"AN INTEGRATED AND STRUCTURED APPROACH TO IMPROVE MAINTENANCE"

Part I: Concepts

by

S. G. VANNESTE*
and
Luk N. VAN WASSENHOVE**

93/49/TM

* Professor at Tilburg University, P.O. Box 90153, 5000 LE Tilburg, The Netherlands.

** Professor of Operations Management and Operations Research at INSEAD, Boulevard de Constance, Fontainebleau 77305 Cedex, France.

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An integrated and structured approach to improve maintenance. Part I: Concepts

S.G. Vanneste[1]
Tilburg University
P.O. Box 90153, 5000 LE Tilburg, The Netherlands

L.N. Van Wassenhove
INSEAD
Bd. de Constance, 77305 Fontainebleau, France

Following a brief review of recent developments in maintenance theory and practice, and in information technology and decision support models, we present an integrated approach that combines elements from these domains into a powerful tool for dealing with maintenance problems. We show how this framework can be used to set up a continuous improvement program for maintenance management. A companion paper (Part II) applies the concepts to an industrial case.

1 INTRODUCTION

In the past few years reliability and quality have become important topics in industry. As a consequence, maintenance management has become a more prominent management issue. Along with this process, theoretical developments in the field of maintenance management took place and advances were made in the mathematical modelling of maintenance and replacement problems. In addition, the progress in information technology has created new opportunities for data gathering and processing.

While each development on its own is of limited importance for solving real maintenance problems, together they can contribute much to the development of a powerful, integrated tool for maintenance management. It is therefore important to

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[1] Present address: Shell Research Amsterdam, P.O. Box 3003, 1003 AA Amsterdam, The Netherlands

analyze the integration and to stimulate discussion about the objects of integration and the process itself. Furthermore, from this integration positive effects on the component fields are to be expected as well.

This paper is an outgrowth of the project "Computer Aided Maintenance Management", initiated at INSEAD in June 1991. The motivation for this project came from the observation that current approaches to computer-aided maintenance management were not able to properly satisfy the needs of the practitioners. The existing maintenance management information systems are limited to administrative and accounting control, and are very static in nature. More advanced systems are desired and in our view possible provided that recently developed tools stemming from different fields are brought together. During the course of the project, which included field work at three factories, it became clear that there was a need for an integrated methodology. This methodology is the subject of the present paper. Companion papers discuss the prototype Maintenance Management Tools and the specifics of the software design and implementation (Angehrn et al., 1993, Angehrn, Jacxsens and Van Wassenhove, 1993).

The purpose of the suggested methodology is twofold. First, it offers the maintenance manager a general, systematic framework which is transferable and comprehensible to all the people involved. It is therefore useful as an alternative to the current practice of unstructured and ad hoc problem solving. Secondly, the methodology embeds scientific models into a broad decision support system, allowing the user to access models in a very natural way. We thereby hope to break through the isolated position of models and to contribute to a better integration of quantitative tools in maintenance management practice.

Developments in maintenance management

Since the importance of adequate maintenance has grown, the impact of a good preventive maintenance program on the reliability of production systems and the quality of the products is better recognized. With this growing management awareness one of the biggest obstacles in implementing maintenance programs and models has been potentially removed.

The attention received by several concepts in production management such as MRP, JIT, OPT (see Pintelon and Gelders, 1992) and the wide acceptance of these concepts in industry have contributed to a better appreciation of maintenance as well. For example, a good understanding of the role of a bottleneck machine helps in correctly assessing the cost of downtime resulting from failures of this machine or related ones. These so-called *hidden* costs do not appear in the financial reports but often largely outweigh directly visible, or *tangible* maintenance costs. Pintelon and Gelders refer to this phenomenon as the iceberg of maintenance costs.

