A STEPPING STONE TOWARDS KNOWLEDGE BASED MAINTENANCE

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ABSTRACT

Maintenance decision making becomes more and more a management concern. Some decades ago, maintenance was still often considered as an unavoidable side effect of production. The perception of maintenance has evolved considerably. One of the current issues is the maintenance concept, being the mix of maintenance interventions and the general framework for determining this mix. In this paper we describe a modular framework, called Knowledge Based Maintenance, for developing a customised maintenance concept. After describing the general framework and its decision support use, some case experiences are given. This experience covers some elements of the proposed framework.

INTRODUCTION

The potential impact of maintenance at the level of operations and logistics (flexibility, throughput time, quality etc.) is considerable and interrelationships of maintenance with other operating functions cannot be denied. Maintenance becomes more and more part of the integrated business concept, and is more and more recognised as a potential profit-generator [11]. Today, there is a growing trend towards outsourcing (external partnerships). Greater emphasis is put on the availability, reliability and safety of the production facilities. Highly qualified personnel is required and continuous training efforts are needed. Appropriate computer support has become indispensable for stock tracking, personnel management, job order tracking, processing of historical data, efficient document control and the like. Maintenance has become more and more integrated, as shown by the renewed interest in Life Cycle Costing (LCC).

The development of an appropriate customised maintenance concept is crucial for the integration of maintenance in the total business concept. A customised maintenance concept is necessary to obtain world class competitiveness. This maintenance concept is the set of maintenance interventions of various types (corrective, preventive, condition-based, opportunistic, design-based, ...) and the general structure in which these interventions are foreseen. Whereas some decades ago, there was a shift from corrective to preventive maintenance, many companies are now wondering if they are not doing "too much" preventive maintenance (or preventive maintenance of the wrong type), and if changing their maintenance concept would not bring considerable savings.

Action research and case studies conducted in the past revealed that there is need for a structured framework for maintenance concept development [11]. The framework for developing a customised maintenance concept described in this paper consists of different modules. Each module represents a step in the development process of the maintenance concept. In every module there are different options to address its goal, for every situation the most suited option should be picked. The framework uses ideas of existing concepts like Reliability Centred Maintenance (RCM) [2], Business Centred Maintenance (BCM) [1] and Total Productive Maintenance (TPM) [3]. Also the option "outsourcing" as a new alternative was added to the in-house determination of the maintenance policy.

A MODULAR FRAMEWORK

Observing the changes that maintenance has been through as well as the drivers for these changes makes apparent that, a suitable maintenance concept is an important aid for a company to achieve world class competitiveness [7].

Action research and case studies addressed the most important questions of today's maintenance managers. The main question is "What is the most appropriate maintenance concept for this specific company?" This question, however, consists of some other questions, and based on these questions, the important factors to be taken into account in a maintenance concept can be determined (table 1). Starting from these factors, the different modules can be identified. Each module represents a step in the development process of the customised maintenance concept. The proposed modular framework is illustrated in figure 1.

