Applications of maintenance optimization models: a review and analysis

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In this paper we give an overview of applications of maintenance optimization models published so far. We analyze the role of these models in maintenance and discuss the factors which may have hampered applications. Finally, we discuss future prospects. © 1996 Elsevier Science Limited.

1 INTRODUCTION

Throughout the years, the importance of the maintenance function, and therefore also of maintenance management, has grown. The widespread mechanization and automation has reduced the number of production personnel and has increased the capital employed in production equipment and civil structures. As a result, the fraction of employees working in the maintenance area has grown, as well as the fraction of maintenance spending on the total operational costs. In refineries, for instance, it is not uncommon that the maintenance and operations departments are the largest and that each comprises about 30% of total manpower. Furthermore, next to energy costs, maintenance spending can be the largest part of the operational budget (see Ref. 113). Yet, the main question faced by maintenance management, whether its output is produced both effectively, in terms of contribution to company profits, and efficiently, in terms of manpower and materials employed, is very difficult to answer.

In theory, maintenance management, facing these problems, could have benefited from the advent of a large area in operations research, called maintenance optimization. This area was founded in the early sixties by researchers like Barlow, Proschan, Jorgenson, McCall, Radner and Hunter, whose results are nicely summarized in the review by McCall97 and the book from Barlow & Proschan.5 Basically, a maintenance optimization model is a mathematical model in which both costs and benefits of maintenance are quantified and in which an optimum balance between both is obtained. Well-known models originating from this period are the so-called age and the block replacement models. Later on, the area proved to be fruitful for researchers. Reviews were made by Pierskalla & Voelker,96 Bosch and Jensen,14 Sherif & Smith109 and Sherif;110 the latter two even reporting on 524 and 818 articles respectively and many more have appeared since. Valdez-Flores & Feldman118 report on more than 120 papers since 1982, while Cho & Parlar24 give the latest survey (on multi-unit models). Besides, many textbooks on operations research use replacement problems as examples.

Considering the foregoing, the following questions arise. First of all, what has been the value of maintenance optimization models for maintenance management? How often and in what sense have these models been applied successfully? Here, we do not focus on theoretical applications, but on applications yielding advice to management concerning maintenance on existing systems. In 1960 Mayer56 and in 1967, Turban116 had already formulated the same question and concluded, after some research, that optimization models were applied in only a small minority of firms. As a quick glance indicates only a small number of applications (see Ref. 61), we also investigate what is needed for successful application of these models on maintenance problems and what presently constitutes the main bottlenecks. This analysis will also make clear to what extent future applications may be expected.

Our approach to these questions follows three routes. First of all, a literature search has been made on applications of maintenance optimization models and on tools developed to assist in maintenance optimization. Furthermore, discussions have been held with various people concerning the value of maintenance optimization models. Thirdly, the author has been involved with developing and implementing...
decision support systems for maintenance optimization. Combining information from all sides, a general evaluation of the value of maintenance optimization models as tools for management is given.

The structure of this paper is as follows. After a review of maintenance management, we introduce maintenance optimization models in Section 3. In Section 4 we present a review of applications and discuss bottlenecks for application in Section 5. This leads to future prospects which are dealt with in Section 6.

2 MAINTENANCE MANAGEMENT

2.1 Objectives

Maintenance can be defined as the combination of all technical and associated administrative actions intended to retain an item or system in, or restore it to, a state in which it can perform its required function. The maintenance objectives can be summarized under four headings—ensuring system function (availability, efficiency and product quality); ensuring system life (asset management); ensuring safety; ensuring human well-being.

For production equipment, ensuring the system function should be the prime maintenance objective. Here, maintenance has to provide the right (but not the maximum) reliability, availability, efficiency and capability (i.e., producing at the right quality) of production systems, in accordance with the need for these characteristics. In principle it is possible to give an economic value to the maintenance results, and a cost-balance can be done. Ensuring system life and asset management refers to keeping systems as such in proper conditions, whilst there are only indirect links to a possible production of goods or services. This objective is appropriate for civil structures, like buildings, dams, offshore platforms and roads, as their function is complex and not easy to measure. Often norms have to be set to define failure and the benefits of maintenance are therefore more difficult to quantify. In this case one has to minimize maintenance costs in order to meet the norms or conditions on states. Safety plays a role in case failures can have dramatic consequences, e.g., in the case of airplanes, nuclear and chemical plants. In this case testing and inspection activities constitute an important part of the maintenance work. Here, costs of maintenance have to be minimized while keeping the risks within strict limits and meeting statutory requirements. Finally, we refer to human well-being or shine as an objective, if there is no direct economic or technical necessity but primarily a psychological one (which indirectly may be economical). An example is painting which is not for protective reasons. This objective is the most difficult one to quantify.

