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ILKKA VIRTANEN

SIMULATION MODEL FOR OPTIMIZING THE MAINTENANCE POLICY OF A PULP AND PAPER MILL

SIMULATION MODEL FOR OPTIMIZING THE MAINTENANCE POLICY OF A PULP AND PAPER MILL

ILKKA VIRTANEN, FINLAND.

1. Maintenance of an industrial enterprise

1.1. Introduction

Attention has been vigorously drawn in recent times to the importance of maintenance among the branch activities of a production plant. This is the result of such matters as growing automation, increased speed of output and rising quality requirements. All these factors impose higher demands than ever on maintenance. Fulfilment of these demands means an increase of costs. Finding a solution to this series of problems must be regarded as the prime objective in every study of the maintenance question.

The maintenance of an industrial plant fulfilling specific purposes of production has been defined as follows[1]: "Maintenance is organized purposeful activity and preparedness applied to the machinery, equipment, buildings and grounds of a production plant with the principal aim of making the planned use of the latter as reliable as possible, and with a minimum of outlay."

The task of maintenance, therefore, is to arrange the investments which guarantee production according to aims in such a way that expectations and requirements are fulfilled to the utmost. It must be borne in mind, however, that objectives sometimes conflict: on

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1) Malaska, p. 87. A similar definition appears in the English Glossary of General Terms Used in Maintenance Organization: "Maintenance - work undertaken in order to keep or restore every facility, i.e. every part of a site, building and contents, to an acceptable standard. Planned maintenance-work (as above) organized and carried out with forethought, control and records.'

the one hand the plant must be made to work dependably and a state of preparedness achieved which reduces the effect of breakdowns to a minimum; on the other, costs must be kept as low as possible. In consequence, maintenance is a function of an enterprise which constantly gives rise to situations where decision-making is necessary within the framework of the conflicting objectives mentioned above. The purpose of the present study is to analyze a situation of this kind and to introduce one procedure which provides suitable assistance.

1.2. Structure of maintenance

The organization responsible for maintenance creates the activity and preparedness mentioned in the definition by:

(a) reserving and making available the necessary resources;
(b) organizing the appropriate use of these resources.

Chiefly important in the gauging and reservation of resources are the maintenance staff, machines and equipment, working premises and spare parts store, also arrangements for the employment of outside maintenance services if required. In the gauging of resources note must be taken of regularly recurring or otherwise predictable maintenance work, and also of unforeseen breakdowns.

For achievement of results the main factors are the distribution of staff in shifts, the amount of overtime, stock policy and the division of maintenance activities into categories of work. Noteworthy questions with regard to these categories include the following: should a fault be repaired immediately it appears, or should repair be left till a more suitable time (at the risk of further damage) ? ; should equipment under repair merely be restored to its former state, or improved? ; should a programme for prevention of faults in advance be adopted?

1.3. Maintenance strategy and policy

By using the means which have been referred to above in general terms the maintenance organization of a production plant establishes an operational reliability which grows with the size of the maintenance contribution. Maintenance strategy can now be defined as a collection of methods and activities by which the operational reliability aimed at by the general maintenance policy of an enterprise can be achieved. A certain level (R_o) of reliability can generally be achieved by several different strategies; the best of these is the strategy which keeps maintenance costs to a minimum (see Fig. 1).

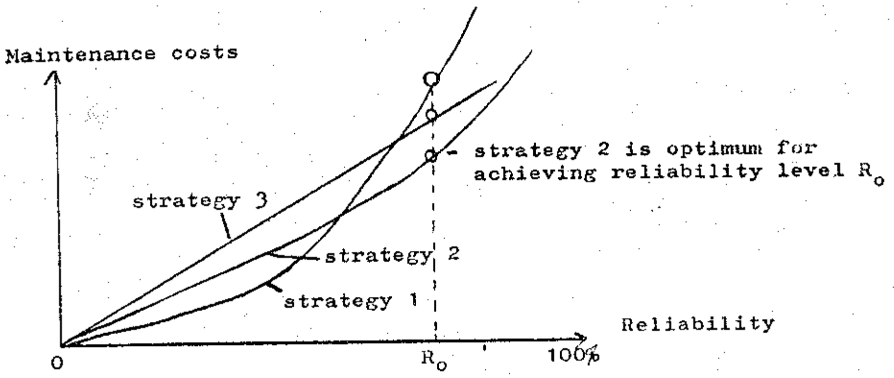

Fig. 1. Dependence of maintenance costs on operational reliability and the maintenance strategy producing it.

Satisfaction with a certain operational reliability signifies acceptance of a certain degree of deficiency in that reliability. This deficiency is revealed in such matters as work stoppages and falling productivity, and in the losses caused by them. In the search for maintenance optima these deficiency costs must be taken fully into account alongside maintenance costs proper. Thus an optimal maintenance policy is formulated by a combination of operational reliability and optimum maintenance strategy in which maintenance costs proper and operational deficiency costs are part of optimal values as determined by the aims of the enterprise.

1.4. Criteria for optima

The criteria according to which an optimum maintenance policy may be fixed are largely dependent on the enterprise concerned. For this purpose, however, enterprises can be divided into the following basic types.

a) Enterprises in which the effects of breakdowns can be measured in money terms. Here the criterion is minimization of the total volume of maintenance costs and production losses caused by deficient operational reliability. The optimum maintenance policy is in this case composed of (see Fig. 2) the operational reliability R_1 and the (optimum) strategy S_1 by which that operational reliability is brought about with minimum costs in maintenance itself. C_1 represents optimum total costs.

