A Review of Planning Models for Maintenance & Production

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Econometric Institute Report 2006–44

October 9th, 2006

Abstract

In this article we give an overview of the relation between planning of maintenance and production. On the one hand we consider production planning and scheduling models where failures and maintenance aspects are taken into account. Next we discuss the planning of maintenance activities, where we consider both preventive as well as corrective maintenance. Thirdly, we consider the planning of maintenance activities at such moments in time where the items to be maintained are not or less needed for production, also called opportunity maintenance. Apart from describing the main ideas, approaches and results we also provide a number of applications.

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1 Introduction

Maintenance is the set of all activities meant to keep a system into a condition where it can perform its function. Quite often these systems are production systems. Some maintenance can be done during production and some can be done during regular production stops in evenings, weekends and on holidays. However, in many cases production units need to be shut down for maintenance. This may lead to tensions between the production and maintenance department of a company. On one hand the production department needs maintenance for the long-term well-being of their equipment, on the other hand it needs to shut these down in periods they could well be used for production. It will be clear that both can benefit from decision support based on mathematical models.

In this research we give an overview of mathematical models that consider the relation between maintenance and production. The relation exists in several ways. First of all, when planning maintenance one can take production into account. Secondly, maintenance can also be seen as a production process which needs to be planned and finally one can develop integrated models for maintenance and production. Apart from giving a general overview of models we will also discuss some sectors in which the interaction between maintenance and production can be specified in detail.

Many review articles have been written on maintenance, e.g. Cho and Parlar (1991), but to our knowledge only one on the combination between maintenance and production, Ben-Daya and Rahim (2001). This review differs from that one in several aspects. First of all, we also consider models which take production restrictions into account, rather than integrated models. Secondly we discuss some specific sectors. Finally, we are able to discuss the most recent articles since that review.

The articles referred to in this study were found using Google Scholar, Scirus and Scopus as search engines and ScienceDirect, JStor, MathSciNet and Emerald as online databases. We primarily searched on keywords, abstracts and titles, but we also searched within the articles for relevant references. Overview articles on maintenance (e.g. Cho and Parlar (1991), Dekker (1996), and Wang (2002)) and the review of Ben-Daya and Rahim (2001) on production, maintenance and quality models have been very useful sources for detecting important articles in different fields within production planning and/or maintenance scheduling. Moreover, we have applied a citation search (looking both backwards in time and forwards in time for citations) to all articles found. This citation search is an indirect search method, whereas the above methods are direct methods. The advantage of this method is that one can easily distinguish clusters of related articles. Note that studies published in books or proceedings that are not electronically available, are likely to have escaped.

The following terms and/or a combination of them were used for searching the literature: maintenance, maintenance optimization, production, production planning, downtime cost, airlines, railways, road, process industry, opportunity, manpower.

Classification scheme

Maintenance is related to production in several ways. First of all, maintenance is intended to allow production, yet to execute maintenance production often has to be stopped. This negative effect has therefore to be considered in maintenance planning and optimization. It comes specifically forward in the costing of downtime and in opportunity maintenance. All articles taking the effect of production on maintenance explicitly into account fall into this category.

Secondly, maintenance can also be seen as a production process which needs to be planned. Planning in this respect implies determining appropriate levels of capacity (e.g. manpower) concerning the demand.

Thirdly, we are concerned with production planning in which one needs to take maintenance jobs into account. The point is that the maintenance jobs take production capacity away and hence they need to be planned together with production. Maintenance has to be done either because of a failure or because the quality of the produced items is not good enough. In this third category we also consider the integrated planning of production and maintenance.

The relation between maintenance and production is also determined by the business sector. We consider the following sectors: railway, road, airlines and electrical power generation maintenance.

The outline of this article is now as follows. In section 2 we recapitulate the main elements of maintenance planning as these are essential to understand the rest of this article. Following our classification scheme, in section 3 we review articles in which maintenance is modelled explicitly and where the needs of production are taken into account. Since these needs differ between business sectors, we discuss in section 4 the relation between production and maintenance for some specific business sectors. In section 5 we consider the second category in our classification scheme: maintenance as a production process which needs to be planned. In section 6 we are concerned with production planning in which one needs to take maintenance jobs into account (integrated production and maintenance planning). Trends and open research areas will be presented in section 7. Finally, in section 8 some conclusions are drawn.

