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PREVENTIVE MAINTENANCE
SCHEDULES AND PRACTICES

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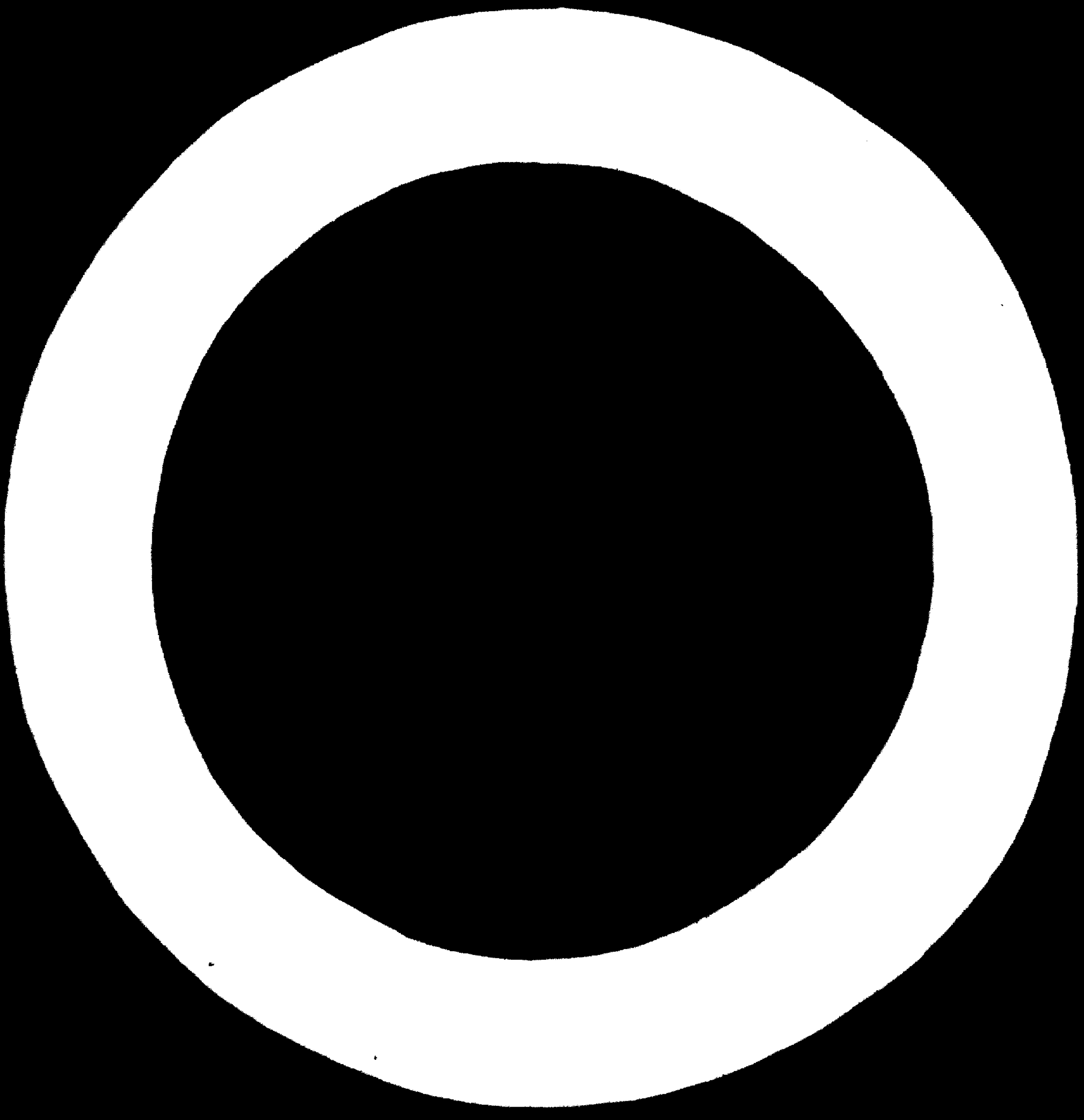

I. Introduction

The increasing significance of maintenance as a cost - factor due to the increase of construction-intensity on account of rising automation in the field of machine fabrication makes a systematic and careful planning of maintenance absolutely necessary today. This planning must comprise both the moment of maintenance as well as the completion of the maintenance planning as its objective is the minimization of the total maintenance costs.

II. Application of Maintenance Policies

To begin with it must be established that unexpected failures usually occurring at the most unsuitable moments can be anticipated by preventive actions which can be shifted to more advantageous times. Hereby the downtime of an aggregate, however, has not been avoided but in certain cases it may cause less damages or costs than an accidental breakdown. The preventive actions have to be planned in advance and here the time-series of application and the size of actions have to be arranged according to the ratio of the single costfactors to the failure distribution of the aggregate. Such a layout defining time-series and size of preventive actions is called "strategy". The strategy essentially depends on the kind of the objective which is to be applied, i.e. whether

a) the attainable profit is to be maximized by the actions

b) the appearing costs are to be minimised or

c) the reliability of the aggregate at fixed budget is to be maximized.

1. Objectives of Application of Strategies

1.1 Maximization of Profit

The maximization of profit is the most essential objective of every entrepreneur. Therefore the insertion of this objective function would also be desirable for the optimization of the maintenance-strategies. As the profit is strongly influenced by the trade condition on the one hand, and the distribution of profits on the single machines is endangered if bottlenecks are amongst them on the other hand, the objective function of the profit maximization for maintenance problems is not very suitable.[1] It is very seldom used in literature of maintenance[2] and shall not be discussed here either.

1.2 Minimization of Costs

With the reduction of costs of maintenance actions an indirect maximization of profit is pursued and therefore this objective is specially suitable for the exact calculation of costs.

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1) see [illegible], Untersuchungen zur Bestimmung der optimalen Organisation von Instandhaltungsarbeiten an Fertigungsmaschinen bei Werkstättenfertigung anhand eines Simulationsmodells, Diss. TH München 1968, page 87; McCall J.J., Maintenance Policies for Stochastically Failing Equipment A. Survey, Management Science 11 (1965) page 493 - 513

2) compare Drenick R.F., Mathematical Aspects of the Reliability Problem, Journal of the Society of Industrial and Applied Mathematics 9 (1960) page 125 ff.

According to the structure of maintenance problems 1) simple cost-estimations with average costs were chosen, e.g.

$$K = X_a C_a + X_p C_p \qquad (II.1)$$

Xa or Xp gives the number of failure or the planned actions while Ca or Cp gives the average costs per failure 2), or else, all single costs per failure or preventive action were considered and summed up for the total costs 3). Among these extremes there are of course many combined opinions operating more or less with average or single costs 4).

In any case the maintenance costs will have to be divided into 3 groups in order to be able to calculate all parts and then decide whether an average account is sufficient or not 5):

a) downtime costs
b) material costs
c) personal costs

a) The downtime costs of a machine contain all costs which can be sorted to this machine for the period of its downtime and the increase of value which could have been attained with the manufactured product of this machine. Additionally lost profits have to be considered, too. By the additional

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1) Often a simple cost-estimation was chosen in order to allow an analytic treatment of the problem.

2) compare McCall J.J., a.a.O. page 490

3) compare Kreß H., a.a.O. page 88 ff.

4) compare Bovaird R.L., Characteristics of Optimal Maintenance Policies, Management Science 7(1961), page 238 ff., Kettelle J.D., Least Cost Allocations of Reliability Investments, Operations Research 10(1962), page 249 ff., McNeill J.G., Forecasting of Equipment Maintenance, Diss.with Cambridge 1955, Lindsay G.F., Bishop A.B., Allocation of Screening Inspection Effort - a Dynamic Programming Approach; Management Science 10(1964), page 342 ff., Parson J.A., Preventive Maintenance Policy Selection, Industrial Engineering 16(1965) page 321 ff.; Weiker E.R., Relationship between Equipment, Reliability, Preventive Maintenance Policy and Operating Costs, ARINC Research Report Nr.7, Washington 1957

5) compare Kreß H., a.a.O., page 88 ff.

application of expediency costs, the significance of the machine may be expressed in regard to the manufactures (e.g. bottleneck machines) and thus a long waiting period for maintenance may be avoided by a planning of the maintenance-completion according to costselection.

b) Materialcosts include spare-part costs or reparations of the respective spare-parts as well as costs arising from defective goods caused by machine failure.

c) Personalcosts include all costs concerning the maintenance-department, directly applicable costs as well as general costs of maintenance.

The sum of all these cost-shares must be minimized. The policy essentially influences the downtime costs as well as the materialcosts.

A suitable policy causes more downtimes, however, but less downtime expenses, because the waiting periods for service are reduced, if the standstill of an aggregate is planned in advance. The material costs for spare-parts rise, on the other hand the occurence of defective goods is abolished, and no other parts of the machine will be damaged by the failure 1).

