ODC
323
375.4

FOLIA FORESTALIA 125

METSÄNTUTKIMUSLAITOS · INSTITUTUM FORESTALE FENNIAE · HELSINKI 1971

RISTO SEPPÄLÄ

SIMULATION OF TIMBER-HARVESTING SYSTEMS

PUUN KORJUUKETJUJEN SIMULOINTI

N:ot 1—18 on lueteltu Folia Forestalia-sarjan julkaisuissa 1—41.
Nos. 1—18 are listed in publications 1—41 of the Folia Forestalia series.
N:ot 19—55 on lueteltu Folia Forestalia-sarjan julkaisuissa 19—96.
Nos. 19—55 are listed in publications 19—96 of the Folia Forestalia series.

1969 No 56 Terho Huttunen: Länsi-Suomen havusahatukkien koko ja laatu vuonna 1966.
The size and quality of coniferous sawlogs in western Finland in 1966. 1,50

No 57 Metsäntutkimuslaitoksen päätös puutavaran mittauksessa käytettävistä muuntoluvuista ja kuutioimistaulukoista.
Skogsforskningsinstitutets beslut beträffande omvandlingskoefficienterna och kuberingstabellerna, som används vid virkesmätning. 28,80

No 58 Paavo Tiihonen: Puutavaralajitaulukot 2. Maan eteläpuoliskon mänty, kuusi ja koivu.

No 59 Paavo Tiihonen: Puutavaralajitaulukot 3. Männyn ja kuusen uudet paperipuutaulukot.

No 60 Paavo Tiihonen: Puutavaralajitaulukot 4. Maan pohjoispuoliskon mänty ja kuusi. 2,—

No 61 Matti Aitolahti ja Olavi Huikari: Metsäojien konekaivun vaikeusluokitus ja hinnoittelu.
Classification of digging difficulty and pricing in forest ditching with light excavators.

No 62 Kullervo Kuusela ja Alli Salovaara: Etelä-Pohjanmaan, Vaasan ja Keski-Pohjanmaan mestävarat vuonna 1968.
Forest resources in the Forestry Board Districts of Etelä-Pohjanmaa, Vaasa and Keski-Pohjanmaa in 1968. 3,—

No 63 Arno Uusvaara: Maan ja metsän omistus Suomessa v. 1965 alussa ja sen kehitys v. 1957—65.
Land and forest ownerships in Finland 1965 and their development during 1957—65.

No 64 Timo Kurkela: Haavanruosteen esiintymisestä Lapissa.
Leaf rust on aspen in Finnish Lapland. 1,—

No 65 Heikki Ravela: Metsärunko-ojien mitoitus.
Dimensioning of forest main ditches. 1,50

No 66 Matti Palo: Regression models for estimating solid wood content of roundwood lots.

No 67 Terho Huttunen: Suomen puunkäyttö, poistuma ja metsätase vuosina 1967—69.
Wood consumption, total drain and forest balance in Finland in 1967—69. 2,50

No 68 Lauri Heikinheimo, Seppo Paananen ja Hannu Vehviläinen: Stumpage and contract prices of pulpwood in Norway, Sweden and Finland in the felling seasons 1958/59—1968/69 and 1969/70. 2,50

No 69 U. Rummukainen ja E. Tanskanen: Vesapistooli ja sen käyttö.
A new brush-killing tool and its use. 1,—

No 70 Metsätilastollinen vuosikirja 1968.
Yearbook of forest statistics 1968. 6,—

No 71 Paavo Tiihonen: Rinnankorkeusläpimittaan ja pituuteen perustuvat puutavaralajitaulukot.

No 72 Olli Makkonen ja Pertti Harstela: Kirves- ja moottorisahakarsinta pinotavaran teossa.
Delimbing by axe and power saw in making of cordwood. 2,50

No 73 Pentti Koivulehto: Juurakoiden maasta irroittamisesta.
On the extraction of stumps and roots. 1,50

No 74 Pertti Mikkola: Metsähukkapuun osuus hakkuupoistumasta Etelä-Suomessa.
Proportion of wastewood in the total cut in southern Finland. 1,50

No 75 Eero Paavilainen: Tutkimuksia levitysajankohdan vaikutuksesta nopealiukoisten lannoitteiden aiheuttamiin kasvureaktioihin suometsissä.
Influence of the time of application of fast-dissolving fertilizers on the response of trees growing on peat. 2,—

1970 No 76 Ukko Rummukainen: Tukkimiehentäin, Hylobius abietis L., ennakkotorjunnasta taimitarhassa.
On the prevention of Hylobius abietis L. in the nursery. 1,50

No 77 Eero Paavilainen: Koetuloksia suopeltojen metsittämisestä.
Experimental results of the afforestation of swampy fields. 2,—

No 78 Veikko Koskela: Havaintoja kuusen, männyn, rauduskoivun ja siperialaisen lehtikuusen halla- ja pakkaskuivumisvaurioista Kivisuon metsänlannoituskeokentällä.
On the occurrence of various frost damages on Norway spruce, Scots pine, silver birch and Siberian larch in the forest fertilization experimental area at Kivisuo. 2,—

No 79 Olavi Huikari—Pertti Juvonen: Työmenekki metsäojituksessa.
On the work input in forest draining operations. 1,50

No 80 Pertti Harstela: Kasausajan ja valtimonlyöntitiheyden sekä tehollisen sahausajan määrittäminen järjestettyjen kokeiden, pulssitutkimuksen ja frekvenssianalyysin avulla.
Determination of pulse repetition frequency and effective sawing time with set tests pulse study and frequency analysis. 1,50

No 81 Sulo Väänänen: Yksityismetsien kantohinnat hakkuuvuonna 1968—69.
Stumpage prices in private forests during cutting season 1968—69. 1,—

No 82 Olavi Huuri, Kaarlo Kytökorpi, Matti Leikola, Jyrki Raulo ja Pentti K. Räsänen: Tutkimuksia taimityyppiluokituksen laatimista varten. I Vuonna 1967 metsänviljelyyn käytettyjen taimien morfologiset ominaisuudet.
Investigations on the basis for grading nursery stock. I The morphological characteristics of seedlings used for planting in the year 1967. 1,50

Luettelo jatkuu 3. kansisivulla

FOLIA FORESTALIA 125

Metsäntutkimuslaitos. Institutum Forestale Fenniae. Helsinki 1971

Risto Seppälä

SIMULATION OF TIMBER-HARVESTING SYSTEMS

Puun korjuuketjujen simulointi

Seloste sivulla 31

PREFACE

This paper is connected with the studies in which the Department of Mathematics of the Forest Research Institute has been engaged in recent years to develop statistical methods used in forest research.

Discussions with Messrs. JUHANI JÄRVINEN, KLAUS RANTAPUU, JAAKKO SALMINEN and UNTO VÄISÄNEN contributed to a better understanding of the timber-harvesting systems. They also assisted with the collection of empirical material. In addition to Messrs. Järvinen and Väisänen, Dr. MATTI PALO and Acting Professor HANNU VÄLIAHO perused the manuscript.

Mrs. HILKKA KONTIOPÄÄ, M.A., translated the manuscript into English and DAVID COPE, A.B., checked the translation.

Grants from the Finnish Cultural Foundation and the Niilo Helander Foundation helped free me from other duties so that I could concentrate on this study.

I wish to express my gratitude and appreciation to these people and institutions and to anyone else I may have inconvenienced during the course of my study.

Helsinki, September 1971.

Risto Seppälä

14857—71/80

CONTENTS

0. SUMMARY

A timber-harvesting system is a typical example of a real-world system which is so complex and contains so many random variables that its overall description and analysis by means of an analytic model is difficult. Furthermore, investments associated with harvesting systems are generally so costly that a trial of various alternatives using the systems themselves involves an unreasonably high cost and takes a long time. Starting from these points, it was decided in the present investigation to study the potential uses of simulation as a means of describing and analyzing harvesting systems.

A theoretical basis for empirical study is first created by a discussion of the relevant concepts in system simulation. Particular attention is devoted to the task-phase spacing in simulation and to the design of simulation experiments. The simulation language selected was the General Purpose Simulation System (GPSS); it is described in broad outline.

The empirical part of the study presents the harvesting systems chosen for simulation. The study is confined to the harvesting phases from the felling of trees through short-distance transport. For the sake of simplicity, the word "harvesting" is used to mean this part of the overall harvesting process. The harvesting systems studied represent two main types based on the shortwood method: the common labour-intensive method, and the method based on the use of a limbing-bucking machine operating on a strip road. Two types of limbing-bucking machines are considered: the Finnish PIKA 50 and the Swedish KOCKUM PROCESSOR. In all systems, short-distance transport is carried out with a forwarder (load-carrying forest tractor).

The goals of the simulation project were originally divided into two consecutive parts. The first step was to construct a simulation model in GPSS language suitable for describing the structure and operation of the timber-harvesting systems selected for simulation with sufficient accuracy for simulation experiments. The second step was to carry out such simulation tests as would reveal the effect of the variables in the harvesting systems on the operation of the system and would define the sets of levels of the variables considered which are peculiar to each system.

Empirical material related to the harvesting systems had to be collected first. It was quickly discovered that information on both the whole processes and some of their parts in particular was incomplete and to some extent unreliable. As a result, the scope of the second half of the project had to be curtailed. The main task ultimately was the construction of the simulation models themselves; the simulation tests, in the main, served only to validate the model. Once the models are created, it is easy to expand the simulation experiments at the same rate as the amount of information required increases.

The construction of simulation models was started by first building a system model of the harvesting systems capable of serving the ends of simulation. Basic features of the system model were modularity on the one hand and flow interactions on the other. The latter were reviewed on the basis of general process thinking, according to which the points of work (phases of harvesting) remain fixed and the material (stands marked for cutting) flows.

The simulation models were constructed on the basis of the system model, separately for each of the three harvesting systems. The models were constructed stepwise by making first a simple model, which was gradually made more and more consistent. Like the system model, the simulation models were made modular. As a result, modifying them is simple.

Following validation, the models were found to approximate the true harvesting systems with the desired accuracy. The systems operated separately from one another. In further development of the models, they must be fitted with the possibility of studying the harvesting systems in parallel. This would make it feasible to use the models as an auxiliary phase in

production planning; a true population of stands, with its true characteristics, can be fed into the model system. Simulation helps to regulate the decision-making process in which the stands are allocated between alternative systems in as optimal a way as possible.

Finally, an experimental design for simulation is presented. It is based on the use of four factors (stand volume, mean stem size, interruptions in the working process, and movements from one stand to another) and three levels (average, below-average, and above-average). To reveal the main effects and the most substantial interactions of these variables in each of the three systems with sufficient accuracy, simulation of a total of over 3700 months of work is required. The unit of treatment is a whole stand and the time unit is one hour. The cost of such a simulation experiment would be around 4,800 Fmk.

1. INTRODUCTION

11. The process of timber harvesting

The competitive position of the wood-processing industry is decisively affected by the price of timber arriving at the place of use. If the stumpage-price level remains constant, only a reduction in harvesting costs affords a possibility of lowering the mill price of timber. The cost of harvesting, in turn, can be reduced only by increasing the productivity in work. The key position for the future is held by the mechanization of various tasks. This is based on the likelihood that the cost of human labour will increase at a faster rate than the cost of work done by machines.

A fundamental feature of the study of timber harvesting is that harvesting represents a *process* composed of a series of job phases between the tree growing in the forest and the arrival of the wood at the mill or other point of consumption. These job phases are the interrelated phases of timber preparation and transport. In addition, the harvesting system may also include measurement and storage. By and large, the harvesting process has two main phases: (1) the *forest phase,* beginning with the felling of a growing tree and normally ending with storage at a loading point after short-distance transport in the forest; and (2) the *long-distance transport phase* which begins with loading at the storage site and ends with unloading at the point of use.

The methods of harvesting are often divided into the full-tree, tree-length, and shortwood methods. The full-tree method comprises limbing and bucking after short-distance transport in the forest. In the tree-length method, limbing is done before short-distance transport, while in the shortwood method both limbing and bucking take place in the stump area. So far, the shortwood method has predominated in Finland; in the felling season of 1969/70 its share of the harvesting methods in the whole country was about 90 % (SAVOLAINEN 1970, p. 2).

The present study is confined to the forest phase of the timber-harvesting system, and to the shortwood method among the methods of harvesting. For the sake of simplicity, the word "harvesting" means here the forest phase of the harvesting process. The number of harvesting systems to be studied is limited to two main types: the *manual system* and the *processor system.* In the manual system, the felling, limbing, bucking and bunching are done by the power-saw man. In the processor system, the power-saw man fells the tree, but a processor does the limbing, bucking and bunching. In both systems, a forwarder (a load-carrying forest tractor) is used for short-distance transportation.

12. Simulation as a tool of analysis

It is impossible, or at least very difficult, to study a large number of real-world phenomena either as such or using strictly analytic methods. Investigating a real system by experiments with various alternatives often produces insurmountable difficulties, since it is too expensive and too time-consuming. An analytic solution, on the other hand, is hampered by insufficient information about the relationships between the variables involved, a lack of applicable deterministic techniques, or random processes within the real system. For this reason, the construction of non-analytic models capable of describing real systems with sufficient accuracy has become increasingly common. Experiments are then carried out with these models.

Experiments made with a model reflecting real-world phenomena fall under the heading *simulation.* Although simulation models actually are used intuitively very often in everyday life, conscious applications are of relatively recent origin. On an extensive scale, their use was not established until the 1960s, when the increased performance of computers and the development of general simulation languages made sufficiently efficient applications of simulation models possible.

The use of computer simulation in forestry has lagged a few years behind the spearhead of development. Some sectors in which it has been applied are sawmill operations (REYNOLDS 1970); forest management planning, especially cutting-budget calculations (GOULD & O'REGAN 1965; KILKKI 1968); problems associated with sampling (ARVANITIS & O'REGAN 1967; SEPPÄLÄ 1971); increment and yield studies (FABER 1967; NEWNHAM & SMITH 1964); and, among the specific problems of timber harvesting, the use of processors (NEWNHAM 1970; SJUNESSON 1970) and skidding methods (la BASTIDE & BOL 1969). Almost without exception, the simulation tool has been one of the general computer languages, such as FORTRAN.

The system of timber harvesting is a typical example of a system which is so complex and contains so many random variables that its overall investigation by means of an analytic model is difficult. Furthermore, investments required by the real system are often so high that experimenting directly with it is unduely expensive and time-consuming. For this reason, the use of simulation in the study of harvesting systems seems appropriate.