A conceptual development particularly relevant to this paper is the Maintenance

Management Tool, suggested by Pintelon and Van Wassenhove (1990). This tool consists of a control panel with key performance indicators and is functionally linked to a structured network of detailed reports. In this paper we elaborate on this concept. For a review of maintenance management decision making we refer to Pintelon and Gelders (1992). For a further discussion of maintenance concepts we refer to Kelly (1984) and Geraerds (1990).

Unfortunately, the increased awareness of the importance of maintenance, has not yet led to a more structured approach to the maintenance problem. The most widely used concept in practice still seems to be the 'fire fighting' approach. While there is a better understanding of the 'invisible' cost caused by poor maintenance, almost no attempts are made to routinely estimate these costs. Even worse, in several industries which gather numerous data on failure history, these data remain largely unused.

Trends in automation

Many rapid developments take place in the field of information technology. Advances in hardware make it possible to gather and process huge quantities of data. For example, in several modern production organizations machines have automatic recording capabilities of the most important functions.

Advances on the side of the user-interface (e.g. hypermedia, graphics) provide powerful technological possibilities for processing data into a tractable format for interaction with the user.

Advances on the software part complete the picture. Rapid software development and prototyping capabilities are important to keep systems up-to-date in the rapidly changing environment which management is facing. The integration of standard packages has become much easier, thus facilitating the use of packages in developing tailor made systems rapidly.

Together these technological developments create big opportunities for systems that support decision making and analysis (including so-called 'executive information systems').

Recent developments in maintenance modelling

The Operations Research literature contains a large number of models that can be helpful in obtaining insight in maintenance decision making. In the past few years an increase in the number of maintenance articles can be observed. Recent attention has been largely focused on maintenance and replacement theory, while other fields, such as spare parts provisioning and maintenance scheduling, developed more slowly. In comparison with the models introduced in the sixties and seventies, more attention is paid to complex configurations of components (multi-component systems) and interaction with production (e.g. Vanneste, 1992). Practical usefulness and computational feasibility have become more important. An overview of applications of models is given in Dekker (1992).

It is not always straightforward to apply the models presented in literature. The input parameters are often difficult to obtain and require a thorough analysis of the department under study. Furthermore, these models do not always answer the right questions. To get around these problems we embed the models in a larger framework.

Methods from Industrial Engineering

An important role in our framework is played by problem analysis methods from industrial engineering and quality control. These methods can be very useful in a broader setting of maintenance management. Recent advances in this field are sketched in Watkins (1990). Below we explain how some of these techniques can help in the analysis phase of the problems and in assessing the effectiveness of a given solution. A systematic procedure seeking effectiveness is very valuable since it helps in structuring and quantifying problems. In addition it provides a context for applying decision support models (or efficiency models) and aids in determining some of their input-parameters.

An outline of our approach is given in the next section, followed by a more elaborate discussion of the concepts of effectiveness and efficiency in a maintenance context in Section 3. Section 4 deals with embedding the concepts of effectiveness and efficiency in a maintenance management information system. Part II is devoted to a practical application of the approach.

2 AN INTEGRATED APPROACH

Our approach consists of two major parts. The first part is effectiveness analysis. The aim of effectiveness analysis is to detect the most important problems and potential solutions. Once the potential solutions to the most important problems are identified and prioritized, it becomes clear which task or procedure has to be carried out more efficiently. To reach maximal efficiency a further analysis of the given task or procedure is necessary. This is the second part, the efficiency analysis. While effectiveness is concerned with '*doing the right thing*', efficiency aims at '*doing the thing right*'. The effectiveness analysis ensures that the effort put in improving efficiency is indeed dedicated to important tasks.

Our approach reads as follows:

Figure 1

Approach

Phase 1. Obtain a clear picture of the current factory performance
Phase 2. Analyze quality and downtime problems
Phase 3. Analyze effectiveness of alternative solutions to (major) problems
Phase 4. Analyze efficiency of maintenance procedures
Phase 5. Plan actions
Phase 6. Implement actions and gather data
Phase 7. Monitor actions and process data
Phase 8. Adapt plans or information procedures in case of undesired deviations. Goto Phase 1.

