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Abstract

The maintenance concept of a technical system is the set of rules prescribing what maintenance is required and how demand for it is activated. The requirements to be met by a maintenance concept are specified. A framework for the designing of maintenance concepts is presented.

1. Introduction

Essentially, the maintenance concept of a technical system is the set of directives prescribing maintenance to be carried out. For a long time, the concept was not considered to be a problem requiring attention. The consequences of failure were relatively slight and the demand for maintenance was activated purely by breakdown. However, the introduction of large, complex systems in production and refined production-control, the growing awareness of the natural environment and increasing labour costs have made the improvement of maintenance control imperative. Improvement of control presupposes the introduction of more sophisticated maintenance concepts. In the field of operations research, maintenance models mainly aim at optimal decisions on activating maintenance demand ([1,2]). The applicability of these models is rather disappointing. More practical approaches to designing maintenance concepts are scarce. Geraerds [3], presenting a general survey of maintenance theory, makes several fundamental remarks. Kelly [4] advocates a rather pragmatic approach, in which maintenance plan and maintenance concept are not clearly distinguished. Finally, Nowlan and Heap [5] discuss a method for designing "reliability-centered maintenance programmes", which come down to qualitative maintenance concepts.

The present paper concentrates on an "satisficing approach" [6] to the designing of maintenance concepts. The maintenance concept is discussed in Section 2. Section 3 deals with the specification of the requirements to be met by a concept. A framework for designing maintenance concepts is presented in Section 4. Finally, in Section 5, some concluding remarks are made.

2. Maintenance concept

The primary process in an industrial organization is production in which the primary production input (material, energy, manpower) is transformed into the primary production output (the desired product). This transformation process makes use of technical systems. A *technical system* is a collection of physical elements fulfilling a specifiable function. The *state* of a technical system is the physical ability considered relevant to fulfilment of its function. External causes, ageing and use impair its state, inevitably leading to a secondary production output; maintenance demand. On being carried out, this leads to a secondary production input; that is potential production capacity. *Maintenance* (Fig. 1) is the total of activities required to retain the systems in, or restore them to the state necessary for fulfilment of the production function. In this definition, "retaining in" corresponds to *preventive maintenance*, "restoring to" with *corrective*
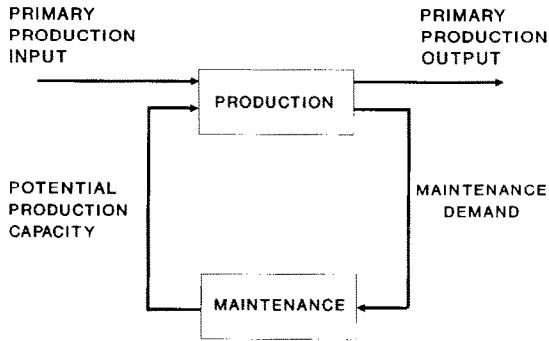
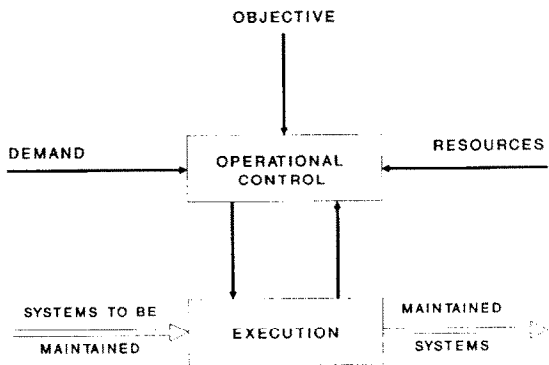Fig. 1. The relationship between production and maintenance.

Fig. 2. Operational control.

maintenance. Failure denotes the transition of a technical system to the state in which it is inadequate for fulfilment of its function.

Operational maintenance control (Fig. 2) refers essentially to timing the allocation of maintenance resources to the maintenance operations which require them. The maintenance objective and the maintenance resources are considered to be decided upon on a higher level of control. Maintenance demand specifies what maintenance should be carried out and when. It is the total of maintenance demand for the individual technical systems. Information on the future demand of an individual technical system is to be had from the production plan, which specifies the future use of the system, and from the maintenance concept, which is the set of maintenance rules on what maintenance operations are to be carried out for the system and how the demand for these operations is activated.