2. SYSTEM SIMULATION

21. The concept of a system

The term *system* is used in so many contexts that it is impossible to give it any general and unequivocal definition. Therefore, the concept should be defined separately every time according to the system being examined. For the purpose of the present study, a system is defined as *a set of elements, viewed as a whole, with relationships between the elements and between their states (*cf. PALO 1971, p. 10).

Elements can be any physical or abstract entities, such as men, machines, orders and goals. The *state* of the elements is determined by attributes describing their properties. *Relationships* associate the elements and their states to one another, creating a holistic system. These consist of any specified or non-specified interactions between the elements, such as logical interactions, flow interactions, computational steps, and chronological relationships. From the point of view of the present study, physical flow interactions are fundamental.

Hierarchy is an essential characteristic of systems: every element of a specific system can be reviewed as a system on its own, and accordingly, the specific system is an element of another system at a higher level. Hierarchy is associated with two problems of delineation: on the one hand, it is necessary to draw a line between the system being studied and its environment; on the other, the environment must be distinguished from the whole universe, i.e. from all possible systems.

The *system environment* can be defined as the set of systems outside the system being studied, with which the system being studied interacts in a fundamental way. All action directed towards the system being studied is termed *input* and that directed outwards is *output.* Input and output, like any relationships, can be either abstract or physical, i.e. information, energy and/or material.

A system interacting with its environment is *open.* A *closed* system has no such interaction. It can be said, in fact, that a closed system contains both the system itself and its environment.

A graphic model of an open system can have the appearance of Fig. 1 (cf. PALO 1971, p. 12).

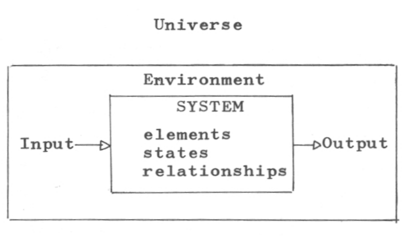

Fig.1. An open system.

22. The concept of a model

Systems present in the real world are called *real systems.* If we wish to describe a given real system, it is necessary to create a new system through words, sketches, mathematics, modelling wax or some other means. This new system transmits the desired information on the real system to be described. We try to create such an information-transmitting system as will imitate the real system in all characteristics essential to the task at hand without being identical to it. Such a transmitting system is called a *system model,* or simply a *model.*

Models are often classified dichotomously according to the real systems behind them. They may be either *continuous* or *discrete, deterministic* or *stochastic.* If classification is based on the model itself, the division can be into *physical* and *abstract* models. Various miniature models are examples of physical models. An abstract model may be mathematical-logical, graphic or verbal.

Furthermore, models can be termed either *static* or *dynamic.* A static model reflects the equilibrium of the system, a dymic model the state of the system as a function of time. Linear programming represents static models, whereas most simulation models are typical examples of dynamic models.

Mathematical models can be divided into *analytic* and *numeric* models. Analytic models require solubility, the numeric ones do not necessarily. Differential equations are analytic models, whereas simulation models are numeric.

23. The concept of simulation

231. A simulation model versus the real system

Once a mathematical-logical model has been created from a real system, it is often possible to obtain information on the subject system by analytic means. Where an analytic solution is not possible in practice, it is necessary to use numeric methods. If the model is dynamic, *numeric simulation* is an excellent auxiliary.

The goal of simulation often is to come as close to the optimum as possible. Unlike analytic models, however, simulation never produces an unequivocal optimum solution. For this reason, the construction of a mathematical-logical model underlying simulation is different from the construction of a model for analytic solution. Freedom in construction, resulting in continuous interaction with the real system, is typical of simulation models. This interaction is illustrated in Fig. 2 (cf. ANDERSIN 1967, p. 2).

The starting point in a simulation model is the real system, either physical or abstract. The goal is to understand the properties and behaviour of the real system in order to be able to control, change or construct it. The tool is the

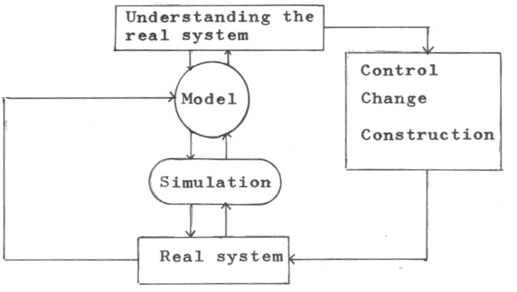

Fig.2. The simulation model as related to the real system.

simulation model, which, through simulation experiments, produces information required for understanding the real system.

232. The steps in the simulation process

The steps in the simulation process partly depend on the type of simulation task. In Fig. 3 is a list of the basic steps associated with any simulation task (cf. GORDON 1969, pp. 21–22; ANDERSIN, pp. 15–18).

The steps listed must be seen as an *iterative* process in which, in principle, the compatibility of the result with earlier phases must be checked after every step and particularly at the test steps of Fig. 3. If necessary, a return to earlier steps must take place. Hence the original task outline may differ considerably from the final one. Similarly, as the simulation project advances, the course of the process must be continually compared with the original design, and checked if necessary.

Collection of data, or treatment of existing material to fit the structure of the model, is the basic condition to be met before the model can be made to correspond even approximately to the real system. The kind of data available is also crucial to the construction of the model. It should always be remembered that the model, even at its best, is only as good as the input data, never any better.

An abstract system model is to a great extent a mathematical-logical model. Its construction is composed of three phases: definition of the components of the model, definition of the variables and parameters, and definition of the functional relationships. Of particular importance in the construction of the model is to decide which of the aspects of the real system are so important for the treatment of the problem that it is worthwhile to include them

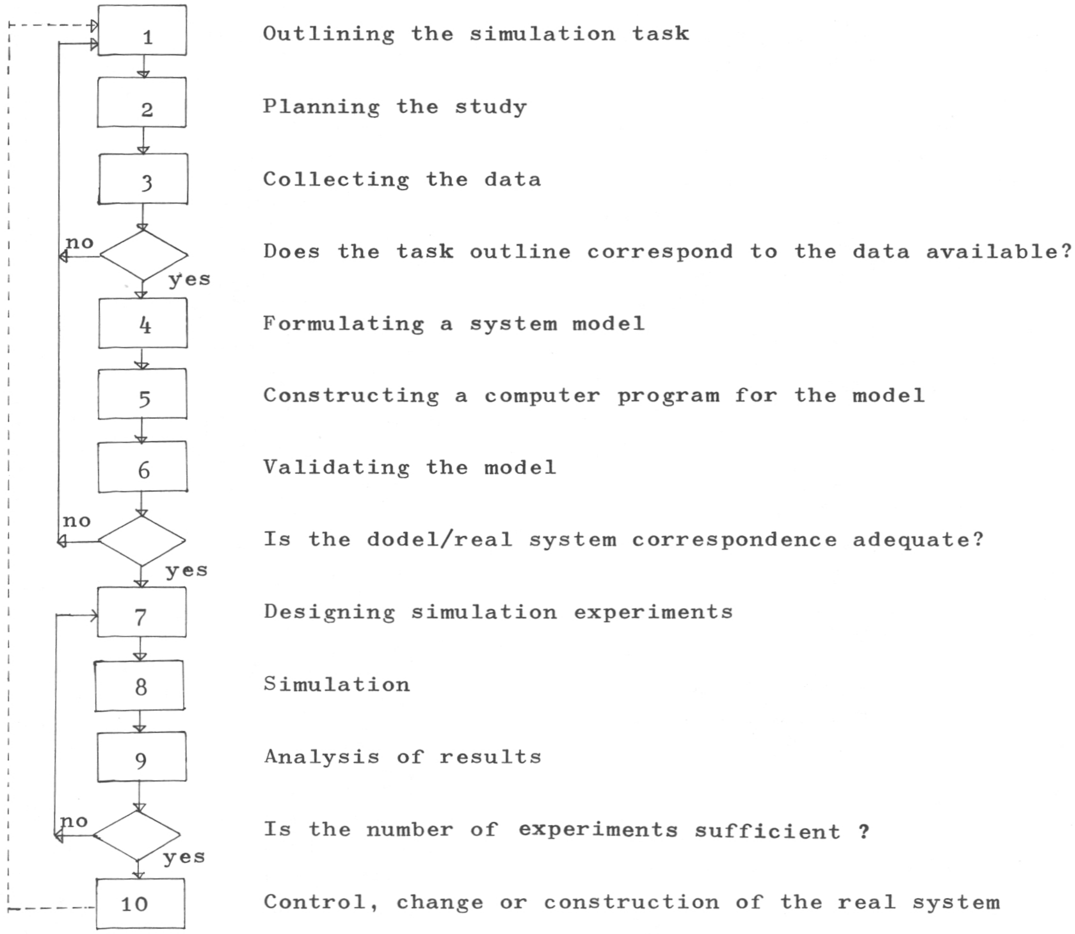

Fig.3. Steps in the simulation process.

in the model. It is characteristic of the simulation model that it divides the real system into *subsystems* whose behaviour is known, or can be predicted at least in terms of probability distributions.

Before the computer program required for simulation experiments is constructed, it is necessary to decide which programming language is going to be used. In programming, the usual tasks associated with a computer program must be carried out. The program should be made as *flexible* as possible to permit modifications should they prove necessary. This is achieved when the system model is composed of subsystems which can be treated as separate *modules* in programming. The ease of program construction is fundamentally affected by how well the system model is formulated. As a result, steps 4 and 5 are better considered in parallel than consecutively.

The validity of the model must be tested by comparing the results of simulation with data obtainable from the real system. This is very hard, and subjective consideration must often suffice. Errors arising from the model must be distinguished from programming errors. If possible, the model should be tested even before the program is worked out.

A difficult problem in designing simulation experiments is how to bridge the gap between two goals: obtaining as much information as possible from simulation, and minimizing the often considerable computer costs arising from the use of the model. A systematic and intelligent design of simulation experiments is important enough to warrant a re-discussion in the next section.

Once the simulation model is complete and the simulation experiments have been carefully designed, simulation itself is completely mechanical. But the analysis of the results is a major effort, for simulation experiments, particularly if they have been poorly designed, may produce large amounts of unessential information. The collection of essential information, the calculation and analysis of statistical characteristics, and the interpretation of the results all belong to step 9.

Finally, it is necessary to weigh whether the number of experiments made is sufficient, and if not, the necessary number of further experiments must be designed. If the experiments are no longer continued, i.e. if the behaviour of the real system is adequately understood (Fig. 2), control, change or construction of the real system may lead to a situation where the simulation project must be re-started (broken line in Fig. 3).

233. Design of simulation experiments

2331. The nature of experimental design

Experimental design has found widespread application in biological and physical experiments. Since the simulation experiment is indeed a true experiment, there is every reason to take its designing as seriously as is common for traditional experimental design. The goals of a simulation experiment usually differ from those of biological and physical experiments, which test hypotheses or the significance of differences between given parameters (usually means). The ultimate goal of simulation experiments is very often to find an optimum.

According to CONWAY (1963, p. 47), the experimental design in simulation, from a statistical point of view, can be divided into strategic planning and tactical planning. *Strategic* planning refers to the designing of an experiment to yield the desired information. *Tactical* planning implies the determination of how each of the test runs specified in the experiment design is to be executed.

2332. Strategic planning

Strategic planning involves choosing the *method of designing the experiment.* From this point of view, it is essential to recognize the purpose for which the simulation model was built. As for practical applications, the goal of simulation may be (cf. ANDERSIN 1967, p. 157):

1) describing and explaining the behaviour of the real system,
2) studying the effect of certain procedures, and/or
3) optimizing according to a given criterion function.

As a rule, the understanding of the behaviour of a real system is increased during the process of formulating the system model, since in this phase particular attention must necessarily be devoted to the basic features of the real system. This understanding can be substantially improved by means of simulation experiments. Furthermore, validating the model necessitates running the model. In validation, experiments are usually carried out with the normal values of the real system, in other words, with the values valid at the time of the experiment.

The general behaviour of the model is often studied by means of sensitivity tests, which help reveal the decision rules and those structural components of the model which significantly affect the behaviour of the model. Sensitivity analysis is mostly heuristic. Statistical methods of experimental design, however, are becoming increasingly accepted.

When the effect of certain measures is studied, the importance of the systematization of simulation experiments increases, especially from the point of view of cost minimization. The commonly used methods are factorial experiments, ranking methods, sequential analysis, time-series analysis and spectral analysis.

The *factorial experiments* are often confounded and/or fractionally replicated. By these means the number of design points can be considerably reduced. If, for instance, there are seven factors to be studied, each with two levels, a full factorial experiment would require 2^7 = 128 design points. By using 1/16 fractional replication, it is possible to reduce the number to 8 (COCHRAN & COX 1957, p. 280). Caution is recommended in the interpretation of results, however, since the risk of misunderstanding is great.

A very simple method is the *ranking method,* which is based on the fact that independent normally distributed statistical characteristics can be ranked in a magnitude sequence. The ranking method reveals not only the existence of the effect of a change, but also shows easily the relative intensities of these effects (see BECKHOFER 1964).

In *sequential analysis,* the number of tests is a random variable, because a decision is made, at a given risk, after every step (change in the levels of the factors being studied) as to

1) whether the change had a significant effect, or
2) whether the change had no significant effect, or
3) whether more experiments have to be made.

After every step, therefore, the question was whether the effect of the change was one that justified the conclusions (see WETHERHILL 1966).

The methods of *time-series analysis* make it possible to study the statistical-dynamic properties of the simulated process and establish the effect of the various measures on them. This method, so far primarily used to study physical, time-dependent processes, seems promising when applied to the analysis of time series produced by stochastic simulation models (ANDERSIN 1967, p. 160). A time series may also be regarded as the summation of oscillations of different frequencies. Essentially the same calculations as are involved in the estimation of autocorrelation in a time-series analysis can be applied to derive a *spectral analysis* (GORDON 1969, p. 291).

The objective of simulation may be an improvement of the real system or its replacement by a new one. This involves finding the combination of the different levels of system variables (factors) which will minimize or maximize the function of the system concerning the desired factor (response function). Both economic and time aspects limit the number of studied alternatives so that experimental work often cannot be expanded to a real search for the optimum. Rather, in practice the experiments represent a heuristic, casual search which tries to find a solution to meet given minimum requirements, i.e. a kind of a *satisfying* solution.

There are also systematic methods of optimum-finding. One is the *single-factor method* (cf. HUNTER & NAYLOR 1970, p. 431). According to this method, the level of a single factor is varied while the levels of all other factors are held constant. When a level producing a minimum (or maximum) is found, this level is fixed and another factor is chosen to be varied. As soon as all factors have been so treated, the run starts again. The process is completed when the levels of the single factors no longer change.