These steps constitute a closed loop which is repeated in a continuous improvement program of maintenance and information procedures (see Figure 1). Our approach is closely related to the Plan-Do-Check-Act concept developed by Deming (the Deming wheel, see e.g. Pintelon and Van Wassenhove, 1990). This concept is summarized in the following four steps: *Plan*: make plans to improve a given activity; *Do*: carry out plans; *Check*: follow-up of actions; *Act*: make corrections if necessary. Our approach puts more emphasis on the analysis phase and makes a distinction between effectiveness and efficiency analysis. Furthermore, attention is paid to the role of information procedures and systems and to the use of models. Below we elaborate on the eight phases of our approach.

Phase 1. Obtain a clear picture of current factory performance.

In this step the following questions should be addressed: Which (part of the) department are we going to analyze? What are the goals of this department? How is production and maintenance organized (flow chart of production process, maintenance procedures)? What is the performance of production and maintenance? What is the role of this department vis-a-vis the factory as a whole? The purpose of this step is to obtain a clear picture about what will be analyzed and how this department functions. The list is not exhaustive.

Phase 2. Analyze quality and downtime problems.

This step entails the location of the major quality and downtime problems, their relative importance, the frequency of occurrence, their causes as well as their consequences. Several problem structuring and analysis tools can be helpful at this stage. Histograms and Pareto-analysis (ABC-classification) can be used to analyze the relative importance of failures. Quality control charts give insight into the magnitude of deviations. Cause- and effect diagrams (fishbone charts), failure mode and effect analysis (FMEA) and other variants are useful in structuring problems and their root causes (see e.g. Watkins, 1990). This phase requires a close collaboration with people from the shop-floor.

Phase 3. Analyze the effectiveness of alternative solutions to (major) problems.

Once the problems are identified and prioritized, the obvious next step is to generate solutions and judge them on their costs and benefits. A distinction has to be made between directly visible or *tangible* costs and what we call *hidden* costs. Tangible costs are known or easily measurable. For example, the tangible costs of a repair include direct labour cost, subcontracting, spare parts, etc. Hidden costs are usually not directly visible from the cost accounting system. They include production losses and costs of delayed shipments.

The same distinction can be made in benefits, since the expected benefits of a solution are identical to the costs saved compared to not implementing it. Both costs as well as benefits of a solution, especially the hidden part, are often uncertain and difficult to estimate. Even if it appears impossible to obtain an exact value it is very important to secure an idea of the magnitude. It may be necessary to include scenario analysis.

By comparing the results of the cost-benefit analyses, one obtains an idea of the absolute and relative magnitude of the profitability of the solution in relation to the cost and benefits of other solutions as well as of the uncertainty related to different alternatives. With this information it is easier for management to make a prioritized list according to their preferences (risk-aversion etc.).

Phase 4. Analyze the efficiency of maintenance procedures

In some cases problems of downtime or quality will be avoided most effectively by other solutions than better maintenance in the narrow sense, such as modification of the design. In other cases the improvement of maintenance procedures may seem to be effective. The decision maker may then be confronted with questions such as how much preventive maintenance (e.g. replacement of critical parts, overhaul) should be performed to operate this machine in the most efficient way, or how many spares should be kept in stock.

Several decision support models can contribute to the analysis of the efficiency of performing a specific task. These models quantify trade-offs between costs and benefits of certain actions and provide insight in what the optimal action is and how much it improves the current policy (e.g. in terms of costs). Furthermore, models can be used for prediction and target setting. The input for the models (e.g. costs, lifetime distribution) can be obtained from the effectiveness analysis, from additional data analysis and from expert opinion.

Phase 5. Plan actions.

Based on the information of the previous phases it is now possible to select actions to be taken. These actions have to be planned and organized. Together with the planning of actions one has to plan the information process to keep track of the results. This comprises defining the appropriate performance measures and organizing the data gathering process. Finally targets have to be set.

