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SIMULATION MODEL FOR MAINTENANCE

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1. Maintenance of an industrial enterprise

1.1. Definition of maintenance

The following deals with the question of maintaining an industrial enterprise from the point of view of the production plant as an implementer of known productive aims. Therefore, the maintenance activities of hospitals, government institutions and other similar establishments lie beyond the scope of this examination.

"Maintenance is organised and purposeful activity and activity-readiness, which is directed onto a production plant's machinery, installations, buildings and grounds, and the main aim of which is to make the planned use of the latter as reliable as possible, using as little outlay as possible for this activity" (Malaska /8/, p. 87).

The task of maintenance is, therefore, to look after the

investments which have been made in accordance with the enterprise's objectives, to guarantee production activity, in such a way that they are able, during their service life, to fulfil expectations and demands. The definition of maintenance also contains the conflict which exists between particular objectives: on the one hand the aim is to make the production plant's operations as reliable as possible and, in addition, to maintain such activity-readiness that, in spite of everything, any disturbances which arise are kept to a minimum; on the other hand the aim is to minimize the costs incurred through activity.

Maintenance is, therefore, a certain function of an enterprise in which genuine decision situations constantly arise. The framework of the decision-making is composed of the conflicting aims mentioned above. The significance of this decision-making as regards an enterprise's total activities has in recent times grown considerably - and is still growing. In particular, increased automation and production speed, and the rise in quality requirements, are making ever greater demands on maintenance. This also means that the proportion of maintenance costs out of total costs and the proportion of maintenance personnel out of total production personnel, etc., is growing. Thus it is important that those person who are responsible for an enterprise's maintenance should have the use of methods by which the activity may be systematically planned, directed and supervised.

1.2. Optimum maintenance policy

1.2.1. Maintenance work-types

The organisation responsible for maintenance brings about the activity and activity-readiness described in the definition by:

(a) making available the necessary resources e.g. personnel, tools and machinerv, working-areas, spare part stocks, and

(b) organising the appropriate use of these resources.

The use of resources raises the question of the different ways in which maintenance activities can be carried out. One possible division of maintenance organisation tasks into different work-types is shown in figure 1.

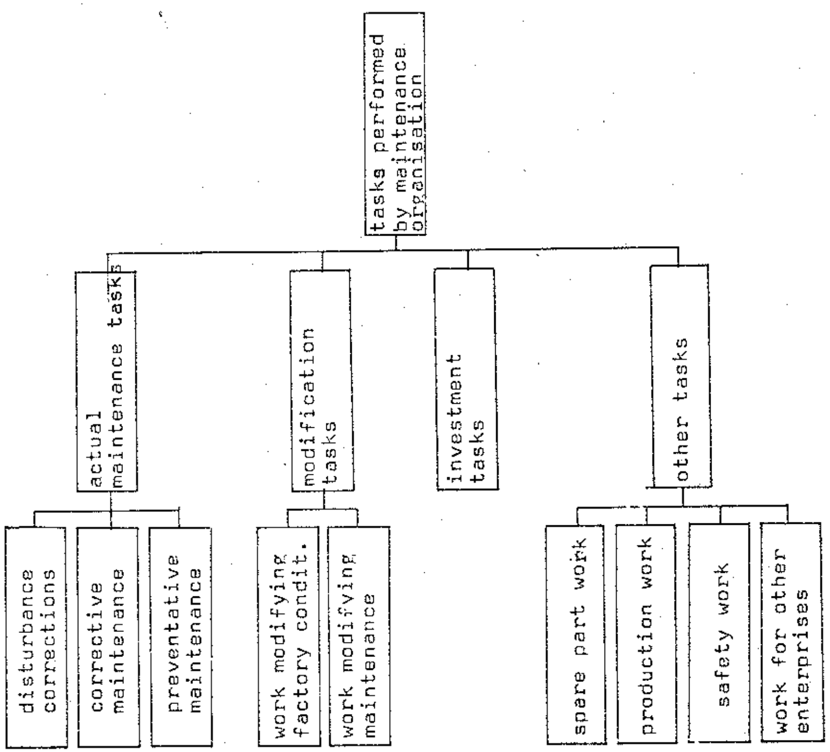


Figure 1: Tasks performed by maintenance organisation

By actual maintenance work is meant work which is directed towards a production plant's machinery, installations, buildings and grounds, and the purpose of which is to keep the latter at the level of operational reliability laid down by the management. These tasks can be further devided into the following sub-types.