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1) The following literature gives information on the composition of maintenance costs: Cziner R.M., How to control Maintenance Costs, Petroleum Refiner 33(1954) page 106ff., Althoff F., Müller K.D., Das Problem der Reparaturkosten in den USA-Chemie Ingenieur 8(1956) page 296ff., o.V., What should Maintenance Cost, Factory Management - and Maintenance 111(1953) page 113; o.V. Refinery Maintenance what it costs, The Oil and Gas Journal 58(1960) page 100; Clapham 7 C.R., Economic Life of Equipment, Operational Research Quarterly 8(1957) page 181ff; Kölbel H., Schulze J., Wirtschaftlichkeits-kontrolle der Instandhaltung in Chemiebetrieben, Zeitschrift für Betriebswirtschaft 35(1965) page 29ff.,(Ergänzungsheft); Margo B.A., A new System for Maintenance Control, Petroleum Refiner 36(1957) page 235 and 6 page 171; Lude W.S., Six Steps to Equipment Cost, Petroleum Refiner 38(1959) page 139; Pretzger A.A.B., The Setting of Maintenance Tolerance Limits, Industrial Engineering 14(1963) page 80ff; Rachal E.A., Dough [illegible] W.E., Reports for Maintenance Cost Control, Petroleum Refiner 40(1961) 7, page 165; Teel H.L., Use Data Processing to Control Maintenance Costs, Petroleum Refiner 42(1963) 1, page 115.

1.3 Maximization of Reliability

In certain cases - especially aviation or military projects - the reliability of the function of an aggregate is most important. Here no estimation in the sense of cost-consideration can be realized, because the operational readiness of an aggregate which might determine the end of a war (e.g. use of rockets) or even human lives (transport aircraft) cannot be calculated. With very complex aggregates e.g. systems of news transmission, computers or complicated methods of fabrication, the reliability of the various aggregates is of special importance because a failure might cause extremely high costs; important informations might be lost or catastrophes caused. (Atomic reactor, chemical works, pipe-lines)

It may be convenient to manufacture the less accessible parts of even the smaller fabrication aggregates very carefully, (e.g. by redundancy in order to avoid expensive repair).

The objective of maximization of reliability essentially differs from the minimization of costs. The policy in the first case does not consider a series of cost-shares, because a calculation fundament is lacking and it endeavours to improve conditions with given measures. [1] In the second case a failure of the system is purposely accepted as it is calculable, whereby only the sum of all cost-shares is minimized, i.e. the policy regards only valueable aggregates worthy of receiving careful treatment. It is therefore necessary to strictly distinguish between these objective functions and these models.

In order to be able to formulate the objective function the word "reliability" must still be defined. The definitions given in literature are very different [2]. The scale varies from very general definitions, like e.g. "The Reliability of a System is the probability that it can satisfactorily fulfil

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[1] compare Barlow R.E., Proschan F., Hunter C.L., Mathematical Theory of Reliability, New York 1965 - page V.

[2] compare Barlow R.E., Proschan F., Hunter C.L. a.a.O. page 5; Drenick R.F., a.a.O. page 125

the required duties under certain work-conditions for a certain period of time," 1) to exact mathematical definitions which must unconditionally be preferred. Some of the most important of these shall be described here and the following concepts have to be distinguished:

a) reliability
b) efficiency
c) operational readiness
d) interval reliability

a) If you look at single conditions of a system at time t and they are described by a probability size $X(t)$ with the values $X_1(t)$, $X_2(t)$.....,$X_n(t)$ and the distribution function $F(x_1, x_2, \ldots, x_n, t)$, these conditions may receive a certain profit function $G(x)$. Hereby we rather think of a technical than an economic profit; e.g. the probability that the aggregate does not fail. The reliability $R(t)$ is then given by the expected value of this profit-function at moment. 2)

$$R(t) = E\{g[X(t)]\} = \int_{x_i = x_1}^{x_n} g[X(t)] \cdot dF(x_i) \qquad (\text{II.2})$$

b) The efficiency Eff_t 3) is, contrary to the reliability $R(t)$, independent of the time. It has the value

$$Eff_t = \frac{1}{T} \int_0^T R(t) \cdot dF(t) \qquad (\text{II.3})$$

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1) compare Barlow R.E., a.a.O., page 6

2) compare Barlow R.E., Hunter L.C., Mathematical Models for System Reliability, Sylvania Technologist 13(1960) page 16 ff., especially page 17.

3) compare Barlow R.E., u.a., a.a.O. page 7

and here F(t) represents the probability that the system is ready to operate at a certain time. Eff_t being the mean value of the reliability, represents the expected time of operation in the interval T, allowing maintenance actions as they can easily be considered by changing R(t) and F(t).

c) The operational readiness [1] expresses the probability that a system is ready to operate at any time. This value is influenced by the reliability and possible maintenance actions. It is calculated out of the efficiency of a system in case that the time interval T increases infinitely. The simple conception that probability is expressable by the number of favourable cases to the number of possible cases (Application of the counting rule [2]) easily makes this diversion clear.

$$P_{up} = \lim_{t \to \infty} \frac{1}{t} \int_0^t R(t)\, dF(t) \qquad (II.4)$$

d) The reliability of intervals [3] is the probability of the readiness of a system within an interval beginningat mo -

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[1] see Bhashyam N., Jaiswal N.K., Operational Readiness of a Complex System, Opsearch 1(1964), page 13ff.; Colemann J.J., Abrams I.J., Mathematical Model for Operational Readiness, Operations Research 10(1962), page 126ff.

[2] see Heinhold J., Gaede K.A., page 21

[3] see Barlow R.E., Hunter L.C., Reliability Analysis of a one-unit System, Operations Research 9(1961) page 200; Flehinger B.J., A General Model for the Reliability Analysis undder various preventive Maintenance Policies, Annals of Mathematical Statistics 33(1962), page 137ff.; Pugh E.L., The best Estimation of Reliability in the exponential Case, Operations Research 11(1963) page 57ff.

ment T and lasting at least t_0 time units. Until T maintenance actions are allowed. Let it be X (t) = 1 or 0, if the system works or has failed at moment t. Then it has the value

$$R(t_0,T) = w\left[X(t)=1;\ T \leq t \leq T+t_0\right] \tag{II.5}$$

This value cannot be explicitly calculated as it depends very much on the events within interval 0 to T and hereby reflects the policy.

Besides these values there are of course a number of other definitions which, however, may be diverted mostly from these concepts. So we find e.g. the strategic reliability (1), i.e. the probability of using a machine at any interval (2) from the interval reliability with the threshold crossing $T \to \infty$. No further special definitions (3) shall be given here.

These measured numbers may be influenced by the separate preventive actions. It is the objective to choose the strategy in such a way that the given costs maximize the measured values or that the costs are minimized by the given limits (minimum demand).

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1) see Truelove A.J., Strategic Reliability and Preventive Maintenance, Operations Research 9(1961) page 22ff.
2) Barlow and Hunter call this function a Limiting Interval Reliability; compare Barlow.R.E.-page 8
3) see Weiss G.H., On the Theory of Replacement of Machinery with a Random Failure Time, U.S.Naval Ordonance Laboratory Report, White Oaks, o.J.; Corcoran W.J., Weingarten H., Zelma P.W., Estimating Reliability after Corrective Action, Management Science 10(1964) page 786ff.

2. The Strategies and Models of Preventive Maintenance.

2.1 Suppositions for intelligent application of preventive actions.

The maintenance costs can be reduced, if either the expenses per action or the number of actions or both are reduced. Smaller savings are achieved, if the influence of the one factor is strongly reduced by raising the other one. In maintenance these factors are mainly represented by downtime costs [1] which strongly vary between preventive action and reparation of failure, and by the number of downtimes which is essentially determined by the failure distribution. It is impossible to reduce both factors simultaneously. Only redundancy could influence failure distribution. The redundancy costs, however, would strongly raise the costbalance, even if only insignificant improvements are desired. Therefore the redundancy is reserved for those special cases where rather the reliability should be maximized than costs minimized, because downtime - or failure costs are incomparably higher than the total costs of an aggregate, or because failure costs are not at all or not easily calculable. To begin with it may be attempted thus to reduce downtime costs without preventive actions. This is achieved by shortening the reparation periods or reducing downtime costs per time unit.

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[1] The personnel- and material costs are usually very low in comparison to the downtime costs. Although they shall still be considered in the later exposition, they shall be neglected for the time being.

The second value cannot be influenced as it is predecided by the production; the first effect could be attained by an increase of personnel. But this action again raises the expenses. It is achievable, however, to reduce the downtime costs per time unit by means of optimum dimensioning of the maintenance crew to such an extent that a minimum of total costs arises which depends on the ratio of downtime costs to personal costs. The next step screening these problems covers the material expenses. High material costs arise from breakdowns of single machine parts which involve complex mechanical systems. Often such involvements are unnecessary - an objective construction 1) considering the failure conditions, too, may help to avoid high material costs and also high downtime costs due to unnecessarily high periods of repair of the affected series of parts. Starting from one of such best constructed aggregates the cost may be further reduced under certain conditions by raising the amount of downtimes - i.e. by preventive actions - simply because hereby the downtime costs are reduced. The time when this occurs will be discussed in the following. To begin with a table shall be given here, shortly stating the result of the following commentary.

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1) The value-analysis as a strongly growing division in our days complies with this demand with regard to every possible objective.

failure rate	Cost ratio	
	$C_p/C_a \geq 1$	$C_p/C_a < 1$
$\frac{dr(t)}{dt} < 0$	no PM	no PM
$\frac{dr(t)}{dt} > 0$	no PM	Preventive Maintenance

T1: Determinant table for the execution of preventive maintenance.