A practical problem is the desirable length of the steps between the levels. If a very small step is chosen, a large amount of work is wasted, and computer time may become unreasonably great. If the step is too long, there is the risk that the optimum point is easily overshot.

2333. Tactical planning

Two important aspects are associated with tactical planning. The first is the question of *equilibrium;* it usually takes some time before the simulation model is "filled up" and begins to operate in a *steady-state* condition. The second aspect is the consideration of *variability* and *sample size.*

Many simulation models have been constructed to describe real systems which operate continuously in a steady-state condition. The simulation model itself, however, does not operate in this way; it must be started and stopped. At the beginning of simulation the model is usually in a zero state; only after some time does it start approaching a kind of equilibrium. This steady state, however, is only a limiting condition that may be approached but never actually attained exactly.

The time interval before the equilibrium is attained depends essentially on the initial state. Instead of from the zero state, the simulation can in some cases be started from an initialized model. Either the starting condition has been fed in advance, or simulation is continued directly after the end of the former simulation run. In the latter case the terminating condition of the preceding run is the starting condition of the following run. If the starting condition differs from equilibrium, the data output during the time interval required to reach equilibrium should be disregarded.

The sample size in simulation refers to the number of replications belonging to the same design point. In most experiments, the goal is to obtain information on certain parameters of the population. A stochastic simulation experiment produces estimates of these parameters. Therefore the result of every separate simulation run is susceptible to random variations. Stochastic convergence enters into force with the replications.

The precision of simulation estimates can be increased, or the experimental error reduced,

1) by increasing the number of factors, or
2) by enlarging the experiment, either
   a) by increasing the length of a single simulation run, or
   b) by increasing the number of simulation runs.

In some cases, the precision of the estimates can be increased in simulation by reducing the length of the time unit used.

All possible effective factors cannot in practice be included. As a result, the normal means of reducing the experimental error is by enlarging the experiment. There is no point in extending the length of a single simulation run excessively. Therefore repeating the experiment often is the only means of increasing the precision of the estimates.

Since the random variation of simulation results seldom is well-enough known, it is difficult to determine beforehand how many replications are required for a desired precision. Sequential analysis lends itself for use in replications too. Time-series and spectral analyses can also enter into question (see GORDON 1969, pp. 290—292).

234. Simulation programming languages

Simulation systems are either *fixed simulators* or *free simulation languages.* The former are ready-programmed standard models, the latter are task-oriented programming languages with the aid of which certain model types can be described. It is also possible to construct simulation models with any general programming language. When a simulation model describing a given real system has been constructed either with some simulation language or a general programming language, the result is a specific simulator.

As a rule, simulators and free (general) simulation languages supply their user with a number of descriptive systems which directly carry a computer program. The user is thus spared a large amount of programming work, compared with doing the same work using a general computer language such as FORTRAN. When desirable, the programs in most simulation languages can be extended by modules using general computer languages.

The real systems were classed above (p. 7) as continuous or discrete. Simulation languages can be divided similarly. Among the best known continuous simulation languages are DYNAMO (Industrial Dynamics), CSMP (Continuous System Modelling Program), and MIMIC. The most extensively used discrete simulation languages are GPSS (General Purpose Simulation System), SIMSCRIPT and SIMULA.

Discrete simulation languages can be classified as particle-oriented or event-oriented (GORDON 1969, p. 123). GPSS represents the former, SIMSCRIPT and SIMULA the latter. In a particle-oriented simulation system, the main attention is on the flow interactions of the system. Event-oriented systems focus on certain activities.

235. General Purpose Simulation System

GPSS is one of the most extensively used simulation languages. It is a flow-chart language, with blocks representing the activities. Lines joining the blocks indicate the sequence in which the activities can be executed. The blocks also implicitly contain the grammatical rules of the language. As a graphic model, the GPSS model is easy to combine with the structure and operation of the real system it is to describe.

The GPSS language is divided into four categories of entities: dynamic entities, equipment entities, operational entities, and data entities. The language also comprises a simulation clock, random-number generators, and various activity-scheduling algorithms.

The *dynamic entities* or TRANSACTIONS are entities moving from block to block in the model. Their properties are described by certain parameters. Thanks to the parameters, highly differentiated transactions can move in the same model. Motor cars in a traffic system, product components in a factory, and trees in forestry processes are examples of transactions.

The second category of entities comprises the *equipment* used by the transactions. These consist of FACILITIES handling one transaction at a time, STORAGE handling several transactions at a time, and LOGIC SWITCHES occurring in two alternative states.

Operational entities represent system relationships, control activity in models, and provide information to serve as the basis of the logical structure of models. Operational entities in GPSS are: BLOCKS, which, in addition to their descriptive role, measure the flow of transactions and serve as the timing system of the model; and QUEUES, which measure the queues in the model at points where queues are expected to develop and where measurement of their behaviour is desired. This category also covers USER CHAINS, GROUPS and SAVEVALUES which serve as auxiliaries for improving the flexibility of model operation.

Data entities facilitate the entry of system data in the model, represent data relationships, and record user data during simulation. FUNCTION entities are the primary mechanism for entering established system data in a model. VARIABLES are entities designed to represent established system-data relationships. TABLE entities provide a tool that the analyst can use to define data-collection procedures for the operation of a model.

3. SIMULATION MODELS OF HARVESTING SYSTEMS

31. Simulated harvesting systems

The harvesting systems discussed in the following cover the phases of timber harvesting from felling through short-distance transport. Of the alternative systems, two main types based on the *shortwood method* were studied: the *customary labour-intensive method,* and the *method based on the use of a limbing-bucking machine* operating on a strip road (cf. PÖLKKI & VÄISÄNEN 1970, p. 6). The former was called the MANU system and the latter the MOTO system (cf. JÄRVINEN 1970, p. 8). Two types of limbing-bucking machines were used in the MOTO systems: the PIKA type (the Finnish PIKA 50) and the KOCKUM type (the Swedish KOCKUM PROCESSOR 78 ATK). A description of the systems by job phases is presented in Table 1; both the executor of the job phase and the basic capacity in simulation are mentioned. The harvesting-system models do not explicitly contain planning and supervision, whereas servicing and movements are included. Servicing comes under interruptions, and movements as a separate module.

Table 1. Simulated harvesting systems, by phases of work.

Harvesting system	(1) Felling		(2) Limbing, bucking and bunching		(3) Short-distance transport	
	Executor	Basic capacity	Executor	Basic capacity	Executor	Basic capacity
MANU	power saw man	2 teams of 3 men each	power saw man	2 teams of 3 men each	forwarder	1 tractor
MOTO/PIKA	-"-	1 man	PIKA 50 processor	1 machine	-"-	-"-
MOTO/KOCKUM	-"-	2 men	KOCKUM PROCESSOR	1 machine	-"-	2 tractors

32. Study outline

The result of a simulation project is, first, a simulation model, which is usually programmed for a computer, and then information obtained from simulation experiments with the model concerning the properties and behaviour of the real system. Accordingly, the goals of the project at hand were divided into two consecutive parts:

1) Construction of such simulation models in the GPSS language as describe the structure and operation of the chosen timber-harvesting systems in sufficient detail for simulation experiments.
2) Execution of simulation experiments which would demonstrate the effect of the variables (marked-stand characteristics, terrain characteristics, structure of systems, etc.) in the harvesting systems on system operation, and which would help to find the combinations of different levels of the variables which are peculiar to each system.

The realization of part (1) depends very much on part (2). The latter is very exacting and presupposes availability of good empirical material. The goals should not be regarded as too binding, since pursuing them exactly might be too ambitious an undertaking. *It is better to begin with a relatively rough approximation and first strive to obtain tentative results only.* With a broadened understanding of the real system, and accumulation of more of the relevant data, the structure of the model can be improved and the experiments carried out with it can be expanded. It should be remembered that, in principle, *the simulation project continues until the real system itself becomes redundant.*

Collection of the empirical material associated with the harvesting systems chosen to be simulated soon revealed that the data available on the whole processes, and particularly for some of their parts, was incomplete and sometimes unreliable. The data on the operational reliability and work achievements of processors, in particular, was based on material which both in time and considering the number of machines tested was fairly limited (cf. PÖLKKI & VÄISÄNEN 1970, p. 5). This was due to the fact that the machines had been in use for only a very limited time.

Owing to the short supply of currently available and sufficiently reliable material it proved necessary to reduce the goals of part (2). *The principal aim,* therefore, *became the construction of the simulation models* themselves; the simulation experiments in this phase served mainly to validate the models. Once the models are finalized, simulation experiments can easily be expanded proportionately to the increase in data required.

33. Construction of the models

331. System models of harvesting systems

When a general simulation language is used (Section 234), the real system must be viewed in the light of the "philosophy" contained in this language. *The philosophy of the GPSS language is characterized by a process-like nature:* a GPSS model has fixed working points between which a number of dynamic entities (transactions) move (Section 235). These transactions enter the working points in a given sequence, stay there for a fixed period, and continue their course to the following working points.

When the harvesting systems are viewed in the light of the GPSS language, a choice must be made: either the marked stands are fixed working points and the executors of the different job phases (Table 1) are transactions moving from one point to the next, or the job phases are fixed working points and the marked stands are transactions moving from one point to the next. The former agrees with the traditional way of thinking, while the latter may seem strange. However, the latter is closer to both general process thinking and the philosophy of the GPSS language. A consideration of industrial processes supports the view that *the material* (marked stands) *flows and the working points* (phases of harvesting) *are fixed.*

Process thinking can be illustrated by taking the harvesting system as a *hierarchic, open system* (Section 21). The systems studied are *subsystems* of the total timber-harvesting system (long-distance transportation, measurement, etc., included). The latter, in its turn, is a subsystem of timber production, which is itself a subsystem of the system of the next order (cf. PALO 1971, p. 22). Similarly, the systems of the present study can be divided into subsystems, these further into subsystems, and so on. On the basis of the job phases in

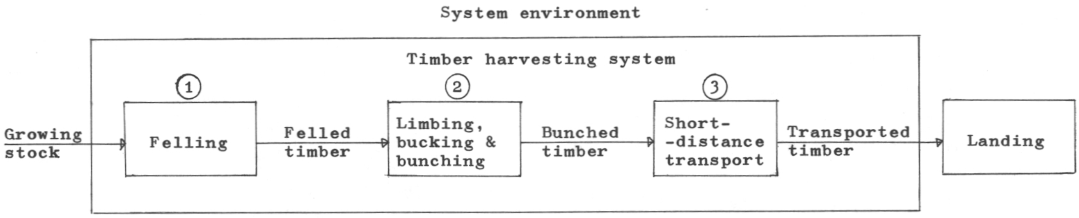

Fig.4. A system model of the timber harvesting system based on the shortwood method.

Table 1, the system chart of Fig. 4 was obtained for the harvesting systems chosen to be simulated (cf. Fig. 1, p. 6).

Growing stock represents the *input* and the timber transported from the forest the *output* of the system. The *elements* of the system are the job phases in the harvesting-process. The *state* of the elements can be either "in operation" or "out of operation". The *relationships* in this case are physical flow interactions, i.e. timber. Every element forms a subsystem which can be further divided into new elements (e.g., element 2 of Fig. 4 can be divided into limbing, bucking and bunching).

332. Operational principles of the models

As pointed out in the study outline (Section 32), *too ambitious goals for the construction of simulation models are not to be recommended.* It is wisest to proceed by stages, starting from the construction of a relatively simple model which can gradually be made more consistent as required. When dynamic real systems are to be simulated, the construction of a model is, in principle, a never ending job. The results of simulation in themselves can produce a need for modifying the real system, with the result that the model must be modified accordingly.

Making a model which describes a given fixed real system more consistent is, in a way, a search for an optimum. On one hand, too simple a model can produce misleading results, and on the other, consistency exceeding a certain limit makes control of the model difficult and increases the cost of computer runs without essentially improving the standard of the information being produced. When optimizing the running time in particular, it is worth remembering that *a small loss of realism in the model can sometimes remarkably reduce the running time without appreciably impairing the results* (IBM 1969, p. 210).

Step-wise construction of the harvesting-system simulation models started from a very simple first version. The version in use at the time of this writing was the fourth. The models were constructed *modularly,* which makes an exchange of their parts a very simple task. Modularity is based on the system model of Fig. 4, in which the elements are modules of the simulation model.

So far there are three alternative systems (Table 1) which operate individually. The next steps should be to increase the number of systems and linkage to allow operation in parallel through time. The goal cannot be the construction of any final model, for the existing harvesting systems are constantly changing and, furthermore, new serviceable alternatives develop.

Fig. 5 presents the main features of the operating principles of harvesting-system simulation models. GPSS symbols are used to designate the blocks. In the different systems, the modules of the models vary to some extent. For example, in the MANU system, felling was referred to the same module as limbing, bucking and bunching.

The models have a total of five operational modules. Modules 1–3 correspond to elements 1–3 in Fig. 4. Module 0 corresponds to the input and module 4 to the output of the system model. Modules 1–3 are identical in their operational principles.