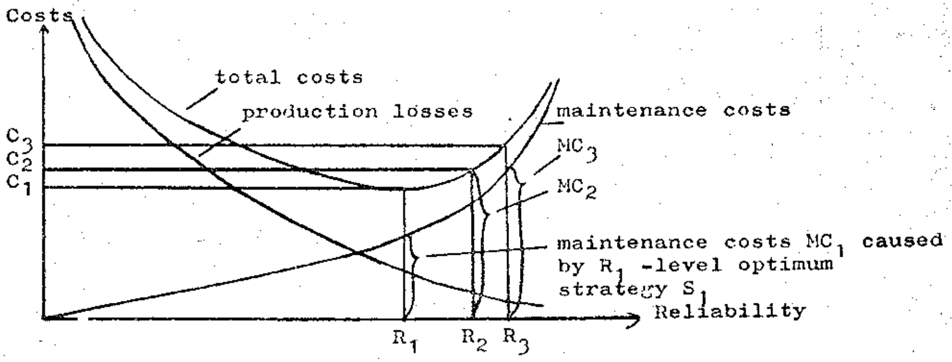

Fig. 2. Determination of optimum maintenance policy.

b) Enterprises like those in a) except that they demand a certain level of operational reliability (R_2) because of production requirements. This implies minimization under constraints, and frequently also a rise in costs compared with the unrestricted optimum (costs C_2 in Fig. 2).

c) Enterprises in which deficient operational reliability may have fatal results, e.g. a human life may be jeopardised. Maximum operational reliability within the budget available for this purpose is the only possible criterion. In the case of Fig. 2, with maintenance budget MC_3 it is possible to achieve operational reliability R_3 ; total costs are then C_3.

2. Formulation of the problem

In the foregoing a general framework for the study of maintenance is briefly described. Within this framework the problem arising in each separate case is specified and formulated in detail. For the empirical study with which we are concerned this implies a detailed description of the enterprise taken as an example, and a clarification of its maintenance objectives.

2.1. Description of the enterprise

A combined pulp and paper mill has been chosen for examination [1] as a representative of industrial processing. In this type of factory maintenance problems are particularly acute. There are several hundred machines and a great variety of equipment whose operations are so interlinked that the breakdown of a single piece of machinery may, in the worst cases, bring the whole plant to a standstill. Also, the level of capacity employed is so high that it is impossible to compensate for lost production later.

2.1.1. Activity diagrams

The structure of the production plant is illustrated by means of diagrams composed on three levels to serve as a model: plant, machineline and department diagrams. The plant diagram illustrates the structure of the factory with the accuracy of process diagrams

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1) Oy W. Rosenlew Ab, pulp and paper mill in Pori.

and a machine card index containing plant information. The components of a plant diagram are machines, machine parts, equipment, piping and storage containers, i.e. parts of a process which function independently. Components of the plant diagram number about 200.

The next level is the machine-line diagram. This is obtained from the plant diagram by combining its components on a certain principle to form a machine-line. The latter signifies here the greatest number of consecutive apparatuses to be found between two storage containers without the process dividing into branches in this interval. Fig. 3 illustrates the formation of machine lines.

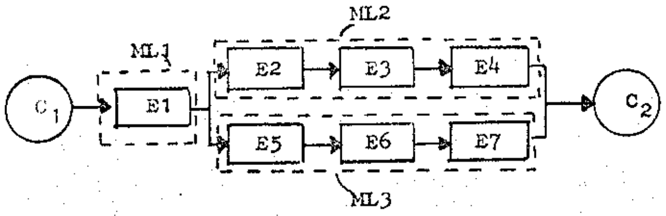

Fig. 3. Formation principle for machine-lines.

The machine-line is therefore the widest group of equipment in which damage to one apparatus can put the whole group out of action. The production plant to be examined is shown in the form of a machine-line in Fig. 4.

The third level is the department diagram, formed from the machine-line diagram by combining the machine-lines between two containers. In many cases the "departments" thus formed correspond to the true physical departments of a production plant (e.g. cooking department between chip silo and blowing container in Fig. 4.), but sometimes a department in a diagram consists of one machine-line only (e.g. chip carriers between chip store and silo).

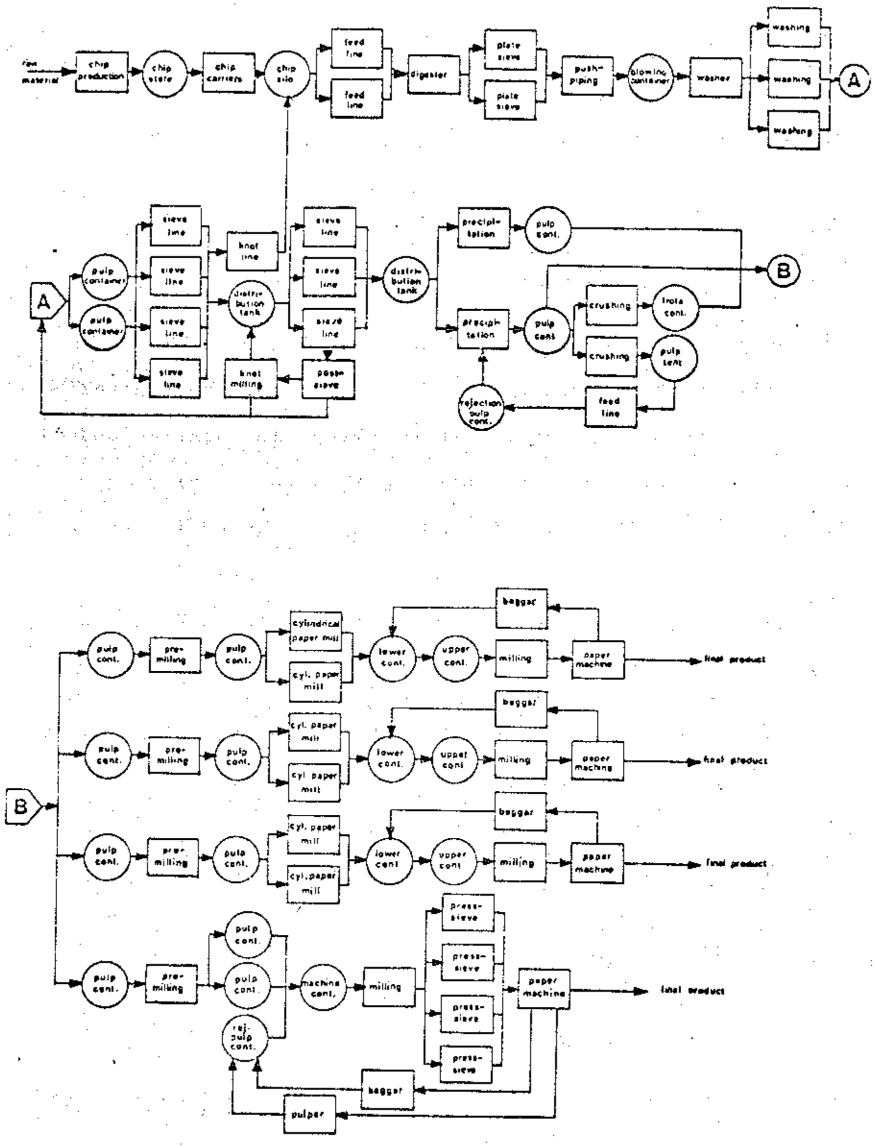

Figure 4. Machine-line diagram of the plant

In the machine-line and department diagrams the importance of intermediate containers in the process is emphasized. Although the primary significance of containers lies in their improvement and balancing of raw material quality, they can also be used with effect for maintenance purposes. A work stoppage caused by planned repair work or sudden breakdown can be confined to one part of the process if containers are appropriately used as buffers.