2 Maintenance planning and optimization: a recap

In this section we give a review of the most important maintenance decisions. In this respect we follow Wang (2002). We distinguish between (i) the long term strategic and maintenance concept, (ii) medium term planning, (iii) short term scheduling and finally (iv) control and performance indicators.

Major strategic decisions concerning maintenance are made in the design process of systems. What type of maintenance is appropriate and when should it be done? This is laid down in the so-called maintenance concept. Many optimization models address this problem and the relation with production is implicitly covered by them.

Another important strategic problem is the organization of the maintenance department. Is maintenance done by production personnel, in the way Total Productive Maintenance prescribes, or is there specific maintenance personnel? Secondly, where is it located, are specific types of work outsourced, et cetera. Although they are important topics, they are more the concern of industrial organization than the topic of mathematical models.

Further important strategic issues concern how a system can be maintained, whether specific expertise or equipment needed, whether one can easily reach the subsystems, what information is available and what elements can be easily replaced. These are typical maintainability aspects, but they have little to do with production.

In the tactical phase, usually between a month and year, one makes a plan for the major maintenance / upgrade of major units and this has to be done in cooperation with the production department. Accordingly, specific decision support is needed in this respect. Another tactical problem concerns the capacity of the maintenance crew. Is there enough manpower to carry out the preventive maintenance program? These questions can be addressed by models and we will come back to them.

In the short term scheduling phase one determines the moment and order of execution, given an amount of outstanding corrective or preventive work. This is typically the domain of work scheduling where extensive model-based support can be given.

We will next consider another important aspect in maintenance, which is the type done. A typical distinction is made between corrective and preventive maintenance work. The first is carried out after a failure, which is defined as the event by which a system stops functioning in a prescribed way. Preventive work however, is carried out to prevent failures. Although this distinction is often made, we like to remark that the difference is not that clear as it may seem. This is due to the definition of failure. An item may be in a bad state, while still functioning and one may consider this as a failure or not. Anyhow, an important distinction between the two is that corrective maintenance usually cannot be planned, but preventive maintenance typically can be.

The execution of maintenance can also be triggered by condition measurements, in other words, condition-based maintenance. This has often been advocated as more effective and efficient than time-based preventive maintenance. Yet it is very hard to predict failures well in advance, and hence condition-based maintenance is often unplannable. Instead of time based maintenance one can also base the preventive maintenance on utilization (run hours, mileage) as being more appropriate indicators of wear out.

Finally, one may also have inspections which can be done by sight or instruments and often do not affect operation. They do not improve the state of a system however, but only the information about it. This can be important in case machines may start producing items of a bad quality. There are inspection-quality problems where inspection optimization is connected to quality control.

Another distinction is about the amount of work. Often there are small works, often grouped into maintenance packages. They may start with inspection, cleaning and next some improvement actions like lubricating and or replacing some parts. These are typically part of the preventive maintenance program attached to a system and have to be done on a repetitive basis (month, quarter, year or two-years). Next, one has replacements of parts or subsystems and overhauls or refurbishments where a substantial system is improved. The latter are planned long ahead and carried out as projects with own budgets.

A traditional optimization problem has been the choice and trade-off between preventive and corrective maintenance. The typical motivation is that preventive maintenance is cheaper than corrective. Maintenance costs are usually due to manhours, materials and indirect costs. The difference between corrective and preventive maintenance costs is especially in the latter category. They represent loss of production and environmental damage or safety consequences. Costing these consequences can be a difficult problem and it is tackled in section 3.1. It will also be clear that preventive maintenance should be done when production is least effected. This can be done using opportunities, which has given rise to a specific class of models dealt with in a separate section (i.e. section 3.2).

