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On the impact of optimisation models in maintenance decision making: the state of the art

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In this paper we discuss the state of the art in applications of maintenance optimisation models. After giving a short introduction to the area, we consider several ways in which models may be used to optimise maintenance, such as case studies, operational and strategic decision support systems, and give examples of each of them. Next we discuss several areas where the models have been applied successfully. These include civil structure and aeroplane maintenance. From a comparative point of view, we discuss future prospects. © 1998 Elsevier Science Limited.

1 INTRODUCTION

Maintenance expenditure tends to grow in all sectors of our society, despite technical advances. One principal reason is the continuous expansion of our capital inventory. All man-made structures, like roads, bridges, buildings and industrial plants need maintenance in order to remain fit for use. Another reason is that the requirements for the functioning of systems have increased (consider e.g. the just-in-time production philosophy). Hence non-performance of systems, like electric power generators, has become less acceptable; this all puts greater requirements on maintenance. A third important trend is the outsourcing of maintenance. This puts higher requirements on management since then most work has to be described precisely. In this case there is also more time to focus on the fundamental problems of maintenance instead of being busy with day-to-day fire-fighting. In conclusion, maintenance management is gaining importance and support from science is needed to improve it. One such scientific approach is maintenance optimisation.

Maintenance optimisation consists in broad terms of those mathematical models aimed at finding either the optimum balance between costs and benefits of maintenance or the most appropriate moment to execute maintenance. It is a well-established area as several reviews show; Sherif [1] reports on 818 articles and Valdez-Flores and Feldman [2] on many more since. For introductions and frameworks we refer to [3–5]. For recent problem oriented overviews we refer to [6–8].

Both engineers and mathematicians have contributed to the area. From a mathematical viewpoint the area is interesting as most models exhibit a special structure which can be exploited in their analysis. Due to the complexity of these models, applications have come slowly off the ground, as data are often lacking and the models are not easy to apply. Furthermore, maintenance management first has to structure itself. Other, more qualitative techniques played a role in this respect, such as Reliability Centred Maintenance (RCM) and Total Productive Maintenance (TPM). They may have seemed to compete with the optimisation approaches (see Section 2.3 and Smith [9] and Rausand and Vatn [10] for a critique).

In Dekker [7] a review on applications of maintenance optimisation models is given. The number of applications found is not overwhelming, yet the author concludes that more are to be expected. The constant improvement in the ratio of performance versus cost of computers is a big incentive to quantitative methods. This is accompanied by better software tools which allow the development of decision support systems more rapidly than in previous years. The only other bottlenecks, a proper structuring of the maintenance problems and data collection, are facilitated by better management techniques, automatic data capturing programs and other tools.

In this paper we will consider a number of applications in detail and discuss the state of several areas. The purpose is to show that optimisation is economically attractive and progressing in many areas. We will be open in our

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evaluation since it is our purpose to learn from shortcomings of attempts in the past. The structure of this paper is as follows. We start with a problem and approach classification (Section 2), which is then applied in the sections following. In Section 3 we discuss an operational decision support system and in Section 4 a strategic one. Section 5 deals with a successful class of models based upon the delay-time concept and compares it with cancer screening. Finally, Section 6 discusses some application areas: civil, aeroplane and power system maintenance.

2 PROBLEM AND APPROACH CLASSIFICATION

2.1 Problem hierarchies

Maintenance decision problems can be classified according to several aspects (see [6,7]). A common classification is with respect to the time scale involved. Consideration of maintenance should start early in the *design phase* of systems. The type of equipment, the level of redundancy, and the accessibility then strongly affect the maintainability. When purchasing systems, future maintenance costs should be taken into account as well; to cover the costs over all phases of system life the life-cycle-costing concept was introduced. The maintenance *concept* or *strategy* describes what events (e.g. failure, passing of time) trigger what type of maintenance (inspection, repair, replacement); it can be determined both after the design phase or in the operations phase. Most mathematical models concentrate on this problem area, especially on the optimum interval for inspection or preventive maintenance. Once a system is in operation, maintenance has to be planned and scheduled. Here we denote by *planning* the following tactical activities: the determination of the execution moments of (major) maintenance activities in accordance with other (e.g. production) plans (e.g. planning shutdowns of major refinery units); the work preparation; and the determination of the required maintenance capacity. *Scheduling* of maintenance usually occurs over a shorter time horizon and consists of determining the order of execution of activities. It involves priority setting and using available manpower as efficiently as possible. Finally, there is maintenance *control*, which consists of comparing outcomes with plans, indicating to management where problems are; this area concentrates on performance indicators.