With reference to the components of activity diagrams at the various levels it should now be noted that components of plant and machine-line diagrams are assumed to be either in working condition or out of order, whereas departments are able to function at some stage between the two. If, for instance, apparatus E3 is broken (Fig. 3), machine-line ML2 is put out of action, whereupon the department between containers C_1 and C_2 is reduced to half its normal functioning rate.

It has proved expedient to include all three activity diagrams in the model: the plant diagram is an indispensable guarantee of correspondence between the model and reality, while the machine-line and department diagrams enable the condition of each part of the process to be observed, e.g. the necessity to use buffer containers, production losses etc.

2.1.2. Data relating to the plant

The foregoing picture of a production plant, provided by activity diagrams, can only be sufficient when the components of diagrams are supplemented by data on their capacity, functioning etc. These data are gathered mainly from structure specifications and activity reports, with some recourse to estimates by responsible personnel.

Information has been collected from the following factors connected with the plant and affecting its activity:

- distribution of failure rate for each apparatus
- distribution of repair time for each apparatus
- proportion of faults which have caused a stoppage in the use of apparatus
- distribution of size of repair teams used in maintenance work
- capacity of containers
- performance capacities of individual machine-lines (as parts of adjoining lines) compared with normal level of use.

2.2. Objectives of maintenance in a pulp and paper mill

It is necessary for operational reliability in a production plant of the type described to be relatively high, because breakdowns rapidly extend their effects to final output, causing expense in the form of production losses. Owing to the great size of the units (paper machines) which manufacture the final product, stoppages of only a few hours may be equivalent to the maintenance costs of days and even weeks. Thus, considerable efforts are worth making for the prevention of heavy machine damage or for its rapid repair.

In view of the complicated interlinking of components, however, it is not worth while to make the whole system fully reliable, nor is this possible in practice. The optimum policy must clearly tolerate a modicum of deficiency in operational reliability.

When deciding the degree of deficiency to be permitted in a wood-processing plant, the earlier stated alternative a) will serve as a criterion: minimization of the combined cost of maintenance proper and deficient operational reliability. The character of the plant ensures that operational reliability will be high. The problem therefore is to determine, by applying the above criterion, an acceptable degree of deficiency, a corresponding operational reliability and the optimum strategy by which this policy can be realized.

3. Structure and functioning of model

3.1. Introduction

In order to examine the problem described in the last section it was decided to compose a model which should be used for experiments or simulations aimed at the discovery of an optimum maintenance policy.

The essential features of simulation are revealed by the definition$^{1)}$: "Simulation is a numerical technique for conducting experiments with certain types of mathematical model which describe the behaviour of a complex system on a digital computer over extended periods of time".

Simulation, therefore, is a method by which the actual course of events - the real system - is illustrated by a model which is usually put into the form of a computer programme and elucidated by computer. In connection with analytic mathematical models the normal techniques (e.g. optimation) are replaced for simulation purposes by experiments to be performed through the model. Simulation thus enables questions of the type "What is the result if we do this?" to be answered instead of "What is the best procedure in these circumstances?"$^{2)}$ If simulation is performed

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1) Naylor, p. 2.

2) Andersin - Sulonen, p. 13.

a sufficient number of times - by studying all alternatives which logically arise - the best alternative is discovered.

The following factors have been mainly responsible for the choise of simulation as a study method (instead of the analytic model):

- in view of the extent of the problem the analytic model would become unavoidably large, and thus awkward to handle and elucidate;
- owing to the intricate correlations prevailing in the system of realities the analytic model would become either impossible to elucidate or over-simplified;
- the inclusion of stochastic elements in an extensive analytic model is difficult.

The simulation model, which counterbalances all these factors, is fairly easy to compose: it can include stochastic elements, it is graphic and easily understood, and its elucidation by means of large, efficient computers is economical. It is noteworthy of maintenance study in general that investigations from the macrocosmic standpoint - observation of maintenance as one complete whole, with all production devices and operational alternatives considered - are based on simulation models as a rule$^{1)}$. Analytic methods are at their best in microcosmic scrutiny, which aims at the optimum maintenance of a specific device or group of devices. Replacement problems, for instance, belong to this field.$^{2)}$

3.2. Assumptions in the model

A basis for composition of the model and planning of its working principles was provided by the activity diagrams of a production plant and the data linked with their components. Within the scope of these factors illustrating the structure of the plant rules of

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1) See e.g. Jeanniot and Bodnarchuk, Burling, Widawsky

2) See e.g. Barlow and Proschan, Jorgenson et al.

operation have been drawn up which accord as far as possible with the general principles to be observed in the working and maintenance of the plant. The activity diagrams with their relevant data are explained in section 2.1. In the model the following assumptions are made regarding principles of working and maintenance.

The factory in question is a three-shift process plant where the maintenance staff must always be on hand. On evening and night shifts and at weekends only urgent work is performed, however, and the staff is considerably smaller at these times than during the day shift. The model is so constructed as to allow variation in the size of staff in accordance with weekdays and shifts.

Work is carried out in obedience to the following principles. When a fault appears its nature is first examined in order to decide whether urgent repair is needed (apparatus has stopped working) or not (apparatus still works despite fault), and how many men are needed for the task. Urgent work is started immediately and continued without a break till finished. Non-urgent work is performed only during day shifts.

It sometimes occurs that sufficient repairmen are not available when a fault appears. Repair work must then await its turn. Urgent and non-urgent have separate priorities, the former taking preference.

In cases where insufficient men are available, overtime may be resorted to if the overtime quota laid down in maintenance policy has not been exhausted. Overtime costs are naturally higher than those of normal work.