- Preventative maintenance. This is regular activity carried out according to a programme laid down in advance, the object of which is to prevent disturbances arising.
- Corrective maintenance. This is repair work to correct a fault in machinery, installations etc.; the fault must be such that it has not caused operational disturbances.
- Disturbance-correction work. This is work undertaken as a result of an operational disturbance in the object of maintenance; continuation of the plant's normal activity demands immediate correction of the fault.

Modification work is work directed at objects of maintenance resulting a change in the object's level of activity or condition, and which, as far as its cost is concerned, is such that it does not require the management of the enterprise to make any investment decisions. Modification tasks by their nature either:

- change factory conditions so that the activity of installations after the change is substantially different from what it was before it, or
- they change the maintenance, so that installations are not operationally altered; these modifications are essential only from the point of view of maintenance.

Investment work is work resulting in an increase in the enterprise's property which, as far as its cost is concerned, is such that it requires the management to make investment decisions.

The maintenance organisation also has to perform tasks which cannot directly be labelled maintenance work. The most notable of these are illustrated in figure 1.

In the organisation of maintenance it is the actual maintenance work and the modification work which are of the greatest interest. The appropriate allocation of resources among the forms of activity contained in these two types of work has great influence on the success of the enterprise's activity.

1.2.2. Maintenance strategy and policy

The opposition between reliability or operational certainty and costs, which was pointed out in the definition of maintenance, can be shown as in figure 2.

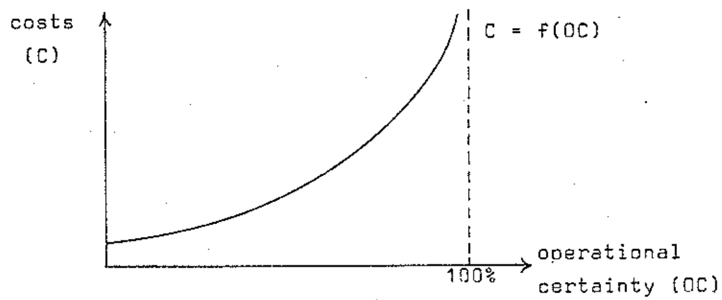


Figure 2. The dependence between operational certainty and costs

A maintenance strategy can now be defined as a group of those methods and activities by which both aims can be achieved in the relative proportions given by the enterprise's general maintenance policy (Malaska /8/, p. 87). The methods available are the dimensioning of resources, and their allocation among the various forms of activity as, for instance, the work-types.

However, in practical maintenance activity it is difficult to measure directly the interpendence of operational reliability

and maintenance costs using suitable criteria. On the other hand the lack of operational reliability shows itself in the form of expences caused by stoppages or by reduced production efficiency. Indeed, when making a critical appraisal of maintenance, one must examine not merely the maintenance costs themselves, but the total volume of maintenance costs together with costs caused by deficient operational reliability.

Thus, an enterprise's maintenance policy consists in defining the relation of these costs and giving an aimed ratio of them to one another. The best maintenance policy is that by which this ratio corresponds to the optimum value by the chosen criterion, and by which the operational certainty which accords with this value can be realised through the optimum strategy.

1.2.3. Criteria for optima

The criteria according to which optimum maintenance policy may be fixed, are to a large extent dependent on the enterprise in question. Enterprises can, however, for this purpose be devided into two basic types.

(a) Enterprises in which the consequences of deficient operational certainty may be fatal e.g. a person's life may be jeopardised. Maximum operational certainty within the framework of the budget which it has been able to use for this purpose, is the only possible criterion. Examples of this kind of enterprise may be e.g. establishments producing energy and air transport companies.

(b) Enterprises in which the effects of disturbances can be measured in money terms. Here the criterion is the minimisation of the total volume of production losses caused by deficient operational certainty and maintenance costs (figure 3).