The transaction (p. 11) chosen for the model was the stand marked for the cutting. Another practical alternative would have been a bundle of wood of a given volume, say 10 m^3 (m^3 = cubic metre, solid measure). An individual stem, on the other hand, would have been too small a unit from the point of view of simulation, since its use would have made the number of transactions in the model unreasonably large. If it is desired to divide the marked stand into parts, the division is best done on the

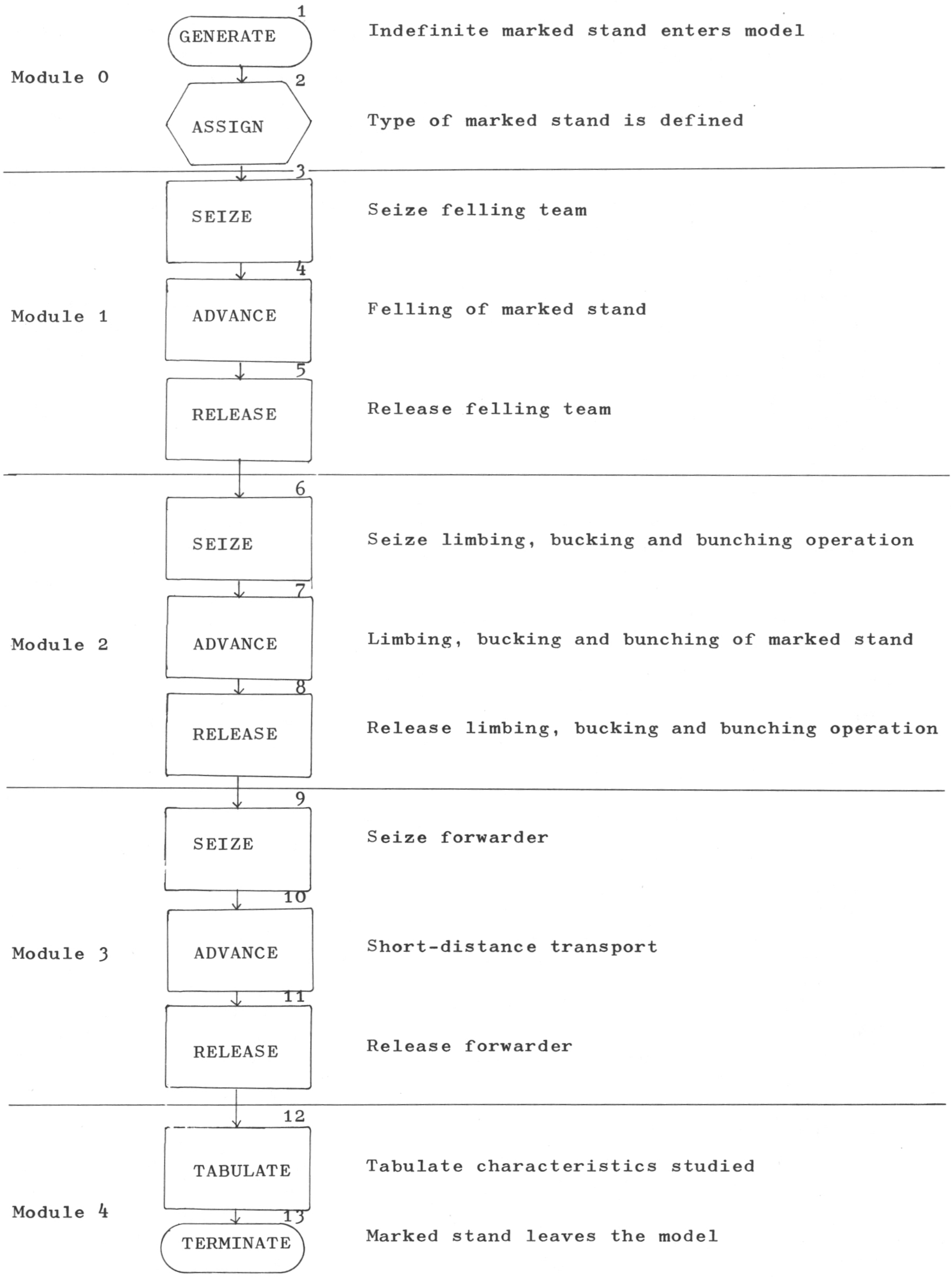

Fig.5. The operation principle of harvesting system simulation models based on the shortwood method.

basis of timber assortments and tree species. Owing to the definition used for a transaction, the various job phases operated separately in time. In reality, a felling team, processor and forwarder can be in operation simultaneously in large stands.

As the type of marked stand is defined, the stand is given a number of *parameters* which indicate the volume of the stand, its density, mean stem size, type of tree species, and terrain type. Additional parameters are the season of the year and the distance from one stand to the next. The season parameter in modules 1–3 is changed every time the season changes. Stand characteristics, in principle, can be more numerous than in the models presented (in the latest GPSS version, the maximum number of parameters exceeds 1 000).

The parameter values are determined by *distributions* indicated separately. The stands, therefore, are not counterparts of any true stand. But true stands can also be used as input for the model in the GPSS simulator. Instead of stand properties being based on various distributions, the stands are given properties of certain true stands.

When a simulation model is constructed and its validity is tested, it is often better to use distributions produced by a long empirical series of observations than to define the stands precisely as copies of some existing stands. Results obtained from input data based on distributions often correspond to the average situation better than results based on real-stand input, which is perhaps limited in time. In the simulation itself, however, it may be attractive to use precisely defined stands. This is true especially of situations in which simulation is used along the lines of production planning.

Modules 1–3 will be discussed in detail in the following section. In Fig. 5, the tabulation of the results obtained from simulation (average utilization in the different job phases, duration of treatment per stand, the queues observed, etc.) was concentrated in one block (module 4, block 12). In reality, the collection of statistical output is decentralized over the various job phases (modules 1–3) so that its structure is uniform in all.

333. Simulation model of the MANU system

In the MANU system, modules 1 and 2 were combined since felling, limbing, bucking and bunching are carried out by the same cutting team (p. 12). Fig. 6 shows the main features of the block diagram for the simulation model of these job phases. In its details, the diagram is far from complete in comparison to the true model.

When passing through modules 1 and 2, the marked stand only stops in blocks 1, 4 and 7. The model has a total of two cutting teams, and therefore the "capacity" of the cutting phase is two. Waiting for one of the cutting teams to be free, i.e. for cutting capacity to exceed the number of marked stands in the cutting operation at the time of observation, takes place in block 1. The delay in block 4 is that required by the duration of the cutting. Cutting time is determined by stand characteristics (stand size, stand density, mean stem size, tree species and terrain type) and by the season of the year. In block 7, the cutting teams move to the next stand to be cut. Not until this movement has taken place can a new stand be taken up for treatment. The duration of movement, for simplicity's sake, was made constant for all cutting teams (1 hour).

In block 6, a copy must be made of the original transaction (marked stand). This is because the stands usually are not adjacent to each other and the cutting team must move (e.g. by car) to the next stand to be cut. In the GPSS simulator, *only transactions can produce activities* in the model. For this reason, in block 6 the stand is transformed into a movement transaction (e.g. a car), while at the same time an identical copy of the original stand is formed. The copy continues its course to the next job phase (module 3, short-distance transport). Once the movement is completed, the movement transaction is destroyed in block 9.

When the cutting phase is completed, the marked stand moves on to the short-distance transport (forwarder) phase. A simplified block diagram of this phase is shown in Fig. 7.

In passing through module 3, the marked stand stops in blocks 1, 5 and 8. These correspond to the blocks in which the stand stops during the cutting phase. The duration of movement is not constant this time, but is obtained by adding to a certain basic duration (preparation of movement) the time taken for the movement itself, which is calculated as a function of the distance to be moved (obtained on the basis of distribution) and the speed.

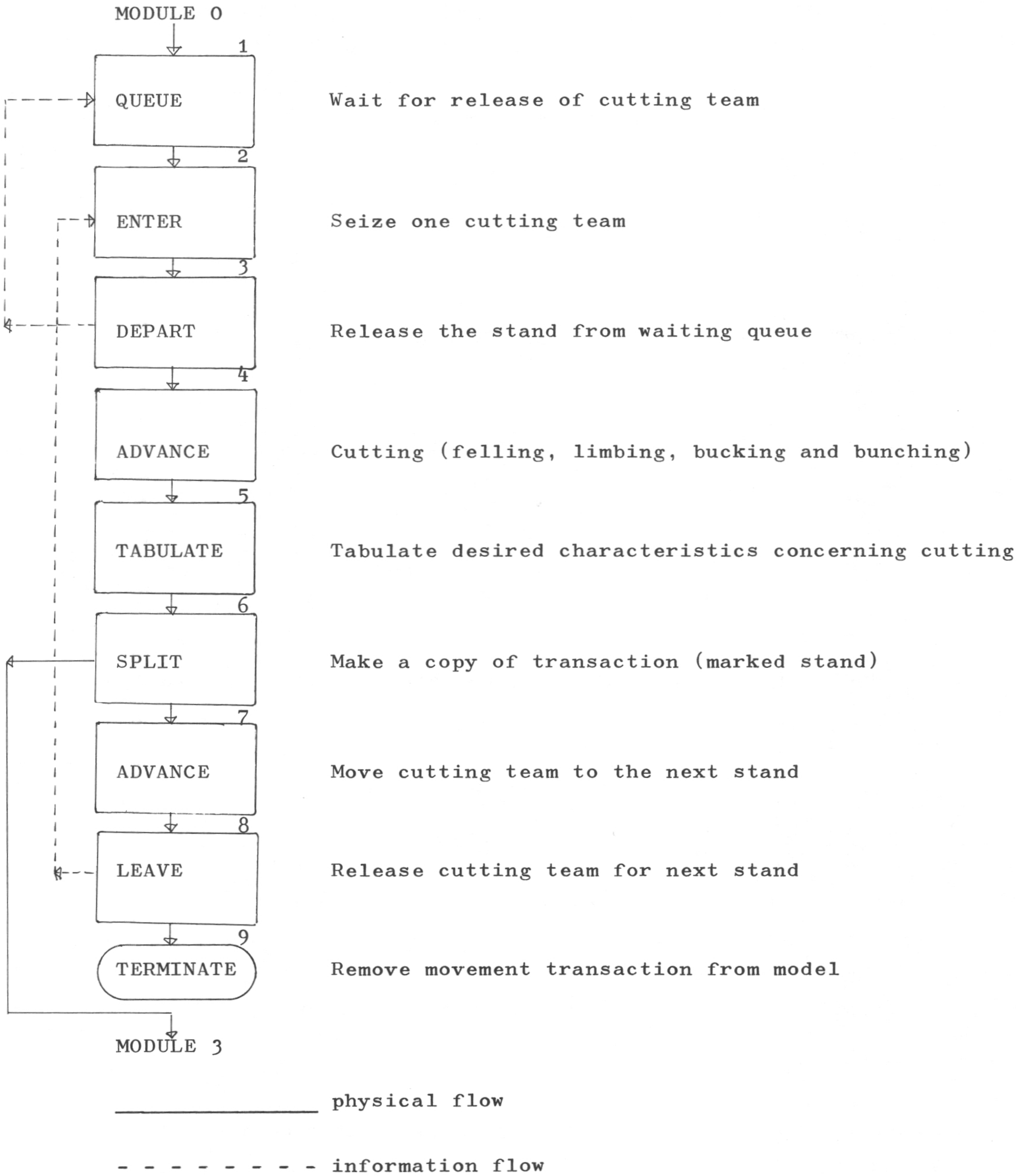

Fig.6. A simplified block diagram for the cutting phase (modules 1 and 2) in the simulation model of the MANU system.

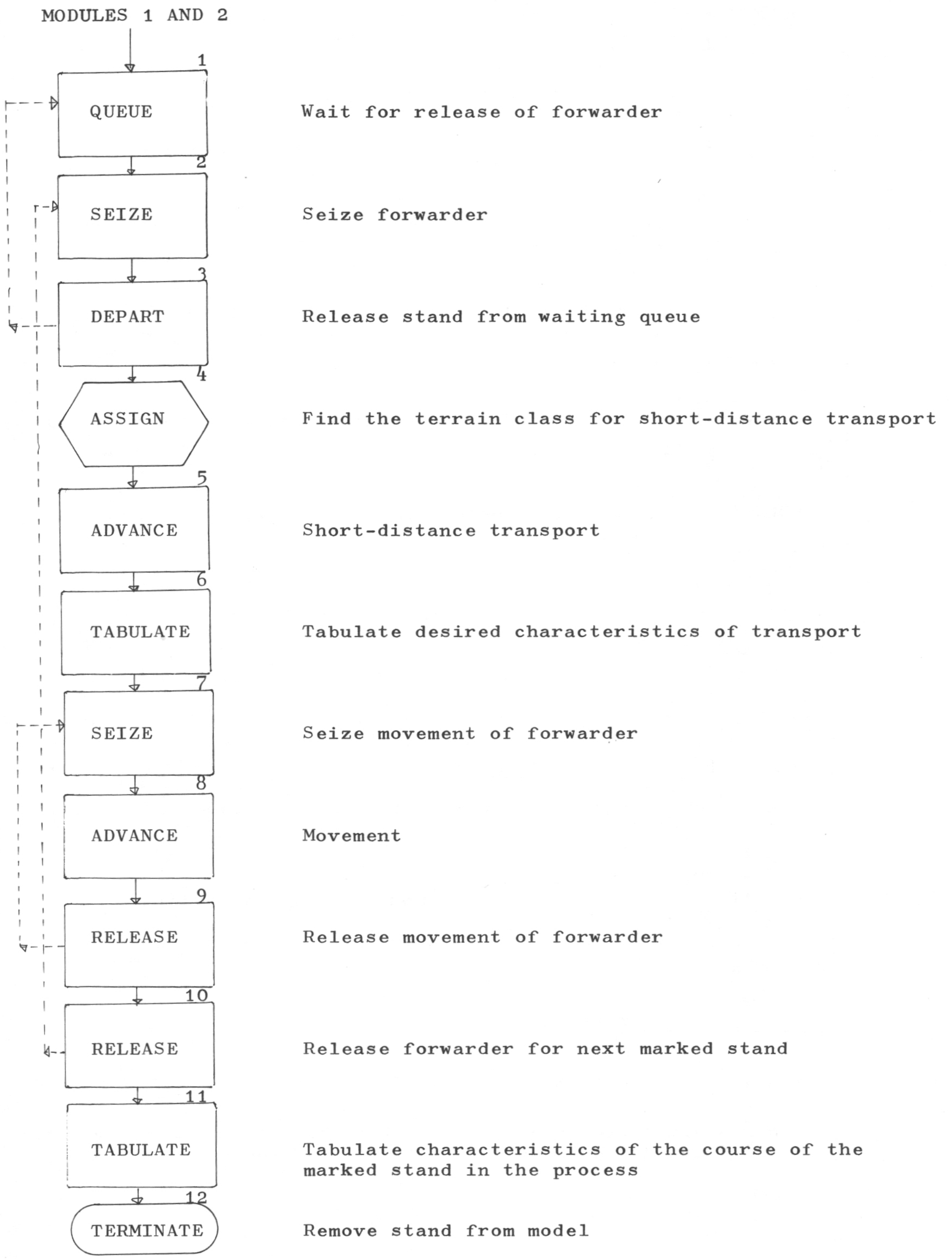

Fig.7. A simplified block diagram for the short-distance transport phase (module 3) in the simulation model of the MANU system.

The basic capacity of short-distance transport chosen for the MANU system was one forwarder. Owing to this, the ENTER and LEAVE blocks of cutting (refer to STORAGE, which may have a capacity exceeding one) are replaced in short-distance transport by the blocks SEIZE and RELEASE (refer to FACILITY, which always has the capacity one) (p. 11).

In block 4, the terrain class is re-defined, since the classification used in short-distance transport was different from that in cutting. In addition, the season of the year may be different from that of the cutting phase. Changes of this type are recorded before the duration of stand transport is determined.