3. Requirements

The relationship between maintenance concept, demand and control implies that the maintenance concept should first of all contribute to attainment of the maintenance objective, which is twofold. On the one hand, maintenance costs have to be acceptable as they add to the cost of the products. In relation to the maintenance concept this aspect requires maintenance rules to be both effective and efficient. On the other hand, maintenance has to comply with constraints imposed by the primary process and the environment of the organization. This aspect of the maintenance concept means laying down requirements ensuring the safety of operation of the technical system and the continuity of the production process. Apart from the objective, requirements originate from maintenance control which has to deal with demand as implied by the maintenance concept.

3.1 Effectivity

Effectivity of a maintenance rule is determined by its correctness at the time (potential effectivity) and its physical correctness (technical effectivity).

Potential effectivity of a maintenance rule in view of a failure concerns the relationship between failure behaviour and maintenance initiation. Three types of maintenance initiation have to be distinguished:
- failure-based maintenance,
- use-based maintenance, and
- condition-based maintenance.

Failure-based maintenance prescribes initiation of maintenance in the event of failure. Failure based maintenance is always potentially effective.

Use-based maintenance prescribes maintenance initiation on expiration of a specific period of use. It is based on a statistical model of forecasting failures in which the information about failure behaviour is limited to the duration of failure-free operative periods. Use-based maintenance is potentially effective if it results in lowering the *failure rate*, the probability of the failure occurring within a specified interval of
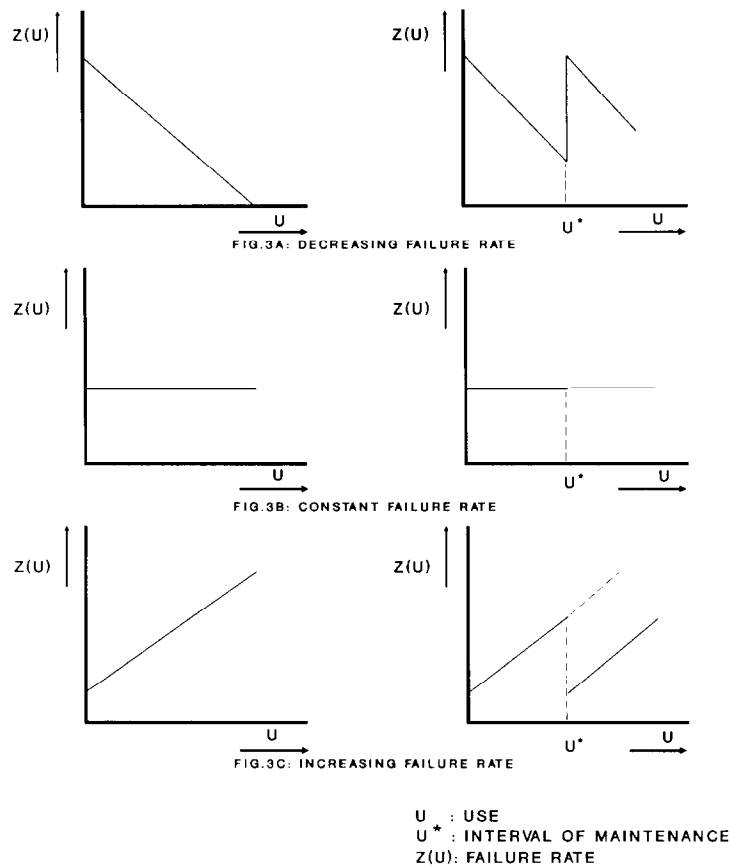
Fig. 3. The effect of use-based maintenance.

use, given that it did not occur before the start of that interval. Use-based maintenance where the failure rate is decreasing (Fig. 3a) would result in increasing the rate. When the failure rate is constant (Fig. 3b), it does not alter the rate and it is only when the failure rate is increasing (Fig. 3c),that it results in lowering the rate. Hence, use-based maintenance is potentially effective if the failure rate increases.