2.2 Historical overview

Here we briefly mention some main trends in the history of maintenance management, following the reviews given by Kelly and Pintelon & Gelders. The first scientific approaches to maintenance management date from the 1950's and 1960's. At that time preventive maintenance was advocated as a means to reduce failures and unplanned downtime. In many companies large time-based preventive maintenance programs were set-up. First operations research models for maintenance appeared in the sixties, attempting to optimize these programs. In the 1970's condition monitoring came forward, focusing on techniques which predict failures using information on the actual state of equipment (e.g., lube oil debris analysis, vibration monitoring). This proved to be more effective than the large time-based preventive maintenance programs. Detailed studies by manufacturers about the failures of their products resulted in better designs, with less failures as a result. In the 1980's the computer was brought to the maintenance function. Initially most attention was paid to facilitating administrative processes, later on by making management information readily available (e.g., the registration of the causes for overtime); yet their influence on decision making has been limited. An important approach worth mentioning is Reliability Centred Maintenance (RCM), which was founded in the sixties and initially oriented towards airplane maintenance. It is only now, more than twenty years later, that it has started to break through in many industries. It directs maintenance efforts at those parts and units where reliability is critical. It can be regarded as the more qualitative approach to maintenance where optimization models are the quantitative approach, yet it is far more all-embracing than models which have only a limited applicability (see Ref. 58 for a comparison between cost-optimization and RCM). Another, qualitative approach which should be mentioned is Total Productive Maintenance, originating from Japan, which centres about solving maintenance problems using a quality circles method.

2.3 Comparing maintenance management with other management areas

Maintenance has sometimes been described as the last frontier of scientific management. Lately it has attracted scientific attention and received greater status. The area is dominated by technically oriented people whose prime knowledge lies in solving
Thinking on maintenance should start in the design

technical problems (e.g., ‘why did a pump fail?’) and
in managing people, but who are not familiar with
reliability theory or operations research. Two aspects
are typical for maintenance management.

First of all, maintenance faces an inherently
stochastic deterioration and failure process. The state
of affairs in a maintenance organization is often
dominated by unplanned events. Failures of important
equipment may delay long-planned activities. Major
decisions, e.g., choosing between replacement or
repair, may have to be taken quickly. Management,
being under constant time pressure, therefore lacks
time to become familiar with abstract management
science techniques.

Secondly, maintenance consists of a multitude of
different activities. At an individual activity level it is
often difficult to quantify benefits of maintenance.
Hence, at a macro level, it is very difficult to balance
the maintenance budget with its contribution to
company profits. Therefore, maintenance is often seen
as a cost function only, with all associated negative
implications.

2.4 Problem hierarchies

Thinking on maintenance should start in the design
phase of systems. The type of equipment, the level of
redundancy and the accessibility will then strongly
effect the maintainability. When purchasing systems,
future maintenance costs should be taken into account
as well. To cover the costs over all phases of systems
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 and in the
operations phase. Most operations research models
concentrate on this problem area. Once a system is in
operation, maintenance has to be planned and
scheduled. Here we denote by planning 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 at 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 actuality with plans, indicating to manage-
ment where problems are.

2.5 Areas where maintenance is important

Whenever there is a large amount of capital employed
in technical systems, there will be a lot of
maintenance (except, for example, space satellites, for
obvious reasons). So, apart from the service sector,
maintenance plays a large role in most sectors of
society. Even in the software sector maintenance is
growing in importance, but due to the special
character of the systems to be maintained—software—
we will leave it out of consideration in this paper. The
medical sector can also be captured under the
definition of maintenance, when humans are con-
sidered to be the systems of interest. Despite many
similar concepts (e.g., lifetime distributions and
screening for diseases corresponds to inspection), we
will not consider this here either. The main industries
considered are the oil and chemical industry, railways,
transport companies, airlines, steelworks and the
discrete parts manufacturers. Also considered are: the
public sector, for example electricity generation;
defence; and infrastructure, for example roads.