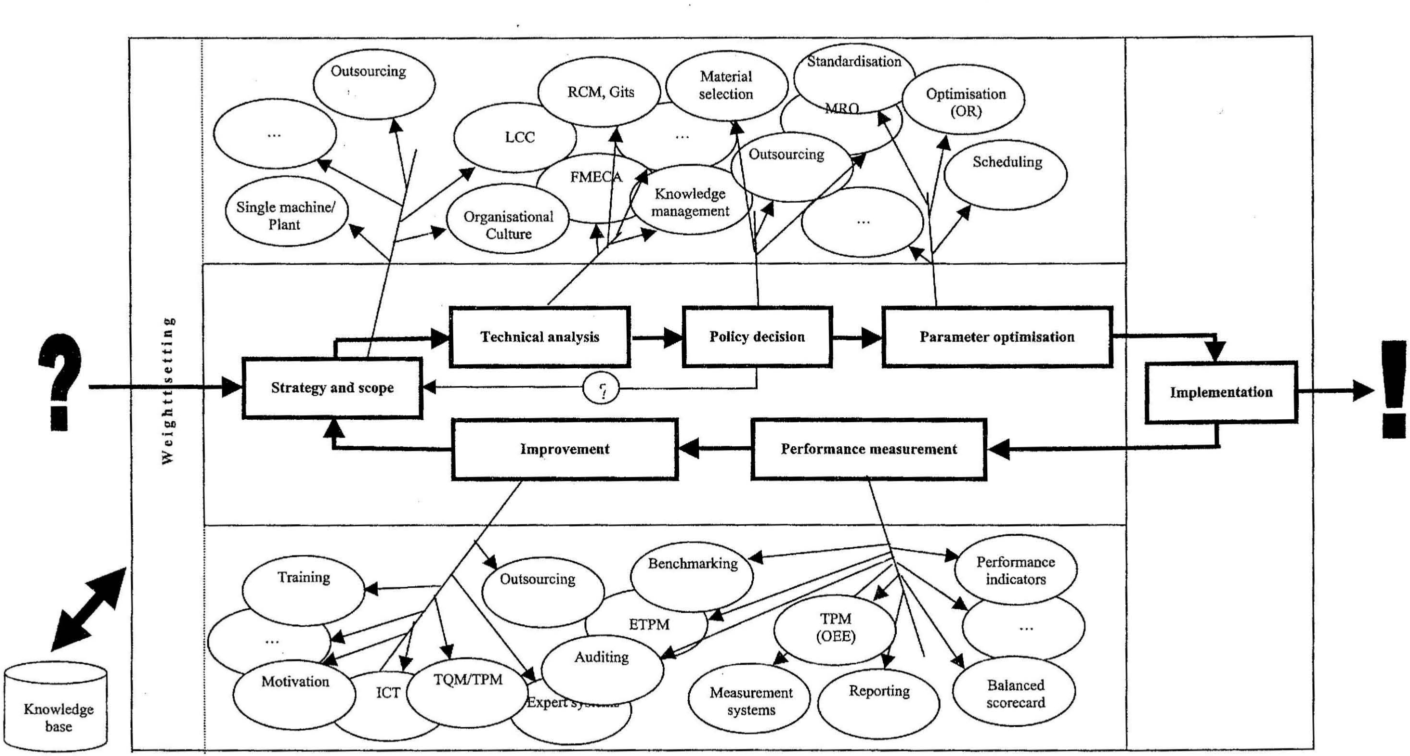

Figure 1. The KBM framework

An important element in developing the modular framework is the "knowledge base". How to use all available information, which is often partial or scattered and not always properly recorded? It is obvious that recent trends in Information and Communication Technology (ICT) are able to support and optimise this knowledge base. There are very promising developments in ICT which can help to improve the knowledge gathering and as such create better competitiveness. Buying highly sophisticated ICT hardware or software, however, is not the complete answer, ICT is only an enabler.

Table 1: From management questions to maintenance modules

<table>
<tr><th>Management question</th><th>Important factor</th><th>Maintenance module</th></tr>
<tr><td>What do we want to achieve?</td><td>Business, strategy</td><td rowspan="10">• Data/knowledge management
• Strategy and scope
• Technical analysis
• Policy decision
• Parameter optimisation
• Outsourcing
• Material selection
• Spare parts inventory control
• Performance measurement
• Auditing
• Benchmarking
• ...</td></tr>
<tr><td>What are the available resources?</td><td>Technology, HRM, cost</td></tr>
<tr><td>Which type of maintenance is needed?</td><td>Strategy, technology, business</td></tr>
<tr><td>Who has to perform these activities?</td><td>HRM, cost</td></tr>
<tr><td>What is the workforce qualification criterion?</td><td>HRM, cost</td></tr>
<tr><td>Which materials and processes should be used?</td><td>Technology, logistics, cost</td></tr>
<tr><td>Which supporting systems are needed?</td><td>Technology, support</td></tr>
<tr><td>How to evaluate the performance?</td><td>Performance, business</td></tr>
<tr><td>Is outsourcing interesting in this case?</td><td>Strategy, business, cost</td></tr>
<tr><td>...</td><td>...</td></tr>
</table>

HRM: Human Resources Management

In the proposed framework, tacit knowledge is used as an aid to gather data and to make knowledge more generally available (see figure 2). The step-by-step gathering of knowledge and the development of the knowledge base will be an engine for continuous improvement. Accessibility of the knowledge base by every worker is of major importance here (e.g. with an intranet) [11].

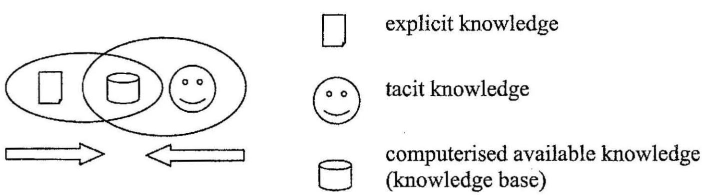

Figure 2: Gathering knowledge [11]

The integration of maintenance will become much easier through integrated information and communication systems. Communication systems have changed in a way that not only internal business contacts get easier, but they have opened the way toward inter-enterprise computing. Pintelon et al [6] describe some changes that may result from this enabling technology.

In this paper, only a few modules will be described and illustrated. As it will become clear, much of the modules are frameworks on their own, providing guidelines on how to perform a certain task in the development of the maintenance concept. In the future, the proposed framework should be completed with a Decision Support System (DSS), which can help the maintenance manager to choose the appropriate method for his specific situation.

Data- and knowledge management

The efficiency of maintenance procedures is increased if the knowledge in the knowledge base has been normalised and if it is easily accessible. In this module, guidelines to develop an integrated knowledge system are provided.

Strategy and scope

This module deals with the strategic level. The decisions are long-term decisions, and usually made at top management level. The integration of maintenance with the corporate strategy is addressed. Like all operating functions, maintenance management needs clear objectives, which have to be in line the company's strategy. In this module, guidelines to formulate the scope for maintenance are provided, together with guidelines for team formation.

Technical analysis

This module offers guidelines to perform a technical analysis in order to gain insight in the working principles of the technical system and the processes it is used in. An important feature here is the focus on different levels of detail in the technical analysis, ranging from quick rough cut to time consuming but very thorough.

Policy decision and Parameter optimisation

In these modules, the technical information obtained in the 'technical analysis' is used to choose the most appropriate maintenance policy. After the policy is chosen, the corresponding parameters are optimised and the result is a maintenance program. It documents for each specific technical system what type of maintenance is required and at what scheduled intervals or conditions.

Outsourcing

Outsourcing is the transfer of assets and/or people from the using company to a service vendor (contractor). In this module, a framework for structuring the outsourcing process is provided. In order to obtain successful outsourcing co-operation between the different partners and a thorough outsourcing procedure is necessary. This framework should prevent outsourcing to become another problem instead of being the catalyst of a substantial improvement.

Material selection

This module supports the selection of the right material or the right protection measured.

MRO module

This module addresses the problem of MRO (Maintenance, Repair and Operating supplies). It helps to decide which inventory models to use and where to locate efforts to optimise the service level or to reduce the inventory value.

Performance measurement

This module gives an overview of performance measurement systems, with their advantages and disadvantages.