First of all this model shows the rate of failure r(t) in its periodic development as a substitute of the failure distribution. As already shown the periodic development of the failure rate is a measure of the change of the failure probability over a period of time. Therefore it is easily conceivable that a preventive action, i.e. a periodic pre-shift of a failure, is put on only, if this failure can thereby be avoided or stated more precisely, if the probability of a failure is decreased by the preventive actions.[1]

The second criterion of the ratio of average costs for a planned action (or preventive action) C_p to the average costs of a failure reparation C_a still needs commentaries. If more downtimes are caused by preven -

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1) Preventive actions seldom pay with electronic parts which often at first show falling - and then rising failure rates due to cauterization processes, because the prevention causes costs only, without changing the failure situation, or even aggravating it.

tive actions [1] one should be sure that then the costs per downtime are essentially less in order to reach a minimum. It is therefore necessary in each case to examine how the costs of a preventive action in relation to a failure reparation can be reduced. Generally the following reasons are determinant:

a) The waiting time of the machine for reparation in cases of preventive maintenance is not important as the actions can be planned while the failure usually happens when the maintenance personnel is engaged elsewhere.

b) The period of repair is shorter, too, as the replaceable parts are exactly known while the defects of a failure have to be searched for first. Other parts are usually involved, too, and these are also replaceable.

c) For the same reason the material costs are usually higher.

d) The personal costs rise too, because there is more work and more workers are required during failures.

In special cases, however, it may by all means happen that the costs C_p are higher than C_a, perhaps because the downtime costs are very high so that with less

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[1] As preventive actions are applied before the failure the mean operation interval of the machine is shortened and thus the amount of downtimes per time unit increases.

technical complexity of the machine parts there are no essential cost differences per time unit between prevention and failure, whereby the greater amount of downtimes may have a negative result, if they are prevented. In the majority of cases, however, especially those with technical equipment, the application of planned prevention actions brings the expected cost advantage. Then it is important, however, to find the suitable strategy which is to be optimized in order to totally scoop the cost advantage.

This strategy is then applied to an object of which the structure still has to be screened in the respective cases as it will surely be of great importance whether the strategy is used per part of machine, per part-set per machine or per machine-set. In order to describe this object more precisely the concept "maintenance unit" was formed, which is to determine the application area of the strategy. It cannot be described here in details as this maintenance unit very much varies in literature and it is more appropriate to leave a specially favourable choice of this maintenance unit to the specific problem of practice.

2.2 Criteria for the division of maintenance

As described before the maintenance policies can be divided according to several viewpoints. Fundamentally we here find the same criteria for cost-and reliability-models, even if the problems with regard to the executed maintenance actions (e.g. inspection, reparation, replacement) are partly considered differently:

a) time lapse
b) knowledge of condition
c) distribution
d) complexity of machine
e) Reliability of information

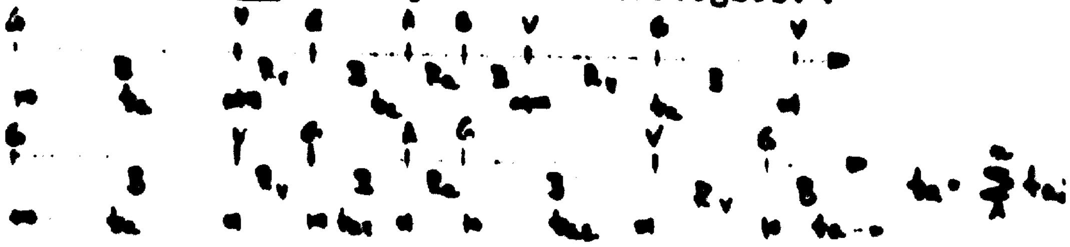
These criteria are to be explained more precisely in the following:

2.11 Time - series of actions

Preventive measures may be applied periodically or sequentially with regard to their succession of time. A periodic strategy is based on the fact that specific moments of preventive actions during the duration time of a machine must be repeated in regular time intervals. On the contrary a sequential strategy gives sequences of differing periods or calculates these during the utilization time of the machine.

The period between the preventive actions of a machine may be based on various moments what the periodic strategy is concerned. Principally a machine is maintained preventively after the period has passed or if it has previously failed.

72: The periodic strategies. .



Picture 1 shows a time-axis which is to demonstrate a sector of the durability of a machine. This machine is in use (B), fails (A), is repaired (R_a), is set going again (B), is closed down for prevention (V), and this is carried out. The difference between the time-axes (a) and (b) is that by (a) we mean the period t_p between the initial points of the respective preventive measures, while (b) is the period determined by the sole operation time of the machine between two downtimes. Thus one discerns two strategies:

a) exact periodic strategy
b) periodic strategy after operation time.

The exact periodic strategy is optimum only, if the downtime periods of the machine in relation to the periods are short, because only then it can be guaranteed that the carrying capacity and durability of the machine parts are uniformly utilized. If one allows big oscillations of the duration time of the parts, or if one forces them by an exact periodic strategy, material reserves will not be fully utilized which naturally increases the maintenance costs. The periodic strategy, however, allows a possibility to fully utilize the operation pauses for the maintenance which is particularly advantageous, if

a) the optimum period is not to be essentially changed in order to fall into the operation pauses,

b) the optimum above the period runs flat (see P.5)

c) the fabrication capacity is strongly utilized.

P 5: Cost pattern above the period of a periodic strategy:

The optimum period may then be changed within the limits which arise due to the avoidance of downtime costs ΔKs during the operation pause. If one succeeds thus to change the period within t_u..........t_o, so that it coincides with the period of operation pause, the total costs may still be reduced.

This is not possible with the periodic strategy after operation time, as the interval between two planned downtimes is obtained as a sum of reparation times, waiting times for reparation and operation time. The interval is a contingent value because only the operation period can be given. Yet this strategy is normally to be preferred to the exact periodic strategy, although it causes slightly greater planning expenses because a registration of operation hours has to be kept for every aggregate. As, however, the waiting- and reparation times are usually not to be neglected and additionally only few plants will carry out reparation during night shifts, if they operate on a one-shift production basis (operation pauses!) thus also causing increased personal costs, the slight extra costs of management will be acceptable and the exact periodic strategy will be limited to special cases (e.g. at very high downtime costs).

The sequential strategies also carry out preventive measures after certain time intervals and immediately repair failures, if they occur. The difference in relation to the periodic strategy consists of the shaping of the interval for the prevention. For the sequential strategy a sequence of time intervals is supposed or calculated in the course of utilization. One hereby assumes that with increase of age a machine changes its failure condition because the general idea of a repaired machine being as good as new proves to be an approximation in practice. Accordingly the time interval will be again calculated after every failure or after each preventive action. Here one considers the experiences of known data and the remaining interval of utilization of the machine. The objective is the minimization of the total costs over the remaining period of utilization. The method shall not be described in details here 1) as it is very costly and has little significance on the other hand. It can be shown that the sequential strategy alone is indeed optimum for final utilization periods of machine, that the deviation, however, of an optimum periodic strategy from this general optimum is only very slight. 2)

The series of interval, however, may also be accidental. In the first instance there is the possibility to use Monte Carlo methods to generate a given failure distribution. They are fixed after a corresponding diminution by means of a factor smaller than 1 as preventive interval-series. As, however, the contingency of such number-series between contingent numbers and effective failure moments may cause great differences, this method seems to be unsuitable in practice. The contingency of such intervals, however, may be a result of the fact that an originally periodic pre-planned preventive measure cannot be carried out because at the preventive moment there is no available worker so that the machine of course continues operation until it fails or until it may be controlled. 3) In

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1) see Barlow R.E., Proschan F., Planned Replacement, page 68

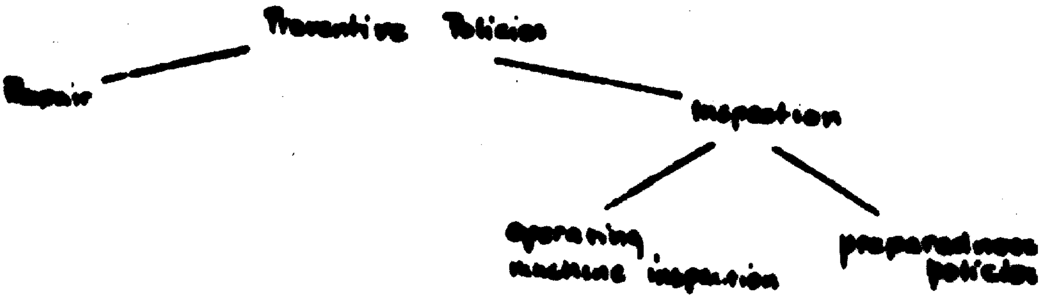
2) see Kreß H., page 38

3) see Kreß H., page 43ff.,Kreß speaks of a periodic operating time strategy,in the strict sense of classification this strategy has to be defined as sequential strategy with incidental periods.

this case the series of the preventive intervals automatically results in the contingent sequence, even though the measures were planned periodically. Similarly various other application-acquainted sequential strategies may be suggested which are certainly preferable to pure periodic strategies what specific cases are concerned.

[illegible].22 The known degree of the condition of a machine

Thus far we have always regarded the condition of a machine as "good" or "failed". This is not always the case, however, as many parts of a machine don't cause the breakdown of a machine, if they are defective, even though they have a negative influence of the production outcome. Thus it may happen that one part of the machine breaks down unnoticed, with the consequence of a gradual-neither noticeable-aggravation or even unnoticed defective goods. An example is the only occasionally controlled con - veyer belt, where a tap inside a workpiece might break off and the defective result will only be noticed at final control. Every workpiece following this one is to be regarded defective, sometimes causing high damages of reconditioning afterwards. Such examples and many other different cases may surely be avoided by a suitable strategy. As the determination of the condition is always connected with an inspection, such strategies may also be called "inspection strategies." Contrary to this are the reparation strategies not requiring any inspection as the condition is known. These inspection strategies can again be divided into strategies for operating aggregates and into those applying to aggregates ready for insertion at a certain moment - the readiness strategies. (see P. 4) 1)



P. 4

Division of preventive strategies in view of the variable known degree of the condition of a machine.