3 MAINTENANCE OPTIMIZATION MODELS

Here we define maintenance optimization models as
those mathematical models whose aim it is to find the
optimum balance between the costs and benefits of
maintenance, while taking all kinds of constraints into
account. In almost all cases, maintenance benefits
consist of savings on costs which would be incurred
otherwise (e.g., less failure costs). This definition does
not include all operations research models applied in
maintenance. Scheduling outages of electric power
plants for maintenance is left out of consideration,
unless typical maintenance aspects (like deterioration)
are modelled explicitly. We exclude project manage-
ment techniques, although some are used in shutdown
planning of major installations in the process industry,
as these lack the cost-benefit aspects of maintenance.
We also exclude spare parts models as these primarily
focus on inventory control.

In general, maintenance optimization models cover
four aspects: (i) a description of a technical system, its
function and its importance, (ii) a modelling of the
deterioration of the system in time and possible
consequences for the system, (iii) a description of the
available information about the system and the actions
open to management and (iv) an objective function
and an optimization technique which helps in finding
the best balance. For example, for the age
replacement model the four aspects consist of: (i) ‘one
component, operating continuously’, (ii) ‘deterioration
is not visible and failures occur suddenly, causing a
loss of functioning’, (iii) ‘the component is replaced
upon failure by an identical one against costs c' (includ-
ing costs of loss of functioning) and preven-
tively against costs c' (whenever it takes place),
replacement times are recorded: a pdf f(.) or a hazard
rate r(.) as function of component age is known’, (iv)
objective functions are either the long-term average costs, or the long-term discounted costs; the renewal reward theorem provides an explicit formula for the objective function as a function of the replacement age, which may be minimized by a standard bisection method.

Sherif & Smith classify the models according to the modelling of the deterioration into:
1. Deterministic Models
2. Stochastic Models
   A. Under Risk
   B. Under Uncertainty.

They further distinguish between a simple system (single component) and a complex system. The difference between risk and uncertainty is that in case of risk it is assumed that a probability distribution of the time to failure is available, which is not so in the case of uncertainty. The latter therefore includes models with adaptive policies. The optimization methods employed include linear and nonlinear programming, dynamic programming, Markov decision methods, decision analysis techniques, search techniques and heuristic approaches.

Maintenance optimization models yield various results. First of all, policies can be evaluated and compared with respect to cost-effectiveness and reliability characteristics. Secondly, results can be obtained on the structure of optimal polices, like the existence of an optimal control-limit policy. Thirdly, models can assist in the timing aspect: how often to inspect or to maintain. These results all refer to the maintenance concept; the last one also to maintenance planning. Finally, models can also be of help in determining effective and efficient schedules and plans, taking all kind of constraints into account.

4 A REVIEW OF APPLICATIONS

4.1 Introduction

As models may be applied in several ways, we will make the following distinctions. A paper is classified as a case study if (maintenance optimization) models have been used with real data to provide advice to management on a real problem. A second type of paper is one in which a new model is put central, but in which indications are given about (not just possible, but real) applications of the model. This can occur in several ways, varying from just suggesting applications or overviewing real applications to showing examples with real data. The last type of paper is that which focuses on an application tool, like a decision support system or expert system and which mentions applications of the tool.

A literature search was conducted in the database INSPEC using the search words ‘maintenance’, ‘replacement’, ‘repair’, ‘optimization’ and ‘application(s)’ or ‘case study/ies’. This resulted in some fifteen papers. Next, we wrote to a number of leading experts asking them about applications. Then we traced as many references on applications as possible. A problem encountered in this respect was that practitioners more often publish in proceedings than in regular scientific journals, yet this category is far more difficult to trace and is often not covered by the regular databases, like INSPEC.

4.2 Applications

The number of real case studies found was 43. [References: 3, 6–8, 13, 15, 16, 18, 20, 23, 25–32, 35, 46, 49, 55, 59, 63-65, 69, 79, 84, 89, 92, 93, 96, 99, 101, 106, 111, 114, 115, 117, 120, 123, 128.] Furthermore, there are 22 papers which present a model and apply it to real data [Refs 11, 21, 22, 34, 40, 44, 45, 52, 57, 76, 82, 83, 85, 91, 94, 97, 104, 105, 108, 112, 121, 131] and 8 papers which give some overview and give some discussion of case studies [Refs 10, 17, 33, 47, 48, 60, 75, 78]. There are 26 papers which focus on a model and state that it has been applied to a real case, without giving further details (like data) [Refs 2, 9, 12, 36, 37, 39, 41, 42, 53, 56, 62, 67, 68, 70, 72, 74, 77, 81, 88, 90, 102, 103, 107, 126, 129, 132]. Finally, there are 14 papers (including 4 which also present a real case) describing an application tool and mention its application [Refs 38, 43, 51, 54, 65, 66, 73, 80, 117, 119, 122, 125, 127, 130]. If we add up all papers from which we have an idea that an application has occurred we arrive at a total of 112 applications of maintenance optimization models, which is more than we initially expected.