3 When to do maintenance in relation with production

In this section we discuss articles in which maintenance (planning or scheduling) is modelled explicitly and the needs of production are taken into account. The latter however, is not modelled as such, but it is taken into account in the form of constraints or requirements. Alternatively the effect of maintenance on varying production scenarios may be considered. Following this reasoning we arrive at three streams of research. A first stream assesses the costs of downtime, which is important in the planning of maintenance. The second stream deals with studies where one tries to schedule maintenance work at those moments that units are not needed for production (opportunities) and in the last stream articles are considered which schedule maintenance in line with production. Each stream is dealt with in a separate section.

3.1 Costing of downtime

Assessing the costs of downtime is an important step in the determination of costs of preventive and corrective maintenance. Although exact values are not necessary as most optimization results show, it is important to assess these values with a reasonable accuracy. It is easier to determine downtime costs in case of preventive maintenance than in case of corrective maintenance as failures may have many unforeseen consequences. Yet even in case of preventive maintenance the assessment can be difficult, e.g. in case of highway shutdowns or railway stoppage.

Another problem to be tackled is the system-unit relation. A system can be a complex configuration of different units, which may imply that downtime of one unit does not necessarily halt the full system. Accordingly, an assessment of the consequences of unit downtime on system performance has to be made. This is especially a problem in case of k-out-of-n systems or even more general configurations.

Several articles have been found on this issue. Some give an overall model, others describe a detailed case. Geraerds (1985) gives an outline of a general structuring to determine downtime costs. In Dekker and Van Rijn (1996) a downtime model is described for k-out-of-n systems used on the oil production platforms. Edwards et al. (2002) give a detailed model for the costs of equipment downtime in open-pit mining. They use regression models on historic data.

Knights et al. (2005) present a model to assist maintenance managers in evaluating the economic benefits of maintenance improvement projects.

3.2 Opportunity maintenance

Opportunity maintenance is that maintenance that is carried out at an opportune moment, i.e. moments at which the units to be maintained are less needed for their function than normally. We speak of opportunities if these events occur occasionally and if they are difficult to predict in advance. There can be several reasons for a maintenance opportunity.

- failure and hence repairs of other units/components.

  The failure of one component often is an opportunity to preventively maintain other components. Especially if the failure causes the breakdown of the production system it is favourable to perform preventive maintenance on other components. After all, little or no production is lost above that resulting from the original failure. An example is given in Van der Duyn Schouten et al. (1998) who consider the replacement of traffic lights at an intersection.

- other interruptions of production

  Production processes are not only interrupted by failures or repairs. Several outside events may create an opportunity as well. This can be market interruptions, or other work by which production needs to be stopped (e.g. replacing catalysts etc.) and this is an opportunity to combine preventive maintenance on.

According to the foregoing there are two approaches to opportunities. The first models a whole multi-component system in which upon a failure preventive maintenance can be carried out on other components as well. In the latter stream the opportunities are modelled as an outside event at which one may do maintenance. In the simplest form one considers one component, with maintenance which may be done at opportunities or also with a forced shutdown.

Bäckert and Rippin (1985) consider the first type of opportunistic maintenance for plants subject to breakdowns. In this article three methods are proposed to solve the problem. In the first two cases the problem is formulated as a stochastic decision tree and solved with the aid of a modified branch and bound procedure. In the third case the problem is formulated as a Markov decision process. The planning period is discretized, resulting in a finite state space to which a dynamic programming procedure can be applied.

In Wijnmalen and Hontelez (1997) a multi-component system is considered where failures of one component may create an opportunity, but the opportunity process is approximated by an independent process with the same mean rate. In this way they circumvent the problem of dimensionality which appears in the study of Bäckert and Rippin (1985).

There are quite some articles considering the other stream. Tan and Kramer (1997) propose a general framework for preventive maintenance optimization in chemical process operations. The authors combine Monte Carlo simulation with a genetic algorithm. Opportunities are the failure of other components.

In Dekker and Dijkstra (1992) and Dekker and Smeitink (1991) it is assumed that the opportunity-generating process is completely independent of the failure process and it is modelled as a renewal process. Dekker and Smeitink (1994) consider multi-component maintenance at opportunities of restricted duration and determine priorities of what preventive maintenance to do at an opportunity.