Phase 6. Implement actions and gather data.

Along with the implementation of the actions, the information organization has to be implemented or adjusted and the data gathering can be started.

Phase 7. Monitor actions and process data.

A follow-up of the actions comprises the monitoring of the process resulting from the implemented actions and processing of the data. The performance indicators (P.I.'s) provide a tool to measure certain quantities and to check whether and to what extent targets are met.

Phase 8. Adapt actions or information procedures in case of undesired deviations; Goto Phase 1.

In case of deviations, minor adaptations to the process may be necessary. Alternatively, one may start a new round of analysis and planning.

P.I.'s play an important part in each step and have a function in linking different steps together. They are useful to obtain a diagnostic view of the department (effectiveness) and for target setting and monitoring of actions (efficiency). An information system is necessary to gather data and process them into useful information. Note that in our approach, the analysis 'pulls' the information, since the organization of the information process follows the analysis of the problems. In addition to internal information it may be very useful to have information from other companies (not necessarily competitors) to serve as benchmarks. The role of information procedures is discussed further in Section 4.

3 A CLOSER LOOK AT EFFECTIVENESS AND EFFICIENCY

3.1 Effectiveness analysis

In this subsection we discuss some further aspects of the effectiveness analysis phase of the approach, in which the costs and benefits of several solutions to the major problems are established. The costs of a particular solution are the costs for organizing and implementing the actions, and the benefits are the cost savings due to the action. We made a distinction between tangible and hidden costs.

In many cases, production losses are an important hidden cost factor. The production loss caused by a certain type of failure depends on the impact of the failure on production (downtime, quality) and the relation between production and sales. Let us consider an example. Suppose the plant faces a demand which exceeds capacity and suppose we are interested in the production losses due to failures at the bottleneck machine (the slowest machine in the line). One hour downtime at the bottleneck translates into one hour lost production, which in its turn leads to lost sales. Hence, the cost of an hour lost production equals the sales of the number of products that is produced in one hour minus the associated variable costs. By reasoning in this way, the cost of failures and the potential benefits of preventive measures to avoid them can be determined. A fully elaborated example is given in Part II of this paper. Failures of non-bottleneck machines can also have impact on the bottleneck, for example because it becomes starved (no input from the preceding machine(s) or buffer). For a good account of the role of bottlenecks we refer to Goldratt and Cox (1986).

Preventive maintenance of the bottleneck machine(s) as well as major overhauls also affect production, but their impact can be better controlled under a careful planning. In some situations opportunities can be used to perform maintenance without affecting the production. For example a shutdown because of frost can be used for maintenance without additional downtime cost. Also, during a shutdown one can perform maintenance tasks on several machines simultaneously, so that the downtime costs can be spread over the machines. Note that it may be very cost-effective to hire subcontractors in order to make optimal use of each hour of planned downtime. Careful (i.e. cost-effective) planning of shutdowns is very important. For non-bottleneck machines, the idle time can sometimes be used to perform preventive maintenance without affecting production.

Deterioration of the machines does not only affect up-times but also quality. Quality problems are typically more difficult to quantify than downtime problems, since product quality relates to service to the client and customer satisfaction, which is difficult to express in monetary terms. There are two exceptions, viz. when quality problems at one stage relate to downtime at other stages and in the case of discounts for poor-quality products (in the extreme case, defective items are not sold).

For each (major) problem the costs and benefits of the alternative solutions have to be established. Based on this information a prioritized list can be made from which the best solution is chosen. The effectiveness analysis phase thus consist of four steps:

1. Obtain a list of alternative solutions to each (major) problem.
2. Estimate the cost and benefits of each solution.
3. Make a prioritized list.
4. Select one or more solutions.

The cause-and-effect analysis carried out in Phase 3 may be helpful in the search for alternative solutions. In addition, ideas from people on the shop-floor, other companies or manufacturers of equipment may be useful.