Another classification is with respect to the level at which maintenance decisions need to be taken. We distinguish the following levels: national or company-wide, plant, system, unit and finally component level. At the national or company level decisions with respect to size of the total budget need to be taken. This is especially important in the civil sector, dealing with roads, bridges, dams etc., where the budget comes from the government. This decision allocates the budget over the regional authorities or over the plants. Also at this level, a budget decision has to be made. A system is defined here as a combination of equipment and civil structures capable of fulfilling a specific function. Examples are a bridge, a feedwater system and a building. Within a system there may be different physical entities which are capable of providing a more detailed function on their own and which cannot be split up into lower entities without losing the ability to function; they will be called units. Examples are pumps, vehicles, compressors, etc. Finally components are parts of a unit which can be addressed as independent entities by maintenance. Examples are bearings, filters, seals etc. The definitions given here bear some element of subjectivity: although these terms are often used, their exact meaning differs from case to case. The consequence of this classification is that at the highest levels we have to take all lower levels into account, which can only be done in a simplified and hence always inaccurate way. Next, only at the system level can an independent evaluation of the economic value of functioning be made and hence a maintenance budget be determined. Both at higher and at lower levels one has to relate to the system level and take all kind of dependencies into account. We will discuss this aspect in more detail in one of the decision support systems discussed. Note that the amount of money involved in maintenance decision making is highest at the national level and lowest at the component level.

2.2 Approach classification

There are several ways in which an optimisation model can be applied. We distinguish here between (i) a case study, (ii) a strategic decision support system and (iii) an operational decision support system. In a case study a specific problem is studied for which a dedicated model is built, analysed and run. Using the model, advice is given to management. The strategic decision support system is used each time for one-off problems at a high level (systems or units), just as in the case study. The only difference now is that a comprehensive model is already available in a decision support system at the start of the problem. Finally the operational decision support system is a system developed for a repetitive problem, like the planning and scheduling of road or other maintenance. The system has a database in which all relevant information is stored and analysed. We will give examples of all three approaches.

2.3 Reliability centred maintenance

Reliability Centred Maintenance (RCM) is a structured way to determine the maintenance requirements of complex systems (see [9] and [11]). It was derived from the approaches to structure aeroplane maintenance in the sixties. Maintenance is based on an analysis of failure modes, their effects and the ways to prevent them. It took a long time before it was applied in other industries and it is only now, some thirty years later, applied on a large scale. Some consultants argue (see [11]) that quantification and therefore optimisation is a costly affair and hence not needed. This may be true for many cheap components for which optimisation is not really worth the time spent on the analysis. For expensive equipment optimisation is cost-effective as is also the case for systems with a high degree of commonality, like roads and lamps. Moreover, qualitative approaches miss the what-if analysis options which strategic decision support systems have (see Section 4). Hence, we are of the opinion that RCM is a useful technique to structure maintenance and that, where appropriate, optimisation should be done. This view is supported in [10] and [12]. Optimisation also does not conflict with Total Predictive Maintenance (TPM), which originated in Japan (see [13]). TPM stresses that maintenance should be taken within the production umbrella, with problems resolved by teams of maintenance and production engineers. Maintenance optimisation tools facilitate this process by putting both maintenance and production consequences under a common cost denominator.