When a fault in any department leads to a fall in the activity rate, recourse is had to the department's buffer container in order to prevent a decrease in the amount of the end product. If this buffer reserve does not suffice, use is made of the pulp store proper, the pulp tent. If the latter is emptied or the production line following it broken, production loss is unavoidable. Containers depleted during breakdowns are refilled when normal conditions prevail. Emptying and filling speeds are calculated according to the differences in activity rate between departments limited to the container in question.

3.3. Action principles of the model

3.3.1. Events

The real system to be examined, a pulp and paper factory with its operations, is continuous in character with regard to time. The simulation model illustrating it, however, may be built as a discrete system based on events. By an event is meant a phenomenon which changes the conditions prevailing in the system at that moment. In the model this takes the form of changes in the values of the endogenous variables. Conditions between events remain as before, and so, therefore, do the values of variables in the model.

Events arise:

1. in accordance with laws deterministically known (e.g. events such as shift changes which are based on the calendar)
2. stochastically, in accordance with the probability distributions of the system (e.g. damage to apparatus)
3. from the combined influence of deterministic and stochastic factors (e.g. emptying container).

The timing and interdisposition of events are the concern of the model's internal "clock", which indicates the time at which each event occurs and places the event at its correct point in the calendar of events. Steps to be taken in the handling of an event include the following:

- the nature of the event is analyzed
- new events originated by the current event are searched for and placed at their correct points in the calendar of events
- events are removed from the calendar which are already placed there but have been made insignificant by the event examined
- the values of the model variables illustrating the state of the system are changed by amounts corresponding to the effect of the event
- statistics on the effect of the event are gathered in quantities relevant from the reporting standpoint, i.e. the values of the model's output variables are updated.

The performance of one simulation run signifies that a certain preselected period is passed through in the model. Forward progress is obtained by moving from one event to another. Thus the time interval to be advanced through on one occasion is of varying length, equal to the interval between two consecutive events. After each time addition all counters of the model are updated - the internal, endogenous variables and the output variables constructed for reporting. At the end of the simulation period summaries are drawn up and the desired quantities illustrating an operation and its success are put out.

3.3.2. Stochastic elements in the model

The real system to be examined is subject to many stochastic factors. This is most clearly apparent in the processes by which

faults arise and are corrected. Separate values for the interval between faults, type of fault, duration of repair and resources demanded by repair cannot be known with certainty in advance; over a long period, however, the values acquired by these quantities follow a certain regularity which can be presented in the form of distributions.

In the model distributions of random variables are shown as empirical cumulative distribution functions. For the generation of these events, whose origin is wholly or partly stochastic, the model contains special random number generators which produce values for the random quantity distributed as desired. Generators are based on the production of uniform distribution whose values are converted through the cumulative distribution function into those of the particular distribution concerned.

3.3.3. Flow diagrams of the model

The basic logic structure of the model is shown in simplified form as a flow diagram in Fig. 5. In the framework of this simulator the main sections are:

1. Preliminary measures. Values are here given to the model constants and parameters, output variables are reduced to zero, the length of the simulation period is indicated, the values of exogenous variables are fixed (the maintenance policy to be followed is defined) etc.
2. Generation of the initial situation. Starting values are assigned to the endogenous variables of the model, i.e. the state of each unit of the system is generated at the start of the simulation period, the first event for each unit is generated, repair work in hand or awaiting performance is

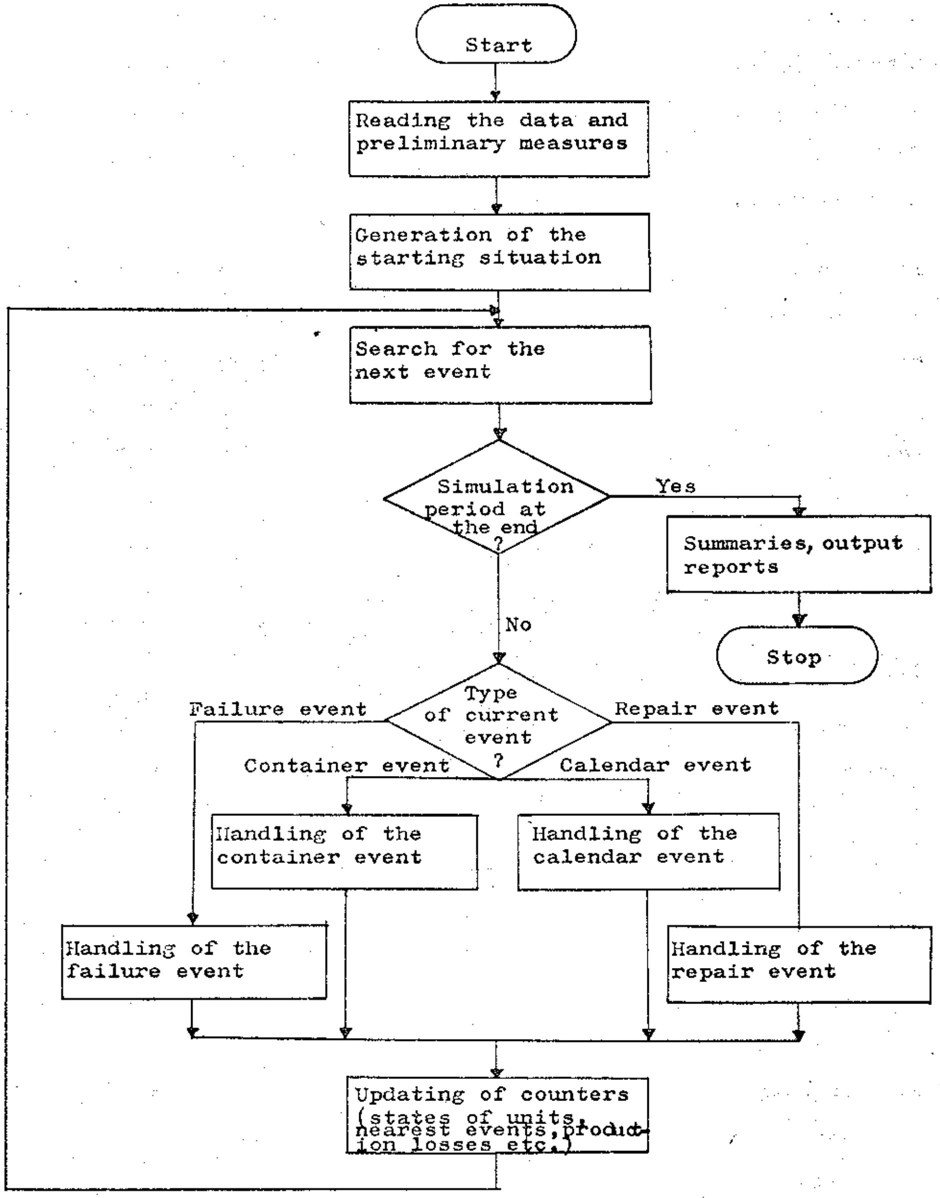

Figure 5. Simplified flow diagram for the model

specified together with positioning of the work crew, etc.