Auditing and Benchmarking

A maintenance benchmark is a rating of a company's maintenance department services, processes and policies, in comparison with other companies or departments. The objective is to see how the company or department is performing the maintenance activities. A maintenance audit is a detailed analysis of the firm's maintenance department, the maintenance operations, the spare parts supply chain, etc. to obtain an in-depth understanding of the current performance. An audit is conducted because there is a perception that improvements can be made and the audit gives a baseline for improvement. It is obvious that these two modules are closely linked.

MODULE 'STRATEGY AND SCOPE'

The strategy and scope module is a strategic module. The decisions are long-term decisions, usually made in dialogue with top management level. The reason is that besides the maintenance aspects, also more general issues such as capacity, flexibility, impact of technological changes, economic factors and investment criteria should be considered. Also interrelationships with other (operating) functions cannot be denied. As a consequence, for this module, co-operation of other departments and top-management is needed (figure 3).

The tasks that should be carried out here are the following:

- Evaluation of the current situation and culture
- Formulation of the ideal situation (setting the objectives of maintenance) (figure 4)
- Identification of performance parameters and levels
- Team formation and task assignment

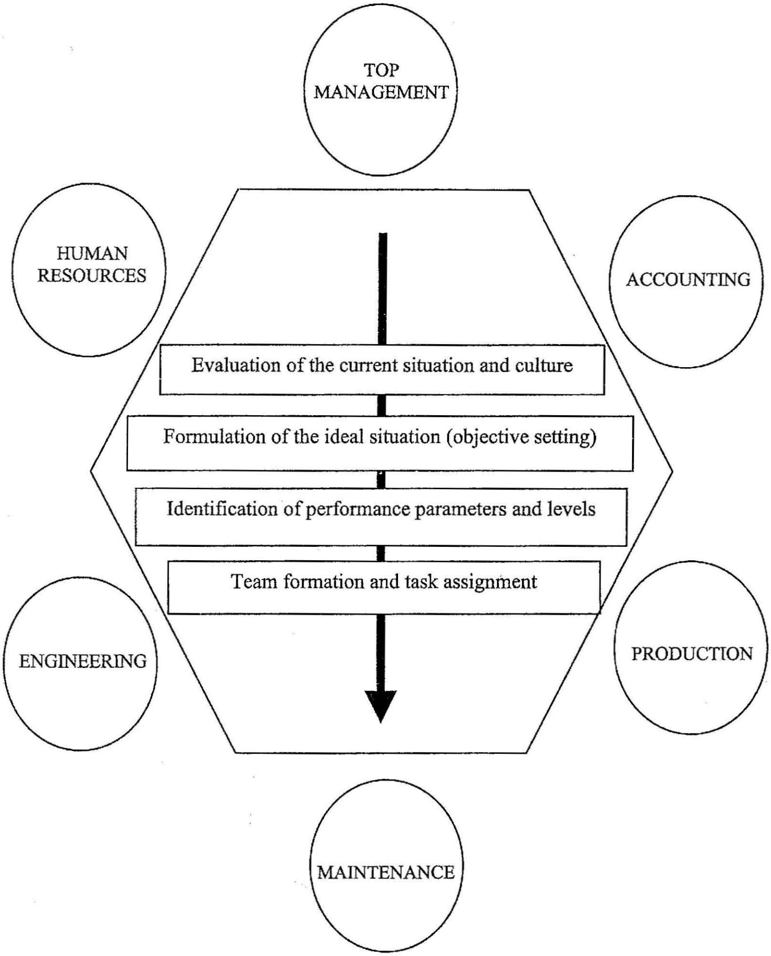

Figure 3: The strategy and scope of a maintenance concept are defined by a co-operation between different departments.

Like other operating functions, maintenance management needs clear objectives. The first step in a customised maintenance concept is setting and describing the objectives. The main factors that should be taken into account are shown in figure 4 [1].

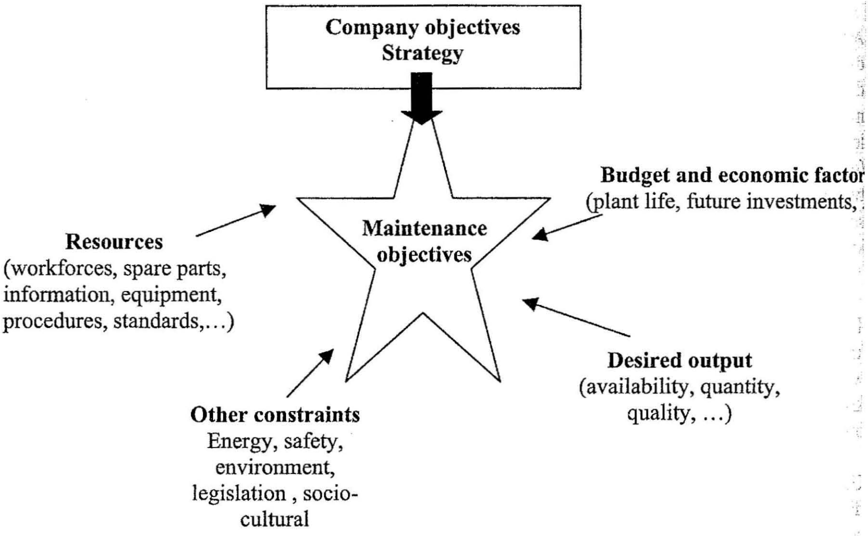

Figure 4: The main factors in the maintenance objectives [1]

Evidently, the first objective of maintenance is to ensure that assets continue to do what users want them to do (securing reliability and availability). But in order to avoid suboptimisation, the maintenance objectives must fit with the overall company objectives. Today companies use maintenance to reduce cost and protect commercial margins, but also to meet safety and environment regulations and to enhance productivity. The overall maintenance objectives can thus be divided into sub-objectives concerning plant availability, product quality, longevity, safety, flexibility, performance, overtime, cost, etc.