3 OPERATIONAL DECISION SUPPORT SYSTEMS

In this section we discuss operational decision support systems for maintenance optimisation. In particular we will discuss one system in detail and mention two other systems briefly. These latter systems were developed in [14,15]. The first of these systems is basically a maintenance management information system extended with some options to do data analysis and which has some embedded optimisation models. It was used by a ship yard. The second system focuses on the scheduling and control of maintenance jobs and considers several priority and performance criteria.

Below we discuss a decision support system, called PROMPT, which was developed for planning and scheduling of preventive maintenance activities of gas turbines on an offshore system. Its description is largely taken from [16].

3.1 PROMPT—a decision support system for opportunity maintenance

PROMPT considers preventive maintenance of gas turbines which consists of a multitude of activities varying from checks and adjustments of instruments to replacements of individual components like filters. The problem with respect to the execution of these activities was that they required a shutdown of the turbine. As most platforms have a yearly shutdown for maintenance, this requires that the maintenance interval is a multiple of a year, which is longer than desired in some cases. Furthermore, any reduction of the shutdown would save money. During a year there are occasions on which one of the turbines is shut down for other reasons, like oil-well maintenance. These moments provide opportunities for maintenance, yet they can hardly be predicted in advance and are of limited duration. Hence a prioritisation of the work is necessary. At the same time, maintenance management requires an assessment of the cost-benefit and optimal interval of all preventive maintenance. To overcome these problems the decision support system was developed.

Note that this problem has both operational (which activities to do now) and strategic aspects (what frequency is best in the long run). The problem required support for repeated decision making, i.e. at each opportunity advice was needed.

An economic evaluation of preventive maintenance on components requires that the costs and benefits are translated from a system level (e.g. water injection) to a unit level (i.e. the gas turbine) and further downwards. Even at a system level it may already be difficult to determine a value of lost production, as the production may be indirect (e.g. water injection) and a complex tax regime may complicate things. Yet this is a task which can be solved by a company's economics department. For the translation from the system to the unit it was assumed that the system can be thought (in reliability terms) as a series configuration of subsystems which each consist of a parallel configuration of units. A generalisation of the well-known k-out-of-n model (i.e. k out of the n units need to function for the subsystem to function) was used in this respect. This allows the calculation of the economic value of a one hour reduction of downtime for each unit in the system. The costs of a component failure then consist of the costs due to a repair (manhours and materials) together with the expected downtime multiplied with the downtime penalty.

Within a unit more than 100 components had to be considered which were addressed by a comparable number of maintenance activities, either instrumental, mechanical or electrical. To keep the administration tractable and to make use of the advantage to maintain similar components at the same time (in order to save set-up work) the activities were permanently grouped into maintenance packages. The grouping of activities into the packages was based on engineering judgement although models can also help in this respect. Activities were also divided into safety related and non-safety related; for the former a fixed time schedule was used and execution was aimed at the last possible opportunity.

For the non-safety related activities at a component level two basic models were used. The first was a mixture of an age and a block replacement model for revealed failures and the second was a simple inspection model for unrevealed failures. These models were developed in the sixties (see [17]) and are well analysed. Yet they could not be used directly, since maintenance was in this case restricted to opportunities. Also the few existing models on opportunistic maintenance could not be used since these all assumed that opportunities were generated by failures of the components themselves, whereas in this case they were generated by causes outside the unit. Hence new models were developed (see [18,19]). From the models a priority criterion was constructed by considering the expected costs of deferring maintenance from one opportunity to the next one and subtracting from that the minimum average costs. That is, at each opportunity one would calculate the expected costs due to deferring the execution of the package to the next opportunity and subtract from that the minimum average costs.