It is no longer necessary in the transportation module, as it was in the cutting module, to create an identical copy of the stand because the process to be simulated ends with transportation. Hence the stand transaction ultimately operates as the transaction producing the forwarder movement. Before the stand is removed from the model, the desired characteristics are tabulated, mainly those applying to the whole process chosen for study. One of these characteristics is the time which the stand remains in the system. It is of importance whenever simulation is used for such purposes as production planning or contol.

334. Simulation models of the MOTO systems

In the MOTO systems examined, limbing, bucking and bunching were carried out by a processor. Two types were studied, the Finnish PIKA 50 and the Swedish KOCKUM PROCESSOR machines. The basic structure of the systems associated with the two processors was the same. The output of the KOCKUM PROCESSOR, however, was about twice that of the PIKA machine. For this reason, the basic capacity in the KOCKUM system is two power-saw men and two forwarders, whereas the PIKA system has only one of each (Table 1).

Since the basic structure of the two MOTO systems, apart from capacity differences, is the same, they are discussed in parallel below. The simplified block diagram of the simulation models of the felling phase for both processors is shown in Fig. 8.

It is possible that the output of a felling team under some conditions does not equal that of the processor. If so, the processor may have to wait on the felling work. To forestall this, the possibility of introducing an extra felling team (or over-time work for the basic team) was added to the felling module. The condition for the introduction of this group is in block 2. This condition, of course, can be different from that used here. The extra felling group is in blocks 11–18. In the simplified diagram of Fig. 8, these blocks are identical to blocks 3–10. In the true model, blocks 11–18 contain an additional test which guarantees that the basic felling team is not unemployed while the extra team is at work (Appendix, p. 33).

Although in the KOCKUM system the felling team comprises two power-saw men, the basic capacity of this job phase in the model was defined as one, since the two power-saw men work in the same stand. Otherwise blocks 3–10 and 11–18 are analogous to the cutting section of the MANU system (blocks 2–9, Fig. 6).

The basic structure of module 2 in the simulation models of the MOTO systems is similar in type to the felling team of module 1 (Fig. 8, blocks 1 and 3–7), apart from movement. The structure of processor movement, again, corresponds to the model of forwarder movement in the MANU system (Fig. 7, blocks 7–12).

The short-distance transport phase in the simulation models of the MOTO systems is identical in its basic structure to the corresponding phase in the MANU system. The KOCKUM system differs from the MANU and the PIKA systems in that it has two forwarders operating in different stands. All systems foresee the possibility of increasing transport capacity through over-time work. The procedure is comparable to the introduction of an extra felling team in the felling phase of the MOTO systems (Fig. 8). The test characteristic, however, is different; it is based on the volume of the stands awaiting transportation. When the model is developed, it is useful to select the need for prepared timber as a time-dependent quantity to serve as one test characteristic.

335. Separate operations of the models

In addition to the simulators of harvesting systems, the models contain a number of special routines. They are the simulators of run timing, seasonal change, and interruptions.

Run timing of the model, i.e. determination

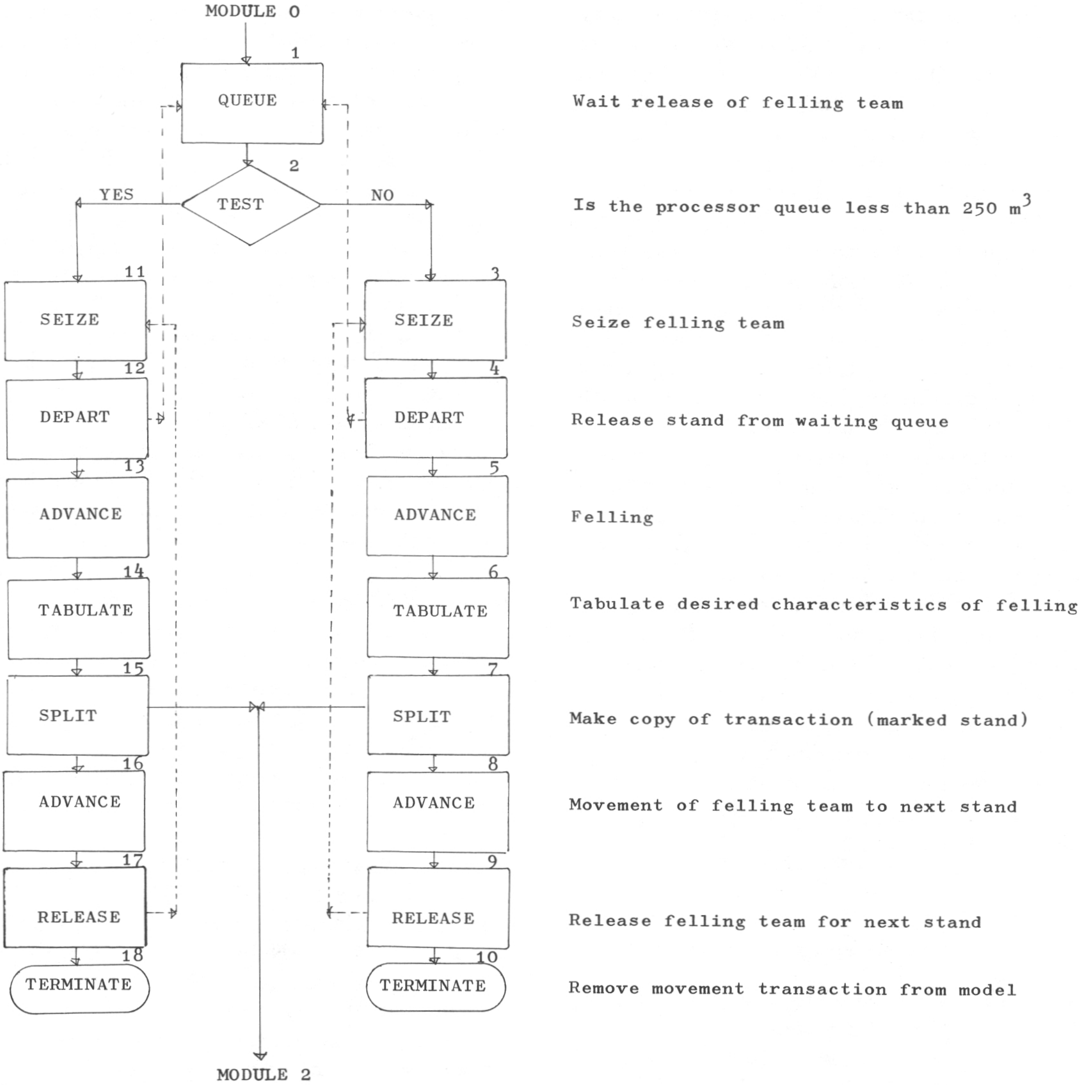

Fig.8. A simplified block diagram of the felling phase (module 1) in the simulation model of the MOTO systems.

of the time interval to be simulated, is firmly associated with the selection of the time unit to be used. This in turn depends very much on the determination of the transaction of the model: the smaller the transaction, the smaller the time unit. Selection of the transaction and time units greatly affects the running of the model. It is again worth remembering that a minor simplification of reality may lead to a considerable cost saving in the simulation phase (p. 14).

In the present models, *the stand marked for cutting was selected as the basic transaction.* As a result, one hour was considered a sufficiently precise time unit. If the time unit is longer than one hour, too much simplification is introduced, since the duration of movement for power-saw men, for example, was fixed at one hour.

Time units smaller than an hour, e.g. one-tenth of an hour, may enter into question later, especially if the stand is divided into timber assortments and tree species. Running time in the present models would in this case be far from tenfold, because it has been possible, by means of USER CHAINS

(p. 12), to reduce the number of active transactions, which consume computer time, to an average of five transactions.

Besides the duration of simulation, the timing routine of the model also defines the points in time at which intermediate results are produced. In the present models, the length of the time period to be simulated was chosen to be one year, and the intermediate results in the final simulation tests were taken after the initialization phase (p. 10) and the close of the winter season (January-April). The duration of simulation could have been determined also on the basis of the number of stands simulated. For example, 20–50 stands marked for cutting could have been simulated and intermediate results taken after the simulation of perhaps every 10 stands.

The *season* (especially winter, primarily because of snow and frozen ground) affects the determination of the output of the different phases of harvesting systems. In the model, the change in season was included so that as the season changed, the seasonal parameter was modified in all the stands of the model.

Especially in the MOTO systems, *interruptions* arising from machine servicing and the need for repairs are an important factor. In the model, these interruptions appear as separate modules, which at time intervals based on a given distribution produce special interruption transactions. These transactions are directed to a desired job phase, where they produce an interruption in the job process for a given period. The duration of the interruption is obtained on the basis of the given distribution. Interruptions lasting less than an hour were combined; they are taken into account when the duration of each job phase is calculated. For power-saw men the proportion of such interruptions was set at 18 %, for processors 20 %, and for forwarders 10 % of the working-site time (movements from one stand to another excluded). No interruptions other than those lasting less than an hour were produced for power-saw men.

34. Validation of the models

The *validation* of a model involves ascertaining that *the model is in sufficiently precise agreement with the real system.* The wording "sufficiently precise" is highly important in this definition. On one hand, it makes the validity of the model a *relative* concept, while on the other it permits *subjective* ascertaining of validity.

It is important to bear in mind when validating a model that *the model must be considered in relation to its intended use.* The model, therefore, may be valid for one purpose but invalid for some other. Adding redundant features to the model produces not only additional cost both in model construction and simulation but also the risk that important properties become masked by excessive details.

Ascertaining the validity of a model is always to some extent subjective, even though it may be based on experiments with the model. Usually the input data for the validation experiments is the basic values of the real system. The simulation experiments themselves, however, must often test the effect of certain modifications. On the basis of subjective interpretation, it then becomes necessary to assume that the model is valid also after modifications are introduced. FORRESTER (1961) states that the validity of the model can be definitely considered only after the model user has been able to accept the results produced as forming an adequate basis for decision-making.

The present simulation models of harvesting systems were constructed by stages, with precision increasing in the models step by step. After every stage, the validity was tested by running the models with the basic values of both the structure and the parameters of the harvesting systems. In the early stages, the simulated time was only one month, but as the structure of the models became more complicated a simulation period of one year was introduced.

The statistical output of the simulation models as they were at the time of writing is discussed in the following. The purpose was to have the initial distributions of the parameter values correspond to the average situation in the clear-cutting areas of southern Finland. The data on distributions, at the time of model simulation, was relatively incomplete. This was particularly true for the effect of the different values (e.g. mean stem size > 0.5 m^3/stem or mean stem size < 0.5 m^3/stem) of an individual parameter (here, stem size) on the output. Apart from stand size, interruptions and distances of movement, the distributions concerning the parameters had only two values (as did stem size above). Stand-volume distribution had nine values, interruption distribution (duration of interruption) three, and movement distribution six.

A flaw in all the parameter values was that, in the absence of suitable material, an almost complete independence had to be assumed. This is not true in reality, since a change in the density of the marked stand, for example, affects the output of a given job phase differently for different terrain classes.

Deficiencies relating to distributions do not, in themselves, affect the formation of model structure. When validity is tested, it must be remembered that inaccuracies in the distributions may mislead the interpretation of the results. When empirical material is increased and becomes more reliable, the initial distributions can be easily modified. This is based on the fact that input data in the model constitutes a module distinct from the work process itself.

The work year in the model was 11 months (paid annual holiday was assumed to have been one month), or just under 48 weeks. The basic length of the working week was 40 hours. The initialization or "filling" phase (p. 10) of the model took two months (p. 27).

Tables 2–4 describe parameters obtained for the different systems. The length of the simulation period was two working years. Owing to the nature of the MANU system, it included

Table 2. Average utilization and treatment times for the different systems, by job phases for two working years.

Job phase	Average utilization			Average treatment time, hrs/stand		
	MANU	PIKA	KOCKUM	MANU	PIKA	KOCKUM
1A. Cutting/felling team, normal hrs.	1.000	1.000	1.000	80.6	64.9	31.9
1A1. Cutting/felling	.987	.984	.968	79.6	63.9	30.9
1A2. Movement	.013	.016	.032	1.0	1.0	1.0
1B. Cutting/felling team, overtime		0	0		-	-
1B1. Cutting/felling		0	0		-	-
1B2. Movement		0	0		-	-
2. Processor		1.000	1.000		72.2	45.6
21. Process		.923	.828		66.7	37.7
211. Effective time		.740	.663		53.4	30.2
212. Interruptions		.183	.165		13.3	7.5
22. Movement		.076	.171		5.5	7.8
3A. Forwarder 1	1.000	.801	.951	78.1	62.6	66.2
3A1. Short-distance transport	.962	.754	.877	75.2	58.9	61.0
3A11. Effective time	.862	.682	.786	67.3	53.3	54.7
3A12. Interruptions	.100	.072	.091	7.9	5.6	6.3
3A2. Movement	.037	.047	.074	2.9	3.7	5.2
3B. Forwarder 2			.192			91.6
3B1. Short-distance transport			.182			87.1
3B11. Effective time			.159			76.1
3B12. Interruptions			.023			11.0
3B2. Movement			.009			4.5
3C. Forwarder, overtime	.774	.189	.593	64.5	241.3	133.6
3C1. Short-distance transport	.741	.185	.568	61.7	237.3	128.1
3C11. Effective time	.673	.171	.512	56.0	218.2	115.3
3C12. Interruptions	.068	.014	.056	5.7	19.1	12.8
3C2. Movement	.032	.003	.024	2.7	4.0	5.5

Table 3. Mean volumes of harvested stands and output figures for the different systems per job phases for two working years.

Job phase	Mean volume, m^3/stand			Output, stands			Output, m^3/effective hour		
	MANU	PIKA	KOCKUM	MANU	PIKA	KOCKUM	MANU	PIKA	KOCKUM
Cutting/felling	435	376	395	95	59	121	6.6	7.1	15.6
Processing	-	371	399	-	53	84	-	9.2	17.6
Short-distance transport	394	375	405	95	52	80	7.2	6.7	6.5

Table 4. Queue lengths in m^3 per job phase for the different systems at the end of the simulation of two working years

Location of queue	MANU		PIKA		KOCKUM	
	Current	Average	Current	Average	Current	Average
In front of - processor	-	-	4 475	2 899	16 085	7 356
- short-distance transport	4 147	1 584	0	164	739	776

no processor phase. This system had two cutting teams, but foresaw no possibility of overtime cuttings, in contrast to the MOTO systems. In the KOCKUM system, a second forwarder can be used to help in short-distance transport. In all systems, it is possible for the forwarders to do overtime work. Unlike true situations, the processors were allowed to work for only one shift. (Cf. Table 1, p. 12).