In Dekker and van Rijn (1996) a decision-support system (PROMPT) for opportunity-based preventive maintenance is discussed. PROMPT was developed to take care of the random occurrence of opportunities of restricted duration. Here, opportunities are not only failures of other components, but also preventive maintenance on (essential) components. Many of the techniques developed in the articles of Dekker and Smeitink (1991), Dekker and Dijkstra (1992) and Dekker and Smeitink (1994) are implemented in the decision-support system. In PROMPT preventive maintenance is split up into packages. For each package an optimum policy is determined, which indicates when it should be carried out at an opportunity. From the separate policies a priority measure is determined with which maintenance package should be executed at a given opportunity.

In Dekker et al. (1998b) the maintenance of light-standards is studied. A light-standard consists of n independent and identical lamps screwed on a lamp assembly. To guarantee a minimum luminance, the lamps are replaced if the number of failed lamps reaches a prespecified number m. In order to replace the lamps the assembly has to be lowered. As a consequence, each failure is an opportunity to combine corrective and preventive maintenance. Several opportunistic age-based variants of the m-failure group replacement policy (in its original form only corrective maintenance is grouped) are considered. Simulation optimization is used to determine the optimal opportunistic age threshold.

Dagpunar (1996) introduces a maintenance model where replacement of a component within a system is possible when some other part of the system fails, at a cost of c_2. The opportunity process is Poisson. A component is replaced at an opportunity if its age exceeds a specified control limit t. Upon failure a component will be replaced at cost c_4 if its age exceeds a specified control limit x, otherwise it will be minimally repaired at cost c_1. In case of a minimal repair the age and failure rate of the component after the repair is as it was immediately before failure. There is also a possibility of a preventive or "interrupt" replacement at cost c_3 if the component is still functioning at a specified age

T. A procedure to optimize the control limits t and T is given in Dekker and Plasmeijer (2001).

3.3 Maintenance scheduling in line with production

In this section we consider models where the effect of production on maintenance is explicitly taken into account. The models only address maintenance decisions, but they do not give advice on how to plan production.

The models developed in the articles in this category show that a good maintenance plan, one that is integrated with the production plan, can result in considerable cost savings. This integration with production is crucial because production and maintenance have a direct relationship. Any breakdown in machine operation results in disruption of production and leads to additional costs due to downtime, loss of production, decrease in productivity and quality, and inefficient use of personnel, equipment and facilities. Below we review articles following this stream of research in chronological order.

Dedopoulos and Shah (1995) consider the problem of determining the optimal preventive maintenance policy parameters for individual items of equipment in multipurpose plants. In order to formulate maintenance policies, the benefits of maintenance, in the form of reduced failure rates, must be weighed against the costs. The approach in this study first attempts to estimate the effect of the failure rate of a piece of equipment on the overall performance / profitability of the plant. An integrated production and maintenance planning problem is also solved to determine the effects of PM on production. Finally, the results of these two procedures are then utilized in a final optimization problem that uses the relationship between profitability and failure rate as well as the costs of different maintenance policies to select the appropriate maintenance policy.

Vatn et al. (1996) present an approach for identifying the optimal maintenance schedule for the components of a production system. Safety, health and environment objectives, maintenance costs and costs of lost production are all taken into consideration, and maintenance is thus optimized with respect to multiple objectives. The approach is flexible as it can be carried out at various levels of detail, e.g. adopted to available resources and to the management's willingness to give detailed priorities with respect to objectives on safety versus production loss.

Frost and Dechter (1998) define the scheduling of preventive maintenance of power generating units within a power plant as constraint satisfaction problems. The general purpose of determining a maintenance schedule is to determine the duration and sequence of outages of power generating units over a given time period, while minimizing operating and maintenance costs over the planning period.

Vaurio (1999) develops unavailability and cost rate functions for components whose failures can occur randomly. Failure can be detected only by periodic testing or inspections. If a failure occurs between consecutive inspections, the unit remains failed until the next inspection. Components are renewed by preventive maintenance periodically, or by repair or replacement after a failure, whichever occurs first (age-replacement). The model takes into account finite repair and maintenance durations as well as costs due to testing, repair, maintenance and lost production or accidents. For normally operating units the time-related penalty is loss of production. For standby safety equipment it is the expected cost of an accident that can happen when the component is down due to a dormant failure, repair or maintenance. The objective is to minimize the total cost rate with respect to the inspection and the replacement interval. General conditions and techniques are developed for solving optimal test and maintenance intervals, with and without constraints on the production loss or accident rate. Insights are gained into how the optimal intervals depend on various cost parameters and reliability characteristics.