Table 1. Opportunity maintenance advice—non-safety MPs

Installation:	System: A.06 Main Oil Export
Sub-System: Pumping	Unit: P-306 Avon/Mather & Plat
Current Opportunity: 01 02 89	
	— 0 Days later with prob. 0%
Next Opportunity: 01 03 89	— 28 Days later with prob. 100%
	— 0 Days later with prob. 0%

No.	MP Code	MP Name	Effort	Ranking	Execute
1	M 23	Vents	2.00	5.1	←
2	M 16	Fuel Valves	1.00	–.0	
3	M 32	Anti Vib Pads	3.00	–.1	
4	I 38	Hi SPD Shut Off	8.00	–.2	
5	E 48	O/H MTR CONT CEN	8.00	–.2	
6	M 22	Dampers	3.00	–.3	
7	M 34	Cell Bypass Door	4.00	–.3	
8	E 19	SWBOARD AUX SUPP	2.00	–.3	
9	E 21	AUX DIST BOARD	3.00	–.3	
10	E 41	O/H MRT CON CENT	16.00	–.4	

For further information enter MP No.

PF1	PF2	PF3	PF4	PF5	PF6	PF7	PF8	PF9	PF10
Safety		Return		Next Screen	Previous Screen		Help		

Theory then yielded that deferring the execution of the package was cost-effective (and thus smaller than the average costs) provided that the first opportunity was below the optimum threshold time for maintenance.

Three types of age measures, namely runhours, starts and stops, and calendar time were considered to relate the use of the machine to the probability of failure. Exponential filters were used to estimate on-line the average use in runhours and starts/stops, since these indicators had to be transformed to calendar time in order to allow predictions on the use till the next opportunity.

3.2 Parameter estimation and expert judgement

The parameter estimation turned out to be a major task since maintenance management, with the new insights obtained in the study, decided to use a new definition of maintenance activity and package. After this engineering task was completed, a major difficulty was encountered with respect to the reliability data at component level. The data present in the maintenance management system turned out to be unreliable and inadequate for the purpose. It was unreliable, since personnel had been sloppy in the data recording. Furthermore, the reliability data did not show many failures; for one third of the failure modes there had been no failure occurrence and finally, the data only indicated that maintenance had been done, but not whether it brought back the component to an as-good-as-new state or to the as-good-as-before condition. To overcome these problems it was decided to make use of the judgement of the engineers for the elicitation of statistical lifetime distributions. A questionnaire was set-up and filled in by the engineers at the platform. There was quite a difference in the answers between the experts. Sometimes the values were estimated relatively rather than absolutely, which is caused by anchoring on the interval scale used (estimating probability of one failure mode by comparing it to another). This led to very low estimates (once in hundred years for failure of some component). The few literature items available on elicitation focused on probabilities rather than on distributions. In the end reasonable estimates were obtained, and it was the idea to update them regularly based on the reported experience. Later on more research on the elicitation of expert judgement was done. For further discussion, see [20,21] which developed and analysed Bayesian methods for elicitating, combining and updating expert opinions for maintenance optimisation.

3.3 The decision support system

The operational decision support system (DSS) was developed on an IBM mainframe using a FOCUS database and with several FORTRAN routines for optimisation. In addition to the DSS there was a maintenance management information (MMI) system available on-shore residing on an IBM mainframe. On-shore staff ran the analysis, and examined the list of advised maintenance activities which then was sent by internal mail to the platform. The off-shore crew reported back on paper and data were fed manually into the computer. It was envisaged that in a later stage there would be a terminal on board the platform.

Table 1 shows an example of a ranking list which is produced by the operational DSS. The user has specified the date at which an opportunity occurs and for which he wants advice (this may be some date in the future). Next he specifies the system, subsystem and finally the unit for which he wants advice. An important element in the decision making procedure is the first alternative moment for maintenance, being the next opportunity. By default the system uses an historic three point distribution for the time to the next opportunity, but this can be overruled.

The table gives the ranking value (or priority criterion) for the first maintenance packages addressing unit P-306. It also shows the package code (indicating whether it is an M—mechanical, E—electrical or I—instrumental package), a short description of the package and the total man-effort required to execute it. The ranking value indicates the expected money loss by deferring execution of the package to the next opportunity, as specified before.