In the cutting (felling) phase and the processor phase, the total utilization (the ratio used time/total time) of these work points in all the systems was unity (Table 2). In the KOCKUM system, the utilization of forwarder 1 remained only slightly below unity while in the PIKA system the difference was relatively great. An explanation is that overtime work (for forwarder 1) was readily introduced in short-distance transport. This was done as soon as there was a queue of 1000 m^3 in front of the work point. For this reason, forwarder 2 in the KOCKUM system was used relatively little compared with the overtime work. The situation for overtime work is in fairly good agreement with the real situation in which the total working time of a forwarder is nearly 60 hours per week.

The treatment times (Table 2) and outputs (Table 3) for the different job phases may be considered to agree sufficiently with reality.

The distributions of the distances of movement varied according to the system. In the MANU system, the average distance (for forwarder) from one stand to another was 18 km, in the PIKA system (for processor and forwarder) 40 km, and in the KOCKUM system (for processor and forwarders) 63 km. The time required for movement of the cutting (felling) team was fixed at one hour.

When the proportions for interruptions in the total working-site time are examined, it should be remembered that the effective times of Table 2 contain all interruptions of less than one hour (p. 21). But the effective time of the output figures of Table 3 (output, m^3/effective hour) contain only the true effective time. The proportion of separately simulated interruptions (longer than an hour) was almost exactly 20 % for processors and very nearly 10 % for short-distance transport.

On the basis of queue data (Table 4), it could be concluded that the work input of the felling teams can satisfy the timber requirements of the processors. For this reason no overtime work at all was required for felling in the simulation stage itself (Table 2, cf. Table 6). In the KOCKUM system, the output of the power-saw men even exceeded the capacity of the processor, which operated on one shift only. The rather low average utilization of the forwarder of the PIKA system (0.801) is further explained by the observation that, at the end of simulation, there was no queue in front of it.

The mean stand volume is generally slightly smaller than the mean volume calculated directly from the distribution (443 m^3). This is due to the fact that few very large stands (over 3000 m^3) had been generated in the model.

4. DESIGNING THE SIMULATION EXPERIMENTS OF HARVESTING SYSTEMS

41. Goals of the design

Under study outline (Section 32), it was seen that the information available on the harvesting systems to be simulated was incomplete and partially even unreliable. As a result, the main goal of the present study was the construction of a simulation model, with simulation experiments mainly serving for the validation of the model. Although it had been decided to carry out no simulation experiments proper, it was found necessary in this phase to design the experiments so that, once the necessary data is available, they can immediately be carried out.

In Section 233, the designing of simulation experiments was divided into strategic and tactical planning. Strategic planning encompasses the selection of the method of experimental design. Tactical planning deals with the solution of the problems associated with equilibrium and the precision of simulation results.

42. Strategic planning

In the present harvesting systems, experiments with the different alternatives consist mainly of those with the different values of stand parameters (p. 16). The goal is not so much to find an optimal set of parameters as to ascertain how modification of parameter values and certain structural parts of the systems affects the output of the systems and by this means the benefit/cost ratio. In this light, *factorial designs* seem a suitable method of experimental design.

In the harvesting systems studied, among the most essential factors (variables) are, without any definite order of importance, the volume of the stand marked for cutting, the mean stem size of the stand, interruptions in the working process, and movements from one stand to the next. These are followed by the density of the stand, type of tree species (includes the effect of branching), type of terrain and short-distance transport. The season, primarily winter with its snow and frozen ground, also is an important factor, but it cannot be selected in the same way as the other factors mentioned. The vocational skills of the workers are of decisive importance, especially for machines, but it is not easy to include this effect as an explicit factor.

In the following plan, the start is a consideration of *four factors*. In order to make the simulation information sufficient, it is necessary to include at least *three levels* per factor: mean values, values below the mean, and values above the mean. In a complete experiment, therefore, the number of design points per system is $3^4 = 81$, a total of 243 for all three systems. Although the model can be run relatively rapidly, an experiment of this magnitude is nevertheless fairly expensive. There is thus every reason to consider the use of *fractional replications* (cf. p. 9).

Several alternative experimental designs can be suggested for fractionally replicated factorial designs. It is useful for the experimental design to be *rotatable,* i.e. to include the possibility of fitting a second-order (or higher order) polynomial to the output data. Rotatable design quarantees that the standard deviation of the fitted response at any point depends only on the distance of the point from the center of the factor space and not its direction

Table 5. A fractional 3^4 factorial design of 27 experimental runs.

Run	Factor				Run	Factor				Run	Factor			
	A	B	C	D		A	B	C	D		A	B	C	D
1	-1	-1	0	0	10	-1	0	0	-1	19	0	-1	0	-1
2	1	-1	0	0	11	1	0	0	-1	20	0	1	0	-1
3	-1	1	0	0	12	-1	0	0	1	21	0	-1	0	1
4	1	1	0	0	13	1	0	0	1	22	0	1	0	1
5	0	0	-1	-1	14	0	-1	-1	0	23	-1	0	-1	0
6	0	0	1	-1	15	0	1	-1	0	24	1	0	-1	0
7	0	0	-1	1	16	0	-1	1	0	25	-1	0	1	0
8	0	0	1	1	17	0	1	1	0	26	1	0	1	0
9	0	0	0	0	18	0	0	0	0	27	0	0	0	0

(HUNTER & NAYLOR 1970, p. 428). It is also very useful to be able to achieve *orthogonal blocking*, i.e. the arrangement of block contrasts so that they are uncorrelated with all the estimates of the coefficients in the polynomial.

BOX and BEHNKEN have presented a rotatable second-order design which is suitable for studying four variables with three levels in 27 trials. It is also capable of being blocked in three sets of nine trials. This experimental design is set out in Table 5 (BOX & BEHNKEN 1960, p. 458).

"O" refers to the mean level of the factor (e.g. movements from one stand to another equal the current distances; "−1" is a level below the mean (e.g. movements are half the current distances); "+1" is a level above the mean (e.g. movements twice the current distances).

On the basis of Table 5, orthogonal blocks can be made up from runs 1–9, 10–18 and 19–27. In the simulation experiments, the formation of blocks may be of minor importance, since the "experimental material" can generally be considered homogeneous.

With fractional replications, it is necessary to assume that a number of the higher-order interactions are of no importance. Here lies the greatest risk in the application of this method, which otherwise is very much to be recommended. For this reason, the intensity of the interactions should be either preliminarily tested or at least intuitively inferred. As a rule it can be said that in the case of four factors, 3- and 4-factor interactions are of no importance. In the present experimental design, not only the main effects but also the majority of the 2-factor effects can be estimated (for estimation procedure, see BOX & BEHNKEN 1960, pp. 464–470; COCHRAN & COX 1962, pp. 272–273 & 290).

If more information is needed, an additional 27-run 3^{4-1} fractional replication can be employed and the data from all runs analyzed. If a third similar fractional replication is carried out, the result is a complete factorial design. This stepwise progress (cf. sequential method, p. 10) is useful even though no fractional replication had originally been intended. In most cases, adequate information is obtained before a complete experiment is arrived at.

43. Tactical planning

431. Steady-state condition

A simulation model must be started and stopped. In order for the simulation model to reach the *steady-state* condition of a true system, it must be run for a given period of time. Determining this initialization time is one of the two main goals of tactical planning (p. 10).

The time required to reach the steady-state condition was studied by testing at monthly intervals initialization periods of varying duration. The main attention was focused on the average utilization of the various job phases; they reflect the equilibrium well. An initialization period of one month produced a result suggestive of equilibrium in the cutting phase and partly in the processor phase. But the last phase of the process, short-distance transport, definitely did not reach equilibrium.

An initialization period of two months began to produce information indicative of equilibrium. Table 6 presents the average utilization produced by two months of initialization and the subsequent four months (winter period) of simulation. After the period of initialization, all transactions (marked stands) were left unchanged in the model, but collection of data on average utilization and other statistical output covered only the post-initialization period.

Compared with the initialization period of two months, the simulation proper of four months gave a result showing considerable differences, primarily in the cutting and short-distance transport phases. In the MOTO systems, a noticeable amount of overtime work (or a second felling team) was necessary for the felling during the initialization phase in order that the timber requirements of the processor could be met (cf. p. 19). In the simulation proper, however, this overtime work was not required.

In the short-distance transport phase, the effect of initialization was very distinctly noticeable. Owing to the slow rate of the process, there was little timber to be transported in the initialization phase. Hardly any additional capacity (forwarder 2 and overtime work) was used, and the average utilization of the basic forwarder also was remarkably low.

A comparison of the average utilization in four-month simulation with that in two-year simulation (Table 2) shows that the differences are small. In the MANU system, the values are practically the same. In the PIKA system, no overtime work had been used for short-distance transport after four months of

Table 6. Average utilization for the various harvesting systems after two months of initialization (0 months) and four months of simulation (4 months), by job phases.

Job phase	MANU		PIKA		KOCKUM	
	0 months	4 months	0 months	4 months	0 months	4 months
1A. Cutting/felling, team, normal hrs.	.995	1.000	.994	1.000	.994	1.000
1A1. Cutting/felling	.981	.988	.979	.991	.974	.975
1A2. Movement	.014	.012	.015	.009	.020	.025
1B. Cutting/felling team, overtime			.859	0	.436	0
1B1. Cutting/felling			.847	0	.425	0
1B2. Movement			.012	0	.011	0
2. Processor			.931	1.000	.965	1.000
21. Process			.876	.933	.830	.806
211. Effective hours			.681	.731	.629	.644
212. Interruptions			.195	.202	.201	.162
22. Movement			.054	.066	.135	.193
3A. Forwarder 1	.790	1.000	.339	.804	.692	1.000
3A1. Cross-country transport	.758	.959	.298	.767	.649	.949
3A11. Effective hours	.640	.856	.253	.694	.590	.838
3A12. Interruptions	.118	.103	.045	.073	.059	.111
3A2. Movement	.031	.040	.040	.037	.043	.050
3B. Forwarder 1					0	.031
3B1. Cross-country transport					0	.031
3B11. Effective hours					0	.028
3B12. Interruptions					0	.003
3B2. Movement					0	0
3C. Forwarder, overtime	.002	.747	0	0	0	.416
3C1. Cross-country transport	.002	.724	0	0	0	.393
3C11. Effective hours	.002	.658	0	0	0	.353
3C12. Interruptions	0	.066	0	0	0	.040
3C2. Movement	0	.022	0	0	0	.022

simulation. After two years of simulation, the rate of overtime work was almost 20 %. In the KOCKUM system also, the average utilization of additional capacity in short-distance transport after four months of simulation was slightly lower than after two years of simulation. Short-distance transport, therefore, requires a slightly longer period of initialization than two months. Since the additional time required is small, and other job phases generally need no more time, *two months of simulation may be considered sufficient to bring the model into satisfactory equilibrium.*

Instead of the zero state, it is possible in some cases to begin the simulation with the simulated system in a typical state, either by pre-feeding the initial state, or by continuing simulation immediately after the completion of the preceding simulation run. Applying these alternatives causes difficulties in the present case, since the proposed experiments (Section 42) presuppose that the distributions of certain parameter values are changed every time a new experiment is undertaken. Furthermore, after some experiments the queues may be excessively long for the equilibrium state of the next experiment.

432. Sample size in simulation

The results of a stochastic simulation experiment are *random variables* and therefore only estimates for certain parameters. The precision of these estimates can be increased either by increasing the number of effective factors or by enlarging the experiment (p. 11). In the present harvesting-system models, the scanty empirical information obtainable from the real system does not allow an increasing of the effective factors.

The experiment is enlarged either by prolonging the individual simulation runs or by increasing the number of simulation runs belonging to one design point (p. 11). The minimum length of a simulation run that can be recommended is one year, if the seasonal effects are to be visible. On the other hand, there is no point in making a simulation run too long, for the differences between consecutive years in the model are mainly due to its stochastic

Table 7. Parameters of the different systems after one-year and 2-year simulation.

Parameter	MANU		PIKA		KOCKUM	
	1 year	2 years	1 year	2 years	1 year	2 years
Average utilization (total job phase)						
- cutting/felling	1.000	1.000	1.000	1.000	1.000	1.000
- processing	-	-	1.000	1.000	1.000	1.000
- short-distance transport						
- forwarder 1	1.000	1.000	.798	.801	1.000	.951
- forwarder 2	-	-	-	-	.201	.192
- overtime work	.864	.774	.204	.189	.569	.593
Output, m^3/effective hour						
- cutting/felling	6.3	6.6	7.5	7.1	13.8	15.6
- processor	-	-	9.7	9.2	18.4	17.6
- short-distance transport	7.2	7.2	5.8	6.7	6.7	6.5
Average queues, m^3						
- in front of processor	-	-	2 002	2 899	4 265	7 356
- in front of short-distance transport	1 441	1 584	184	164	791	776
Completed (transported) stands						
- number	55	95	23	52	42	80
- mean volume, m^3/stand	357	394	373	375	395	405
- duration of passage, hrs.	285	323	585	754	598	836

nature. In order to determine the suitable length of a simulation run, results obtained on the basis of one-year and two-year simulations were compared. The period of initialization was two months. The results are shown in Table 7 (cf. Tables 2–4).

No systematic differences between one-year and two-year simulation are visible other than in the duration of passage and the queues in front of the processors. The duration of passage (from the beginning of felling to the completion of short-distance transport), especially in the MOTO systems, increases substantially in the second year of simulation. Queue formation is closely associated with it. Felling capacity is definitely over-dimensioned as long as the processors are allowed to operate on only one shift.

The greatest random variation is that in output volumes per effective hour. The sampling variance can be reduced by increasing the number of replications. After several one-year-long replications, the mean estimate of the coefficient of variation obtained for the output volumes was 0.084. If there are four replications, the standard error obtained will be about 4 % of the corresponding mean. This precision can be considered sufficient for the estimation of output volumes produced by the various experiments.

On the basis of the above, *a simulation period of one year was considered sufficient for the estimation of the most important characteristics.* However, the output volumes in particular contain so much random variation that it is indispensable to carry out replications in the same design point. If it is desired that the replications be independent, the model must first be initialized for every replication. Compared with the length of the simulation period itself (11 months), the period of initialization (2 months) is relatively long. If the replications are carried out so that the next replication continues directly from the state of the model at the end of the preceding replication, only one initialization per design point is required. The statistical output in this case cannot be cumulative (as in Table 7), but starts from the beginning after every year. When there are four replications, a total simulation of $2 + 4 * 11 = 46$ months is sufficient. If every replication had a special initialization period, total simulation would take $4 * 13 = 52$ months. The cost saving in computer runs is therefore over 10 %.