Van Dijkhuizen (2000) studies the problem of clustering preventive maintenance jobs in a multiple set-up multi-component production system. As far as the authors know, this is the first attempt to model a maintenance problem with a hierarchical (tree-like) set-up structure. Different set-up activities have to be done at different levels in the production system before maintenance can be done. Each component is maintained preventively at an integer multiple of a certain basis interval, which is the same for all components, and corrective maintenance is carried out in between whenever necessary. So, every component has its own maintenance frequency - the frequencies are based on the optimal maintenance planning for single components. Obviously, set-up activities may be combined when several components are maintained at the same time. The problem is to find the maintenance frequencies that minimize the average cost per unit of time.

Cassady et al. (2001) introduce the concept of selective maintenance. Often production systems are required to perform a sequence of operations with finite breaks between each operation. The authors establish a mathematical programming framework for assisting decision-makers in determining the optimal subset of maintenance activities to perform prior to beginning the next operation. This decision making process is referred to as selective maintenance.

The article of Haghani and Shafahi (2002) deals with the problem of scheduling bus maintenance activities. A mathematical programming approach to the problem is proposed. This approach takes as input a given daily operating schedule for all buses assigned to a depot along with available maintenance resources. Then a daily inspection and maintenance schedule is designed for the buses that require inspection so as to minimize the interruptions in the daily bus operating schedule, and maximize the reliability of the system and efficiently utilize the maintenance facilities.

Charles et al. (2003) examine the interaction effects of maintenance policies on batch plant scheduling in a semiconductor wafer fabrication facility. The purpose of the work is the improvement of the quality of maintenance department activities by the implementation of optimized preventive maintenance (PM) strategies and comes within the scope of total productivity maintenance (TPM) strategy. The production of semiconductor devices is carried out in a wafer lab. In this production environment equipment breakdown or procedure drifting usually induces unscheduled production interruptions.

Cheung et al. (2004) consider a plant with several units of different types. There are several shutdown periods for maintenance. The problem is to allocate units to these periods in such a way that production is least effected. Maintenance is not modelled into detail, but incorporated through frequency or period restrictions.

4 Specific business sectors

In this section we will discuss the relation between maintenance and production for some specific sectors. The idea is to illustrate the interdependence between the two in a much more detailed way. Moreover, it shows what ideas were employed in which sector and the difference between them. Although many sectors could be distinguished we take those where maintenance plays an important role. Not surprisingly, these are all capital intensive sectors, hence with high maintenance expenditure. Below we will discuss railway, road, airline and electric power generation maintenance.

4.1 Railway maintenance

Since rail is an important transportation mode, proper maintenance of the existing lines, repairs and replacements carried out in time are all important to ensure efficient operation. Moreover, since some failures might have a strong impact on the safety of the passengers, it is important to prevent these failures by carrying out in time and according to some predefined schedules preventive maintenance works. The preventive maintenance works are the small routine works and the projects. The routine (spot) maintenance activities, that consist of inspections and small repairs (see Esveld (2001)), do not take much time to be performed and are done regularly, with frequencies varying between monthly and once a year. The projects include renewal works and they are carried out once or twice every few years.

In the literature there are a couple of articles that provide useful methods for finding optimal track possession intervals for carrying out preventive maintenance works, i.e. time periods when a track is required for maintenance, therefore it will be blocked for the operation. In production planning terms track possession means downtime required for maintenance. The main question is when to carry out maintenance such that the inconvenience for the train operators, the disruption to and from the scheduled trains, the infrastructure possession time for maintenance are minimized and the maintenance cost is the lowest possible. For a more detailed overview of techniques used in planning railway infrastructure maintenance we refer to Dekker and Budai (2002) and Improverail (2002). In some articles (Higgins (1998), Cheung et al. (1999) and Budai et al. (2006)) the track possession is modelled in between operations. This can be done for occasionally used tracks, which is the case in Australia and some European countries. If tracks are used frequently, one has to perform maintenance during nights, when the train traffic is almost absent, or during weekends (with possible interruption of the train services), when there are less disturbances for the passengers. In the first case one can either make a cyclic static schedule, which is done by Den Hertog et al. (2005) and Van Zante-de Fokkert et al. (2001) for the Dutch situation, or a dynamic schedule with a rolling horizon, which is presented in Cheung et al. (1999). The latter schedule has to be made regularly.