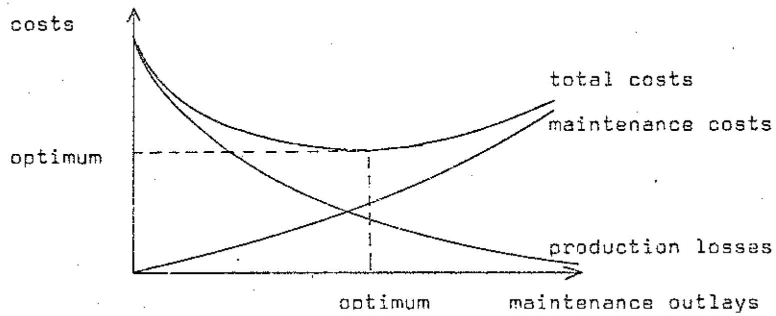


Figure 3. Minimum total costs as criterion for optimum

2. Maintenance model for a pulp and paper mill

2.1. Description of the problem

2.1.1. An example enterprise

The combination of pulp and paper mill, representing industrial processing, has been chosen as the object of examination[1]. In this kind of factory, maintenance problems are particularly great. There are several hundreds of machines and installations and their operations are so linked with one another that the breakdown of a single piece of machinery may, in the worst cases, bring the whole production plant to a standstill. Also the level of capacity employed is so high that it is impossible to compensate for lost production later on.

In this kind of factory operational certainty must be relatively high since the effects of disturbances very soon extend to the final production, and the losses from stoppages of only few hours correspond to several days' maintenance costs. On the other hand, as a result of the complicated linking together

1. Oy W. Rosenlew Ab, Porin sulfaatti- ja paperitehdas.

of components, it is not worth-while to make the whole system completely reliable, and in practice it is not even possible. The optimum policy must clearly allow a given degree of deficiency in operational certainty. The problem is to define the degree of this deficiency, the corresponding operational certainty and the optimum strategy which brings about that operational certainty.

2.1.2. Why a simulation model?

It has been characteristic of examinations into maintenance in production plants to concentrate on micro-examination, the main task of which is to find the best maintenance strategy for a particular production tool or for a group of the same kind of production tools. In addition the greater part of the research in this field examines only certain limited problems e.g. the replacement problem (vide /3/,/4/,/6/,/7/,/11/) or the problem of profitability in preventative maintenance (vide /6/,/9/).

Studies based on a macro-examination, which examine maintenance policy in its entirety, taking into account all production tools and all action alternatives, are, on the other hand, few. Of the studies carried out from this macro aspect we can mention the work of Bodnarchuk and Jeanniot (vide /1/) and the work of Burling (vide /2/). The former deal with the organisation of maintenance for the engines of a fleet of aeroplanes and the latter concerns maintenance of machinery producing electrical components.

As regards the pulp and paper mill under examination, only a macro-examination is appropriate. The optimum strategy for a particular piece of apparatus is only significant when the piece of apparatus is examined in the environment of which it is a part.

In order to be sufficientlv exact, the model which describes this kind of factory complex and its maintenance must of necessity be rather complicated. Moreover, since the model has to contain several stochastic components, the means offered by analytic models are not very significant. On the other hand simulation turns to be useful as a method which is descriptive, experimental and flexible. It should be noticed that both macro-study models mentioned earlier are simulation models.

2.2. Formulation of the model

2.2.1. Reliabilitv diagram

The basis of the model is the reliability diagram of the plant which is drawn up on the basis of a process-diagram illustrating the plant's activity (figures 4a and 4b). The essential structural parts of the reliability diagram are the delayed intermediate containers and the machine-lines which connect them.

The primary task of the containers is to work as quality-equalizers for the raw material. However, maintenance can, in its own activity, make use of these, and with the help of the containers stoppages caused both by repair work planned in advance and by some disturbance can be restricted to a particular part of the process.

'Machine-line' here means the largest possible unit of machines and installations which is to be found between two containers, where the process in the meanwhile does not branch out into other parts. Figure 5 shows the formation of machine-lines. The production process also contains certain possibilities for by-passing and re-connecting. These are taken into account in the model.