Most case studies are written in cooperation with academic reliability researchers (68 out of the 112). Few originate from industry and if they do, often from an industrial research institution. Consultants are badly represented, giving the impression that application of maintenance optimization models was only possible by the people who developed them. This situation has changed with the emergence of commercial decision support systems for maintenance optimization.

Looking at the year of publication of all 112 papers gives the following picture:

<table>
<thead>
<tr>
<th>Year</th>
<th>Number of Publications</th>
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<tbody>
<tr>
<td>1969</td>
<td>1</td>
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<td>1970–1974</td>
<td>4</td>
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<td>1975–1979</td>
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<td>1980–1984</td>
<td>20</td>
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<td>1985–1989</td>
<td>45</td>
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<td>1990–</td>
<td>25</td>
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The fact that the majority of the papers has recently been published may indicate that a number of initial problems have been overcome and that more
We do not have much information about the military sector. Some papers\textsuperscript{17,44,103} suggest that the US forces have access to maintenance optimization models, but precise information is lacking. Some separate applications are manpower requirements planning, inspections in the nuclear industry and lighting maintenance. There are few papers on life cycle costing.

The problems encountered in applying maintenance optimization models mentioned in the case studies frequently concern data collection and analysis. As most papers advocate the technique, negative remarks on maintenance optimization are hard to find, except in the paper from Van Bommel \& Roes\textsuperscript{120} which describes a failure to apply standard models and therefore (successfully) resort to failure analysis.

### 4.3 Software packages for maintenance optimization

The first packages for maintenance optimization ran on micro computers, like the HP 9845. They were developed by academics with an interest in practical applications. An example is the REGINA package, developed at Bradford University, which contains basic optimization models next to data analysis modules. Its use is described in Keller and Giblin.\textsuperscript{24} Another example is the FRANTIC package.\textsuperscript{127} Later, the personal computer became a popular platform for maintenance optimization software. Successful examples are the MAINOPT package,\textsuperscript{130} the AGE/CON, PERDEC and RELCODE packages,\textsuperscript{54} the KMOSS package from the Dutch KEMA,\textsuperscript{125} the OPTIMON package from the Dutch TNO,\textsuperscript{57} all including analytical models. MAINOPT is in fact the most papers advocate the technique, negative remarks on maintenance optimization are hard to find, except in the paper from Van Bommel \& Roes\textsuperscript{120} which describes a failure to apply standard models and therefore (successfully) resort to failure analysis.

### 4.4 General remarks

One can make two remarks on the above. First of all, we are certainly missing some applications published. Secondly, applications of any particular operations research model are not frequently found in literature as it is mostly not sufficiently rewarding for practitioners to publish. If approaches are successful,
companies are afraid of losing a competitive edge. Furthermore, scientific literature focuses on new aspects and the tenth application of the age replacement model will therefore not be published.

One may compare, for example, maintenance optimization theory with game theory, for which there may be even less applications. The main exception in operations research is linear programming which is widely used. In general, there is a long time gap between the emergence of a theory and its application. In the sequel of this paper we will investigate applications of maintenance optimization models in more detail.

5 PROBLEMS IN APPLYING OPTIMIZATION MODELS

In this section we discuss a number of problems which hamper optimization. It is difficult to state scientifically which reasons are dominant, so the selection is based on the authors own experiences with maintenance optimization models.

5.1 Decision support systems needed to optimize maintenance

Almost no maintenance optimization model yields results which only require simple calculations like the EOQ formula for the economic order quantity in inventory control \((\text{EOQ} = \sqrt{\frac{2AD}{vr}})\). To determine the optimal maintenance policy one either has to use numerical integration or to solve sets of equations, except for some very specific cases for which graphical methods have been developed or analytical solutions exist.