However, the objectives set for maintenance must be realistic and specific, so that they can serve as guidelines and targets. Far too often, the aims of the maintenance service are too vaguely formulated. An aim like "keep it all rolling at the lowest possible cost" is not concrete enough. The exact content of each objective should be defined clearly, and relevant performance levels have to be defined. The cases can serve as examples.

MODULE 'TECHNICAL ANALYSIS'

The aim of tactical maintenance planning in an industrial context is to ensure that the means of production are optimally available. This entails high reliability and sound maintainability. Tactical maintenance planning therefore refers to finding the optimum maintenance policy. In order to establish the optimum maintenance policy, a good insight in the technical systems and their failure and repair behaviour is required. This module needs a lot of data input from the knowledge base.

A distinction should be made between first level data and second level data [11]. First level data refers to data recorded as part of the system installation. Second level data is collected during the chain of normal work (i.e. during the normal life cycle). First level data are in most of the cases relatively easy to obtain from the supplier of the installation, while second level data are often for a large part in the head of people - under the form of knowledge (experience) - and only partially on paper and on computer files. Companies should exploit two kinds of knowledge, explicit knowledge and tacit knowledge. Explicit knowledge can be seen as the data, documents and things written down or stored on computers. Tacit knowledge on the other hand, is the data, which reside in workers under the form of knowledge and feeling [4].

Tacit knowledge is an often forgotten item. In the framework proposed in this paper, tacit knowledge is used as an aid to gather data and to make knowledge more generally available within the firm. The step-by-step gathering of knowledge and the development of the knowledge base will be an engine for continuous improvement. Accessibility of the database by each worker is of major importance here, e.g. with an intranet (Knowledge management).

Gathering technical data is done by performing a technical analysis. Different steps can be distinguished. The general approach is top-down. First, the Most Important Systems (MIS) should be determined. Second, the Most Critical Components (MCC) should be determined within these Most Important Systems. Next, possible failures of each component and their connections to upper (effect) and lower levels (cause) have to be analysed. Finally, already implemented (preventive and detective) actions and additional actions to prevent or detect a failure cause have to be discussed and described.

Identification of the Most Important Systems

This analysis aims at supplying the information about the technical systems, which is required in the subsequent phases of the development of a maintenance concept. In order to reduce system complexity, the MIS's (i.e. Most Important Systems) will have to be identified in a first stage. This can be carried out with the aid of a very simple questionnaire (table 2). In order to reduce subjectivity, the identification of the MIS should be carried out by a team.

The decision to select a system as MIS will be influenced by different parameters, like layout and manufacturing system. Failures will usually stop the entire line in a product layout, but in a process layout, diversion to similar machines may be possible. For expensive installations in Flexible Manufacturing Systems (FMS), redundant capacity is usually not available. This problem is frequently solved by opting for modular machines. If a failure occurs, the faulty module is replaced quickly and can be repaired off-line.

The above makes clear that the identification of the MIS`s will depend on different factors and on the maintenance objectives (i.e. criteria) set. Depending on these criteria and the situation, weight factors can be used to underline the relative importance. In most of the cases every possible technical system is an alternative (i.e. a potential MIS), and quite a few criteria have to be taken into account. Multi-Criteria Decision Making (MCDM) can be very helpful here. MCDM allows several alternatives to be compared for different criteria. Many (several tens) of criteria can be taken into account, moreover these criteria can be very diverse (both quantitative and qualitative criteria may be considered). A lot of work was done during the last years to fine-tune the existing techniques. Several multi-criteria methods have been proposed. They are treating the same basic problem, deciding which alternatives are the best choice under certain conditions. MCDM does not only offer decision support in terms of evaluating alternatives, it also offers the possibility of gaining insight in the decision procedure by varying criterion weights and scores. The currently available software is very user-friendly and also allows users who are not familiar with the mathematics behind MCDM to use it in a satisfying way.

Table 2: Identification of the Most Important Systems with the aid of a questionnaire

QUESTION	YES (1) / NO (0)	WEIGHT	SCORE
Does a failure has consequences for safety?			
Does a failure has consequences for the environment?			
Is failure-detection easy?			
Is the system a bottleneck?			
Is there loss of production in case of a failure?			
Are the repair cost (man-hours) high?			
Are the repair cost (material) high?			
Is there a possibility for secondary damage (e.g. on other			
Is the system considered as complex?			
Is there build-in redundancy?			
		TOTAL:	
		MIS	NON-MIS

Criterion

Example:

Score	MIS	Non-MIS
≥ 25	X	
< 25		X

Identification of the Most Critical Components

After identification of the Most Important Systems, the Most Critical Components (MCC's) should be identified within the selected MIS's. This can be done with the aid of a FMECA (Failure Mode, Effect and Criticality Analysis). A FMECA can be described as a systemised group of activities intended to:

- recognise and evaluate the potential failure of a technical system/process and its effects
- identify actions which could eliminate or reduce the chance of the potential failure occurring

- document the process. It is complementary to the process of defining what a technical system or process must do to satisfy the user

The three principal study areas in a FMECA analysis are failure mode, failure effect and failure criticality.

- The failure mode is analysing the operation of the product or the process to see what are the most likely modes where failure can occur. This includes describing the conditions, the components involved, the time elements, location, etc.