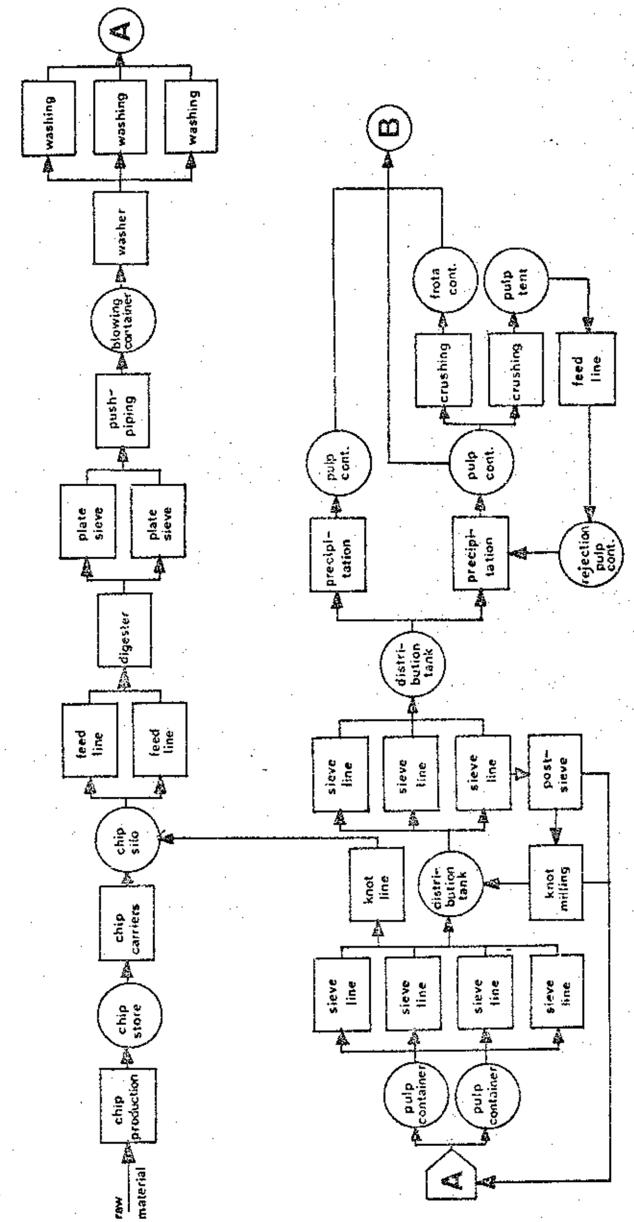
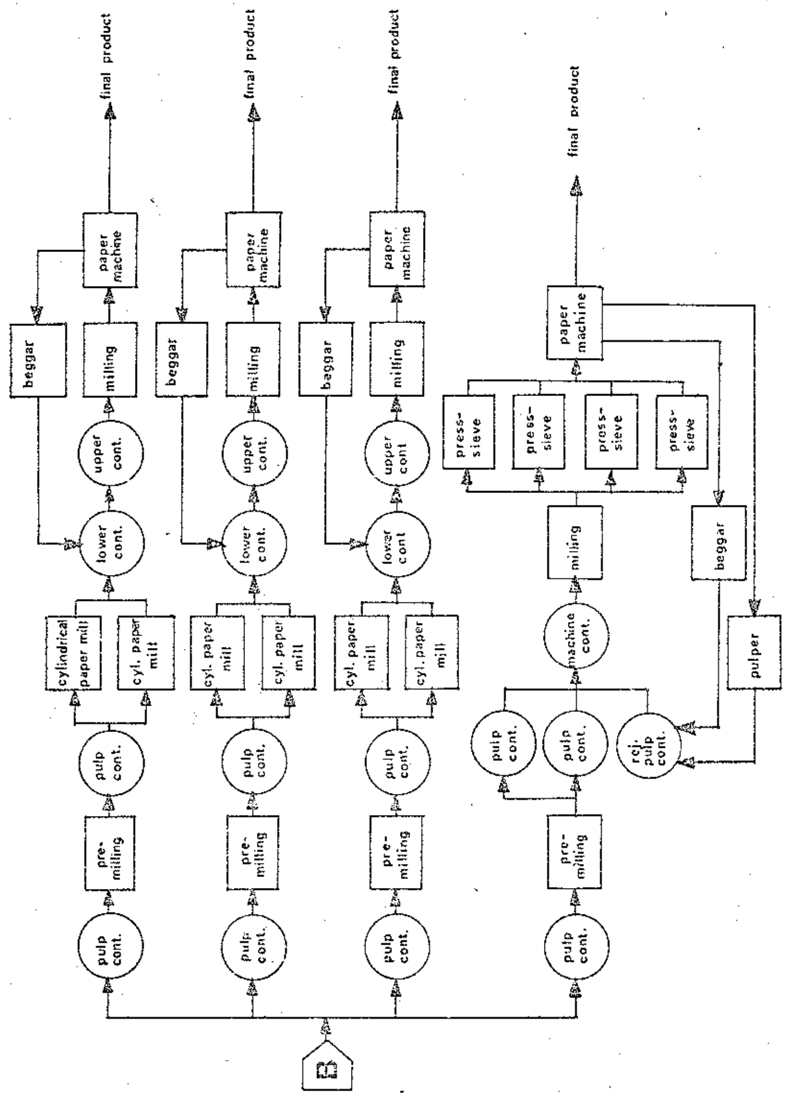


