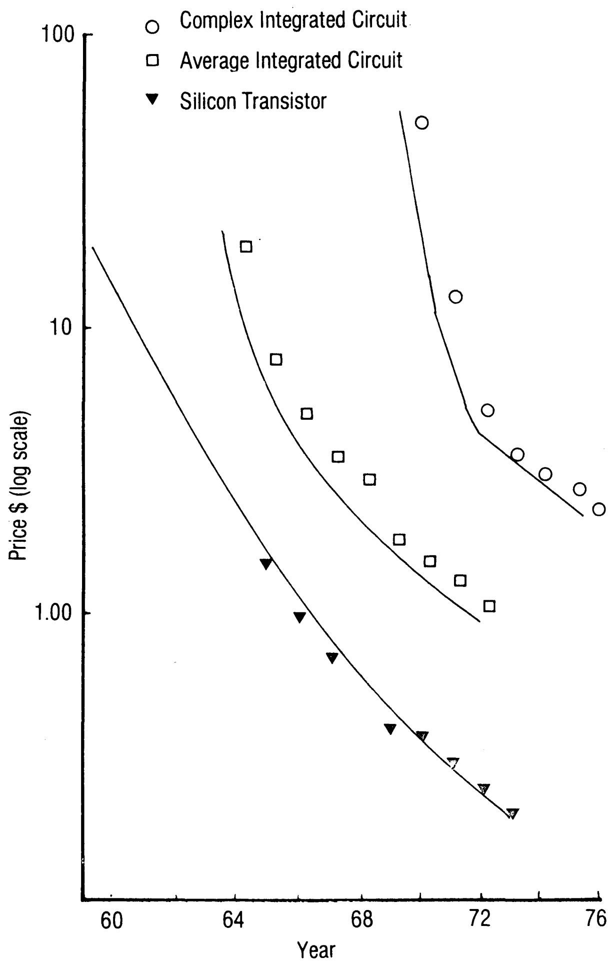

FIG. 3—Price trend of electronic components 1960–76.

However, the use of electronic devices in forest operations study has its particular problems. A harsh working environment and a relatively small potential commercial market mean that a lot of device development will necessarily come from within forestry, rather than the computer industry. Examples of forestry development include an interval timer used in activity sampling studies (Murphy & Newcombe 1979) and a chainsaw activity recorder (described below) developed at CSIRO.

Larger data-collection systems based on microprocessors are coming into use. Cottell *et al.* (1980) described the adaptation of a standard industrial microprocessor data-logging system to the study of cable systems. The development of similar systems for mobile machinery in harsh environments is more difficult, although devices for the study of road vehicles have been developed (Australian Road Research Board 1981). Work is under way at CSIRO Division of Forest Research to develop more compact and robust equipment for use with forest harvesting equipment.

The chainsaw activity recorder developed by the author at CSIRO Division of Forest Research provides an example of development of a special-purpose device for a small market. It measures the total time that an operator is using a chainsaw by recording the period of time that the noise generated by the chainsaw exceeds a certain level. The device is based on a hearing-aid microphone, a number of electronic integrated circuits, and a small battery. Design, construction, and testing of prototypes (Models 1 and 2) required about 4 man-months, and subsequent development of a production prototype took a further month. The printed circuit board layout for each model cost about A$500 in direct expenditure. Construction was carried out commercially for about A$25 per unit, with components about A$100 per unit. Amortising direct expenditures over the first two production runs (25 units) at approximately A$50 per unit, the total direct cost of production was about A$175 per unit.

Electronic components are only a fraction of unit cost, however, the major expenses being in design time and development of the prototype. After a further 2 man-months for testing and documentation, the total uncosted labour input (CSIRO input) stands at 6 man-months. Allowing A$25 000/year for salary and including overheads, the cost per unit over the 25 units produced to date is A$500, giving a total "semi-commercial" price (excluding profit) of about A$675 over the short production run.

There have also been developments in computer programming (software). The widespread availability of computers allows needs for special-purpose programs to be met. However, there are still significant costs in programmer time. An estimate of programmer productivity for a program of "average difficulty", with no documentation other than comments on the compiler listing, is 168 lines of code per month (Griffin 1980). A common problem in forest operational research is the analysis of time-study data. The author has developed programs of about 140 lines each for a cutter study and for processing associated tree volumes. On Griffin's estimates the required programmer's input is 1.5 man-months. Allowing A$20 000/year for a programmer (including overheads) the programs cost A$1250 each.

DISCUSSION

In the years since the Second World War, managers and operations research specialists have recognised the complexity of man/machine interactions and the importance of "models" as ways of describing and experimenting with systems. In operations research, major contributions have been in writing programs to solve mathematically formulated problems, and in the areas of simulation, probability-based decision theory, and heuristic programming.

Many developments in the contributing fields can be expected to influence future information collection and decision-making in the management of forest operations.

The use of small computer-based information systems is currently expanding rapidly and smaller firms will probably apply these systems to recording production and productivity. The use of simulation has been made more practicable by the development of better computer languages and the wider availability of computers. Growth of large-scale industry could lead to the even wider use of simulation to provide insight into the functioning of harvesting operations.

The extent of the impact of computer programs as planning tools depends on the planners' skill in defining the target problems and the programmers' skill in developing suitable programs. In most industries, many of the developments have come from consultants and specialist programming companies, often leading to competitive improvements and standardisation, and usually lower costs. Applications in forestry have for the most part been developed within individual companies or by research institutions; they are commonly difficult to transfer and their cost is relatively high.

Man/computer decision systems currently under development are designed to harness man's ability to develop a strategy and respond to changing conditions while employing the computer's power to calculate and explore alternatives. One potential area of application of these techniques for forestry is in scheduling cutting, harvesting machines, and trucks. Operational conditions are frequently complicated by variations such as wet weather, machine breakdown, market fluctuation, and changes in the resource base. Most computer-based decision-making systems in current use cannot encompass these variables, and so either they are left out (making the model less realistic) or the whole decision process is handled by man rather than by computer.

The changes that are likely to occur will raise important questions about the structure of the industry and the way research is conducted. Some of these include:

- The future of the small contractor – will the difficulties of finding and adopting relevant new management ideas and technologies reduce the role of small contractors?
- Forest owners becoming loggers – to what extent could the likely advances in planning and management technology allow management economies through the adoption of unified control of all forest operations?
- How will researchers, and those who fund them, respond to the current debates about the roles of science and technology in finding solutions to operational problems?
- Will there be enough skilled practitioners to take advantage of future developments?

This last question appears to be significant in small forest economies such as Australia's because of the lack of specialist capacity within our smaller universities and research organisations.

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