3. Search for and analysis of the nearest event. Events are divided into the following types for handling purposes:
   (a) calendar events arising at regular intervals owing to shift changes
   (b) failure events caused by faults in equipment
   (c) repair events signifying the start or finish of repair work
   (d) container events signifying the emptying or filling of a buffer container.

4. Handling of the event. Effects characteristic of the type of event are taken into account. They include changes in the number and positioning of repairmen, in the composition of work priorities and in events to come.

5. Updating of counters. Here the values of the model's endogenous and output variables are updated in so far as handling rules conform to the types of event (states of units, nearest events, production losses etc).

6. 3-5 are repeated until the simulation period ends.

7. To conclude the simulation the values of output variables are reported, also the summaries drawn up on their basis to illustrate the maintenance policy practised.

In the condensed form of this article no detailed presentation of the simulator's operational sections can be attempted. To show the content of the sections more precisely, however, simplified flow diagrams are shown of the section for generating the initial situation (Fig. 6) and the calendar section (Fig. 7).

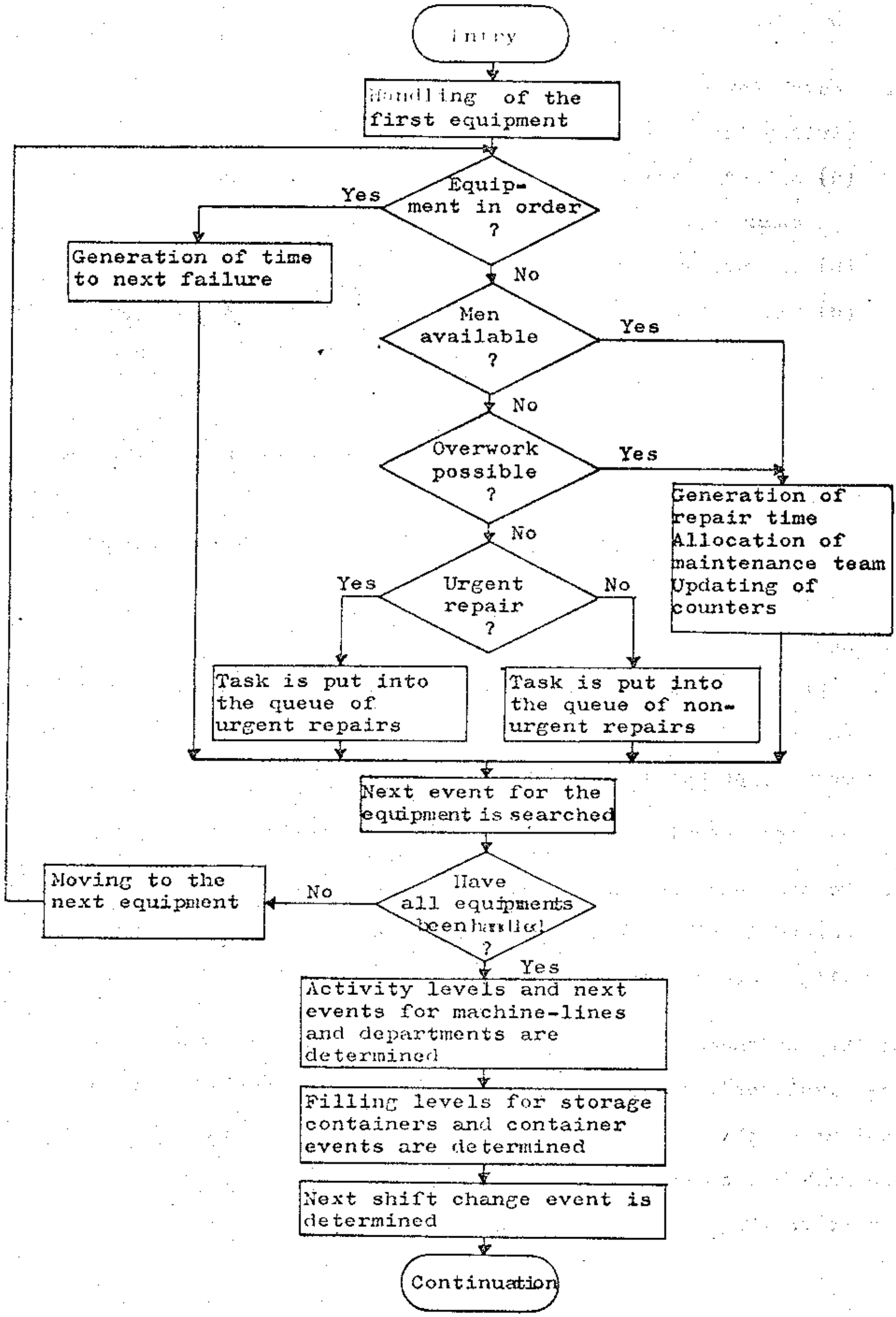

Figure 6. Generation of the starting situation

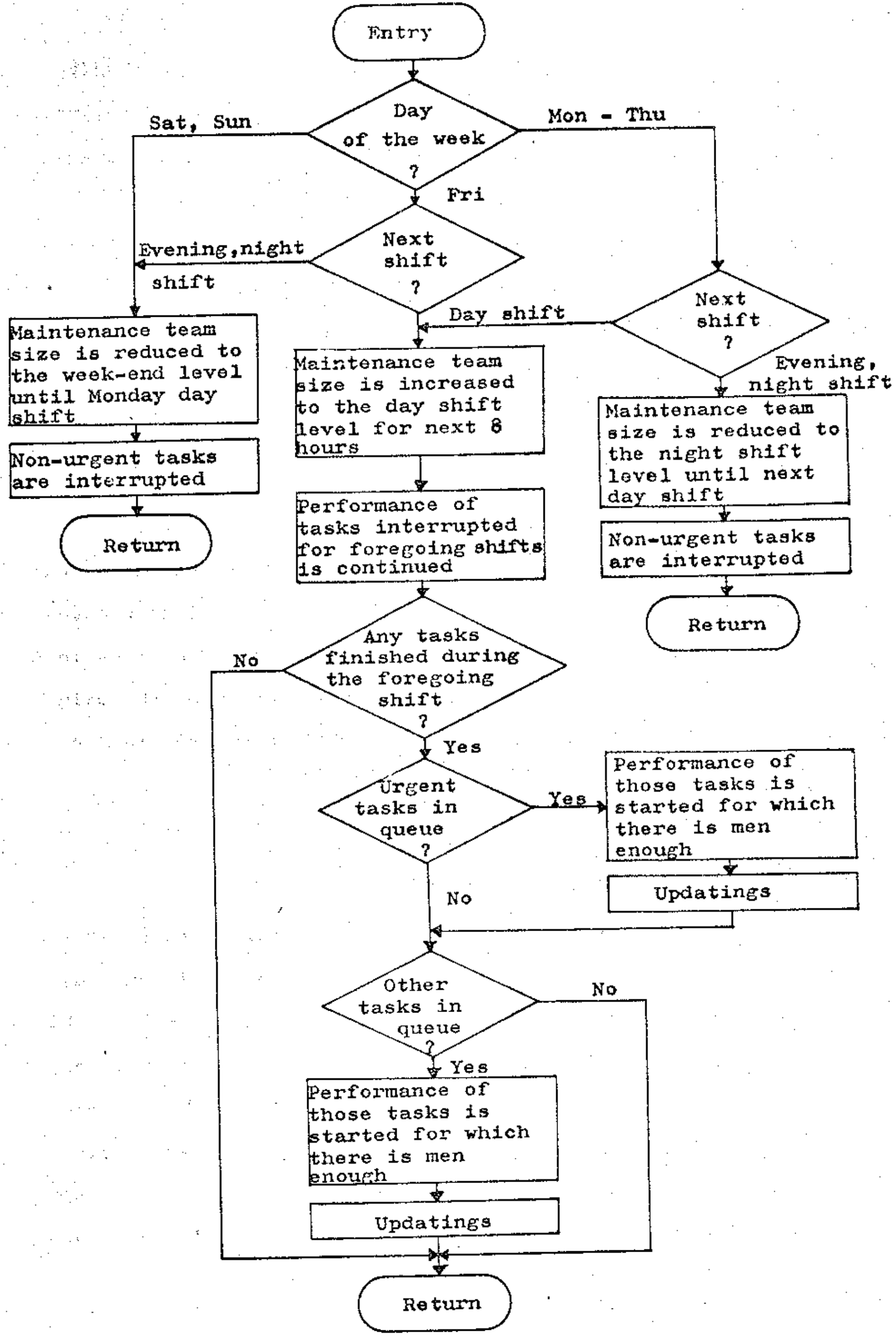

Figure 7. Handling of shift change - event

3.3.4. Programming the model

Available for simulation was a very large and efficient UNIVAC 1108 computer. Of the many programming languages on offer, which included the general languages FORTRAN, ALGOL, PL/I and the special simulation languages GPSS, SIMSCRIPT and SIMULA, the programming language chosen was FORTRAN V. Decisive reasons for this were the model composer's familiarity with the language and its suitability for work of this type. Also, simulation runs with a model programmed in FORTRAN are shorter than when simulation languages proper are used. It must be noted on the other hand that FORTRAN demands a considerable amount of programming work.

Programmes were composed on a module principle. Under the supervision of one main programme are 20 subroutines which deal with the model's various subsections. Module formation ensures adaptability for the making of later additions and changes in the structure of the model. The basic logic structure of the main programme is in accordance with the flow diagram show in Fig. 5.

4. Simulation runs and results

4.1. Performance of simulation runs

When a simulation model is used, a large number of computer runs are required. In the present work there were several hundred. In such a situation it is indispensable for individual runs to be performed smoothly. A data file was opened containing not only the values of constants and parameters but also those of exogenous policy variables. In this way constants and parameters were preserved in the computer memory, and for each run it was only necessary to fix the values of policy variables, i.e. distinguishing marks of the maintenance policy to be practised.