Condition-based maintenance prescribes maintenance initiation on attaining of a specified condition. It is based on a deterministic model of predicting individual failures in which information about failure behaviour includes the physical process underlying failure during failure-free periods. The fundamental model (Fig. 4) allows individual prediction of those failures that result from underlying physical processes exhibiting properties that change from an *initial value*, the "as good as new" value, to a *fatal value*,

at which failure occurs. A *prognostic characteristic* is a physical property which gradually changes from initial to fatal value. Condition-based maintenance is potentially effective if a measurable prognostic characteristic is known.

Technical effectivity of a maintenance rule in view of a failure pertains to the physical result of the maintenance operation to be carried out. Two types of maintenance operations have to be distinguished: inspection and repair. *Inspection* consists of assessing the value of a prognostic characteristic and comparing the assessed value with a predetermined norm. *Repair* consists of altering the existing state of the technical system to the original one.

Failure-based maintenance prescribes repair to be initiated by the event of failure. Consequently, determining technically effective repair has to be based on information about the physical outcome of failure. Use-based maintenance
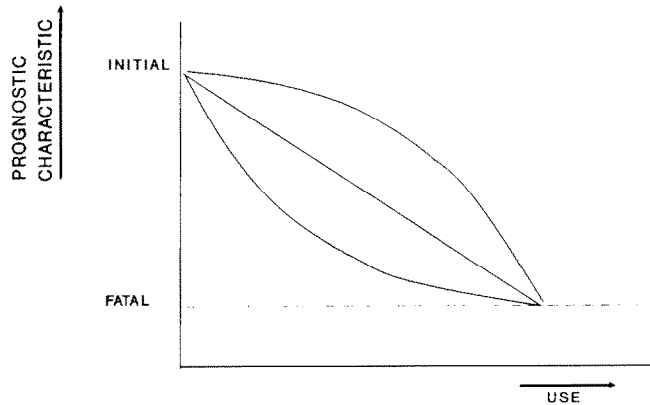
Fig. 4. Endurance curves [3].

3.2 Efficiency

Efficiency of maintenance rules makes it necessary to distinguish between individual efficiency, referring to a maintenance rule in isolation, combinatorial efficiency, taking into account the economic interdependence between rules and final efficiency, dealing with a set of maintenance rules as a whole.

Individual efficiency of a maintenance rule means trading off the ensuing reduction in failure consequences against the cost of maintenance in accordance with that rule.

Failure-based maintenance results in corrective maintenance only. The failure consequences must be accepted. Use- and condition-based maintenance both result in preventive maintenance and in corrective maintenance, in view of the failures that occur in spite of preventive maintenance. The cost involved in use-based maintenance is determined by the length of the interval between repairs: the longer the interval, the lower the cost. The reduction in number of failures also depends on this interval: the longer the interval, the larger the number of failures still occurring and consequently, the less significant the reduction in failures. The same argument can

requires specification of technically effective repair, condition-based maintenance of inspection and, if sufficient knowledge about the physical consequences of degradation is available, of repair.

be applied to the interval of inspection in the case of condition-based maintenance.

Combinatorial efficiency of maintenance rules refers to trading off the benefits accruing from simultaneous execution of individual maintenance operations against increased frequency of demand for some of these operations.

Simultaneous execution of a diversity of maintenance operations results in a reduction in the maintenance effort if these operations have set-ups in common. A *set-up* is an activity to be carried out in order to enable execution of the prescribed maintenance operation. Set-ups are, e.g. disassembly/assembly activities, shutting down/ starting up production and administrative procedures.

Final efficiency of a set of maintenance rules refers to trading off the total maintenance effort against the resulting reduction in failure consequences.

3.3 Safety

Safety of operation of the technical system requires *maintenance regulations*, as to imperative maintenance, to be included in the maintenance concept. These regulations originate, for instance from the government and from insurance companies. Furthermore, safety considerations result in prescribing a specific reliability with regard to functions with hazardous consequences. This requirement defines specific failures to be taken into account in the maintenance concept, limits maintenance initiation to use-based or

condition-based maintenance and ultimately exerts a dominating influence on the determination of maintenance intervals to be prescribed in the maintenance rules concerned.