Hence, in general, a software program is required and this should be ready at the appearance of the problem, unless the problem is repetitive. Such a program can be applied by either the developer, an inside or outside consultant or the problem owner (usually a maintenance or production engineer). The first applications published were in fact from academics who developed a software program. Later one sees professionals developing special decision support software. The problem owner is the ideal person to use the decision support system, yet he/she will often be unfamiliar with maintenance decision support systems, unless the problem is repetitive. The outside consultant is a costly alternative. Hortoneros signals the problem of triggering an optimization, since before doing one, it is unclear what an optimization may save and whether a consultant is justified. Most companies, however, are too small to have a specialized inside maintenance optimization consultant. In any case, a consultant needs an excellent decision support system as well.

One main problem in developing a maintenance decision support system lies in the development of a generic modelling of maintenance problems such that standard models can be used. In fact one does not need a set of models with an user interface: one needs a generic structuring of maintenance problems, which indicates when which methods can be used and how all special aspects can be taken care of. The reason is that there is quite a diversity in maintenance problems and most of them are not repetitive. Application of models also requires a good formulation of the problem which is not easy since most concepts used (such as failure) allow various interpretations. To give a simple example, consider the system which consists of the front lights of a car. In this case one may define a system failure as either the failure of only one or of two lights. Both the distribution of the time to system failure and the cost of system failure depend heavily on the choice of definition. Furthermore, many models are not robust against violations of assumptions or misinterpretation of their concepts. A major shortcoming of most maintenance decision support systems is that they act like a black box. From the foregoing the dangers of such a black box will be clear: since each maintenance problem is likely to be different, it is only the user (and not the d.s.s.) who can validate the calculations and convince his/her management of their value.

For many models (except perhaps for the few multi-component models) there are no major computational problems, and hence there is no need for advanced computers to solve them. Developing a user-friendly system, however, takes much time and is therefore costly. Since the lifetime of personal computers and their operating system (in ten years six DOS versions and presently a switch to either Windows or OS/2) is short, such a program has to regain its initial costs within a few years.

Finally, there is always a threshold in using software systems. If they are not regularly used, there exists a serious danger of losing experience and finally they are put aside. Courses are often provided with packages, but even that is not enough. The average job duration for people can be quite small. Maintenance management has to be convinced to accept and demand quantitative methods as a basis for decision making. They will only do so if they have confidence in them. A focal point in the maintenance organization, familiar with operations research and computers, is therefore vital for the success of decision support systems.

5.2 Data problems

An essential part of a maintenance optimization model is the modelling of the deterioration and the occurrence of failures of a system in time in such a
way that it is clear how both are influenced by the maintenance regime. Maintenance actions will only be effective and efficient if they specifically address the most relevant deterioration and failure mechanisms. Global statistics, like an average failure rate, will therefore be inappropriate for most maintenance actions, and apply only to complete replacements, which tend to be costly. Analysing data without knowing the underlying failure mechanisms can lead to totally wrong results (consider failures caused by wearout and by operator errors). Hence, data have to be collected under strict rules, defining failure and individual maintenance actions precisely, using a well-defined system-component structuring and indicating what events have happened on purpose. This is, however, mostly not the case, except perhaps in the airline industry. Maintenance information systems thus mainly store accounting information on events and there is a wide concern about the value of their data for engineering decision making. As collecting data requires a lot of effort, one should concentrate on the most relevant areas, which is a problem on its own. Exceptions are the condition monitoring programs, for which dedicated manpower is usually available.

An alternative is to make use of the knowledge contained in the maintenance technicians. This, however, requires a reformulation of most maintenance optimization models since it is very difficult to elicit probability distributions from people. Another aspect one should realize is that under good maintenance practices there are little failure data. If failures occur repeatedly, one may either change the system design or its operation to prevent failures, with the result that data collection has to start again.

Apart from problems with data on deterioration, one also has problems with cost data, especially with respect to the indirect costs. It is easy to quantify direct maintenance costs, but very difficult and sometimes subjective to quantify the benefits of maintenance. In the case of maintenance for production equipment one has to value the increase in reliability, availability or efficiency. The latter may be the easiest to judge. The first two are more difficult, especially if the equipment bears a complex relation with the final products (e.g., one may use spare equipment, or there may be over capacity, etc.); besides, all kinds of actions may be taken upon a failure to avoid really high costs. In those cases where extending system life is the maintenance objective one may set norms or ask economists to do a specific calculation. In all cases, decision support systems can help in reducing uncertainty on cost data. By experimenting with different values one gets an impression on the importance of data, which then helps in deciding whether more time should be spent on getting better data.