After the costs and benefits of alternative solutions have been determined, a prioritized list can be made. From this list the most profitable solution(s) can be chosen. Other relevant information such as the uncertainty of the profit can be taken into account. Note that solutions may be dependent, in which case a combination of solution alternatives may yield different effects than the sum of the separate alternatives.

A prioritized list is useful for two reasons. Firstly, capital is constrained and hence the money should be spent in the most profitable way. The profits generated by the first (most profitable) solution can be used to implement the second, and so on. Secondly, it supports a gradual implementation, which is easier for purposes of planning and control. Note that during the implementation of the first solution further information can be gathered before implementing the others. A recalculation may be required in view of the possible impact of the implemented solution on the others.

In carrying out cost-benefit analyses one can use techniques from finance (investment analysis: implementing a solution is like investing in a project) and cost accounting (allocation of costs), although one has to be careful in applying traditional cost accounting methods, because these are developed mainly for reporting purposes and can be very misleading in maintenance decision making.

To conclude this subsection we discuss the relation between downtime costs and maintenance effectiveness in time perspective. In many production situations, the bottleneck is not always the same machine. It keeps shifting from one machine to another in time as a result of technical advances or changes in the production process. This affects the downtime costs associated with failures of the machines, and therefore the maintenance procedures should be adapted to the new situation in order to remain effective. Yet, in practice one often regards the level of maintenance on a particular machine as being determined by technical considerations only. Whilst the production situation changes, the maintenance plans are not adapted.

An example is presented in Figure 2. The horizontal axis represents the budget of the preventive maintenance program on a particular machine, i.e. the tangible costs related to preventive actions. For simplicity it is assumed that the hidden costs due to preventive maintenance are negligible. The vertical axis represents the costs due to failures of the machine, which consists of tangible and hidden costs. The relation between the maintenance budget and the failure costs is given by the curve. The 45°-lines represent iso-total cost lines. It is assumed that, at time 0, say, the machine is not a bottleneck and it faces an efficient maintenance program with minimal total costs (point A). Suppose further that there is a significant amount of downtime as a result of failures. Now suppose that after a year this machine has become a bottleneck machine. As a consequence the downtime cost have increased dramatically (a factor 10 or 100 is not uncommon). Now, when the maintenance budget is not properly adjusted, the maintenance costs are out of balance and the total costs are much higher (point B) than if the maintenance budget had been raised to the optimal level (point C).

Figure 2

3.2 Efficiency analysis

In Figure 2, the balance between the level of maintenance (maintenance budget) and the downtime costs plays an important role. To quantify such a trade-off and strike the optimal balance one has to use models. For many typical situations mathematical models have been formulated, which can be useful in answering questions such as:

How much maintenance should be done on this machine? How frequently should this part be replaced? How many spares should be kept in stock? How should the shutdown be scheduled?

Let us consider an example. Suppose a critical part with given failure and cost characteristics is preventively replaced four times a year and we would like to know whether this frequency is optimal. An obvious optimality criterion is the average costs per time unit in the long run. For this situation, a model is available that can be used to calculate the average costs under a wide variety of policies and input parameters and find the optimal replacement age as well as its sensitivity to certain changes of input parameters (e.g. cost increases). Insight into the effect of a change in the type of policy or maintenance procedures (age-based vs. condition based maintenance, individual vs. group replacement, etc.) can be obtained by comparing models for different situations. Furthermore, the result of the model can be used for prediction and target setting.

If the model allows for gradual policy changes, like in the above example, one can use the results of the model in a gradual improvement framework by making a change in the direction which is proposed by the model and checking whether the results are in accordance with the prediction. Suppose that in the above example, the optimal policy would be to double the frequency of preventive maintenance. To start with, one may increase the frequency by 50%. If the average cost converges to the target level for this policy, then one may consider a further increase. Note again the importance of key P.I.'s to track this. If the model predictions do not materialize, the model and data have to be critically reviewed.