3.4 Continuity

Continuity of the production process results first of all in a preference for preventive maintenance. Preventive maintenance not only yields a reduction in the number of failures interrupting the production process, but also allows some latitude in the choice of the actual time of carrying out maintenance, so as to solve the maintenance control problem. Furthermore, preventive maintenance should preferably be done during the nonproductive periods in the production pattern. This pattern can already be accounted for in the maintenance concept if the planned nonproductive periods occur periodically. The admissible maintenance intervals are then constrained to integer times the periodicity of the production process.

3.5 Controllability

Controllability of maintenance demand is determined by the regularity and contents of demand. The *regularity* of maintenance demand to a large degree determines the quality of control that can be achieved. Regularity of maintenance demand first of all implies a preference for preventive maintenance because it intentionally leads to a reduction of failures. Regularity of preventive maintenance demand itself refers to activation of maintenance demand and to the capacity required. Periodic and cyclic maintenance have to be distinguished with respect to these aspects. *Periodic maintenance* comprises all the maintenance operations carried out at the same intervals of time. This format requires the intervals in the maintenance concept to be integer times the period. *Cyclic maintenance* consists of specified groups of maintenance operations carried out at equidistant times. After execution of the last specified group, the cycle restarts with the first group. This format requires the intervals in the maintenance concept to be divisors of the cycle. The groups of operations to be carried out are specified in the maintenance concept which

allows requirements to be taken into account in view of the regularity of capacity required by each group.

The *contents* of maintenance demand is constrained by the types of capacities and materials available in the organization operating the technical system.

4. Framework

A framework for the design of maintenance concepts specifies the steps needed to determine a set of maintenance rules that meets the requirements. These requirements can be divided into *elementary requirements* concerning individual maintenance rules, and *composite requirements* concerning the eventual set of maintenance rules as a whole. This distinction results in dividing the design process into (Fig. 5):
• generation of maintenance rules, and
• evaluation of maintenance rules.
Generating maintenance rules aims at determining a set of rules which meets the elementary requirements. *Evaluating maintenance rules* deals with the identification of a set of rules that satisfies the composite requirements and which will form the maintenance concept of the technical system.

The elementary requirements essentially refer to potential and technical effectivity, to elemen-
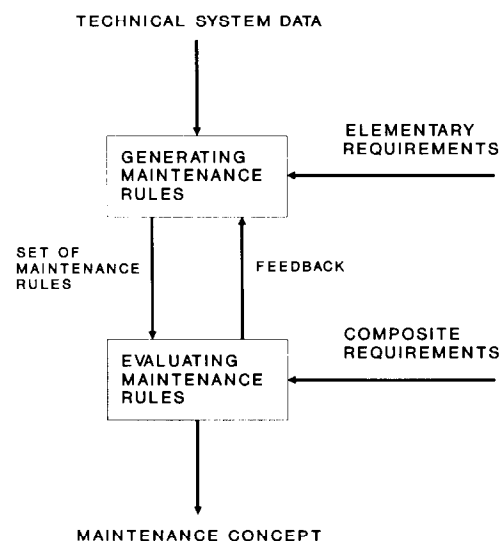