Some other articles deal with grouping railway maintenance activities to reduce costs, downtime and inconvenience for the travellers and operators. Here we mention the study of Budai et al. (2006) in which the preventive maintenance scheduling problem is introduced. This problem arises in other public/private sectors as well, since preventive maintenance of other technical systems (machine, road, airplanes, etc.) also contains small routine works and large projects.

4.2 Road maintenance

Road maintenance has many common characteristics as railway maintenance. Failures are often indirect, in the sense that norms are surpassed, but there may not be any consequences. The production function is indirect, but that does not mean that it is not felt by many. Governments may define a cost penalty due to one hour waiting per vehicle because of congestion caused by road maintenance. Similar as in railway maintenance one sees that work is shifted to nights or a lot of work is combined into a large project on which the public is informed long before. The night work causes for high logistics costs for maintenance, yet it is useful for small repairs or patches.

Other similarities with railroads are the large number of identical parts (a road is typically split up in lanes of 100 meters about which information is stored). Vans with complex road analyzing equipment are used to assess the road quality. For railways special trains with complex measuring equipment is used. Videos are used in both cases. Next, both roads and rails have multiple failure modes. Furthermore, the assets to be maintained are spread out geographically, which causes for high logistics costs in the maintenance. This is also true for airline and truck maintenance. Both road and rail maintenance needs much maintenance and large budgets need to be allocated in both cases.

Although quite some articles have been written on road maintenance, few take the production or user consequences into account. We like to mention Dekker et al. (1998a) which compare two concepts to do road maintenance. One with small work during nights and the other where large road segments (some 4 km) are overhauled in one stretch. In the latter case the traffic is diverted to other lanes or side of the road. It is shown that it is both more advantages for the traffic as well as cheaper, provided that the road is not congested. Another interesting contribution is from Rose and Bennett (1992) who provide a model to locate and size road maintenance depots, to be used for corrective maintenance.

4.3 Airline maintenance

Maintenance costs are a substantial factor of an airline's costs. Estimates are that 20 % of a plane's cost is due to maintenance. Maintenance is crucial because of safety reasons and because of high downtime costs. Besides a crash, the worst event for an airline is an aircraft on ground (AOG) because of failures. Accordingly a lot of technology has been developed to facilitate maintenance. We like to mention in-flight diagnosis, such that quick actions can be taken on ground and a very high level of modularity, such that failed components can easily be replaced. Yet still in an aircraft there is a high level of time-based preventive maintenance rather than condition-based maintenance. A plane has to undergo several checks, ranging from an A check taking about an hour after each flight, to a monthly B check, a yearly C check and a five-yearly D check, where it is completely overhauled and which can last for a month. The presence of the monthly check implies that planes can not always fly the same route, but need to be rotated on a regular basis. It also implies that airlines need several copies of a type in order to provide a consistent service.

Several papers have addressed the issue of fleet allocation and maintenance scheduling. In the fleet allocation one decides which planes fly which route and at which time. One would preferably make an allocation which remains fixed for a whole year, but due to the regular maintenance checks this is not possible. Gopalan and Talluri (1998) give an overview of mathematical models on this problem. Moudani and Mora-Camino (2000) present a method to do both flight assignment as well as maintenance scheduling of planes. It applies dynamic programming and heuristics. A case of a charter airline is considered. Sriram and Haghani (2003) also consider the same problem. They solve it in two phases. Finally, Feo and Bard (1989) consider the problem of maintenance base planning in relation to an airlines fleet rotation, while Cohn and Barnhart (2003) consider the relation between crew scheduling and key maintenance routing decisions.