Figure 4a. Reliability diagram of the pulp and paper mill



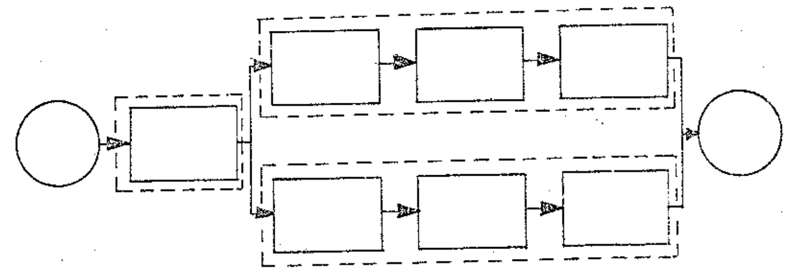


Figure 5. Formation principle for machine-lines

2.2.2. Action-principle of the model

The model drawn up is, in accordance with the simulation method, a model which traces actual activity. The path of the process can be followed in accordance with the reliability diagram, the data relating to its components and the rules laid down by the maintenance policy. The body of the model is formed by an internal 'clock' which links the different events to one another in the right chronological order. Examples of such events to be registered are

- changing of shift
- beginning and ending of week-end
- beginning and end of preventative maintenance belonging to the programme
- appearance of disturbance and its alimination
- emptying and filling of intermediate container
- appearance of waiting situation at a time when all personnel are occupied etc.

Each event is analysed, the changes in the prevailing situation caused by the event are noted. Thus at any given moment it is

possible to find out from the model e.g.
- whether the plant is in action or whether at a standstill because of a holiday or for technical reasons
- whether a given machine-line is in action or whether it is being serviced in accordance with a preventative maintenance programme, or whether it is at a standstill because of some disturbance
- whether a given machine is working normally or whether for some reason at a standstill
- what the contents levels of containers are
- how the work force is being deployed at that moment, and whether there are any repair jobs possibly waiting to be done etc.

The tasks prepared in advance (preventative maintenance, certain corrective maintenance tasks) are placed, with the help of the clock, at points of time in accordance with their programme. Unforeseen, randomly appearing faults and disturbances and the time durations of repair tasks are defined, with the help of random number generators, as following distributions characteristic of each installation. In the model, these distributions are shown as empirical tables. This form of presentation was decided on since it was difficult to find a sufficiently good correspondence between known theoretical distributions and collected, empirical distributions.

At the same time as we move forward in the model one event at the time, and the changes in the state of the system brought about by the events are registered, statistics are collected for results. Examples of information to be collected are
- repairs required by each installation and their costs
- disturbances which have appeared in each installation and the production losses caused by them
- detailed account of the retent to which the work force has been used, and of the total time that there has been a shortage of manpower

- statistics presenting the average contents level of containers and the periods when containers have been empty.