The only disadvantage in carrying out the replications in this way is that the results of consecutive replications are not *independent* as they should be according to the standard statistical techniques for treating material. The simulation period (one year) is, however, so long that the dependence of the observations apparently receives no excessive emphasis.

5. CONCLUSION

The empirical information available from the harvesting systems subjected to simulation is so far incomplete and disorganized. For this reason, no simulation tests proper could be carried out, and the principal task was to construct the simulation models. Studies of the models justified the assumption that *simulation is a useful tool for the study of harvesting systems.* On the basis of the output obtained, it could be concluded that *the constructed models corresponded to the true harvesting systems with the desired accuracy.* This conclusion does not exclude the necessity of a continuous improvement and correlation of the models towards a correspondence to the true systems should the latter undergo fundamental modifications.

At the time of writing, the most important aspects for consideration in the improvement of the model appeared to be a more detailed study of short-distance transport, a consideration of the demand for timber in the decision rules of the model, and a possibility for joint use of harvesting systems of different types. Among factors disregarded in the present models may be mentioned branching, bunch volume in the stand, log length, and quality of work. These factors, however, are such that either their effect is implicitly contained in the parameters already present in the model (e.g. branching in type of tree species) or, in the true system, they are fixed or determined by external factors (e.g. bunch volume and log length).

The forwarding time per stand in the present version of the models is affected by the stand volume, density, terrain, and season of the year, whereas the length and speed of transportation and the size of load do not affect the output of the forwarder. The inclusion of these factors in the models in an explicit form is one of the first steps in the further development of the models.

In true harvesting systems, the demand for timber of a certain type at the point of consumption (or landing) determines the kind of timber harvested. For this reason it will be necessary to include decision rules, based on the demand for timber, in the model in order to permit the control of the system. This presupposes abandoning the stand as the unit of treatment (transaction) in the model. The stand marked for cutting must be divided into parts on the basis of tree species and timber assortments. This makes it possible to carry out the various job phases at the same time in one stand. A result of partitioning a stand, however, is that the number of transactions in the model is multiplied, which slows down the running of the model and in this way increases the cost of running.

The inclusion of simultaneous use of various harvesting systems in the models becomes important when models are used as aids in production planning and control. The true population of stands, with its true parameters, can be fed into the models. Simulation can then be used to show in which way the stands can be optimally allocated to alternative harvesting systems. It may be useful to increase the number of harvesting systems for this purpose.

It is essential in the study of the usefulness of a simulation model to investigate how rapid the model is, i.e. how expensive it is to run. If the model cannot be used because of the high cost involved, the benefit of accurate operation and a high degree of correspondence to the real system is nil. As a rule, a high positive correlation exists between the accuracy of the model and the cost of running it.

In the current version of the models, the simulation of one year (including a two-month period of initialization), when the transaction is a stand marked for cutting and the time unit is one hour, takes on average (the MANU system is fastest and the KOCKUM system slowest) 0.35 minutes (using an IBM–S/360, model 50). The total cost of run per year (11 + 2 months) is about 17.00 Fmk (1 US dollar = 4.24 Fmk). By way of an approximation, it may be assumed that the simulation time is linearly dependent on the length of the true period to be simulated. The cost per simulated month is therefore about 1.30 Fmk. If the design proposed in Section 42 is used, i.e. 27 experimental runs per harvesting system with 4 replications in every design point and using a common period of initialization (p. 27), the total number of months to be simulated will be 3 x 27 x 46 = 3726. This means that the total cost of the simulation experiment is about 4,800 Fmk. When this sum is compared with the price of a KOCKUM processor, approximately 450,000 Fmk, it may be concluded that simulation is a fairly inexpensive method of producing information if the alternative is making the experiments with the real system itself.

REFERENCES

ANDERSIN, H.E. 1967. Johdatus numeerisen simuloinnin käyttöön yrityssysteemien suunnittelussa. Mimeographed. Valtion tietokonekeskus. Helsinki.

ARVANITIS, L.G. & O'REGAN, W.G. 1967. Computer simulation and economic efficiency in forest sampling. *Hilgardia* 38:2.

la BASTIDE, J.G. & BOL, M. 1969. Die Simulation als Hilfsmittel für forstliche Forschungsarbeiten. English summary. *Forstarchiv* 40:1, 7–11.

BECKHOFER, R. 1964. A single sample multiple procedure. *Ann. Math. Stat.* 25, 16–39.

BOX, G.E.P. & BEHNKEN, D.W. 1960. Some new three level designs for the study of quantitative variables. *Technometrics* 2:4, 455–475.

COCHRAN. W.G. & COX, G.M. 1957. Experimental design. John Wiley & Sons, Inc. New York–London.

CONWAY, R.W. 1963 Some tactical problems in digital simulation. *Management Science* 10:1, 47–61.

FABER, P.J. 1967. Die Anwendung des Elektronenrechners in der Waldertragskunde in den Niederlanden. *Mitteilungen der Forstl. Bundenversuchsanstalt* 77:1, 115–128.

FORRESTER, J. 1961. Industrial dynamics. John Wiley & Sons, Inc. New York–London.

GORDON, G. 1969. System simulation. Prentice Hall, Inc. New Jersey.

GOULD, E.M. & O'REGAN, W.G. 1965. Simulation, a step toward better forest planning. *Harvard Forest Papers* 13.

HUNTER, J.S. & NAYLOR, T.H. 1970. Experimental designs for computer simulation experiments. *Management Science* 16:7, 422–434.

IBM 1969. General purpose simulation system/360 OS. Version 2, User's Manual. IBM SH20–0694–0. New York.

JÄRVINEN, J. 1970. Korjuuketjut, puunkorjuun seuraava kehitysvaihe. *Metsä ja Puu* No. 11, 8–11.

KILKKI, P. 1968. Income-oriented cutting budget. *Acta Forestalia Fennica* 91.

NEWNHAM, R.M. 1970. Productivity of harvesting machines designed for thinnings: estimation by simulation. *Department of Fisheries and Forestry of Canada. Information report FMR–X–25.*

NEWNHAM, R.M. & SMITH, J.H.G. 1964. Development and testing of stand models for Douglas fir and pine. *For. Chron.* 40, 494–502.

PALO, M. 1971. A systems-oriented frame model for planning research projects in forestry. *Metsäntutkimuslaitoksen Julkaisuja* 72.4. Helsinki.

PÖLKKI, V. & VÄISÄNEN, U. 1970. Monitoimikoneiden potentiaalinen taloudellisuus. Summary: The potential economicalness of processors. *Metsätehon Tiedotus* 301. Helsinki.

REYNOLDS, H.W. 1970. Sawmill simulation: data instructions and computer programs. *U.S. Forest Service, Research Paper NE-152.*

SAVOLAINEN, R. 1970. Puunkorjuumenetelmät ja korjuutekniset olosuhteet hankintavuonna 1969/70. *Metsätehon katsaus* 18. 1970. Helsinki.

SEPPÄLÄ, R. 1971. Linked systematic cluster sampling for the estimation of timber removals. *Metsäntutkimuslaitoksen Julkaisuja* 72.3. Helsinki.

SJUNESSON, S. 1970. Ett exempel på simulering som analysinstrument för man-maskinsystem vid gallring. Summary: An example of simulation as a tool for analysis of man-machine systems for thinning. *Institutionen för Skogsteknik, Skogshögskolan. Rapporter och Uppsatser* Nr. 42. Stockholm.

WETHERHILL, G.B. 1966. Sequential methods in statistics. Methuen & Co Ltd. London.

SELOSTE

Puun korjuuketju on tyypillinen esimerkki todellisesta systeemistä, joka on niin monimutkainen ja sisältää niin paljon satunnaistekijöitä, että sen kokonaisvaltainen kuvaaminen ja analysointi on vaikeaa laskennallista mallia käyttämällä. Edelleen korjuuketjuihin liittyvät investoinnit ovat useimmissa tapauksissa niin suuret, että eri vaihtoehtojen kokeileminen suoraan itse ketjuilla tulee kohtuuttoman kalliiksi ja vie pitkän ajan. Nämä toteamukset lähtökohtana päätettiin esillä olevassa tutkimuksessa selvittää simuloinnin käyttökelpoisuutta korjuuketjujen kuvaus- ja analysointivälineenä.

Aluksi luotiin empiiriselle tutkimukselle teoreettinen pohja tarkastelemalla systeemien simulointiin liittyviä käsitteitä. Erityinen huomio kiinnitettiin simuloinnin työvaihejakoon ja simulointikokeiden suunnitteluun. Simulointikieleksi valittiin General Purpose Simulation System (GPSS), joka esiteltiin pääpiirteissään.

Tutkimuksen empiirisessä osassa kuvattiin simuloinnin kohteeksi otetut korjuuketjut. Tarkastelu koski korjuun vaiheita puun kaadosta kuljetukseen lähivarastolle. Tutkittaviksi korjuuketjuiksi otettiin kaksi tavaralajimenetelmään perustuvaa päätyyppiä: tavanomainen ihmistyövaltainen menetelmä ja ajouralla toimivan karsinta-katkaisukoneen käyttöön perustuva menetelmä. Viimeksi mainitussa ketjutyypissä tarkasteltiin kahdenlaisia karsinta-katkaisukoneita: suomalaista PIKA 50 -konetta ja ruotsalaista KOCKUM PROCESSOR -konetta. Kaikissa ketjuissa metsäkuljetus tapahtui kuormaa kantavalla metsätraktorilla.

Simulointiprojektin tavoitteet jaettiin alunperin kahteen peräkkäiseen osaan. Ensimmäiseksi tehtäväksi asetettiin sellaisten GPSS-kielisten simulointimallien rakentaminen, jotka simulointikokeiden tekemistä silmällä pitäen riittävän tarkasti kuvaavat simuloinnin kohteeksi otettujen puun korjuuketjujen rakennetta ja toimintaa. Toiseksi tehtäväksi asetettiin sellaisten simulointikokeiden toimeenpaneminen, joilla voidaan todeta korjuuketjuissa olevien muuttujien (leimikon koko, leimikon tiheys, leimikon järeys, keskeytykset, siirrot jne.) vaikutus ketjujen toimintaan sekä löytää kullekin ketjulle ominaiset näiden muuttujien eri arvojen (tasojen) yhdistelmät.

Kun ryhdyttiin kokoamaan korjuuketjuihin liittyvää empiiristä materiaalia, huomattiin varsin pian, että sekä koko prosesseista että varsinkin eräistä niiden osista saatava informaatio oli puutteellista ja osittain epäluotettavaa. Tämä johti siihen, että jouduttiin tinkimään jälkimmäisen osatehtävän vaatimuksista. Päätehtäväksi jäi itse simulointimallien rakentaminen, ja simulointikokeet palvelivat etupäässä vain mallien hyvyyden testausta. Kun mallit ovat valmiiksi olemassa, voidaan simulointikokeita helposti laajentaa sitä mukaa kuin tarvittavan informaation määrä lisääntyy.

Simulointimallien konstruointi aloitettiin rakentamalla ensin korjuuketjuista simuloinnin tarkoitusperiä palveleva systeemimalli. Systeemimallin olennaisia piirteitä olivat toisaalta itsenäisiin käsittely-yksiköihin (moduleihin) perustuva rakenne ja toisaalta virtasuhteet. Viimeksi mainittuja tarkasteltiin yleiseen prosessiajatteluun perustuen, jossa työpisteet (korjuun eri vaiheet) pysyvät paikoillaan ja materiaali (leimikot) virtaa.

Systeemimallin pohjalta konstruoitiin itse simulointimallit, erikseen kullekin kolmelle korjuuketjulle. Mallit rakennettiin asteittain siten, että ensin tehtiin varsin yksinkertainen malli ja sitä vähitellen tarkennettiin. Mallit rakennettiin systeemimallin tapaan modulaarisiksi. Tämän johdosta niiden muuttaminen on yksinkertaista.

Mallien hyvyyden testauksen tuloksena voitiin todeta niiden vastaavan halutulla tarkkuudella todellisia korjuuketjuja. Eri ketjut toimivat toisistaan erillisinä. Malleja edelleen kehitettäessä on niihin sisällytettävä mahdollisuus tarkastella korjuuketjuja rinnakkaisina. Tällöin malleja pystytään käyttämään tuotannonohjauksen apuvälineenä: mallisysteemiin voidaan syöttää todellinen leimikkojoukko todellisine tunnuksineen ja simuloinnin avulla selvittää ne päätössäännöt, joiden mukaan leimikot ovat mahdollisimman optimaalisesti kiintiöitävissä vaihtoehtoisten ketjujen kesken.

Lopuksi esitettiin koesuunnitelma simulointia varten. Se perustui neljän muuttujan (leimikon koko, leimikon järeys, työprosessien keskeytykset ja siirtymismatkat leimikolta toiselle) ja kolmen tason (keskimääräinen, alle keskimäärän ja yli keskimäärän) käyttämiseen. Jotta näiden muuttujien päävaikutukset ja tärkeimmät yhdysvaikutukset kussakin kolmessa ketjussa tulisivat riittävän tarkasti esille, vaaditaan yhteensä 3700 työkuukauden simulointia. Käsittely-yksikkönä on kokonainen leimikko ja aikayksikkönä yksi tunti. Tällaisen simulointikokeen kustannukset ovat noin 4 800 markkaa.