- The failure effect is the study of the potential failures to ascertain the likely impact on the performance of the whole product, the process or service and/or related elements.

- Failure criticality is the examination of the potential failures of the product, process or service to determine how critical the failure would be. The criticality may range from customer irritation, through a lowering of performance or quality, shutdown of an operating plant, a safety problem or an environmental hazard to a catastrophic occurrence.

However, performing a FMECA is a complex and time consuming task. It requires understanding the process and how to eliminate risk and plan the appropriate controls. Often, a simplified, 'quick and dirty' criticality analysis can be performed [11]. Below, in case 2, an example of such a technical analysis is provided.

MODULE 'POLICY DECISION'

After identification of all the MCC's within the selected MIS's the correct maintenance policy for a particular component will have to be chosen. This can be done with a decision tree (figure 5) [11]. It exists of different steps that can be answered positively or negatively. There are two types of questions, technical and economic. If a certain policy is technically feasible, the economic implications have to be examined.

Such a decision diagram may seem too rough at first glance, but it provides quite some valuable decision support. Note also that in developing such a decision chart for the situation on-hand a lot of strategic/tactical considerations may be included: the exact content (e.g. whether to include outsourcing or not) and the sequence in which the different policies are considered (e.g. do we start with FBM because it is a valuable alternative for us or not?).

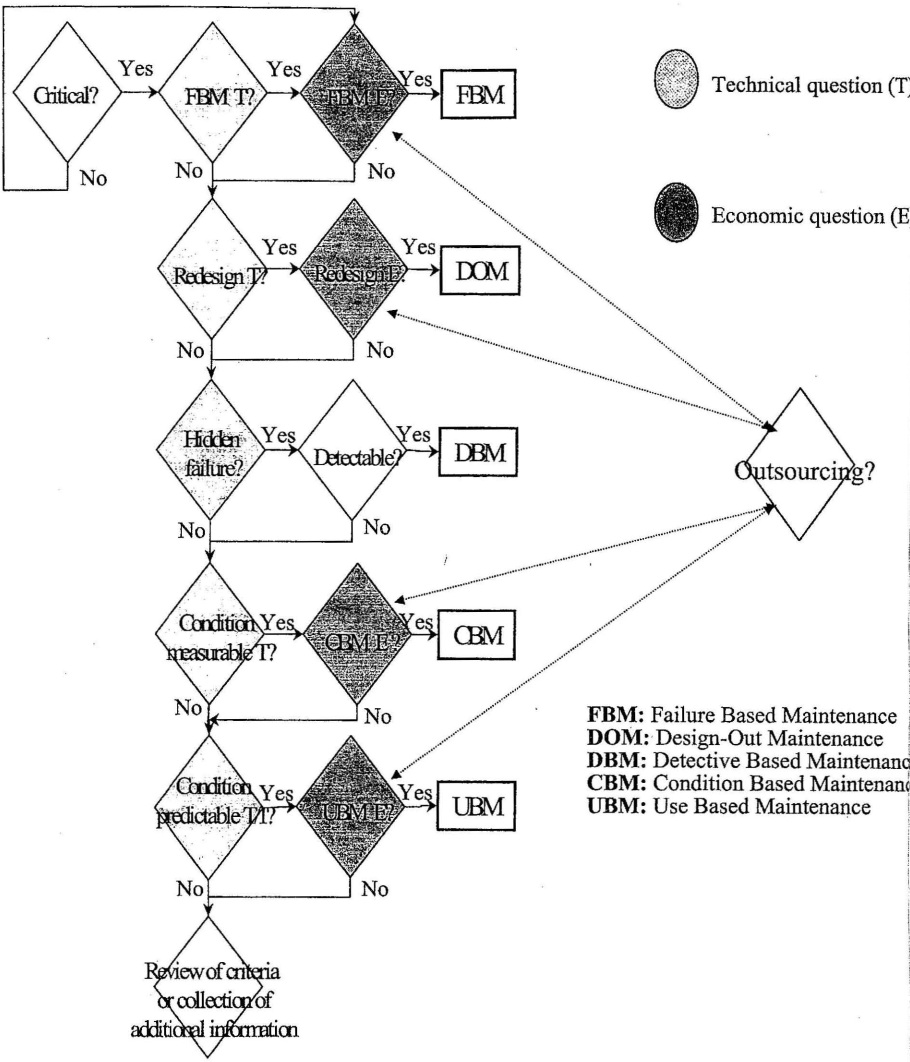

Figure 5: Maintenance policy decision tree [11]

Figure 5 is based on Waeyenbergh et al, [11], where a detailed discussion of the diagram is given. The sequence of policy decisions proposed here is:

- FBM (Failure Based Maintenance): run-to-failure.
- DOM (Design-Out Maintenance): geared at eliminating maintenance or at least making it easier.
- DBM (Detective Based Maintenance): a basic form of condition monitoring based on operator observations.
- CBM (Condition Based Maintenance): predictive maintenance using high-tech monitoring devices and techniques.
- UBM (Use Based Maintenance): traditional preventive maintenance.

If none of these options seems justified, there should be a review of the criteria or a collection of additional information. Another important factor (and a link to the module 'outsourcing'), which has taken into consideration, is the possibility for outsourcing of certain maintenance tasks (e.g. condition monitoring).

MODULE 'PARAMETER OPTIMISATION'

Once the type of policy has been chosen, the parameters of this policy must be optimised (e.g. the parameter 'PM frequency' in UBM). In UBM, there are two classical strategies: block-based and age-based (= time-based) maintenance. These policies are 'classics' and their modelling modes are well documented in literature. Both of these policies are based on the Renewal Reward Theorem (RRT). This theorem is a powerful tool used in optimisation of stochastic systems. Once a regenerative cycle of a controlled stochastic process is identified, one forms an average cost objective function simply as the ratio of the expected cycle cost to the expected cycle time. The resulting objective function is then optimised with respect to the decision variables of the model.