The division of the criterion already shows that the choice of a strategy according to this viewpoint depends on a specific problem, i.e. one has no possibility of free judgement whether this or that kind of strategy would prove more appropriate. Given problems will always easily show, whether the condition is recognizable or not.

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1) see Kroč H., page 55

2.23 The Number of Possible Conditions of an Aggregate

If we expand the case mentioned in the previous paragraph into another direction, we have aggregates which, besides the two extremes "good" and "failed", show up various steps or a continuous course of the quality of a condition. In a strict sense this will almost always be the case as, in most of the practical examples, a failure is caused by wear, whatever the nature of wear may be, and such appearances of wear seldom develop by leaps. (e.g. overburdening leading to breakdown, over - charging electric apparatus) Such pure contingent failures may, however, be avoided by means of preven - tive strategies, too. Inspite of the frequent existence of a continuous course of a condition one finds that there will be no affect of the contingent diminution on the output of an aggregate - this aggregate is to be called "good" - until a certain limit is passed be - low whereby the aggregate fails and receives the con - dition "failed". A typical example is an incandescent bulb of which the glowing filament is continuously thinned due to evaporation without affecting the function until it breaks and the lamp has to be replaced. Most of the technical aggregates react in this way so-that in many instances two conditions are sufficient. With other examples it is more favourable, however, to distinguish among several conditions, if different demands are to be expected of various aggregates.[1)]

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1) e.g. tyres for tractors may be classified in condition grades according to profile depth. New tyres are only for agricultural work and worn tyres for transport.

Here one speaks of multi-staged strategies contrary to single-staged strategies which only allow two conditions. The multi-staged strategies usually apply the theory of Markov Chains in order to be able to describe the various steps.[1] The transition from one quality-step to the next is here described by probabilities. The strategy itself is multi-staged because for all the condition grades rules of optimum proceeding must be found which, however, have a reciprocal influence.

The problem-setting strongly influences the application of a single or multi-staged strategy so that here, too, a judgement of strategies is impossible. It may be stated, however, that in the first instance one should always try to get along with a simple strategy as multi-staged strategies are expensive in their administration and thus increase the management costs which again might absorb the advantage of their application.

2.24 The Reciprocal Dependence of Aggregates

If one speaks of the dependence of aggregates or machines, a distinction must be made between:

a) the statistical dependence
b) economic dependence

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[1] compare e.g. Kolesar P., Minimum Cost Replacement under Markovian Deterioration, Management Science 12 (1966), pp. 694

a) The statistical technical or stochastic dependence of aggregates proves its mutual technical and complex linkage by the injurious effect of a failure of a machine or of a machine part on the operating efficiency of another aggregate or aggregate part. As then the failure distributions of both aggregates are statistically dependent, these interdependencies must be considered when determining the strategies of such aggregates or rather when choosing the maintenance unit. The problem may be simplified by choosing the total complex of such dependent parts as the maintenance unit.[1]

b) The economic dependence must be strictly discerned from the above mentioned paragraph. It is limited to those cases proving to have a cheaper maintenance of a part set as a whole, than a separate maintenance of parts belonging to this set.[2] This happens if repair costs in times of refurnish are relatively high and it would pay to carryout maintenance by exchanging or repairing a single part together with other parts in order to prevent higher downtime costs.[3]

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[1] This thought underlines the more recent and growing tendency towards the exchange of whole construction groups of machine parts (e.g. exchange engine at automobile repair) which more and more substitutes the repair of single parts. Hereby the repair of the failed part and all other affected parts can be brought to a degree of "as good as new" as all damages can be done away calmly.

[2] see McCall J.J., page 501

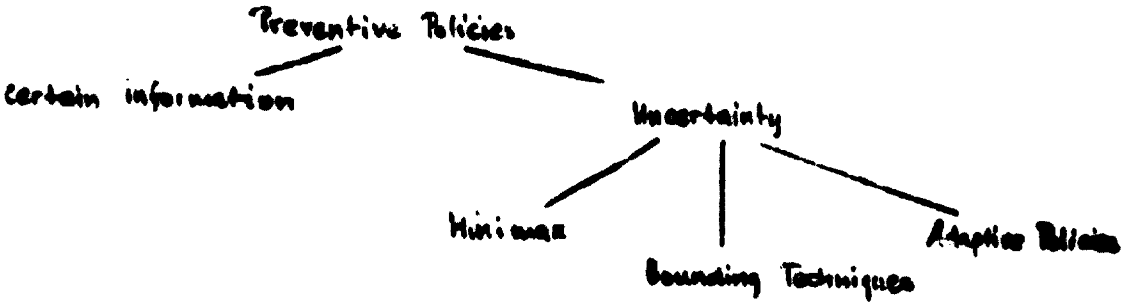
[3] Typical examples are general overhauls of conveyor belts, chemical plants etc.

With the increasing reciprocal dependence of machines it will be necessary to consider whether the experienced downtime of a machine or another preventive action does advise the preventive maintenance of other machines in order to avoid further downtimes or even failures. Here one speaks of opportunistic strategies in opposition to simple strategies. An important problem must here be considered. It is not at all easy to determine such "opportunistic" parts. A cost optimum exists here, but due to the many possibilities of combinations with several machines an attainable calculation would be very costly.

Only a particular case can determine the application of an opportunistic or a simple strategy. Opportunistic strategies are very different. It is hard to find such a normed or typical strategy. Consequently the further proceeding has to be determined by a simple cost comparison of optimum strategies of both cases.

2.25 The Reliability of Information on the Failure Distribution

Thus far we supposed that the failure distribution was known. Only few practical cases submit this. Reality provides very few dates necessary to generate the failure distribution. Correspondingly various strategies have been developed in literature which, according to the degree of uncertainty (i.e. according to the value of existing dates) shall guarantee optimum ways of proceedings. A more precise inspection of these strategies and models at uncertainty shows, however, that in a strict sense no new kinds of strategies are revealed here rather than methods of calculation of how to obtain estimation values for the failure distributions from unreliable information. Of course these proceedings are usually so closely connected with the applied strategies that we prefer to only touch the proceedings here briefly, while the comments together with the corresponding models will be added in a later chapter. 1) If one wishes to agree with the concept given in literature, the result will be the structure of P. 5.



P. 5:

Division of strategies according to degree of reliability of information on failure distribution.

The following is a brief characterization of the processes:

a) Minimax Strategies
It attempts to minimize the expected maximum costs by proposing any strategy. As there is no report on ex-

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1) see paragraph 2.51

periences concerning the failure distribution, we come to the trivial conclusion to do nothing in the case of reparation policies, i.e. to only repair failures. This strategy has significance only with problems of readiness when seeking the optimum inspection strategy in order to prevent failed parts from blocking the pare-stock thus causing unnecessary expenses.

b) Bounding Techniques

Based on spot-checks of failure moments (sporadic measurements) this proceeding endeavours to find limits for the failure distribution as the kind of distribution is unknown. Estimated values for the expected value and extent of scatter of such distributions are formed from measurement results of the spot-check and by means of laws of statistics, evaluations of the upper and lower bounds of failure distribution are proposed. Very evidently the proceeding only aims at a development of the failure distribution based on existing dates.

c) Adaptive Strategies

Starting from the kind of failure distribution (provided that it is known) the parameters are estimated from few values. As new dates and experiences can be collected in the course of machine application, it is obvious to immediately use every date for the improvement of the parameters thus very quickly achieving an adaption of the original roughly estimated parameters to the values o the actual distribution. This proceeding guarantees the best success at uncertainty of information because it continually works out available informations thus reflecting the actual dates and conditions with low expenses-better than every estimation.

2.3 The Models in Particular

It has already been mentioned that the particular strategies are strongly interwoven among themselves. Many authors have forced developments, compared strategies and unrolled entire maintenance models with built-in and often hardly separable strategies. As the particular criteria are often all or sometimes only separately applicable to the strategies, we here attempt to present these models of literature in a simplified total structure 1) in order to define the actual position in the field of strategy research.