In an other line of research, Dijkstra et al. (1994) develop a model to assess maintenance manpower scheduling and requirements in order to perform inspection checks (the

A type) between flight turnarounds. It appears that their workload is quite peaked, because of many flights arriving more or less at the same time (so-called banks) in order to allow fast passenger transfers.

The same problem is also tackled by Yan et al. (2004). The articles in this line of research consider in effect the production planning of maintenance, a topic also addressed in section 5.

As last article in this category we like to mention Cobb (1995), who presents a simulation model to evaluate current maintenance system performance or the positive effect of ad hoc operating decisions on maintenance turn times (i.e. the time maintenance takes to carry out a check or to do a repair).

4.4 Electric power system maintenance

Kralj and Petrovic (1988) presented an overview article on optimal maintenance of thermal generating units in power systems. They primarily focused on articles published in IEEE Transactions on Power Apparatus and Systems. Here we will briefly discuss the typical problems of the maintenance of power systems and review two articles dealing with these problems.

First of all, note that maintenance of power systems is costly, because it is impossible to store generated electrical energy. Moreover, the continuity of supply is very important for its customers.

A second problem of scheduling the maintenance of power systems is that joint maintenance of units is often impossible or very expensive, since that would too much effect production.

Frost and Dechter (1998) consider the problem of scheduling preventive maintenance of power generating units within a power plant. The purpose of the maintenance scheduling is to determine the duration and sequence of outages of power generating units over a given time period, while minimizing operating and maintenance costs over the planning period, subject to various constraints. A subset of the constraints contains the pairs of components that cannot be maintained simultaneously. In this article the maintenance problem are cast as constraint satisfaction problems (CSP). The optimal solution is found by solving a series of CSPs with successively tighter cost-bound constraints.

Langdon and Treleaven (1997) study the problem of scheduling maintenance for electrical power transmission networks. Grouping maintenance in the network may prevent a cheap electricity generator from running, so requiring a more expensive generator to be run in its place. That is, some parts of the network should not be maintained simultaneously. These exclusions are modelled by adding restrictions to the MIP formulation of the problem.

5 Production planning of maintenance

In this section we consider maintenance as a production process which needs to be planned. Planning in this respect implies determining appropriate levels of capacity concerning the demand. It will be clear that this activity can only be carried out for plannable maintenance, e.g. overhauls or refurbishment and that it is only needed when there are capacity restrictions, e.g. in shipyard.

The specific aspect of maintenance production planning with standard production planning is that there tend to be more unforeseen events and intervening corrective maintenance work than in regular production planning.

The articles we found in this category are Dijkstra et al. (1994) and Yan et al. (2004), who both consider manpower determination and allocation problems in case of a fluctuating workload for aircraft maintenance. Shenoy and Bhadury (1993) use the MRP approach to develop a maintenance manpower plan. Bengü (1994) discusses the organization of maintenance centers that are specialized to carry out particular types of maintenance jobs in the telecommunication sector. Al-Zubaidi and Christer (1997) consider the problem of manpower planning for hospital building maintenance.

Another typical production planning problem is with respect to layout planning. A case study for a maintenance tool room is described in Rosa and Feiring (1995). The study by Rose and Bennett (1992), which was discussed in section 4.2, also falls into this category.

6 Integrated production and maintenance planning

In recent years there has been a considerable interest in models trying to integrate production, quality and maintenance (Ben-Daya and Rahim (2001)). Whereas in the past these aspects have been treated as separate problems, nowadays models take into account the mutual interdependencies. Production planning typically concerns determining lot sizes and evaluating capacity needs, in case of fluctuating demand. Both the optimal lot size and the capacity needs are effected by failures. On the other hand, maintenance prevents breakdowns and improves quality. Accordingly, they should be planned in an integrated way (see e.g. Nahmias (2005)).

We subdivide the class of integrated production and maintenance planning models in four categories: high-level models considering conceptual and process design problems (section 6.1); the economic manufacturing quantity model, which was originally posed as a simple inventory problem, but has been (successfully) extended to deal with quality and failure aspects (section 6.2); models of production systems with buffer capacities, which by definition are suitable to deal with breakdowns (section 6.3); finally, production and maintenance rate optimization models, which aim to find the production and preventive maintenance rates of machines so as to minimize the total cost of inventory, production and maintenance (section 6.4). In section 6.5 we discuss articles which do not fit in any of these categories.