The classical age-based maintenance policy model, however, assumes e.g. that the maintenance intervention times are negligible. In most of the cases this approach will not be correct, so that the basic model must be adjusted in this respect. This modification will result in an 'extended' time-based/block-based model, like e.g. described in Pintelon et al [9].

MODULE 'OUTSOURCING'

Outsourcing is often proposed, or used, as a solution to many company problems, especially in the field of maintenance. Several reasons for outsourcing can be indicated. The bottom-line is to enhance competitiveness. This can be realised by (more) focussing on core activities, combined with outsourcing of (all) non-core activities. There are many benefits in outsourcing, e.g.:

- **Financial issues**: Outsourcing often provides a one-time infusion of cash to the company through the resale of assets no longer needed. More important is the potential reduction in operating costs. Contractually defined costs are known in advance. Outsourcing makes capital funds available for projects in more core-activity related areas.

- **Personnel issues**: Outsourcing transfers the personnel training and management to the service provider, and fully uses the competence of the service provider. The outsourced function is the core business of the service provider, who is (or should be) very good at his job. He can build on the experience with many clients (learning process) and may achieve world-class performance. Outsourcing sometimes allows to free in-house personnel from "routine"-jobs and to engage them in more challenging projects.

- **Technology issues**: Outsourcing often gives access to state-of-the-art technology. The reduced risks of technology updating are another outsourcing benefit.

Of course, outsourcing yields potential pitfalls, which can scare companies. These pitfalls can turn into major disadvantages, if not properly taken care of:

- Outsourcing is often not as beneficial as expected because of hidden costs, e.g. the costs of negotiating/contracting with the supplier.

- Outsourcing of a given business function has a considerable impact on the workforce and can stir some social unrest.

- Adaptation to new technologies becomes now partly the responsibility of the supplier. This involves a risk in the sense that sooner or later, it damages your business. Loss of control impedes a lot of companies from outsourcing.

To avoid these pitfalls, one has to focus on the communication within the company and with the supplier. Outsourcing agreements (Service Level Agreements or SLA's) should be carefully considered and clearly specified. For a general framework for structuring the outsourcing process, we refer to Vannieuwenhuyse et al [10].

The outsourcing module is also closely linked to the audit module. By performing a maintenance audit, an in-depth understanding of the current performance of a company's maintenance department is obtained. An audit is the ideal tool to take a picture of the whole maintenance function and its integration in the company strategy. The audit can help to answer the question "Should we consider outsourcing?" and to assess the strengths and weaknesses of the maintenance department. This provides a strong basis to start negotiations with contractors.

MODULE 'PERFORMANCE MEASUREMENT'

Maintenance performance reporting is difficult for several reasons [8]. First, there is a time-lag effect, which makes it difficult to specify the amount and intensity of the service (and the corresponding required amount of money) needed for assuring proper plant performance. Second, maintenance output is difficult to measure because it is so closely related to production activities. Both the merits and shortcomings of the service rendered are not immediately apparent. However, in order to anticipate on problems and opportunities, sound performance reporting is indispensable. Moreover, efficient performance reporting systems support continuous improvement.

Performance reporting systems are based on performance numbers or indicators. They measure the performance concerning a specific aspect of operations or planning in a given period. The resulting numbers are then placed on a "scale". Most maintenance performance indicators are ratios measuring effectiveness (actual output on theoretical output), efficiency (theoretical output on actual output) or productivity (output on input). The process (e.g. the whole of maintenance activities) is considered as a black box, input (e.g. labour hours) and output (e.g. jobs completed) have to be clearly defined. The way these definitions are filled out for a specific company depends on the type of industry, the installation utilisation, the age and state of the equipment, the organisation of the maintenance work force etc.

A more complete description of performance measurement systems, with their respective advantages and disadvantages, can be found [8]. This module will provide guidelines to develop a performance reporting system tailored to the situation on-hand.

CASE 1: AUTOMOTIVE PAINT SHOP MAINTENANCE

This project focuses on the automotive painting process, which is the single most expensive stage of the automobile manufacturing process, and therefore very critical towards cost management. One of the main problems in the painting process, leading to First-Run-Not-OK cars, are the so-called topographical paint defects caused by dust and dirt (i.e. all kinds of contamination). Contamination can lead to a whole range of defects in the applied layer of paint. When these defects occur, they have to be repaired. To avoid these expensive repairs, the paint shop has to be maintained accurately.

A typical paint-shop is a complex installation consisting of several units (phosphating, electro-coating, sealing, spray coating...). The maintenance (lubricating, cleaning, filter replacement, etc.) of each of these units is a key element for the paint quality. However, no objective criteria exist to assess the condition of the different components of the paint shop. The assessment of the condition is often based on visual inspection, which leads to inconsistent judgements. The non-existence of reliable criteria makes it difficult to schedule the maintenance periods efficiently. In addition the relation between the condition of the different parts of the paint shop and the quality of the paint process is not well documented. It is, for example, probably not necessary to clean all units and components of the paint shop at the same degree, or to change all filters after the same time. There will be critical and less critical components and they need to be identified. The consequence of this uncertainty on the condition-quality relation makes that the maintenance frequency is probably often not appropriate (too high or too low), which might have an inverse effect on product quality and cost.