2.2.3. Programming the model

When the maker of a simulation model starts the programming of his model for the computer, he has the choice of 2 essentially different alternatives. As the programming language he can choose
(a) an appropriate general language e.g. FORTRAN, ALGOL, PL/I etc., or
(b) a special language drawn up just for simulation e.g. GPSS, SIMSCRIPT, SIMULA etc.

Questions concerning the choice of programming language should at no stage be dismissed lightly. Some of the most important aspects in the choice of language are
- the computer installation available
- the user's familiarity with different languages
- the scope and nature of the task.

Although fully conscious of the advantages which special simulation languages like GPSS can offer the user, in the form of reduced programming and keypunching work and also in the form of a versatile reporting system, nevertheless the writer finally decided to use FORTRAN. The deciding factor was the writer's much greater familiarity with this language as against other languages. The programs were written on the module principle and here FORTRAN is extremely flexible and appropriate as the programming language for a simulation model.

2.3. Simulations with the model

2.3.1. Data and starting-situation

The collection of data forms an important but also problematic stage in the construction of the model. The most important, necessary information for a maintenance model is as follows:

- distributions of undisturbed operation times according to individual installations
- regular preventative maintenance programmes
- distributions of repair times according to individual installations
- division of repair tasks into different work-types
- material and human resources required by repair tasks
- production losses from disturbances.

The information used in the model was collected from card indexes and statistics, which had been compiled over the last few years concerning the enterprise's maintenance. The machine card index showing the repairs made to each installation, the times of the repairs and costs formed the most important body of basic material. Since it was necessary to use already existing material which had been compiled without taking into account the requirements of the model, it was not always possible to obtain the full information required. This led to a certain degree of simplification and limitation in the use of the model, and this is dealt with in greater detail under 'Results'.

The influence of the conditions which are assumed to be prevailing at the very beginning of simulation extends very far in the model. For this reason the selection of starting values for the model's variables and parameters must be undertaken with care, so that no distorted results will come about in this way. The selection of conditions prevailing at the very beginning in the model drawn up happens to some extent in a

random way: each installation is, in accordance with the characteristics and distributions typical of it, operating normally, undergoing maintenance or being subject to the influence of a disturbance; the deployment of the work force, the state of the production process etc. are defined afterwards in a deterministic manner. This kind of selection of starting-conditions corresponds rather well with the mapping out of the state of the real system at a given moment, and with starting to follow the plant's activity from this moment.

2.3.2. Results

Carrying out one simulation attempt following given rules (it is realised using certain values of the model's variables) now corresponds to one action policy of the real system. The results achieved by the action policy can be seen from the output summaries at the end of the simulation attempt. Searching for the optimum thus consists in experimentation with different rules and in application of the chosen criterion to the results achieved. Factors which may influence maintenance planning and realization, and which have been included in the model, are the size of the maintenance work force, the amount of preventative maintenance and the arrangement for overtime.

Salaries and related costs form a considerable part of maintenance costs. Therefore, the effect of wrongly estimating the size of the work force is clearly reflected in costs. An exessive work force causes extra maintenance costs (wages) whereas too small a work force leads to inordinate production losses (cf. figure 3). The optimum work force size is one where the total volume of wage costs and production losses are at a minimum (it is necessary to take into consideration only wages and social security payments as maintenance costs, since material costs are in practical terms independent of the size of the work force).

An increase in the amount of preventative maintenance can be seen as a decrease in other repairs and as an improvement in operational certainty. On the other hand this form of activity, since it generally utilizes very much material, is relatively costly, and since, despite all advance measures, disturbances nevertheless arise, in any optimum policy preventative maintenance must be kept at a given level. Because of the lack of available data, it was necessary to limit the study of preventative maintenance and its effects to an examination of the following type. Using the model, a study was made of what the effects on other repair tasks and their costs, and the occurrence density of disturbances and production losses from disturbances would be, if by the use of more effective preventative maintenance, the undisturbed operation times of installations or of an individual installation could be increased by e.g. an average of 10%. It was now possible to obtain a detailed account of the profitability of a programme belonging to the preventative maintenance field, by comparing the programme's realization costs with savings made elsewhere.