The data for the model have to be gathered by information systems or can be extracted from expert opinion. Some data follow already from the effectiveness analysis (e.g. cost of production loss) or P.I.'s. Statistical tools may be required to process the data.

Models can be classified into three major categories: maintenance and replacement (how often should a component be replaced), spare parts provisioning (how many spares to keep in stock) and scheduling (e.g. shutdown scheduling). The latter two do not exclusively belong to the maintenance field but respectively to the fields of inventory management and production scheduling (see e.g. Nahmias, 1989). Models for maintenance and replacement aim to answer questions such as how often should a given component be replaced preventively or how often should an inspection be carried out, given the cost savings associated with preventive replacement (compared to replacement upon failure) and the probability of failure. Following Nahmias (1989) we made the following basic selection of replacement models:

- deterministic age-replacement model
- probabilistic age-replacement model
- group-replacement model

A common factor in these models is that the unit deteriorates as it gets older. If the cost or probability of failure increases with age, timely replacement can save money. At the machine level (aggregated) the deterioration is reflected in the maintenance cost per year. The deterministic age-replacement model can be used to find the optimal age of replacement. At the level of the component (disaggregated) the deterioration is expressed by the risk of failure. The probabilistic age-replacement model and the group-replacement model can be used to find the optimal preventive age-limit in this case, where the former considers a single-unit system, and the latter a group of identical components (this model is also known as block-replacement model). A further discussion of these models is postponed to Part II of this paper, where they are applied to a practical problem.

These models are simple and lucid and at the same time fairly robust and general. Although their simplicity is one of the reasons for their attractiveness, they may be too restrictive for practical applications, and more advanced models may be required. Recent advances in age-based replacement modelling are discussed in Vanneste (1992). For a broad overview of models for replacement we refer to the review articles of Sherif and Smith (1981), Valdez-Flores and Feldman (1989) and Cho and Parlar (1991). These overview papers also include also models for inspection and condition monitoring. It is noted however that it is more difficult to select a couple of generic models from the latter fields because these models usually have more complicated assumptions and are more situation specific. A general and flexible tool to handle specific situations is simulation.

In combination with information systems, models can provide very useful decision support. They provide tools to calculate the effects of changes in policies or in parameters that affect the decision problem. As such they add value to the information (Geoffrion, 1992). The data required for the model can be gathered and analyzed within the system and the results can be used for target setting. The follow-up of the actions provides a test for the validity of the model.

We emphasize that the vast majority of maintenance models is aimed at answering efficiency questions, that is questions of the form 'how can this particular machine be operated more efficiently?', and not at effectiveness questions, like 'which machine should we improve and how?'. The latter question is often the one in which practitioners are interested in. From this perspective it is not surprising that practitioners are often dissatisfied if a model is directly applied to an isolated problem.

4 EMBEDDING THE INTEGRATED FRAMEWORK IN AN INFORMATION SYSTEM

The improvement program has to be embedded in an information system to help the maintenance manager with initiating, monitoring and measuring continual improvement efforts. Such a system should be very userfriendly and flexible in the first place. The user should be able to access information in a focused way: the right information at the right time at the right place. For this purpose, hypermedia technology is very useful, since it allows the user to navigate through the information system in a way that resembles the way of thinking in the mind: going from one object to another, focusing, relating objects etc. Flexibility is important since the decision environment often changes quickly. Therefore it should be possible to modify the system or parts of it relatively easily. A modular approach and a programming environment which allows fast prototyping is important in that respect. For reasons of userfriendliness and flexibility, the system can best be implemented on a PC. This PC can be linked with other systems, e.g. for data retrieval.