5.3 The gap between theory and practice

In many areas one complains about the gap between theory and practice. Hence we should concentrate on whether this gap is larger than normal. Here we focus on the following six aspects:

- maintenance optimization models are difficult to understand and to interpret. Many maintenance models have a stochastic nature, which is not only difficult to grasp by technicians and managers, but also difficult to interpret (the frequentist interpretation of probability is often hampered by many interfering circumstances). For example, a Markov decision model is far more difficult to understand and to interpret than a routing problem. Education of mechanical engineers traditionally focuses on deterministic approaches, which hampers effective use of reliability concepts. As maintenance is being underrated compared to other disciplines, academic support is limited;

- many papers have been written for maths purposes only. Mathematical analysis and techniques, rather than solutions to real problems, have been central in many papers on maintenance optimization models. Mathematical results on the existence and structure of optimal policies (e.g., control limit policies), however, are not appealing to practitioners: the structure of policies is generally determined by the problem setting. It is astonishing how little attention is paid either to make results worthwhile or understandable to practitioners, or to justify models on real problems or to consider data problems;

- companies are not interested in publication. Although many good ideas have been developed in industry, only a small amount has appeared in scientific literature. To have academics study industrial problems, they have to be exposed to them and to be rewarded if they solve them. Although academic freedom is a great thing, it does not force academics to tackle industrial problems. So companies should stimulate researchers by offering them problems and allowing them to publish their results;

- maintenance comprises a multitude of different aspects. Maintenance is a generic term referring to a variety of actions on all kinds of technical systems, deteriorating in various ways. Hence it is not surprising that there is no general model covering all possible cases. Despite the multitude of models, there is little knowledge on which models are suited for which practical problems nor which type of data are really driving problems. Instead of publishing new models one would be better unifying existing models and critically reviewing them on applicability;

- optimization is not always necessary. Maintenance optimization models indicate in principle the best decision given a certain problem and available information. The value of such a procedure (i.e., the
computing power, but also with respect to clever
becoming cheaper and cheaper: not only in terms of
economical necessity. First of all, computers are
of two main reasons; the technological push and the
6 FUTURE PROSPECTS
short-term prediction capacity only, which does not
(enable better software development, with more
obtained from process monitoring systems. Further-
more, new developments in software technology
enable better software development, with more
intelligence embedded, in a shorter time span.

Optimization models are so far the only way in which
scientifically justified statements on maintenance can
be made.

Secondly, it is widely accepted that the amount of
capital invested in technical systems will keep
growing. Due to increased demands on performance
of these systems (quality, reliability and safety)
spending on maintenance is likely to grow as well, a
trend which is visible in many companies. Contracting
out maintenance also increases the need
for a higher quality of decision making. Maintenance
optimization models, embedded in decision support
systems, provide an objective and quantitative way of
decision making. One, which is defendable, and
therefore very-well suited for group decision making,
especially since it allows us to evaluate the economic
consequences of decisions. One which is able to save
substantial amounts of money, as Horton shows in
his review of the use of MAINOPT. As maintenance
optimization models are the only approach which
combines reliability with economics in a quantitative
way, they are in fact nothing more than extensions of
the basic economic methods to justify maintenance. It
is their role in the structuring of the decision process
(pointing at which information is essential), the
possibility to reduce uncertainty by investigating ‘what if’
scenarios and the better insight into the effects of
decisions across maintenance and production areas,
which yields most benefits.

7 CONCLUSIONS
Maintenance optimization has flourished as a mathe-
ematical discipline within operations research and it is
likely to do so in the future, considering the problems
listed in recent reviews. Its impact on decision making
within maintenance organizations is limited so far. Yet
there are a number of case studies published which
show that mathematical models are a good means to
achieve both effective and efficient maintenance. As
application tool technology (both soft- and hardware)
is only recently becoming available at low costs and is
rapidly developing, we expect that the near future will
see many decision support systems incorporating
maintenance optimization models. Economic pressure
is likely to enforce the changes in culture that are
necessary to make these packages standard tools for
the modern maintenance manager.

ACKNOWLEDGEMENT
The author would like to acknowledge various people,
especially Adriaan Smit and Cyp van Rijn from the
Koninklijke/Shell-Laboratorium, Amsterdam for their
contribution to the analysis reported in this paper.
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