The first step in the project was to clearly define the problem. Since the project is supported by a group of industrial partners (automotive companies, cleaning companies, suppliers of filtration systems, suppliers of non-paint materials, etc.) this was not easy. Each of these partners had a slightly different point of view stemming from their own business, and as a consequence, they had also slightly different expectations. This hampered the task of setting and describing the objectives. Therefore, the general objectives were specified into several sub-objectives, and the exact content of each sub-objective was described completely.

For a given paint shop the use of the outcome of this project will lead to savings. On one hand there will be savings due to a reduction in direct cost through a better focussing of the cleaning efforts. On the other hand there will be, a considerable, reduction in indirect cost: the improved quality of the painting process will reduce the required number of paint repair jobs. The resulting improved cost control will contribute to cut costs and prices in this very competitive sector. Approximately 25% of the car bodies have to be repaired in some way (spot repair, panel repair or total repair). Considering 1.000.000 car bodies per year in Belgium, this means 250.000 repairs per year or about 750 car bodies per day. Suppose that a 20% reduction can be accomplished, this means a saving of 50.000 paint jobs per year. It is clear that this means a substantial saving in man-hour and materials.

Besides cost reduction, the goal of the project is to reduce the above-mentioned uncertainty. As a consequence, quantifiable criteria for the condition of each unit will have to be defined. In this way it will be possible to define for a given paint shop the conditions that have to be imposed on each of its components. Methods to measure the condition will have to be investigated and appropriate measurement procedures will have to be defined. This should yield the necessary material to define standards for paint shops.

In order to understand the technology of the paint process in detail and to identify the parameters of the painting process that are critical for the quality of the finished paint coat, the paint shop was technically analysed. This analysis was largely based on data made available by the partners in the user consortium. First of all, a 'quick and dirty' criticality analysis was performed. The goal of this analysis was:

- to recognise and evaluate the potential failures of the process and its effects.
- to identify actions, which could eliminate or reduce the chance of the potential failure occurring (especially cleaning actions).
- to document the painting process.

One of the major problems during the technical analysis, was the analysis of the data obtained from the different partners in the user consortium. In order to put them in an adequate format, the data needed to be filtered and assembled. Finally, we came to several data sets, which are representative for the various paint shops and their most common user modes. Based on the data and the knowledge and the practical experience of the user consortium a selection of the most important systems that will be included in the large scale FMECA was made. Also a FMECA team was formed with members of the user consortium. On these most important systems, several large scale FMECA's are now being made. Different FMECA's for each paint shop will be performed for different colours, different models, different situations. In the further study, the parameters will be subject to extensive validation studies across a range of paint shops and employing a variety of validation methods. First of all, the 'content validity' of the parameters has to be checked, i.e. there has to be proof that the parameter is an adequate measure. Based on the practical experience of the user consortium the parameters will undergo a validity check in practice. Next, the 'criterion validity' should be assessed by comparing the parameters with similar problems. Finally, the 'predictive validity' has to be proven.

The final aim is to come to a continuous monitoring system that would trigger the maintenance process by monitoring the condition of all the critical elements in the paint-shop. A more accurate understanding of the relationship between paint quality problems and paint shop maintenance will allow to design technological solutions to improve paint quality. These solutions will consist in the development of an appropriate maintenance concept for a paint shop, including a complete condition monitoring procedure, monitoring techniques and maintenance programs (with optimum frequencies) for all the paint shop components. The concept should include a tool for objective evaluation of the delivered efforts with respect to maintenance, the budgets involved and the condition of the different units. Such a concept will also be highly useful for car manufacturers and their subcontractors to set maintenance targets for their paint shops. It will also benefit the contractor to whom a certain maintenance activity has been assigned. In this way, a method to assess objectively the quality of the performed services, will be available.

CASE 2: A MULTI-PLANT MAINTENANCE PROJECT

This project was carried out at a large company in the process industry. The company in question has several plants, each with different types of installations, using different technologies and of different ages. The maintenance department is only partially centralised, and maintenance is considered as a very important activity, because a breakdown can lead to severe problems.

The goal of the project was the development of a customised maintenance concept, which could take care of all the different plants and all the different installations. The driving force for this development was the expectation of more players on the market in the near future. Till now, the company had a nearly monopoly, but in order to remain competitive in the future, the company has to be more flexible and quicker in response. In a first stage, the objectives of the technical service departments of the company were described, and the available resources were determined. The company preferred a maintenance concept, that did not require lots of information and that could help to gather the knowledge, which is in the head of people who already worked with the installations. Within the company, some plants already had a data-processing package (part of a recently introduced ERP package), other were busy implementing it or were going to implement it. It became clear that the implementation of RCM II [2] as described in literature, would be too complex and expensive.

In order to perform the technical analysis, a company-specific questionnaire was developed to identify the Most Important Systems. This questionnaire contained questions on the following (weighted) issues:

- Danger for Safety and Environment (SE), 7 questions, weight factor 3
- Hidden Failures (HF), 1 question, weight factor 3
- Loss of production (LP), 2 questions, weight factor 2
- Repair cost / Secondary damage (RS), 2 questions, weight factor 1
- System Complexity (SC), 2 questions, weight factor 1

The (weighted) score was then calculated as follows:

$$Score = 3 \times SE + 3 \times HF + 2 \times LP + RS + SC$$

Based on this score (0 to 40), the system was classified as follows: a score ≥ 25 means the system is considered as 'important', a score < 25 means the system is considered as a 'normal' or a 'low impact' system.

After selection of the Most Important Systems, the Most Critical Components were determined and a maintenance policy for each component was chosen with the aid of the maintenance policy decision tree described in figure 5.