2.31 The Cost Models

The most suitable division criterion is given by the objective function. Minimum costs are distinguished so clearly from maximum reliability that a covering

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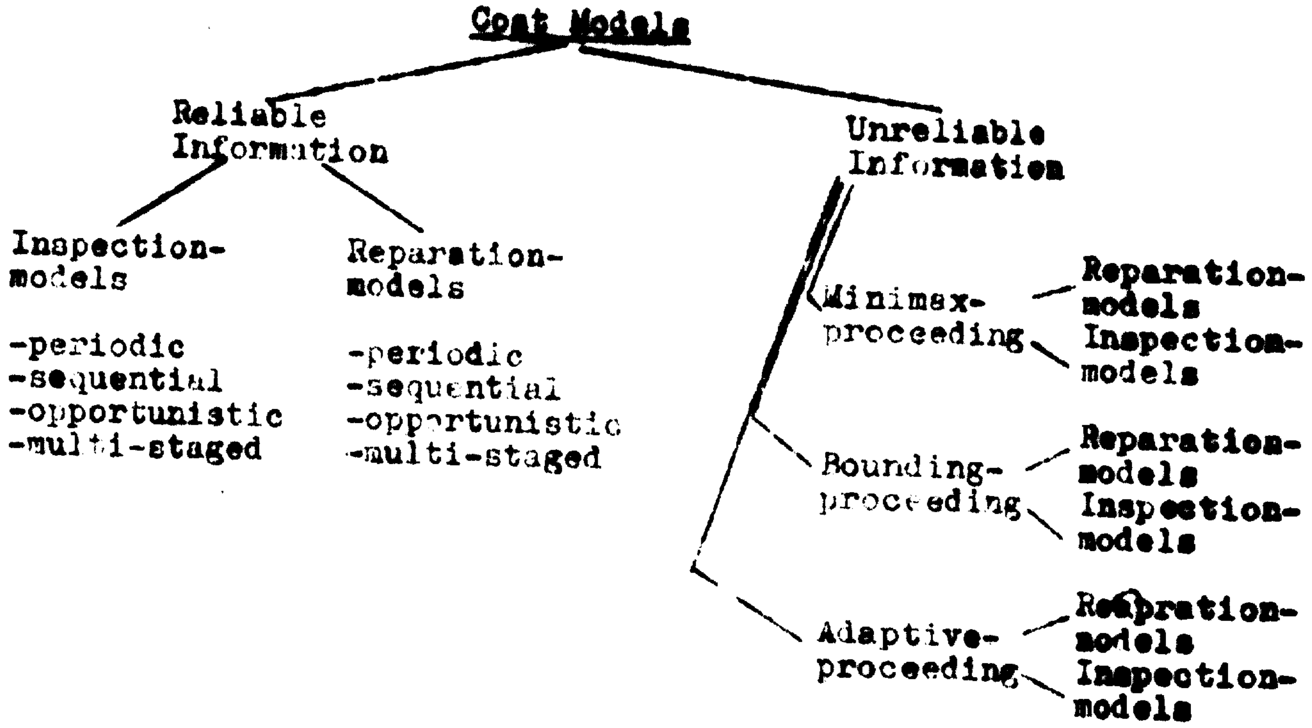
1) Logically only the essential and fundamental models of maintenance strategies can be discussed here. Many application oriented strategies which often developed from slight changes of these basical strategies are not mentioned here, unless by data of literature.

of the problems will not be achieved. The reliability models, however, also deal with costs but there these costs are independent variables or dates. The costs here are dependent variables and objectives in regard to their minimization.

Although a certain inconsequence cannot be avoided, the division pattern of P.6 is to be applied to these cost models. It shows a compromise between the total number of possibilities of all criteria and the merely incomplete existence of strategies touching these criteria.



P.6: Division of Cost Models

2.311 Cost Models at Reliable Information on Failure Distribution

2.3111 Reparation Models

In the case of repair strategies there is a difference above all between preventive reparation and reparation at failure. A failure machine will of course be repaired as quick as possible and according to the organized maintenance (that is a question of availability of personnel and equipment). As we shall realize later it is the size of the operations here which is of importance and not the moment. In this connexion the concept "preventive repair" is not to be applied only to reparation processes. The action comprises maintenance procedures as well as replacements of parts. Here the problem is determined once by optimum planning of moments and twice also by the size of actions of course.

2.31111 Periodic Strategies

Periodic strategies are found very often. A great deal of models could be mentioned here. The strategy which intends a preventive measure at fixed moments, thereby removing failures appearing in the mean time, is the simplest strategy and therefore particularly suitable for practical objectives of application, above all with workshops using simple machines. Some typical examples shall here be quoted from rich sources of literature. 1)

a) The Cox Model with Exact Periods of Time

A unit is repaired in constant periods t_b, 2 t_B, ... independent of the duration of service in this time. Should it fail during the period, it will also be repaired. The average costs C_b are calculated per time unit.

$$C_b = \frac{c_p + c_a H_0(t_b)}{t_b} \quad \text{—} \qquad (II.6)$$

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1) see Barlow R.E., Proschan F., page 63ff., Brender D.M., The Statistical Dynamics of Preventive Replacement, WESCON Convention Record 1959, Cox D.R., Smith W.L., On the Superposition of Renewal Processes, Biometrica 40 (1953) page 1ff., Kamins M., Determining Checkout Intervals for Systems to Random Failures, Rand Corp.1960, RM-2578, McCall J.J., Solution of a Simple Overhaul Model, Rand Corp. 1962, RM-2989 PR., McCall J.J., Maintenance Policies...., page 493ff., Morse P.M., Queues, Inventories and Maintenance, New York 1958, Savage F.R., Cycling, Naval Research Logistics Quarterly 3 (1956) page 163ff., Weller E.L., Bradley C.E., A Model for Scheduling Maintenance Utilizing Measures of Equipment Performance, ARINC Corp. Washington 1959 No.8, White D.J., Optimum Revision Periods International Journal of Production Research 1 (1961) page 44ff. These data are by no means complete as the amount of such models is incalculably big.

C_p respectively C_a represent the costs per planned or else per failure dependent reparation. H_o (t_b) is the exspected amount of failures in the interval 0.......t_b and is termed " Renewal function". This function is given by a multi - staged extremely complicated integral as function of t_b and is calculated from the failure distribution of the unit.

The objective of the model is to define an optimum period t_{popt} which is derived from $dC_b/dt_b=0$.

b) The Cox 1) Model with Running-Time Periods

An aggregate is always repaired at the moment it fails or if since the last reparation (immaterial whether prevention or failure) a certain operation time tc has passed without a failure. The mean costs per time unit which are to be minimized are given from

$$C_c = \frac{c_p - (c_p - c_a)\,F(t_c)}{\int_0^{t_c} [1 - F(t)]\,dt} \qquad (\text{II.7})$$

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1) compare Cox R., Renewal Theory, London - New York 1961

with $F(t)$ representing the failure distribution of the aggregate. The optimum period t_c may be derived from $dC_c / dt_c = 0$.

c) The Model of Barlow and Hunter [1].

By briefly applying the same strategies of constant running-time periods like in paragraph b) this model shows that the optimum period t_o justifies the division

$$q\ (to)\int_{o}^{to}\Big[1 - F\ (t)\Big]\,dt - F\ (to) = Cp/(Ca-Cp)$$

(II.8)

$q(to)$ is the degree of failure of the distribution; Ca respectively Cp are the reparation costs at failure or at prevention. This result corresponds with that of Cox even though it was first found by using a different time function, namely the determination of maximum availability $Eff_{T \to \infty}$ (compare equation II.5). Therefore this model is also useful for reliability inspections and is thus superior to the model of Cox.

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[1] see Barlow R., Hunter L., Optimum Preventive Maintenance Policies, Operations Research 8 (1960), page 90 ff.

d) The Cox Model with Idle Times of the Machine

In model a) it may occur that a part which has just been replaced after failure and which is still new will again be replaced due to consideration of a preventive reparation which is to consist of a replacement of parts in our case. In such cases it may be of advantage not to repair the machine at breakdown, if a preventive action will be performed soon. [1] Thus the part will be replaced at moments t_b, $2\ t_b$........ Should it fail within the r - period in an interval t_d before the termination of this period, that is in the interval $r\ t_b - t_d$ to $r\ t_b$, the part will not be replaced. The mean costs may here be determined as:

$$C_d = \frac{1}{t_b}\left\{c_p + c_a H_0(t_b - t_d) + \int_0^{t_d} (c_i' + c_i'' t)\, h_0(t_b - t)\left[1 - F(t)\right] dt\right\} \qquad (\text{II}.9)$$

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[1] When closing transistor tubes consisting of two glass - tubes a melting process is applied in a machine with 20 parallel incandescent spirals. Should a spiral fail, it will be replaced only, if there will be no preventive replacement of all spirals in the near future, because otherwise a higher charge of the other spirals is caused. If a prevention is planned within a short time, however, the process will be continued with 19 spirals in order to prevent unnecessary downtime costs, material costs and times of refurnish.

Hereby C_c respectively C_i is the share of the fixed or variable costs for the failure period of length t, $h_o (t_b - t)$ is the coefficient of the renewal function $H_o (t_b - t)$ according to t at retained t_b. Equation (II.9) shows at a certain value t_b an optimum value t_d from $dC_d/dt_d=0$. If one realizes the procedure from model a) and model b) for various values t_b, it is possible to obtain the best combination (t_b, t_d).

c) Other Models

Some other models are still to be mentioned here which treat the touching sectors of periodic strategies. To begin with we refer to another model of Cox who tries to make use of the wear of parts for their replacement criterion. This proceeding, however, is unreal, because it might be very difficult in practice to estimate probabilities describing the change-over of the condition "good" to another condition. Only few cases allow experiments on account of which such probabilities may be fundamentally defined. At the same time Terborgh, Rifas and Eisen / Leibowitz developed models optimizing the renewal of entire aggregates depending on the appearing maintenance costs and other costs (Return on Investment etc.) Such models are therefore of mere secondary interest, because the replacement of entire aggregate is less decided by view-points of replacement theory than by those of investment theory.