The advice was well accepted by the maintenance foreman responsible for the planning. It did not prescribe for him what to do, merely it indicated the importance and dueness of each activity. He then had time to check whether the necessary spare parts were available and which number of men with which skills (electrical, mechanical or instrumental) could be put on the job. At some time during the development of the DSS it was considered to build a knapsack module which would optimise the set of maintenance packages to be carried out during an opportunity. The idea was that the planner would enter the amount of time available and that the decision support system would then give the best choice of packages. Luckily this route was not pursued: the ranking list reduced the problem to such an extent that the planner could make his decisions in a short time span. The proposed knapsack procedure would take away his decision freedom, whilst the procedure could not capture all aspects involved (stochastic durations, different skills available, unavailability of spare parts). Moreover, incorporation of a knapsack module would add extra complexity to the DSS whilst it would not save much against the human expert. In many model studies researchers compare "their algorithm" with dumb procedures and never with the results from human experts: this is justified from a scientific point of view, yet in practice it is the human expert which needs to be improved upon.

3.4 Evaluation of the DSS

After 12 months of operation an analysis was made of the benefits of the DSS. Clearly some 30% less maintenance was being done and the, till then, inevitable backlog in preventive maintenance had virtually disappeared. On many occasions, the DSS correctly advised the off-shore staff not to carry out preventive maintenance even if there was an opportunity to do so. Quantification of true benefits could only be done, however, using the developed model of the process. Again the recording of activities in the MMI was too inaccurate to draw statistically valid conclusions.

The operational decision support system did make actual planning and scheduling a lot easier, by reducing the number of alternatives to be considered and by providing easy to handle priority criteria. It also had its effect on long-term strategy, rationalising that maintenance which was not cost-effective, allowing better use of opportunities and hence reducing the work load on the annual shutdowns. It did enforce a coupling between machine importance and the amount of maintenance work spent on the machines. Although this is advocated in an approach like Reliability Centred Maintenance (RCM), PROMPT is the first tool to achieve such a coupling automatically in practice.

A major disadvantage of the system developed was its need for data, requiring extensive data collections for some activities for which the optimisation did not make a large difference. It would be better to develop a simpler procedure for some activities, with less data requirements and less reporting effort, but which would also indicate whether a more advanced procedure was needed.

3.5 General remarks on operational decision support systems

Planning and scheduling of maintenance are operational activities which need to be supported by computer systems. Almost all maintenance management information systems on the market have little or almost no intelligence built in to support their activities. Their main functionality is the provision of relevant information which can be helpful on its own. We can only speak of decision support if a system is able to support the choice between alternatives, that is, if it is able to answer "what-if" questions.

Operational decision support systems do require a lot of data, hence the initial effort is large. Their link with the maintenance information systems is essential. Ideally the DSS would function on top of the information system. This does require that the information system contains all necessary information, especially on the underlying time to failure distribution, modelling whether the hazard rate increases. This is, however, almost never the case. At a component level this requires much work as will be clear from the case study. This kind of information is usually available in failure mode effect and criticality analyses made during the design of the system. Such information should then be used to structure the maintenance management information system. Such a combination would then also allow much better learning of the failure behaviour than the present day unorganised feedback. Unfortunately, such links are rarely made because the manufacturer and buyer seem to have different interests. The first only supplies the maintenance scheme and not the underlying information to the buyer. Perhaps things will improve if the buyer changes into a user only and starts to lease the function instead of having the ownership of the system.

The only exception to this analysis is an operational system which takes all maintenance frequencies as fixed and tries to schedule the work such that it can be coördinated in conjunction with production. In this case data requirements are much less and far more information can be used from the information system. This is the case with the DSS described in [15], and in those used in the airline overhaul systems which will be discussed later.

4 STRATEGIC DECISION SUPPORT SYSTEMS

In this section we discuss strategic decision support systems in general and one, called MAINOPT (see [22]) in detail.