The implementation of the new maintenance concept delivered the company a reduction in UBM going from 0% to 63%, depending on the plant. The company also declared that due to the optimised maintenance concept, maintenance evolved from a cost centre to a profit generator.

CASE 3: A MAINTENANCE PROGRAM FOR A PAINT SPRAYING ROBOT

This project was carried out at an automotive company [5]. The company in question was well aware of the importance of sound maintenance: the operational impact of breakdowns and malfunctioning equipment as well as the high cost of an extensive preventive maintenance program were considered here. In this project, only one technical system was considered: a paint-spraying robot, used in a truck cabin unit. The goal of the project was the development of an efficient and effective maintenance concept for this new, unique and expensive technical system, but also to set up a general framework for applying this concept to other similar complex equipment in the future. Benefits were also expected in terms of shortened learning periods (concerning failure behaviour) and better predictability of systems availability. The project team contained people from different levels and different departments: maintenance, production and engineering. In this way, a wide range of ideas and visions were available.

The study started with a complete analysis and description of the paint-spraying installation as a technical system, focus was on the paint-spraying unit itself. The paint-spraying installation was placed in a painting-line and was used to spray the finishing coat. The robot has several spray heads, placed in two bells, which can turn around. The whole spraying installation can move up and down to reach the upper side and the lower side of the cabin. The whole paint-spraying installation can be decomposed into a number of different subsystems, which can in turn be grouped in 3 different headunits.

- The paint-spraying unit, containing:
  - The paint-spraying installation for painting the front, the rear, the top and the bottom of the cabin,
  - The paint-spraying installation for painting the sides of the cabin,
  - The system for recognition of the type of cabin,
  - The pneumatic steering system of the spraying-heads,
  - The electrical steering system of the spraying-heads,
  - The tube system for the paint

- The mechanical unit:
  - The transport system for the cabin

- The mixing- and flushing unit:
  - The minimix, which mixes the paint
  - The lyofilisator
  - The recirculation of the flushing detergent

In the analysis, only the paint-spraying unit was considered, because in this unit the most failures occurred. Due to the structured approach and the technical analysis, all information for the construction of a maintenance plan, was available. The whole concept design took about 150 man-hours. The study was considered to be a success. Some useful recommendations concerning e.g. operating procedures and PM schedules came out. It became also clear that some modifications could be made to increase the systems reliability (DOM).

CASE 4: THE OUTSOURCING QUESTION

This project was carried out in process industry. The technical service department of the company was audited in order to get an idea of the effectivity and efficiency of their actions. The company in question produces food packaging materials for the food industry. The technology used, is a well-known, proofed technology, which is widely used. About a decade ago, market demand was enormous and the installations worked at 115% of the nominal capacity. As a consequence, a lot of spare equipment was used for the normal production purposes. In this period, also a lot of money was budgeted for maintenance. Currently, the loss of production due to equipment failure is still less then 0.25%. A few years ago, the company was taken over by a company, which among others also sold a substitute product for the "old" packaging material. Since the take-over, there were a lot of changes in management, reorganisations, changing objectives, changes in available resources, etc. Before the take-over, top-management always had a lot of interest in the maintenance department and realised that maintenance could be a profit generator instead of a cost factor. In the past few years, however, demand decreased with 30%, en the investments in maintenance felt back in favour for marketing, R&D and production.

The audit results were presented as a SWOT (Strengths, Weaknesses Opportunities and Threats) analysis. The audit revealed that due to the changed circumstances a reorganisation of the technical department was advisable. Top management considered outsourcing to be a viable alternative to the reorganisation of the technical department. Worth mentioning in this outsourcing context is the fact that the labour unions were very much concerned about potential job loss. Moreover, 20% of the workers of the technical department were active union members, which gave discussions about (negative) impact on the working environment.

This case illustrates that at the moment that the idea of outsourcing grows, an audit is appropriate. By performing a maintenance audit, an in-depth understanding of the current performance of a company's maintenance department is obtained. An audit was conducted here because there was need to take a picture of the whole maintenance function and its integration in the company strategy. It is obvious that performing an audit is a good starting point to search the answer to the question 'outsourcing: yes or no?'. Outsourcing yields some potential pitfalls, like: hidden costs, loss of control, impact on the workforce, loss of know-how, etc. Before starting negotiations with possible contractors, it is interesting to evaluate the current situation first, in order to have a clear view of the current costs and problems, but also of the current possibilities.

CONCLUSION

A first draft of a conceptual framework for developing a maintenance concept is elaborated in this paper. A conceptual framework identifying the most important aspects to consider, allows a company to develop a unique maintenance concept suited to the specific needs (i.e. a customised maintenance concept). The lack of uniform terminology and the lack of proper insight in the strengths and the weaknesses of the concepts described in literature, make it very difficult for a company to determine e.g. whether a given concept is useful (and worthwhile). Moreover they do not have the time to study or to try out these concepts, and certainly not to make their own customised concept without the aid of a structured framework. In order to facilitate this investigation, the KBM framework was developed. The contribution of this framework is that it can assist maintenance practitioners to consider and develop their maintenance concept for their specific company. The framework will allow them to manage and own the process and to utilise the appropriate resources in the development. The existing modules however need to be supplemented with other modules. In future developments of the framework, more modules will be added, and the content of each module will be carefully elaborated upon. Some modules are e.g. material selection, data management, replacement policy, standardisation, etc. This modular approach will further allow maintenance practitioners to 'take ideas' (i.e. a selection of modules) in order to make a customised maintenance concept. In order to assist in selecting the modules, a decision support module will be foreseen (e.g. decision table, multi-criteria decision making techniques, etc.).

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