The P.I.'s should have a central place in the software system, so that they can act as a control panel, from which the performance of the maintenance department can be monitored and analyses can be initiated. The major components of a Maintenance Management Information System (MMIS) are shown in Figure 3. P.I.'s can be classified into budget ratio's, job ratio's, equipment ratio's (e.g. availability) and personnel ratio's (e.g. absenteeism). We refer to Pintelon and Van Wassenhove (1990) and Lyonnet (1991) for specific examples. A structured network of detailed reports can be linked to the control panel to provide the user with more detailed information, including time aggregation or disaggregation and analytical tools such as viewing trends. Thus the control panel acts as platform for interaction between the user and the system. A spreadsheet application can provide a useful representation for the control panel and the detailed reports.

Secondly, a modelbase of practically useful decision support models should be linked to the control panel. The manager should be able to perform in-depth analysis through formal models without requiring advanced technical or mathematical skills. Models can also be helpful in obtaining predictions and in setting targets. Simple models can easily be built into a spreadsheet application, while more complex models require structured languages such as Pascal or C.

Furthermore, the system requires a database. The system should give access to consistent databases and it should be flexible enough to define new elements and delete others (if a new P.I. is defined, it has to be decided which data to gather and in which format). Time aggregation plays an important role since it will not be possible to keep all data on a detailed level for several years. For some datatypes such as budget information only aggregated information is needed, but for other data, for example failure data of a critical component, very detailed and disaggregated information may be necessary. In larger plants, the system database will have to be linked with a factory database, presumably running on a mainframe. In that case, an interface between the databases has to be developed and maintained. Due to the inflexibility of many factory database systems this can cause for a bottleneck. The gathering of the basic data for the factory database can be done by letting the workmen fill out forms (computerized or not) or by capturing useful data automatically on the machines.

Figure 3

Another useful source of information is external information, for example, about the performance of installations in other companies. They can serve as benchmarks for one's own performance. To obtain reliable data, the datagathering can be carried out by an organization that has access to data of several companies or users. An example from the consumer market may illustrate this point: the Dutch consumer organization has kept data about costs and frequency of failures and overhauls of a group of 2000 cars of different types over a couple of years (Consumentengids, 1992). This very useful information can only be gathered properly by a group of users.

The success of the eventual system depends heavily on how well the elements are conceived and integrated and how flexible the resulting product is. We built and tested a prototype software system in which the ideas mentioned above were implemented. For a description of this prototype and a more elaborate description on the demands on computer software for maintenance we refer to Angehrn, Jacxsens and Van Wassenhove (1993).

In our approach the analysis 'pulls' the information. Which information to gather and how is decided concurrently with the analysis. Advantages of this approach are that one knows better which information should be gathered and how important it is and, secondly, that the personnel is better involved and motivated to gather the information because they realize its usefulness. The drawback of course is that during the analysis phase one does not have all required information. In our experience however this is not a serious problem. Usually there is some data available which together with expert opinion and, if necessary, some additional measurements provide enough information to get a rough impression. Besides, it is an illusion to have all required information in a company which actively participates in a rapidly changing environment. However, we note that neither the information system design nor the analysis should be done extensively in isolation but rather concurrently in an improvement cycle of both analysis and information procedures. In practice one often starts with putting a lot of money and effort in setting up elaborate data gathering processes but then it appears to be so time- and money consuming that one does not reach the analysis phase at all, or meanwhile the situation has changed in such a way that the data gathered are no longer relevant.

5 CONCLUSION

In this paper, we have presented a systematic approach for improving preventive maintenance. This approach aims at improving factory performance through reduced downtimes and increased levels of quality by enhancing effectiveness and efficiency of preventive maintenance. It is not a solution technique but rather an approach providing guidelines for setting up a continual improvement program. It combines elements from replacement theory and practice, methods from industrial engineering, replacement models, and is based on the possibilities offered by modern information technology. The analysis has to be performed by a task group with people from the factory and, possibly, external people (e.g. consultants, trainees). Without a thorough analysis of the production process and a deep knowledge of the factory it will not be successful. However, when successfully applied, a major contribution to factory performance can be obtained, yielding a competitive advantage for the factory.