Following developments in computer technology, these kinds of systems were first developed on micro computers or mainframes and moved later to the personal computer. This is the most ideal platform, with good graphical capabilities and widespread availability. Initial packages were developed and marketed by the academics who were studying the underlying models (see e.g. [23]). Later on, some more packages came on the market. We should mention KMOSS from the KEMA (see [24]), LCC-OPT, focussing on life cycle costing from S and G consultancy (see [25]) and MACRO, a successor of MAINOPT (see [26]). All packages claim that substantial savings can be made on maintenance, e.g. LCC-OPT claims savings of 30%.

MAINOPT is one of the first commercial PC-based decision support systems for maintenance optimisation. It uses the standard age, block replacement and efficiency models as analysed in [17]. Its main strength was the embedding of these models in a user-friendly environment in which the input for these models could easily be formulated by a maintenance engineer. This aspect which turned out to be crucial, had completely been ignored in the mathematical analysis provided in [17]. MAINOPT was developed at the beginning of the eighties. It was marketed with emphasis on applicability rather than on sophistication of the underlying models.

MAINOPT has successfully been applied in several companies, including the Royal/Dutch Shell Group (see [27]), with applications saving over millions of dollars. Essential elements in its success were the combination of reliability and economics (people often had little idea of the costs involved) and the possibility to compare options and answer ''what-if'' questions. A major complaint against models is that the input parameters are unknown. This may be true, but in most cases there is some idea of the order of magnitude, which often suffices, and the option to do sensitivity analysis helps to overcome the uncertainty. Just trying two different values and observing that the results are not much different is an important aspect of decision support systems. It is important in this respect that the input questions are formulated in such a way that engineers can give their judgement about them. For example, asking for a Weibull shape parameter is not a good question; instead ask for estimates of the failure probabilities. Horton [12] also gives a good review on the success of MAINOPT and relates it to RCM.

A major difference between operational and strategic decision support systems is that the latter are much more focused on problems at a higher level, e.g. a system or unit. This limits the amount of data necessary considerably. The potential gains are accordingly much higher. Since strategic decisions are each time different, there is little need for complicated databases to store all information. User-friendly interfaces are therefore very important. Accordingly, these systems can work alone, which makes their development much easier. The systems do need some training and the expertise in using them also requires some maintenance.

5 CASE STUDIES

There are far too many cases to be reported in this paper (see [7] for an overview). Therefore we concentrate on a particular model, the delay-time model, on which there are more than 10 case studies reported.

5.1 The delay-time model

The delay-time model was first proposed in [28]. More than 10 successful cases are reported in the overview of [29]. The model concentrates on the frequency of inspections at which prestages of failures, so-called faults, can be observed. The delay-time is the time which elapses between the first moment that a fault can be observed and the eventual failure. It is assumed that corrective actions upon a fault are much less costly than those upon a failure. The delay-time is a generally applicable concept and is much more effective than a preventive replacement based on statistical information regarding an increasing hazard rate. It corresponds in fact to the P–F interval used in RCM (see [11]). However, whereas in RCM it is just stated that inspections should be done more frequently than the estimate of the P–F interval, the delay-time model tries to capture the distribution of this interval to determine an optimal inspection interval. In the cases reported on the delay-time model several statistical techniques have been introduced to determine the distribution of the delay-time together with methods to determine it from expert judgement. The cases also show that by use of the delay-time model the number of failures can be reduced significantly.

For example in [30] the authors consider delay-time modelling applied to a complex system used by a copper products manufacturer. What is interesting about this paper is that it importantly addresses aspects of the problem relating to problem recognition, model development and fitting and validation. Although the specific model described in the paper is applicable to the plant under consideration, the techniques described in the paper are general and could be applied by OR modellers in other outlets. However, delay-time modelling has not yet reached the stage at which it is in the hands of engineers.

5.2 Relation with screening for cancer

There are many similarities between the delay-time model and the models used to determine the cost-effectiveness of various screening policies (see [31] for a screening model). In fact an early stage of cancer (like breast or cervical cancer) corresponds to a fault in a machine. Here again the major requirements for effectiveness of screening or inspection come forward: there should be some observable prestage of the disease (that is the fault) and the treatment upon observation of the prestage should be much more successful than when the disease has manifested itself. In costs terms: the cost associated with a fault should be much less than that associated with a failure (that is the manifestation of the disease).