2.311 Sequential Reparation Strategies

In practice and literature sequential maintenance strategies have shown little significance. In relation to the periodic strategy it requires much administration expenses. Barlow and Froschan worked out a comparison of these strategies. Although they established that the sequential strategy es superior to the periodic strategy with regard to final durability of machines, these improvements would cause maximum 1% of the maintenance costs. The calculation procedures of such a program alone would affect its improvements.

The proceeding of Barlow and Froschan is very complicated and because of its unimportance it shall not be mentioned here.

2.3112 Opportunistic Strategies

Opportunistic strategies are of great importance for multi-furnished aggregates. The intention to decrease downtime costs by saving refurnishing-time is striking inspite of great difficulty of realization and higher material costs. The difficulty consists in the lack of an impartial, actual limit precribing the planned size of the preventively treated parts. The only answer here would be a definition of a limit of the failure-probability beyond which a part shall be treated along with the reparation of another. In a complex aggregate (machine, conveyor-belt) all such endangered parts are now to be processed. The cause requires certain pondering, too. Several possibilities are relevant:

a) Failure of a part

b) Amount of endangered parts

c) Particularly high degree of endangering of parts.

To utilize the failure of one part by preventively maintaining others is very evident, and this is the basis of opportunistic strategies. Of course an optimum defined amount of parts exceeding an optimum defined limit of failure-probability may also lead to downtimes. In this case the costs may be less than in the previous case, because the damage costs caused by this failure are to be estimated very high. The third case is somewhere between these extremes - but it also proves that such da -

mages may often be higher than additional down - times.

Even if the reason for the application of an opportunistic strategy is known, it is necessary to define the optimum proceeding regarding several parts, i.e. the optimum number of the parts to be maintained preventively and the optimum limit of failure possibility. It is very obvious that this procedure is a very complex combinative problem.

Therefore literature only dealt with models of very special assumptions (like the joint maintenance of two parts).

a) A Model with Two Units and Two Conditions

The aggregate is to consist of two machines 1 and 2, with the possible conditions "good" and "failed". A failed unit is repaired. Failures of each machine cause the breakdown of the specific aggregate. Every machine may be repaired separately. A strategy is pursued which minimizes the expected value

$$E\left(\sum_{0}^{\infty} a^{t} \cdot \gamma_t\right) \; ; \quad 0 < a < 1 \qquad \text{(II.10)}$$

whereby

$$\gamma_t (C_1, C_2, C_{12}, C_1+C_p, C_2+C_p \text{ or } C_{12}+C_p) \qquad \text{(II.11)}$$

represents a contingent value which can take up the values in equation (II.11) at moment t. Here C_1, C_2 or C_{12} are the costs of the preventive actions for machines 1, 2 or for a joint prevention, and C_p are the costs arising on account of the failure of a machine. The anticipation-value in equation (II.10) then gives the expected dis - counted costs at the actual moment. The moments t depend on the failure distribution of the machine. The minimization of E from equation (II.10) is solvable in two cases:

a_1) If one of the failure rates e.g. r_2 is constant, the machine 2 will only be re - paired at failure.[1] Thus a strategy has to be developed only for machine 1. It can be shown that the following strategies are optimum here:[2]

- if $t < n$, repair machine 1 at failure
- if $n \leq t < N$, repair machine 1 at failure and at failure of machine 2
- if $N \leq t$, repair machine 1 without delay - preventively.

This strategy has value only if $C_1 + C_2 \quad C_{12}$, at border-line case $C_1 + C_{12} = C_{12}$ is $n = N$, i.e. the result is a periodic strategy. The parameters n,N are non-negative whole numbers (whereby $n \leq N$), which are obtained by mini - misation of equation (II.10) as E represents

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1) see paragraph 2.1

2) see McCall J.J., page 493 ff.

$E = f_1 (n, N, r_1, r_2)$. This procedure of calculation is rather spaceous and will therefore be skipped.

a_2) If the failure costs are given with $C_p = 0$, the problem is also solvable with r_1; r_2 = const. 1) Although no failure costs are saveable on account of prevention, it will pay here to replace both machines together in order to prevent refurnish costs, because $C_1 + C_2 > C_{12}$. The following strategy proves to be optimum:

- if 1 fails, it will only be repaired, if the age of 2 is $t_2 < n_2$, and both, if the age is $t_2 \geq n_2$.
- The procedure is analogous at failure of machine 2, whereby t_1 is compared with n_1.

The calculation of n_1 and n_2 is again derived from equation (II.10) the value again being $E = f_2 (n_1, n_2, r_1, r_2)$.

An expansion of the model with M machines at constant failure rate and 1 machine with increasing failure rate has been developed by Jorgenson and Radner. 2) Here a strategy is formed with M + 1 parameters which are calculated by means of dynamic programming. This model,

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1) see Noonan G., Optimum Preventive Maintenance Policies when Immediate Detection of Failure is Uncertain,Operations Research 10(1962) - page 70 ff.

2) Radner R., Jorgenson D.W., Opportunistic Replacement of a Single Part in the Presence of Several Monitored Parts, Management Science 10(1963) - page 70 ff.

however, is very costly already.

b) <u>The Reparation of Whole Machine-Groups</u>

If the failure rates of several machine-parts are all known, and if the costs of individual and groupwise reparations of such machines are calculable, a model of Rifas may be applied. This model was developed for the case of reparation consisting of a replacement of parts. The strategy advises to change all parts separately, should they fail within a certain period, and to preventively replace all parts at the end of a period. This strategy is based on the opinion that group replacement may avoid refurnish costs. An optimum interval is calculated. The given costs at the end of interim periods determine the necessity of a group replacement. In this way the replacement interval is built up stepwise. The criterion consists of the mean costs per time unit. It is to be

$$X(t)/_t = \left(NC_1 + C_2 \sum_{1}^{t-1} Xa(i) \right) / t \qquad \text{(II.12)}$$

with C_1 or C_2 costs per part at group replacement or at individual replacement, X_a (i) as the number of anticipated failures in the i - interim period, N as the number of parts and t as the number of the considered interim periods. In the optimum point, i.e. t = to, the difference of the mean costs of the previous interval must be negative while it must be positive to the following interval. i.e.

$$\frac{K(t_0)}{t_0} - \frac{K(t_0-1)}{t_0-1} < 0 < \frac{K(t_0+1)}{t_0+1} - \frac{K(t_0)}{t_0}$$

(II.13)

with equation (II.12) it thus gives

$$C_2 x_a(t_0) > \frac{NC_1 + C_2 \sum_{1}^{t_0-1} x_a(i)}{t_0}$$

(.II.14)

and

$$C_2 x_a(t_0-1) < \frac{NC_1 + C_2 \sum_{1}^{t_0-1} x_a(i)}{t_0-1}$$

(II.15)

If hence the costs of individual replacement during a running period are higher than the average costs according to equation (II.12), the group replacement will be carried out at the end of an interim period. 1) Otherwise the next period will be started without replacement.

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1) e.g. The interim period is to last one week. In the 6th week the costs of individual replacement (i.e. caused by failure) appear to be higher than the average costs during the past 5 weeks. Then group replacement will be carried out at the end of the 6th week.

2.3114 Multi-stage Strategies [1)]

The conception "multi-stage" may be used in different ways. On the one hand an aggregate may pass several stages of quality and for the different degrees of demand in these stages it is of course useful to carry out the replacement with old parts of the pre-stage, [2)] in order to save material costs. On the other hand expensive parts can be replaced less frequently than inexpensive ones as far as opportunistic strategies are concerned. Therefore the strategy itself is to make a multi-staged decision, e.g. testing successively

a) which of the parts are to be preventively maintained according to limit of failure-probability?

b) which of the parts are to be removed because of too high material costs?

This last conception of "multi-stage" shall not be dealt with here. There is no corresponding model in literature either. [3)]

2.3112 Inspection Models

The objective of inspection models is not only the optimum planning of reparation, maintenance or replacement

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1) Naik M.D., Nair K.P.K., Multi-stage Replacement with Finite Duration of Transfer, Operations Research 13(1965)-page 828ff.
2) compare example of tractors on page 21
3) This problem is a typical opportunistic strategy which is to be solved in the special case of practice by simulation.

but above all the determination of the unknown condition of an aggregate by means of inspection. This inspection has to be planned optimum, immaterial of the fact that an aggregate is in operation or held in readiness for a certain moment, as too many inspections cause high costs, while too few inspections entail damages with running aggregates (conveyor-belts without continual control) or depot costs for failed aggregates which are kept in readiness.

An optimum inspection strategy does not only treat inspection itself. It also considers the consequent decisions with regard to reparation. It may by all means be appropriate to inspect recently repaired parts only after a long time, as their immediate failure is very unlikely, and to test them more frequently at increasing age. This already hints at what is determinable in practice or in literature, namely that a sequential strategy has a greater significance for inspections than for reparations.

2.312 Cost Models at Unreliable Information

Unreliable information usually means that there are only few spot-checks concerning a frequently statistic distribution, and dates based on statistic laws of a procedure are totally or partly missing. In our case the unreliability refers to the failure distribution of the concerned aggregates or to their single parts.

Type and parameter must be absolutely known at failure distribution in order to be able to strictly apply them as basis for optimum maintenance strategies.

According to the degree of knowledge of these symptoms, however, several procedures may be applied in order to develop good estimations of the missing criterion or significant strategies. T.7 shows which procedures are to be applied for the relative cases.

failure distribution			procedures
kind	parameter		
	expected value	deviation	
unknown	unknown	unknown	minimax-procedure
constantly rising rate of failure	known	known or unknown	bounding-procedure
known	unknown	unknown	adaptive-procedure

T.7:
Division of procedures for determination of failure distribution according to fields of application.