With this study we hope to contribute to a new conceptual basis for the use of computer-aided maintenance systems in organizations, and secondly, to give impulses to a better integration of mathematical models and analytical techniques into management practice.

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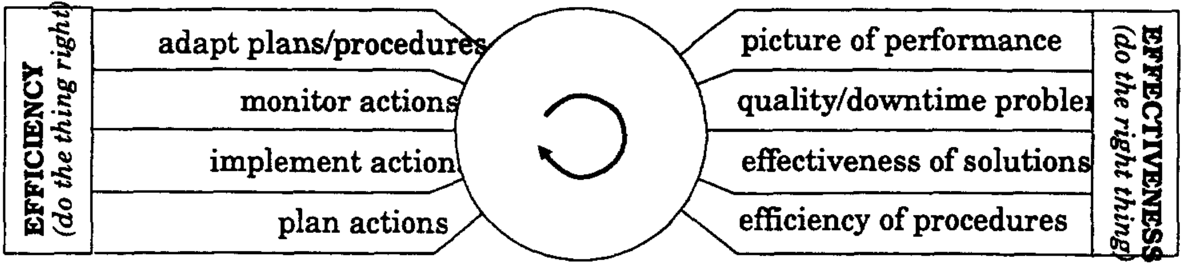

Figure1 The improved Deming Wheel

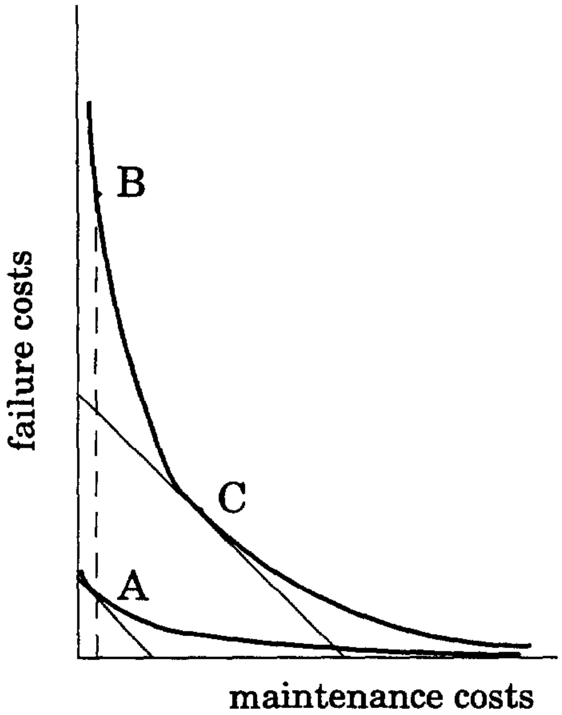

Figure 2 Maintenance effectiveness in time perspective

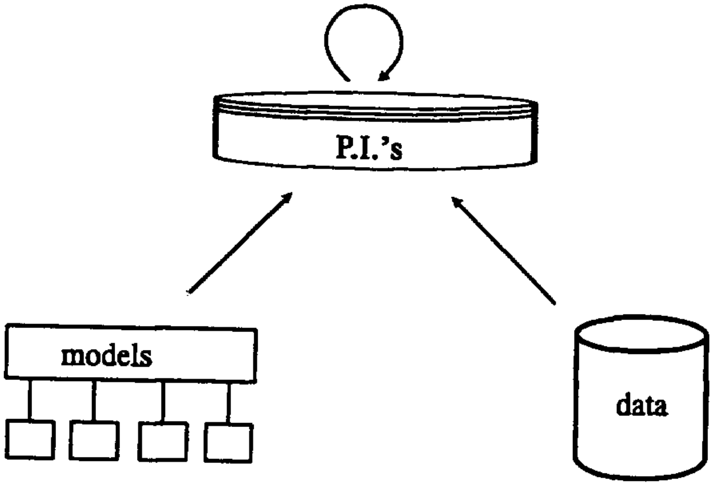

Figure 3 The major components of a MMIS