APPENDIX. A GPSS SIMULATION PROGRAM FOR THE MOTO/KOCKUM HARVESTING SYSTEM (FUNCTIONS, VARIABLES AND TABLE DEFINITIONS EXCLUDED).

```
                SIMULATE   1
          *
          *     KOCKUM SYSTEM
          *
          *
          *     PARAMETERS
          *
          *     1     STAND-SIZE CLASS
          *     2     DENSITY CLASS
          *     3     STEM-SIZE CLASS
          *     4     TREE-SPECIES CLASS
          *     5     TERRAIN CLASS
          *     6     YEAR SEASON
          *     8     STAND SIZE M**3
          *     9     MOVEMENT DISTANCE
          *
          *
1               GENERATE   1,,,170,,9,H
2               JOIN       1
3         CHARS ASSIGN     1,FN1
4               ASSIGN     2,FN2
5               ASSIGN     3,FN3
6               ASSIGN     4,FN4
7               ASSIGN     5,FN5
8               ASSIGN     6,2
9               ASSIGN     8,FN7
          *
          *     FELLING
          *
10              QUEUE      LODKR
11        LINK1 LINK       1,FIFO,TEST1
12        TEST1 TEST L     GÅLWPR,250,SEIZ1
13              TRANSFER   BOTH,SEIZ2,SEIZ1
14        SEIZ1 SEIZE      KRYH1
15              DEPART     LODKR
16              SAVEVALUE  1,C1
17              SEIZE      KAATO
18              MARK
19              ADVANCE    V1
20              RELEASE    KAATO
21              TABULATE   1
22              SPLIT      1,WAIT4
23              ADVANCE    1
24              RELEASE    KRYH1
25              UNLINK     1,TEST1 ,K1
26              TERMINATE
27        SEIZ2 SEIZE      KRYH2
28              DEPART     LODKR
29              SAVEVALUE  2,C1
30              GATE NU    KRYH1,SEIZY
31              UNLINK     1,TEST1,K1
32        SEIZY SEIZE      YTKTO
33              MARK
34              ADVANCE    V1
35              RELEASE    YTKTO
36              TABULATE   1
```

```
37              SPLIT       1,WAIT4
38              ADVANCE     1
39              RELEASE     KRYH2
40              TEST L      QÅLWPR,250,TERM1
41              UNLINK      1,SEIZ2,K1
42        TERM1 TERMINATE
      *
      *         KOCKUM PROCESSOR
      *
43        WAIT4 QUEUE       LODPR
44              QUEUE       LWPR,P8
45        LINK4 LINK        4,FIFO,SEIZ4
46        SEIZ4 SEIZE       KOCKM
47              DEPART      LODPR
48              DEPART      LWPR,P8
49              SAVEVALUE   4,C1
50              SEIZE       KOCK
51              SEIZE       APU4
52              ADVANCE     V4
53              RELEASE     APU4
54              RELEASE     KOCK
55              TABULATE    4
56              SPLIT       1,WAIT7
57              ASSIGN      9,FN17
58              SEIZE       KCSRT
59              ADVANCE     V5
60              RELEASE     KCSRT
61              RELEASE     KOCKM
62              UNLINK      4,SEIZ4,K1
63              TABULATE    5
64              TERMINATE
      *
      *         FORWARDER
      *
65        WAIT7 QUEUE       LODTR
66              QUEUE       LWTR,P8
67        LINK7 LINK        7,FIFO,TEST7
68        TEST7 TEST G      QÅLWTR,1000,SEIZ7
69              TRANSFER    BOTH,SEIZ9,TRAN7
70        TRAN7 TRANSFER    BOTH,SEIZ7,SEIZ8
71        SEIZ7 SEIZE       TRAK1
72              DEPART      LODTR
73              DEPART      LWTR,P8
74              SAVEVALUE   7,C1
75              ASSIGN      5,FN6
76              SEIZE       AJO1
77              SEIZE       APU7
78              ADVANCE     V7
79              RELEASE     APU7
80              RELEASE     AJO1
81              TABULATE    7
82              ASSIGN      9,FN17
83              SEIZE       TRSR1
84              ADVANCE     V8
85              RELEASE     TRSR1
86              RELEASE     TRAK1
```

```
87              UNLINK      7,TEST7,K1
88        TABU8 TABULATE    8
89              TABULATE    10
90              TERMINATE
91        SEIZ8 SEIZE       TRAK2
92              DEPART      LODTR
93              DEPART      LWTR,P8
94              SAVEVALUE   8,C1
95              ASSIGN      5,FN6
96              SEIZE       AJO2
97              SEIZE       APU8
98              ADVANCE     V7
99              RELEASE     APU8
100             RELEASE     AJO2
101             TABULATE    7
102             ASSIGN      9,FN17
103             SEIZE       TRSR2
104             ADVANCE     V8
105             RELEASE     TRSR2
106             RELEASE     TRAK2
107             UNLINK      7,TEST7,K1
108             TRANSFER    ,TABU8
109       SEIZ9 SEIZE       TRAKY
110             DEPART      LODTR
111             DEPART      LWTR,P8
112             SAVEVALUE   9,C1
113             TEST E      BV1,1,ASSN5
114             UNLINK      7,TEST7,K1
115       ASSN5 ASSIGN      5,FN6
116             SEIZE       YTAJO
117             SEIZE       APU9
118             ADVANCE     V7
119             RELEASE     APU9
120             RELEASE     YTAJO
121             TABULATE    7
122             ASSIGN      9,FN17
123             SEIZE       TRSR3
124             ADVANCE     V8
125             RELEASE     TRSR3
126             RELEASE     TRAKY
127             TEST G      QÅLWTR,1000,TABU8
128             UNLINK      7,SEIZ9,K1
129             TRANSFER    ,TABU8
        *
        *
        *       SEASON CHANGE
        *
130             GENERATE    1044,,,1
131             ALTER       1,ALL,6,1
132             TERMINATE
133             GENERATE    2262,,,1
134             ALTER       1,ALL,6,2
135             TERMINATE
136             GENERATE    2958,,,1
137             ALTER       1,ALL,6,1
138             TERMINATE
```

```
        *
        *       FORWARDING INTERRUPTIONS 1
        *
139      KESK7  GENERATE    23,22,,,,0
140             PREEMPT     APU7
141             PREEMPT     APU9
142             SEIZE       KESK7
143             ADVANCE     FN18
144             RELEASE     KESK7
145             RETURN      APU7
146             RETURN      APU9
147             TERMINATE
        *
        *       FORWARDING INTERRUPTIONS 2
        *
148      KESK8  GENERATE    23,22,,,,0
149             PREEMPT     APU8
150             SEIZE       KESK8
151             ADVANCE     FN18
152             RELEASE     KESK8
153             RETURN      APU8
154             TERMINATE
        *
        *       PROCESSING INTERRUPTIONS
        *
155      KESK4  GENERATE    12,11,,,,0
156             PREEMPT     APU4
157             SEIZE       KESK4
158             ADVANCE     FN24
159             RELEASE     KESK4
160             RETURN      APU4
161             TERMINATE
        *
        *       RUN TIMING
        *
162             GENERATE    696,,348,3,,0
163             TERMINATE   1
164             GENERATE    2262
165             TERMINATE   1
166             GENERATE    696,,2958,2,,0
167             TERMINATE   1
168             GENERATE    4176
169             TERMINATE   1
        *
        *
        *
        *       FUNCTIONS
        *
        *       VARIABLES
        *
        *       TABLES
        *
                START       1,NP,1
                RESET
                START       2,,1
                END
```

No 83 Ole Oskarsson: Pluspuiden fenotyyppisessä valinnassa sovellettuja valinnan asteita.
Selection degrees used in the phenotypic selection of plus trees. 1,50

No 84 Kari Keipi ja Otto Kekkonen: Calculations concerning the profitability of forest fertilization.
Laskelmia metsän lannoituksen edullisuudesta. 2,—

No 85 S.—E. Appelroth — Pertti Harstela: Tutkimuksia metsänviljelytyöstä I. Kourukuokka, kenttälapio, taimivakka, taimilaukku sekä istutuskoneet Heger ja LMD-1 istutettaessa kuusta peltoon.
Studies on afforestation work I. The use of semi-circular hoe, the field spade, plant basket, plant bag and the Heger and LMD-1 tree planters in planting spruce in fields. 3,—

No 86 Pertti Veckman: Metsäalan toimihenkilöiden koulutustarve 1970-luvulla.
Educational requirements of professional forestry staff in the 1970s. 4,—

No 87 Michael Jones and David Cope: Economics Research in the Finnish Forest Research Institute, 1969—1974. 4,—

No 88 Seppo Ervasti, Lauri Heikinheimo, Kullervo Kuusela ja Veikko O. Mäkinen: Forestry and forest industry production alternatives in Finland, 1970—2015. 6,—

No 89 Risto Sarvas: Establishment and registration of seed orchards. 2,—

No 90 Terho Huttunen: Suomen puunkäyttö, poistuma ja metsätase vuosina 1968—70.
Wood consumption, total drain and forest balance in Finland in 1968—70. 5,—

No 91 Pertti Harstela ja Teemu Ruoste: Kokonaisten puiden esijuonto kaksirumpuvintturilla käytävä- ja riviharvennuksessa. Laitteiden ja menetelmien kehittelyä sekä tuotoskokeita.
Preliminary full-tree skidding by two-drum winch in strip and row thinning. 2,50

No 92 Pentti Hakkila ja Pentti Rikkonen: Kuusitukit puumassan raaka-aineena.
Spruce saw logs as raw material of pulp. 1,50

No 93 Kari Löyttyniemi: Havupunkin ja kuusen neulaspunkin torjunta.
Control of mites Oligonychus ununguis and Nalepella haarlovi var. piceae-abietis. 2,50

No 94 Paavo Tiihonen: Puutavaralajitaulukot 5. Koivun uudet paperipuutaulukot.
Sortentafeln 5. Neue Papierholztafeln für Birke. 2,50

No 95 Jorma Rajala: Nykymetsiköiden kasvuprosentti Suomen eteläpuoliskossa vuosina 1964—68. 2,50

No 96 Metsätilastollinen vuosikirja 1969.
Yearbook of forest statistics 1969. 8,—

No 97 Juhani Numminen: Short-term forecasting of the total drain from Finland's forests.
Suomen metsien kokonaispoistuman lyhytjaksoinen ennustaminen. 1,50

No 98 Juhani Nousiainen, Jukka Sorsa ja Paavo Tiihonen: Mänty- ja kuusitukkipuiden kuutioimismenetelmä.
Eine Methode zur Massenermittlung von Kiefern- und Fichtenblochholz. 4,—

1971 No 99 Yrjö Vuokila: Harvennusmallit luontaisesti syntyneille männiköille ja kuusikoille.
Gallringsmallar för icke planterade tall- och granbestånd i Finland.
Thinning models for natural pine and spruce stands in Finland. 2,—

No 100 Esko Leinonen ja Kalevi Pullinen: Tilavuuspaino-otanta kuitupuun mittauksessa.
Green density sampling in pulpwood scaling. 2,—

No 101 IUFRO, Section 31, Working Group 4: Forecasting in forestry and timber economy. 5,—

No 102 Sulo Väänänen: Yksityismetsien kantohinnat hakkuuvuonna 1969/70.
Stumpage prices in private forests during cutting season 1969/70. 1,—

No 103 Matti Ahonen: Tutkimuksia kanto- ja juuripuun korjuusta I. Kokeilu puiden kaatamisesta juurakkoineen.
Studies on the harvesting of stumps and roots in Finland I. Experiment with the felling of trees with their rootstock. 2,—

No 104 Ole Oskarsson: Plusmetsiköiden valintaero ja jalostusvoiton ennuste.
Selection differential and the estimation of genetic gain in plus stands. 1,50

No 105 Pertti Harstela: Työjärjestyksen vaikutus tynkäkarsitun ja likipituisen kuusikuitupuun teossa.
The effect of the sequence of work on the preparation of approximately 3-m, rough-limbed spruce pulpwood. 2,50

No 106 Hannu Vehviläinen: Metsätyömiesten moottorisahakustannukset 1969—1970.
Power-saw costs of forest workers in 1969—1970 3,—

No 107 Olli Uusvaara: Vaneritehtaan jätepuusta valmistetun hakkeen ominaisuuksista.
On the properties of chips prepared from plywood plant waste. 2,50

No 108 Pentti Hakkila: Puutavaran vaurioitumisesta leikkuuterää korjuutyössä käytettäessä.
On the wood damage caused by shear blade in logging work. 2,—

No 109 Metsänviljelykustannusten toimikunnan mietintö.
Report of the committee on the costs of forest planting and seeding.

No 110 Kullervo Kuusela — Alli Salovaara: Kainuun, Pohjois-Pohjanmaan, Koillis-Suomen ja Lapin metsävarat vuosina 1969—70.
Forest resources in the Forestry Board Districts of Kainuu, Pohjois-Pohjanmaa, Koillis-Suomi and Lappi in 1969—70. 5,50

No 111 Kauko Aho ja Klaus Rantapuu: Metsätraktorien veto- ja nousukyvystä rinteessä. On slope-elevation performance for forest tractors. 2,—

No 112 Erkki Ahti: Maaveden jännityksen mittaamisesta tensiometrillä. Use of tensiometer in measuring soil water tension. 1,—

No 113 Olavi Huikari — Eero Paavilainen: Metsänparannustyöt ja luonnon moninaiskäyttö. Forest improvement works and multiple use of nature. 2,—

No 114 Jouko Virta: Yksityismetsänomistajien puunmyyntialttius Länsi-Suomessa vuonna 1970. Timbers-sales propensity of private forest owners in western Finland in 1970. 6,—

No 115 Veijo Heiskanen ja Pentti Rikkonen: Tukkien todellisen kiintomitan mittaamisessa käytettävät muunto- ja kuutioimisluvut. Sahatukkien mittaus- ja hinnoittelututkimukseen 1970 perustuvat taulukot. 1,—

No 116 Veijo Heiskanen: Tyvitukkien ja muiden tukkien koesahauksia Pohjois-Suomessa. Test sawings of butt logs and top logs in Northern Finland. 2,50

No 117 Paavo Tiihonen: Suomen pohjoispuoliskon mäntytukkipuusto v. 1969—70. Das Kiefernstarkholz der nördlichen Landeshälfte Finnlands i.J. 1969—70. 2,—

No 118 Pertti Harstela: Moottorisahan tärinän vaikutuksesta työntekijän käsiin. On the effect of motor saw vibration on the hands of forest worker. 1,50

No 119 Lorenzo Runeberg: Plastics as a raw-material base for the paper industry in Finland. Muovit paperiteollisuuden raaka-aineena Suomessa. 2,50

No 120 Esko Salo — Risto Seppälä: Kiinteistöjen polttoraakapuun käytön väli-inventointi vuosina 1969/70.
Fuelwood consumption on farms and in buildings, intermediate inventory, 1969/70. 3,—

No 121 Heikki J. Kunnas: Foresty in national accounts. Metsätalouden kansantulo-osuuden laskenta. 2,—

No 122 Pentti Kuokkanen: Metsänviljelytaimien kasvatuskustannukset vuosina 1969 ja 1972. Costs of growing forest-tree seedlings in nurseries in 1969 and 1972. 2,50

No 123 Juhani Numminen: Puulevyjen käyttö Uudenmaan talousalueella v. 1967 valmistuneissa rakennuksissa.
The use of wood-based panels in buildings completed in 1967 in the Uusimaa Economic Region. 2,50

No 125 Risto Seppälä: Simulation of timber-harvesting systems. Puun korjuuketjujen simulointi. 4,—

Myynti — Available for sale at: Valtion painatuskeskus, Annankatu 44, Helsinki 10, p. 645 121
Merkintä O D C tarkoittaa metsäkirjallisuuden kansainvälistä Oxford-luokitusjärjestelmää

14857/71/Offsp.,88

Valtion painatuskeskus