There are only few such models in literature, as one usually starts from failure distributions which, according to existing experiences, appear appropriate and reliable. (Partly due to other research) In many instances this procedure is more practical than the development of lengthy models, because the minimax- and bounding procedures only allow rough estimations. The adaptive procedure appears to be very promising, because by means of few dates it estimates the parameters of a distribution and improves this continually with dates of practice, also allowing repeated checking of the original assumption on the kind of failure. This procedure will be superior to the usual method of proceeding as it was initially described, because it derives its information from actual dates and continually adjusts them. 1)

2.32 Redundancy Systems and Optimum Redundancy

The most effective way to increase reliability is not preventive maintenance - it is the redundancy control of aggregate parts. The grouping of redundancy controls, however, is duty of the construction and not of the maintenance and has thus little in common with the uphold of value, the actual problem of this analysis. We briefly deal with redundancy models here, because it has some significance for the maintenance whether parts are maintained which are directly engaged in the process of operation or those which are in redundance. The maintenance strategy for redundant aggregates can often restrict itself to firstly testing the size of danger of failure by means of inspection, i.e. how many redundancy parts have already failed. For the future such inspections will not be repeated too often, thereby avoiding downtimes and in the end only actually failed parts will be replaced to decrease material costs. The advantage of such redundant systems is the full utilisation of the material until failure, while prevention wastes possible utilisation of material. The

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1) see Kreß H., a.a.O.

price of redundant systems consists of the additional expenditure space and the costs of additional investment. The reliability is generally higher with redundant systems. If we think of redundancy controls, the question immediately arises how such controls are to be set up, how the reliability is hereby influenced, how the redundancy is to be distributed along with restricting secondary conditions (weight of rockets), whether advantages of redundancy may be combined with those of preventive maintenance and others - in short, the question for an optimum redundancy.

The literature on the calculation of reliability of multiple systems is copious. 1) Beyond that there is a

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1) see Barlow R.E., Proschan F., Hunter C.L., Mathematical Models, Birnbaum Z.W., Esary J.D., Saunders S.C., Multicomponent Systems and Structures and their Reliability, Technometrics 3 (1961) page 55ff.; Esary J.D., Proschan F., Coherent Structures of Non-Identical Components, Technometrics 5 (1963) page 191ff.; Esary J.D., Proschan F., The Reliability of Coherent Structures, in: Wilcox, Mann, Redundancy Techniques for Computing Systems, Washington 1962 page 47ff.; Hees R.N., Meesendonk H.W., Optimum Reliability of Parallel Multicomponent Systems, Operation-Research Quarterly 12 (1961) page 16ff.; Lipp J.P. Topology of Switching Elements v.s. Reliability, IRE Transactions on Reliability and Quality Control, o.J.; Moore E.F., Shannon C.E., Reliable Circuits Using Lee Reliable, Journal of the Franklin Institute 262 page 191ff. (Part 1) and page 281ff. (Part 2); Moskowitz F., McLean, Some Reliability Aspects of System Design, IRE Transaction on Reliability and Quality Control 8 (1956) page 7ff.; Weiss G.H., The Reliability... Walter R.M., Dickinson W.E., Reliability Improvement by the Use of Multiple Element Circuits, IBM Journal of Research and Development 2 (1958) page 142ff.

series of research of optimum redundancy in view of the most diverse optimizing criteria. 1)

III. Future Research Tendencies.

Inspite of the large number of the developed strategies it was established that an isolated research of maintenance is favourable only in few instances. If one considers literature, the boom of maintenance researches has considerally declined. At present one attempts to attribute the assistant function of maintenance because it only serves to uphold the operation condition to the right position in the process of manufacture. Especially aviation industry which requires maintenance on a large scale has realized this necessity and has been a signpost in this development.

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1) see Barlow R.E., Proschan F., Hunter C.L., Moskowitz F., McLean, page 7ff., Weiss G.H., On the Theory...Boer J., Some Mathematical Aspects of Reliability Problems, Statistica Neelandica 18 (1964) page 453ff.; Halperin M., Some Waiting Time Distributions for Redundant Systems, Technometrics 6 (1964) 1, page 27ff.; Gordoa R., Optimum Component Redundancy for Maximum System Reliability, Operations Research 5 (1967), page 229ff.; Flehinger B.J., Reliability Improvement Through Redundancy at Various System Levels, IBM Journal of Research and Development 2 (1958), page 148ff.; Proschan F., Bray T.A., Optimum Redundancy Under Multiple Constraints, Operations Research 13 (1965), page 800ff.; Masatunii S., A Simplified Method of Obtaining Highest System Reliability, Journal of the Inst.of Electrical Comm.Eng. (Japan) 45 (1962), page 144ff.

For the fabrication management it has the following significance:

a) In a workshop with simple machines nothing is won by applying complicated strategies, as the cost assets of improved prevention are again consumed by administration costs. Here the objective of maintenance is to guarantee a most inexpensive completion of the maintenance orders. (With simple strategy) 1)

b) In line production the discovery of a very favourable strategy is certainly advantageous. Being an oppotunistic strategy it is usually of a some-what complex structure. It pays here, however, as one will always have personnel in readiness for completion. (Downtime costs outweigh !)

In both cases, however, research in the field of maintenance will have to deal with the problems of manufacture. A real, totally optimum planning of fabrication-completion will also have to be considered but also vice versa - a maintenance research must also be adjusted to a greater extent to the problems of fabrication. The only and almost independent research on the sector of maintenance can be achieved by developing opportunistic strategies - the optimization of which, however, again requires dates of the manufacture - a development which gradually begins to stand out in the literature of maintenance.

IV. Aspects of Preventive Maintenance in Development Countries

1. Optimum Policies

The problems of development countries differ to some extent from those of highly developed, industrial countries. This also has an influence on the parameters of a preventive maintenance.

The essential cost shares are

- downtime costs
- personnel costs
- material costs

The downtime costs are obtained from the lost covering dues, i.e. the possible turnover minus the variable costs for those products which could have been manufactured during the downtime period.

It is to be expected that the downtime costs in development countries are not as dominant as in highly developed industrial countries, because on the one side the automation with its high, fixed cost-shares does not yet outweigh, and on the other hand the machines are usually not fully utilized, so that the failure period does not carry great weight.

The personnel costs are incomparably lower influencing the preventive strategy to a great extent. Due to low personnel costs and the existence of sufficient labour resources it is possible to interchange whole aggregates and repair them very calmly. This shortens downtime periods, operation procedures are simplified and less skilled workers are required. It also solves the problem of insufficient training of professionals who would have to be put into action very universally in case of emergent reparations, because it is simple to teach plain procedures of aggregate-replacements even to unskilled workers.

The material costs in development countries are usually high, because often the rawmaterials and semi-finished products are not available and have to be imported. The reparation of failed parts therefore plays a more important part than in industrial countries, where after wear such parts are simply replaced by new parts, because it would be too costly to repair these parts on account of the high personnel costs.

All these reasons speak in favour of a periodic replacement strategy, repairing the failed parts afterwards. This strategy is of simple application and causes the least costs, especially for medium size and small enterprises where the costs of administrative execution have a relatively big influence. Apart from this there will of course be cases where one of the other strategies - opportunistic or multi-staged or readiness strategies - must be applied. These strategies are very complicated, however, and too expensive for medium size and small companies.

2. Spare Part Problems

The question of stocking of spare parts is important for the maintenance. In many cases one would have to consider, whether it pays to keep up a totally secure spare part depot because of the high depot costs. We do not have this problem, however, in development countries. Here the time of delivery for imported spare parts is so long, that a sufficient stocking must be guaranteed in order to satisfy the demand for spare parts at all times. On the other hand the stocking may be reduced, as the old parts will mostly be reused after reparation.

Thus it is commendable to install at least one reserve equipment beside the basic equipment, and to provide for another location where the failed parts may be repaired after their removal.
The maintenance problem of the spare part depot is not generally solvable. It will strongly depend on the conditioning factors of the specific country, on the regional conditions with regard to the supply of raw-material, on the industry of semi-finished products and on the special economic conditions and Government Regulations on import of spare parts.

V. Describtion of Concrete Schedules in Specific Industries

1. Preventive Maintenance in Aviation Industry 1)

Preface to Maintenance Systems of Aircraft Mechanisms

The necessity of preventive maintenance of aircraft in airtransport is based on the gravitation of absolute security, underlined by the demand for "safety first". The maintenance system - we wish to apply this general

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1) Gräger H., EROS (Engine Repair and Overhaul Simulation) - ein Planungsinstrument für Triebwerkinstandhaltungswerkstätten von Luftverkehrsgesellschaften - in Bussmann K.F., Mertens P.(ed.) Operations Research und Datenverarbeitung bei der Instandhaltungsplanung, Stuttgart 1968 - pp.137-154

conception for the sum of all necessary measures executed to maintain operating conditions of the air - craft - will usually be carried out by the airline company in 3 different levels.

Level 1 : Controls carried out on the way to destination (e.g.: Start control before every take-off)

Level 2 : Smaller maintenance measures executed in certain periodic intervals (e.g.: aircraft basic control after 250 flight hrs.)