Part of the capacity required in carrying out repair tasks can be brought about in the form of overtime. Hours worked as overtime are naturally more costly than others, but, on the other hand, they reduce other costs by allowing normal capacity to remain at a lower level. Thus optimum policy also contains overtime as one of its components.

2.4. Sensitivity analysis

2.4.1. Sensitivity analysis - general questions

When the model has been made, and values which are in accordance with the optimum solution have been found for its variables, there arises the question of examining this optimum in more detail. Interest is mainly directed towards

the optimum's

- reliability i.e. how sensitive the optimum solution and the optimum result are to the possible inaccurary of the model's constants and parameters and towards
- sensitiveness to changing the constants and parameters i.e. whether it is possible and worth-while, by changing the model's constants and parameters, to try to achieve a new and better optimum.

These aspects can be examined more exactly in the following manner:

(a) Inaccurary of constants and parameters. We determine the limits within which the optimum solution and optimum result can vary, if the constants and parameters have had to be estimated, in which case they are known to only a given degree of accurary.

(b) Sensitivity of the optimum result as regards the solution. We determine, whether the result will be greatly changed if, instead of the optimum solution, the realization of another solution near to it is wanted. It is also possible to search for all those solutions which lead to a result which differs by no more than a given amount from the optimum result.

(c) Changes in constants and parameters. The optimum result was arrived at using known values of constants and parameters. However these can generally be changed, although one must pay a given price for the change. It is possible to decide whether changes are worth-while by comparing the costs incurred through changes with the advantages obtained through the new, perhaps essentially better optimum.

The inclusion of the post-optimum sensitivity analysis thus increases the appropriates of the method based on the model. Instead of merely obtaining the optimum solution, we now also obtain information about the reliability of the result and about the development possibilities of the real system under examination. It also becomes possible to take into account considerations based on subjective experience.

2.4.2. Examples of sensitivity examinations carried out on the maintenance model

Below are presented as examples certain particular cases in which the general principles described above are applied to the maintenance model. Here, the greatest interest attaches to the references to development of the real system offered by the model. This is thus a question of factors which cannot be decided by the maintenance organisation and which it is therefore impossible to position into the model as variables.

(a) Operation times and repair times of individual installations. In the model, each installation has a distribution of undisturbed operation time and a distribution of repair time formed on the basis of collected data about the plant's activity. It is often possible to make these distributions more profitable by improvements to the installation, by replacing the installation with another or by some other corresponding measure. With the help of the model it is possible to find out the price which it is worth-while paying for these measures as a counterbalance to reduced repair costs and production losses.

(b) Bottle-necks. In the pulp and paper factory under examination one common phenomenon, which is typical of processing industry, is the fact that certain installations are more important than others as far as activity is concerned, and any stoppage of these immediately involves production losses. Such installations are often provided with reserve installations for disturbances. The simulation model can also be applied here, when the profitability of reserve installatios for a particular installation or part of the production line is carefully weighted up. Here there exists an opposition between the capital lied up in the reserve installations and the improved operational certainty.

(c) Dimensioning of intermediate containers. The significance of containers from the point of view of maintenance has already been mentioned above in connection with the making of the model. Using the model, it is now possible to examine questions relating to the size of containers. Containers which are too small are not capable of smoothing out disturbances to any significant degree, while exessively large containers lie up capital and cause interest losses. However, it is natural that a model drawn up for maintenance purposes cannot finally determine question of optimum container size. This is connected so closely with the production programme and direction strategy[2] that it is neither possible nor even necessary to include it in the maintenance model. We do, however, receive valuable references to the actual size class and necessity of the container.

3. Conclusions

As the work proceeded, the appropriateness and usefulness of simulation for the planning and development of maintenance in a processing production plant was very clearly seen. This kind of examination, carried out using a model, and in particular the post-optimum sensitivity analysis, connects maintenance much more closely than earlier with production activity proper. It is impossible to develop maintenance in isolation from

2. For more information about dimensioning containers see e.g. Golemanov et al. /5/.

production. On the other hand sensible production planning and control must also take maintenance aspects into account. Thus the attempt to achieve optimum maintenance must be seen as part of the whole enterprise's rational development and as a creator of the necessary conditions for the succesful continuation of activity.

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