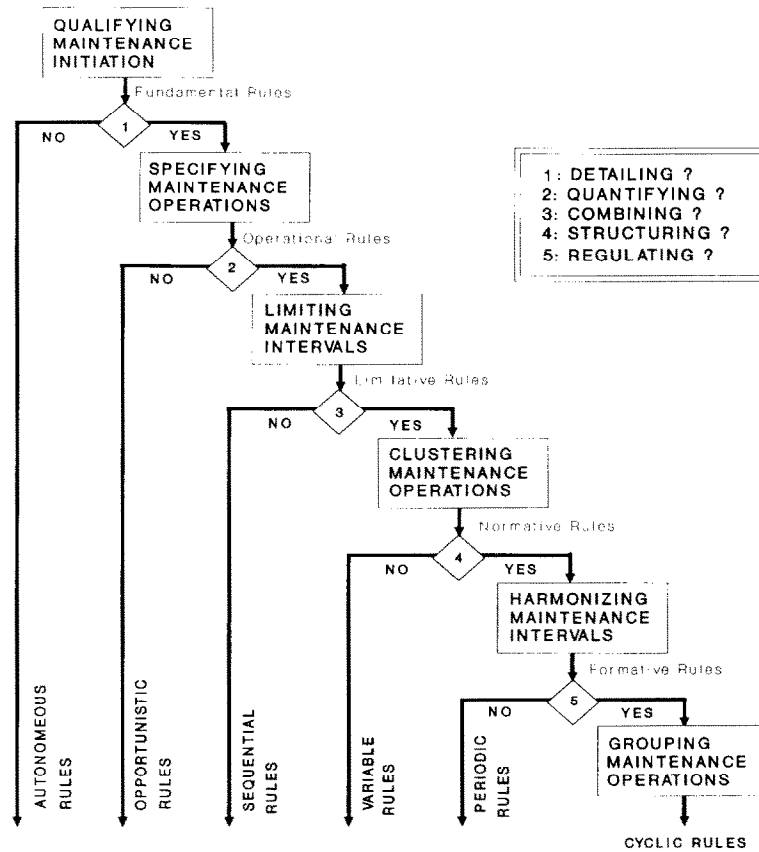Fig. 5. The phases in designing maintenance concepts.

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Fig. 6. The steps in generating maintenance rules.

tary and combinatorial efficiency and to format and workload of demand. Generating maintenance rules will be divided into six steps, each emphasizing one requirement (Fig. 6):

• qualifying maintenance initiation,
• specifying maintenance operations,
• limiting maintenance intervals,
• clustering maintenance operations,
• harmonizing maintenance intervals, and
• grouping maintenance operations.

4.1 Qualifying maintenance initiation

Qualifying maintenance initiation deals with relating a type of maintenance initiation to each of the failures of the technical system. In this step, potential effectivity is the central issue. Determining the potential effective types of maintenance initiation for a failure has to be based on its behaviour, i.e., failure rate and prognostic characteristic. The selection of the eventual type has to be based on efficiency considerations and concerns the failure consequences (failure-based maintenance), the variance of the failure probability–density function (use-based maintenance) and the directness of the prognostic characteristic (condition-based maintenance). Safety requirements exclude failure-based maintenance, continuity and controllability requirements favour preventive maintenance, i.e., use and condition-based maintenance. Selecting maintenance initiation results in a set of fundamental maintenance rules. A *fundamental maintenance rule* defines the type of maintenance initiation to be related to a failure.

The following steps in generating maintenance rules concentrate on detailing the maintenance rules, i.e., determining operations to be carried out and how demand for these operations is activated. Failure-based maintenance prescribes

activation of demand in the event of failure. The operation to be carried out cannot be specified beforehand as it depends on the prevailing circumstances at the time of failure. These *autonomous maintenance rules* will be directly included in the eventual set of rules. The use-based and condition-based maintenance rules are the input for the next step, which specifies maintenance operations.

4.2 Specifying maintenance operations

Specifying maintenance operations aims at relating a maintenance operation to each fundamental maintenance rule. This design step concerns repair in the case of use-based maintenance and inspection and repair, if possible, in the case of condition-based maintenance. Determining technically effective maintenance operations essentially belongs to the area of knowledge of the technical disciplines involved. In the decision process, efficiency considerations and constraints imposed by the available types of maintenance resources have to be included. Specifying maintenance operations results in a set of operational maintenance rules. An *operational maintenance rule* prescribes a maintenance operation and the type of initiation of maintenance.

The subsequent steps in generating maintenance rules focus primarily on the *quantification* of maintenance intervals. For those operational maintenance rules that involve high production losses or considerable set-up activities, it may be deemed advantageous to prescribe activation of demand each time an opportunity to do so occurs. These *opportunistic maintenance rules* will be directly incorporated in the eventual set of rules. The remaining operational maintenance rules are the basis for the next step, that is the limiting of maintenance intervals.