Level 3 : Maintenance measures carried out regularly after longer periodic intervals in the technical basis of the airline company (e.g.: Overhaul of engine after 4.000 flight hrs.or overhaul of cells after 5.000 flight hrs.)

These maintenance measures are partly or totally carried out by the airline company itself.
The mechanic workshops in the technical basis have to execute the maintenance works of level 2 and 3 for the mechanism and mechanism systems.
It is their duty to supply aircraft operation with ready mechanisms at any time.
We wish to briefly deal with their function and their problems.

1.1 Objectives of a Simulative Circulation of Mechanism.

The objectives which are attainable by means of a circulation of the mechanism are multi-levelled and shall be briefly patterned as follows:

a) Time-planning - long range and medium range - for the mechanic workshops by pre-defining planned and unplanned replacements of mechanisms.

b) Prediction of the required man-hour capacity and operation capital derived from the pre-defined number of replacements.

c) Determination of expected need of material.

d) Prediction of capacity reserves for the maintenance of mechanisms of foreign companies or failure capacities by prediction of removals and workshop supplies.

e) Listing the development of the stock of spare mechanisms.

f) Quantitative determination of the risk level when no spare engine is ready for x-days at given initial value.

g) Listing of consequences at change of parameters, (e.g. reliability of mechanism or rate of passage through workshop).

1.2 Maintenance Completion

Maintenance uses a strictly periodic strategy in each of the mentioned levels which is supplemented by actions at unpredictable moments of failures of machine parts.

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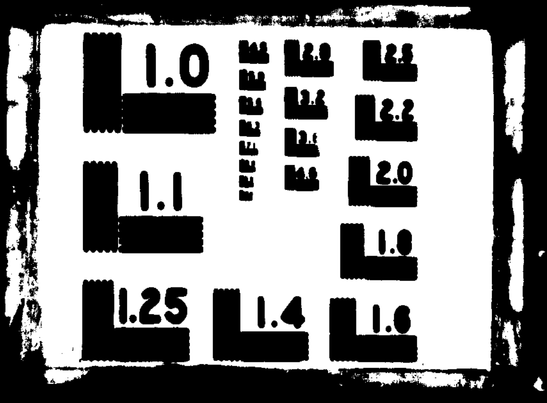

The maintenance system is simulated in order to determine the optimum parameters of the maintenance strategy.

A certain key-date is chosen as beginning term of the simulation period. Starting from this moment as a basis of all static parameters, a continous industry calender is kept. Every day all incidents of the total system of circulation will be acted sequentially, just as they might occur in reality under the co-operation of all factors of influence. The show-up of an incident in a program-branch may cause a chain of reactions in another branch. As the contingent-dependent incidents are determined by means of the Monte-Carlo-Method, the results of each test-run contingently differ, even at equal initial parameters. Thus several simulation-runs are executed and concentrated in a final program into arithmetical mean values in order to obtain the most probable value.

The result of simulation provides the most important record of a short-ranged workshop scheduling with weekly and monthly concentrated workshop inputs and outputs, as well as workshop and reserve-stock of engines.

2. Preventive Replacement of Aggregates with the Manufacture of Transistors. [1]

A machine, welding the glass coat of transistors, has a particularly failure inclined single part; a heating

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[1] Schwarz F., Die Ermittlung der optimalen Reparatur - oder Ersatzstrategie mit Hilfe der Simulation, Thesis 1967 - TH - München

spiral which has multi-parallel arrangement. Should one spiral fail, we have the following maintenance alternatives:

- replacement of all spirals
- replacement of the failed spiral

The alternatives are only determinable by the examination of the arising costs.

The following strategies have been examined in detail:

One strategy deals with the single reparation or replacement of the respective part at failure; the other strategy proposes the collective reparation or replacement of equal single parts after a certain operation interval which is shorter than the expected durability, or at failure, - according to necessity. By variation of the operation interval the optimum cost-moment of reparation or replacement may be established. The situation of total cost minimum will shift according to the ratio of costs arising firstly from the single reparation or replacement of parts and secondly from total reparation or total replacement.

As the single heating spirals consist of absolutely equal parts, we assume they are of equal durability.

Furthermore the maintenance strategy was varied to that point that single parts which, due to early contingent failure, had to be repaired or replaced just before a total replacement and were not considered again at actual total replacement or total reparation.

This might avoid possible additional costs.

Both alternatives were simulated, whereby the model was constructed in such a way that it could be used for all statistic distributions for the failure periods of the heating spirals.
It was found that the strategy of collective replacement was by all means the superior one. An additional examination [1] proved that the cost-optimum did not occur with strict time-periods (e.g. replacement after 2 weeks) but with running time-periods (i.e.replacement after 10 hrs.of continuous running time)

In the discussed case all heating spirals are thus replaced after having run through a certain operation time, or single spirals are replaced at failure, if this does not occur just before total replacement.

5. Maintenance Scheduling of Workshops

For the optimum maintenance of workshop machines the following model was developed:

By means of preventive actions and completion of the maintenance orders with the aid of priority rules a cost-optimum is to be obtained. The variable values here are the parameters of the strategy which determine the processing series of the orders, the kind of rule and the number of workers.

5.1 Supposition of Models

The examinations were based on the following

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1) Pelz P., Ein Vergleich von präventiven Instandhaltungsstrategien, in Bussmann K.F., Mertens P., page 51-63

supposition:

3.11 The Machine Park

The dependency of the machines in the working process is described by the organisation-type of the workshop fabrication which means that the machines are technically as well as economically independent of each other. There is no grouping of simular machines for the purpose of simultaneous maintenance. In practice the separate machines have only few parts which may really cause a failure. As, on the other hand, the failure distribution as a pure durability distribution is only determinable with machine parts, and moreover a precise calculation of material costs and reparation time is possible only for single parts, those parts were chosen for a maintenance unit which might be determinant for the failure of a machine.

The total utilization time of the machines is without significance, as it shall be assumed that at final shut down of a machine it will be replaced by a simular new unit.

3.12 Maintenance Strategy

A periodic preventive strategy is chosen according to operation hours, and shall be applied to the failure-inclined independent single parts or part groups of a machine.

When applying preventive actions the machines are only shut down, if workers are available for the execution. Filed into the already existing orders of the waiting queue the preventive action is planned, however, for the scheduled moment.

Should the machine fail, however, its downtime is inevitable, and it must wait for maintenance according to its scheduling into the waiting queue.

If there have been maintenance measures for several parts of a specific machine during an operation time, the machine will be classified according to the highest priority of all its parts. All existing measures are considered at the service of maintenance orders.

3.13 Preparation of Maintenance

The time for technical management required for the planning of failures and preventive actions, and the listing of the individual maintenance orders is not considered in the model. Neither is the time of preparation of the works at change of orders.

Furthermore it is assumed that there are no time losses due to insufficient material and tool preparations.

5.14 Priority Rules

The model assists to investigate the effects of priority rules on the maintenance completion planning. 10 rules were given for the model which were developed from rules of the fabrication completion planning with consideration of particular data during maintenance.

5.15 The Maintenance Personnel

The maintenance personnel consists of universal workers with an equal degree of performance. This causes only a waiting queue of orders from which ready workers obtain new work. The necessary working course should be altogether carried out by the same worker.

5.16 Duration of Works

The duration of single maintenance actions is presupposed as known - it is always of similar length with preventive actions for the single part - it is different, however, for the various parts. The time consumption for the settlement of a failure is derived from the time for the preventive maintenance of the failed part plus an inspection time which varies as a machine constance for the single machines according to technical complexity.

3.17 Optimal Costing

Material costs of single parts, costs of maintenance organization and downtime costs are considered. Hereby it is assumed, that the costs of maintenance organization are proportional to the number of maintenance workers. The downtime costs reveal the upset sensitivity of the fabrication process.

3.2 Optimization Criterion of Minimum Total Costs

The quality of an organization system of maintenance works for fabrication aggregates can be judged best from the arising costs. The costs consist of:

a) Personnel costs for the execution of the maintenance works,

b) the material costs of maintenance,

c) the lost profit and the covering share of the fixed production costs for the production fall-out during the period of maintenance (downtime costs),

d) the costs for the solitary set up of an organization system and

e) the running management costs for the planning, guidance and supervision of the maintenance.

The total sum of these cost shares should give a minimum for an optimal maintenance organisation. For the planning of the organization only the quantitative cost shares - personnel costs, material costs and downtime costs - can be used in one model. The cost shares for the set up and continuous control of the system must be considered in the basic concept of the organization according to quality.

It may easily be estimated that a minimum of total costs arises, because the downtime costs and the working costs have a contra - dependency on the number of maintenance workers.

The material costs on the other hand are largely neutral - they only grow with increasing prevention thereby decreasing the downtime costs which has, however, only secondary importance, because by means of repeated preventive maintenances the inspection times of the machine fall away in fact, though this effect is weakened by the frequency of downtimes.

5.9 Results of Investigations

The result of investigations consists of the optimum determination - i.e. of the cost minimum - of the following system-parameters:

a) Type of priority rule for completion planning of maintenance.

b) Preventive period for time planning of maintenance.

c) Number of maintenance workers.

And the calculation of minimum total costs of maintenance.

The underlieing data very precisely proved that a cost minimum can be attained only, if preventive measures are applied. Considering all costs - even the costs of maintenance execution - that periodic strategy is most appropriate of which the period is only slightly below the average failure time of the single parts. The best wind up of orders is obtained, if the machines with the highest downtime costs are treated first.

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