The difference between cancer screening and inspection of industrial machines is twofold. In humans age is a dominating aspect. Cancers hardly occur in youngsters, and if they do, they can hardly be detected beforehand. The delay-time seems to be age dependent. This is much more difficult than what is usually assumed in industrial inspection studies. Secondly, cost minimisation is not the driving force behind screening studies. Instead one tries to determine the efficient cost-benefit frontier. That is, for any given budget one determines the best screening policy and evaluates its success in e.g. the number of cancers detected prematurely or the number of lifeyears gained.

Cancer screening is now well-accepted within all developed countries and much research on its cost-effectiveness is being conducted. The screening policies applied in practice, however, may differ substantially from country to country. These differences are only partly due to differences in cancer characteristics, and to a major extent to differences in management policies. Accordingly much research must still be carried out, since all health expenditures are under great economic pressures. Yet in a cost-effectiveness evaluation of all medical treatments (that is comparing the costs of saving one lifeyear) cancer screening comes out very favourably.

A comparison of cancer screening with inspection of industrial machines does teach us that many problems can be overcome. The success of optimisation models is however dependent on the commonality and repetitiveness of the problem, the cost savings obtained by optimisation and finally by the willingness to develop the models in relation to practice and to share the knowledge gained with others through publications.

5.3 Condition monitoring

Quite often maintenance optimisation is associated with the optimisation of the frequency of routine maintenance, like changing filters. In fact in the fifties large scale planned replacements were advocated. Later on, this policy did not always turn out to be effective. This can well be understood from the models. If the hazard rate is hardly increasing then the optimum will be vary flat and preventive replacements are not that worthwile. Much later, in the seventies, methods were developed to determine more accurately the actual condition of equipment than what follows from statistical information. This approach is called condition monitoring and it includes techniques like vibration analysis and oil debris analysis. It currently takes more of an engineering approach to failures than one of an economic optimisation. Condition-based maintenance in fact replaced many of the planned preventive replacements. Unfortunately, condition monitoring has only been able to indicate that a failure is impending. Its long-term prediction capabilities are limited so far. It has also concentrated on costly breakdowns of major equipment, like gas turbines, in which case the cost-effectiveness was without doubt. In recent years it has, however, been demonstrated that condition-based maintenance can be combined with optimisation and that such a combination is worthwile. For a recent example see [32]; this paper also describes the development of an operational decision support system. A recent case study is [33].

6 DISCUSSION OF APPLICATION AREAS

6.1 Civil maintenance

Civil maintenance is necessary for all civil structures, like roads, dams, bridges and dikes. Quite often large sums of money are involved both in the construction and in the maintenance phase. The speed of deterioration is often much smaller than in mechanical equipment, yet the rate of economic obsolescence is also much lower, implying that the maintenance cost of the structures over the lifecycle is still very substantial. Since World War II many new structures have been built. Now, some 30 to 40 years later we see a steady increase in maintenance expenditure which clashes with the need to control governmental expenditure. It will therefore be no surprise that especially in the USA it is an urgent governmental problem to determine and allocate budgets for maintenance of roads and bridges. A first and important contribution was made [34] for a state wide pavement management system in Arizona (USA). Since that time many studies have been made. Road maintenance optimisation has certainly been a success area as the recent review [35] shows. According to [36] every state in the USA is now obliged to have a pavement management system. The methods employed are Markov analysis and linear programming for the network optimisation. Roads are subdivided in lanes of a fixed length (say 100 m) for which maintenance actions are determined. The Markov analysis is applied to model the deterioration of a sector with the complicating factor that roads deteriorate by several mechanisms (crack forming, longitudinal and latitudinal roughness). Since 1982 many statistical analyses have been done to determine the best modelling of the deterioration, from which the Markov transition probabilities follow. Once the appropriate actions have been determined per section, one combines the actions over several sections and lanes taking all kinds of constraints and set-up savings into account. Finally at the highest level, budgets are allocated across various roads and highways. A nice overview is given in [37]. Although theory is advancing, there is still scope for new developments as the full integration between all problem phases has not yet been achieved. Moreover, new elements, like execution planning to reduce congestion caused by maintenance, have to be included in the planning. Finally, there is the problem of how to determine road conditions: should this be done manually, with experts overriding model advice or can it be done automatically, by expert systems analysing video images of the road.