When an experiment is made by a stochastic system or by a stochastic model illustrating that system, its results always contain a certain random variation: experiments made in precisely the same conditions give different results on different occasions. Random variation was checked by the following procedure. First a simulation period of sufficient length was chosen, namely four years. Second, simulation was repeated with the same policy variable figures several times, so that on different occasions the random processes produced different figures for the random variables in accordance with distribution. By this means not only the average results for each policy under study were obtained, but also measurements of the degree of random variation contained in those results. The figures given are for a period of four years; they indicate average values in general.

Computer time needed for one simulation run varied from one to three minutes. Length of time depended greatly on the maintenance policy under examination: if a maintenance crew in the model was small, for instance, repair work had often to await its turn and much extra time was required for computing.

4.2. Results

4.2.1. Maintenance crew size and its division between shifts

In the model the policy variables connected with the maintenance crew clearly take the central position. Regarded as the first of these is the size and structure of the crew (its division between shifts). With reference to the components of maintenance policy it should be noted that optimation proper is only performed with regard to crew size and composition; for other factors the observations made are to be taken as examples for purposes of quidance. This is owing to the resources of the modal building:

the model had to be constructed on the basis of existing data material, and there was no opportunity for the planning and reorganization of data collection which is so important in this connection.

The results of simulations performed in search of an optimal solution to the crew question are shown in Table 1. Maintenance costs in the table are represented by wage and social costs. The absence of material costs from those of maintenance (and also from total costs) is explained by the fact that they may be considered independent of the crew question. The inclusion of material costs would only raise both maintenance and total costs without affecting the structure of the optimal crew. Observations from the results shown in Table 1 include the following:

1. Minimum total costs were achieved by the crew arrangement: 48 men on day shift, 6 men on evening, night and weekend shifts. Production losses, wage and total costs amounted to 3.80 mill. mks., 6.72 mill. mks. and 10.52 mill. mks. respectively (averages for a four-year period). Deficiency costs were caused by 1520 hours of work stoppages (380 hrs/year), which corresponds to 95.7 % operational reliability.