4.3 Limiting maintenance intervals

Limiting maintenance intervals aims primarily at setting maximum maintenance intervals on the basis of individual efficiency of maintenance rules.

Limiting the interval of repair in the case of use-based maintenance has to be based on statistical analysis of failure behaviour. Limiting the inspection-intervals in the case of condition-based maintenance has to be based on analysis of the relationship between prognostic characteristic and failure behaviour. The constraints to be included in this step originate from the safety requirement and dictate the maximum intervals of the rules applicable to the hazardous failures concerned. This design step will result in a set of limitative maintenance rules. A *limitative maintenance rule* prescribes a maintenance operation and the maximum interval of demand activation.

Generating maintenance rules from now on concentrates on *combining* individual rules resulting in activation of maintenance demand irrespective of the behaviour of the underlying failures. For those limitative maintenance rules prescribing expensive operations, it may be considered worthwhile to refrain from combining rules in order to avoid the inherently expensive loss of potential units of use if a failure occurs. These *sequential maintenance rules* can be directly included in the eventual set of rules. The remaining limitative maintenance rules form the basis for clustering maintenance operations, which is the next step.

4.4 Clustering maintenance operations

Clustering maintenance operations deals with the efficient combination of individual maintenance operations into maintenance clusters. A *maintenance cluster* is a number of maintenance operations with a common set-up.

Clustering maintenance operations comes down to trading off the reduction in set-up cost which results from simultaneous execution of operations against the cost incurred owing to the necessity of shortening a number of limitative maintenance intervals in order to make simultaneous activation of demand for these operations possible. This design step results in a set of normative maintenance rules. A *normative maintenance rule* prescribes a maintenance operation or cluster and the maximum interval of demand activation.

The following steps in generating maintenance rules deal with *structuring* maintenance demand. For those normative maintenance rules not subject to requirements with respect to maintenance demand, the generating process is at an end.

These *variable maintenance rules* will be taken up directly in the eventual set. The remaining normative maintenance rules form the input for the next step, which is the harmonization of maintenance intervals.

4.5 Harmonizing maintenance intervals

Harmonizing maintenance intervals aims at efficiently structuring the normative maintenance intervals into admissible maintenance intervals. The admissible maintenance intervals in the case of periodic maintenance demand are an integer times the basic maintenance demand interval, in short, the period. In the case of cyclic maintenance demand, the admissible maintenance intervals are the divisors of the period times the allowed number of groups of maintenance operations, in short, the cycle. The constraints to be included originate from the continuity requirement and concern the period of maintenance demand. This design step results in a set of formative maintenance rules. A *formative maintenance rule* prescribes a maintenance package and the maximum interval in activation of demand for this package. A *maintenance package* is a number of maintenance operations and clusters.

The final step in generating maintenance rules aims at *regulating* the maintenance workload. For those rules that are not subject to the cyclic maintenance requirement, the generating process is at an end. These *periodic maintenance rules* will be embodied in the eventual set of maintenance rules. The remaining formative maintenance rules are the input for grouping maintenance operations.

4.6 Grouping maintenance operations

Grouping maintenance operations aims at efficiently combining maintenance operations into maintenance blocks which meet the workload requirements. A *maintenance block* is a number of maintenance operations to be carried out simultaneously.

Grouping maintenance operations starts by cumulating the maintenance packages into initial maintenance blocks. Workload smoothing aims at efficiently levelling the workload implied by the initial maintenance blocks. Maintenance clusters and, if needed, operations can be shifted from one initial block to another to be carried out earlier. Shifting clusters or operations implies accepting a loss in potential units of use once only. This loss has to be traded off against the benefits accruing from a levelled workload. Maintenance workload smoothing should eventually include *progressive maintenance* in which the levelled maintenance blocks are further broken down into sub-blocks that can be carried out without interrupting the production process.

Grouping maintenance operations results in a set of *cyclic maintenance rules*.