One may wonder why optimisation has proved to be successful in this area. We could mention the following aspects

1. the problem is repetitive, the problem structure remains more or less the same, and the large duplication of the parts to be maintained (lane sections) allows for structured data collection.
2. a lot of money is involved, hence there is a need for better decision making tools.
3. the problem owner is open about the problem (no competition) and faces an allocation problem which requires objective methods. Finally, the management and execution of maintenance are separated. This allows management to take a much longer term view.

It is not the case that the problem is easy. Instead the models and techniques applied are much more difficult than the standard age replacement problem.

Maintenance optimisation methods have penetrated other areas of civil maintenance as well. We like to mention bridge maintenance, both from an economic point of view ([38]), and from a structural reliability point of view ([39]), dike maintenance ([40,41]), concrete deterioration ([42]) and building maintenance ([43]).

6.2 Aeroplane maintenance

Aeroplanes are amongst the most expensive industrial systems which at the same time have the highest reliability and safety requirements. In this case the manufacturer sets up a list of compulsory maintenance. Any optimisation should be done in this phase when the maintenance concept is designed. Because of high uncertainty the manufacturer tends to have a large safety margin. Most developments have gone into reducing downtime by modularising systems and inflight diagnosis of failures. As a result, there seems to be little scope for optimising maintenance frequencies outside the manufacturer, although it may be worthwile to adapt the maintenance to the use of the aeroplanes. The main challenge then is to plan and schedule the maintenance such that operations are at least unaffected and the maintenance workforce is used as efficiently as possible.

Because of the competitiveness of the various consulting and airline companies, not many papers have been published. Yet any major airline is likely to have a computerised overhaul planning and scheduling system (see [44] for example). A main definition of the underlying problem is job-scheduling-on-parallel-machines with precedence, deadline and machine utilisation and availability constraints. It will be clear that the theory behind this is much different from the more stochastic techniques used to optimise the costs and benefits of maintenance.

Other work worth mentioning concerns maintenance manpower planning and utilisation models. We like to mention [45,46]. Similar conclusions can be made for electric power system overhaul planning and scheduling. Here we refer to the overview paper [47].

7 GENERAL EVALUATION AND CONCLUSIONS

In this paper we have discussed applications of maintenance optimisation models in several contexts, both in the problem area as well as in the way they are executed as a case study or decision support system.

Many arguments have been made against the models and favouring more qualitative approaches like RCM and TPM or other approaches like condition monitoring. It is a fact however, that optimisation models can offer much more than the qualitative approaches, yet at a cost of an increase in complexity and specificness. The case studies and decision support systems presented, as well as the methods mentioned in the areas of road, bridge, aeroplane maintenance and of cancer screening show that there is certainly a need for optimisation. The limited number of applications may be more a transient problem caused by an inadequate organisation of the problems by the problem owners and a lack of training in the education of engineers. In fact, traditional engineering education focuses on the design of systems and not on maintenance.

Problem structuring and sharing with others, well-organised data collection and analysis, development of models in conjunction with the problem owner and application of the newest information technology are certainly needed to take advantage of the potential of optimisation methods. Next, more attempts should be made to integrate the quantitative approaches with the qualitative ones, like RCM. Worthwhile in this respect is the work in [10]. On the educational side we have to increase the efforts to teach the engineers on the economics of maintenance and show them the principles of optimisation. Finally it appears that maintenance optimisation theory is far from complete. All cases (like the PROMPT DSS and road maintenance) show that, especially in the multi-component aspects, we are only at the beginning.

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