2. The optimum result is quite insensitive to small changes in crew structure, especially in the number of men on day shift. A result differing at most 1 % from the optimum (0.1 mill. mk.) is obtained by several different methods (cf. enclosed area in Table 1). If the random component in results is also taken into account, it is perhaps more legitimate to speak of an optimum area than an individual optimum point.

3. The power of random factors is illustrated by the following figures computed from results. The average production loss, standard deviation, largest and smallest value in the optimum point were respectively 3.80, 0.73, 4.62 and 3.08 mill. mk., the corresponding figures in total costs being 10.52, 0.73, 11.34 and 9.80 mill. mk.

Production losses Wages Total costs	Crew size for evening and night shifts						
Crew size for day shift	4	5	6	7	8	9	10
42	6.65 5.48 12.13	5.18 5.80 10.98	4.78 6.12 10.90	4.58 6.44 11.02	4.50 6.76 11.26	4.50 7.08 11.58	4.50 7.40 11.90
43	6.25 5.58 11.83	4.90 5.90 10.80	4.55 6.22 10.77	4.38 6.54 10.92	4.33 6.86 11.19	4.33 7.18 11.51	4.33 7.50 11.83
44	5.88 5.68 11.56	4.65 6.00 10.65	4.30 6.32 10.62	4.18 6.64 10.82	4.15 6.96 11.11	4.13 7.28 11.41	4.13 7.60 11.73
45	5.68 5.78 11.46	4.52 6.10 10.62	4.18 6.42 10.60	4.03 6.74 10.77	4.00 7.06 11.06	3.98 7.38 11.36	3.95 7.70 11.65
46	5.47 5.88 11.35	4.40 6.20 10.60	4.05 6.52 10.57	3.90 6.84 10.74	3.85 7.16 11.01	3.83 7.48 11.31	3.80 7.80 11.60
47	5.30 5.98 11.28	4.30 6.30 10.60	3.93 6.62 10.55	3.75 6.94 10.69	3.70 7.26 10.96	3.68 7.58 11.26	3.65 7.90 11.55
48	5.10 6.08 11.18	4.17 6.40 10.57	3.80 6.72 10.52	3.63 7.04 10.67	3.55 7.36 10.91	3.53 7.68 11.21	3.50 8.00 11.50
49	4.95 6.18 11.13	4.10 6.50 10.60	3.75 6.82 10.57	3.58 7.14 10.72	3.50 7.46 10.96	3.45 7.78 11.23	3.45 8.10 11.55
50	4.80 6.28 11.08	4.02 6.60 10.62	3.68 6.92 10.60	3.50 7.24 10.74	3.43 7.56 10.99	3.40 7.88 11.28	3.38 8.20 11.58
52	4.50 6.48 10.98	3.85 6.80 10.65	3.55 7.12 10.67	3.38 7.44 10.82	3.30 7.76 11.06	3.28 8.08 11.36	3.25 8.40 11.65
56	3.88 6.88 10.76	3.55 7.20 10.75	3.33 7.52 10.85	3.15 7.84 10.97	3.10 8.16 11.26	3.10 8.48 11.58	3.10 8.80 11.90

Table 1. The dependence between structure of the maintenance crew and costs

4.2.2. Overtime

In the foregoing examinations there was no possibility of making use of overtime for fulfilling the crew resource requirements.

Deliberate use of overtime, however, is an essential part of efficient maintenance policy: it makes possible the lowering of production losses (by avoidance of delay) and of wage costs (by keeping total strength of crew smaller). Factors controlling the growth of overtime are higher unit costs and restrictions contained in wage and working agreements. Regarding overtime the following observations were made with the model.

With a crew composition of 48-6 the permitted (not necessarily practised) degree of overtime affected costs as shown in Table 2.

Degree of overtime permitted (%)	Production losses (mill. mk.)	Wages (mill. mk.)	Total costs (mill. mk.)
0	3.80	6.72	10.52
1	3.47	6.74	10.21
2	3.31	6.75	10.06
3	3.26	6.75	10.01
4	3.24	6.76	10.00
5	3.10	6.76	9.86

Table 2. The dependence between the degree of overtime permitted and costs

An overtime degree of 5 % was sufficient to remove all delays and to reduce total costs to 9.86 mill. mk.

By means of overtime it is possible to make up most of the crew requiment of evening and night shifts, and even to lower total costs by so doing. This is clear from the results of Table 3. These results refer to a day shift strength of 48 men.

Number of men on evening and night shifts	Optimum degree of overtime (%)	Production losses (mill. mk.)	Wages (mill. mk.)	Total costs (mill. mk.)
6	5	3.10	6.76	9.86
4	6	3.10	6.17	9.27
2	10	3.10	5.84	8.94
1	13	3.10	5.66	8.76

Table 3. Optimum degree of overtime with different structures of the maintenance crew (48 men in the day shift)

To continue in this way would be possible. It might even be thought that an "optimal overtime policy" could be looked for, i.e. a crew composition and a degree of overtime corresponding to it which would enable total costs to be reduced to a minimum. But the problem is not so simple. As the figures in Table 3 already indicate, the degree of overtime in that case would be very high, and operation at such a level, if continued, produces several injurious effects which cannot be measured (restricted freedom in planning, susceptibility to risk). The work of the model would thus be confined to observations which are merely suggestive, like those already described.

4.2.3. Pre-servicing

By pre-servicing is here meant not only lubrication, oil-changing and other indispensable measures of care, but also the prescribed or regularly repeated inspection and repair work by which hidden faults are found and corrected before they cause breakdowns.

A pre-servicing programme to put operations on a secure basis - by reducing breakdowns and/or shortening repair times - involves certain costs when put into effect. It is profitable, however, if it reduces production losses to an extent at least equal to those costs. The following typical example will explain the use of the model in dealing with these questions.

The Jordan mill is an important device in pulp milling. There are several mills in each paper machine line, both in pre-milling and in milling itself (cf. machine-line diagram, Fig. 4). They are somewhat liable to damage, and require a good deal of maintenance. It was now postulated that a pre-servicing programme might be carried out which would decrease the average breakdown frequency of the mills by 10 % and also shorten repair times by 10 %. In the model such a pre-servicing programme can be expressed by converting failure rate and repair time distributions in these respects.