4.7 Evaluating maintenance rules

Evaluating maintenance rules aims at identification of a set of maintenance rules that will constitute the maintenance concept of the technical system. A set of maintenance rules is acceptable in the event that its performance satifies the composite requirements. The composite requirements are essentially concerned with final efficiency, amount and regularity of preventive maintenance demand. Evaluating maintenance rules is divided into three steps, each concentrating on one requirement (Fig. 7):
- appraising maintenance cost,
- characterizing maintenance demand, and
- classifying preventive maintenance.

Appraising maintenance cost scrutinizes performance with a view to final efficiency. The costs associated with a generated set of maintenance rules are determined and compared with a norm.

Characterizing maintenance demand aims at establishing the performance of the generated set of rules, in view of the preference for preventive maintenance which results from the continuity of production and controllability of maintenance demand.

Classifying preventive maintenance concentrates on the performance of the set of rules with respect to the regularity of preventive maintenance demand which originates from the subsets of opportunistic, sequential, variable, periodic and cyclic maintenance rules.

The specification of suitable performance indicators and the norms to be satisfied depends on situational characteristics. A set of mainte-
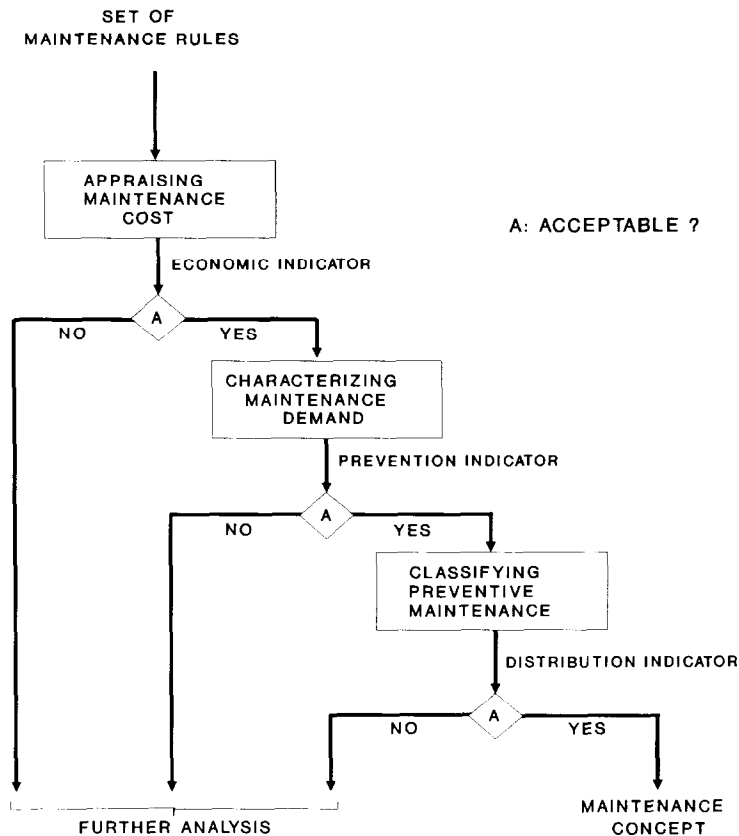
Fig. 7. The steps in evaluating maintenance rules.

nance rules meeting the norms is the maintenance concept of the technical system. If the norms are not met, then further analysis is necessary. This analysis results either in feedback of information to generating maintenance rules or in the initiation of nonmaintenance activities, such as modification of the technical system.

5. Conclusion

Designing of maintenance concepts is complex. Structuring the problem into autonomous steps is necessary for reducing this complexity. The framework presented is based on a great number of research projects in which theoretical notions on subproblems were tested in practical situations. The complete framework has been successfully applied in a number of different settings [7-9]. It should be noted that an actual design process is preceded by defining the failures of the technical system under consideration. In

view of a number of these failures, it may be deemed worthwhile to modify the technical system instead of trying to control the consequences of failure by means of maintenance. The design process itself is characterized by feedback and feedforward loops to any step at any time.

Further research should concentrate on broadening the framework to technical systems having a more complex functional and physical structure.

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