The results of the simulations following these conversions were that average production losses fell from the 3.80 mill. mk. mentioned in section 4.2.1. to 3.42 mill. mk., a decrease of 0.38 mill. mk. This sum of 0.38 mill. mk. is a reduction in deficiency costs achieved by increased operational reliability. A pre-servicing programme is profitable if the cost of its implementation does not exceed this sum. A second important observation was a decrease in the standard deviation of results in simulation rounds from 0.73 mill. mk. to 0.48 mill. mk., i.e. a reduction of the random variation. This means, of course, an improvement in process control from the maintenance standpoint.

4.2.4. Preventive maintenance

By preventive maintenance is here meant action which produces in the object of maintenance such functional or other changes as vitally improve its operational reliability. To the question of whether such action is profitable, whether the saving it effects is greater than the cost of performing it, an answer may be sought by means of the model. First to be ascertained are the effects of the action on the functioning and repairability of the equipment concerned. Thenceforward the model is used in exactly the same manner as for pre-servicing.

4.3. Further uses of the model

Maintenance effectiveness is often limited by factors deriving from the structure of the production plant. Previous dispositions may have given rise to bottlenecks or areas sensitive to breakdown. In the last resort it is a matter of organization whether the responsibility for removal of such production bugbears lies with the general management or with those in charge of maintenance. In the enterprise under study these matters are considered part of investment planning, and the general management is therefore responsible. For this reason the action to improve operational reliability which is now to be described is not regarded as part of maintenance policy, and is therefore examined separately. It should be noted, however, that practical performance is generally a matter for the maintenance organization. But the foregoing remarks have no influence on the use of the model: examinations are performed on the same principle as for the components of maintenance policy.

4.3.1. Reserve equipment

The safeguarding of a process unit by means of functionally similar reserve equipment which can be incorporated in the process if the regular unit is damaged is a frequently used method of improving operational reliability. How far it is economic to carry the use of this method depends naturally on the relation between cost of reserve equipment and decrease of production loss.

The following example will explain the possibilities of the maintenance model as an aid in deciding the profitability of reserve equipment. The model structure was changed by providing a reserve line for the milling machine-line in each paper machine branch. The original results of section 4.2.1. now changed as follows. Operational reliability increased from 95.7 % to 96.3 %, and average production losses fell in consequence from 3.80 mill.mk. to 3.35 mill. mk. The power of the random component in results was so reduced that the standard deviation of production losses in simulation runs shrank from 0.73 mill. mk. to 0.43 mill. mk. For decision-making purposes the model therefore directs as follows: if the improvement in operational reliability indicated by the model, the resultant saving in costs and better process control are considered of greater value than the cost and upkeep of reserve equipment, then these measures can be regarded as profitable.

4.3.2. Comparison of equipment

When new equipment is chosen, the primary question naturally is whether it will meet the technical and productive demands made on it. If several sets of equipment meet these demands, comparisons of economy must be made. It may already be obvious that the model can be of assistance here: data on each set to be considered are fed into the model in turn, and simulations are then made, keeping the model values uniform in other respects. The conclusions reached by the model on the effect of the equipment on operational success will provide an important share of the information needed for a sound purchasing decision.

4.3.3. Dimensioning of intermediate containers

The primary function of containers placed in the centre of the process is production-technical: they act as quality homogenizers of raw material, mixing tanks for chemicals etc. Thus the main criteria in their dimensioning have naturally been the demands made on these activities. Beside their original function, however, their employment as buffer storage has become highly important in cases of breakdown.

Closely linked with this buffer aspect is the question of optimal dimensioning from the standpoint of maintenance. Too small a container is not fully capable of counteracting a breakdown, while large containers are expensive from the construction and other points of view.

Numerous examinations were made with the simulation model to determine the effect of container size. The pulp tent between the pulp and paper factories (see Fig. 4) is purely in the nature of a buffer storage point. In earlier examinations its capacity has been for 48 hours. In the simulations carried out its capacity was varied within the limits 0-120 h, with results as shown in Fig. 8.

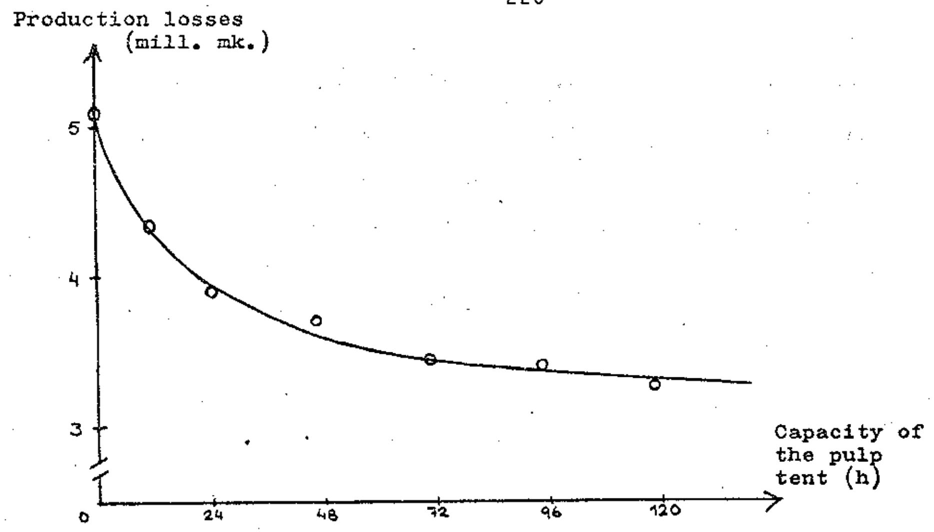

Figure 8. Dependence of production losses on capacity of the pulp tent.

The fall in production loss achieved by the container (depending on container size) may be regarded as the gain secured. The optimal container size can now be determined if the cost function of the container (also depending on size) is known.

Other examinations concentrated mainly on pulp containers in the final stage of the process. A special case to be mentioned here is the following hypothetical example. A change was made in the model to place in advance of the paper machines containers which were not present in the actual process. Their importance from the production loss standpoint was negligible. The model thus confirmed what was already known in practice, that the placing of containers at this stage of the process is pointless.

5. Conclusions

As work proceeded, the suitability and usefulness of simulation for the planning and development of maintenance in a processing

production plant were very clearly seen. Examination by means of a model links maintenance much more closely than before with production activity proper. Maintenance cannot be developed in isolation from production. On the contrary, wise production planning and control must take maintenance aspects into account. Thus the achievement of optimum maintenance must be considered part of the rational development of the enterprise as a whole, a creator of the conditions necessary for continued successful activity.

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