6.1 Conceptual and design models

In a number of articles conceptual models are developed that integrate the preventive and corrective aspects of the maintenance planning, with aspects of the production system such as quality, service level and priority and capacity activities. For instance, Finch and Gilbert (1986) present an integrated conceptual framework for maintenance and production in which they focus especially on manpower issues in corrective and preventive work. Weinstein and Chung (1999) test the hypothesis that integrating the maintenance policy with the aggregate production planning will significantly influence total cost reduction. It appears that this is the case in the experimental setting investigated in this study. Lee (2005) considers production inventory planning, where high level decisions on maintenance (viz. their effects) are made.

Another group of articles deal with integrating process design, production and maintenance planning. Another group of articles deal with integrating process design, production and maintenance planning. Already at the design stage decisions on the process system and initial reliability of the equipment are made. Pistikopoulos et al. (2000) describe an optimization framework for general multipurpose process models, which determine both the optimal design as well as the production and maintenance plans simultaneously. In this framework, the basic process and system reliability-maintainability characteristics are determined in the design phase with the selection of system structure, components, etc. The remaining characteristics are determined in the operation phase with the selection of appropriate operating and maintenance policies. Therefore, the optimization of process system effectiveness depends on the simultaneous identification of optimal design, operation and maintenance policies having properly accounted for their interactions. In Goel et al. (2003) a reliability allocation model is coupled with the existing design, production, and maintenance optimization framework. The aim is to identify the optimal size and initial reliability for each unit of equipment at the design stage. They balance the additional design and maintenance costs with the benefits obtained due to increased process availability.

6.2 EMQ problems

In the classical economic manufacturing quantity (EMQ) model items are produced at a constant rate p and the demand rate for the items is equal to $d < p$. The aim of the model is to find the production uptime that minimizes the sum of the inventory holding cost and the average, fixed, ordering cost. This model is an extension of the well-known economic order quantity (EOQ) model; the difference being that in the EOQ model orders are placed when there is no inventory. Note that the EMQ model is also referred to as economic production quantity (EPQ) model.

In the extensive literature on production and inventory problems, it is often assumed that the production process does not fail, that it is not interrupted and that it only produces items of acceptable quality. Unfortunately, in practice this is not always the case. A production process can be interrupted due to a machine breakdown or because the quality of the produced items is not acceptable anymore. The EMQ model has been extended to deal with these aspects and we thus divide the literature on EMQ models into two categories. Firstly, we consider EMQ problems that take into account the quality aspects of the items produced. The second category of EMQ models analyzes the effects of (stochastic machine) breakdowns on the lot sizing decision.

6.2.1 EMQ problems with quality aspects

One of the reasons why a production process is interrupted is the (lack of) quality of the items produced. Obviously, items of inferior quality can only be sold at a lower revenue or cannot be sold at all. Thus, the production of these items results in a loss (or a lower profit) for the firm. This type of interruptions is usually modelled as follows. It is assumed that at the start of the production cycle the production is in an “in-control” state, producing items of acceptable quality. After some time the production process may then shift to an “out-of-control” state. In this state a certain percentage of the items produced are defective or of sub-standard quality. The elapsed time for the process to be in the in-control state, before the shift occurs, is a random variable. Once a shift to the out-of-control state has occurred, it is assumed that the production process stays in that state unless it is discovered by (a periodic) inspection of the process, followed by corrective maintenance.

One of the earliest works that consider the problem of finding the optimal lot size and optimal inspection schedule is the article of Lee and Rosenblatt (1987). They show that the derived optimal lot size is smaller than the classical EMQ if the time for the process to be in the in-control state follows an exponential distribution. Lee and Rosenblatt (1989) have extended this work by assuming that the cost of restoration is a function of the elapsed time since a shift from an in-control to an out-of-control state of the production process has occurred. In addition, the possibility of incurring shortages in the model is allowed.

Many attempts have been done to extend these two models. For instance, Tseng (1996) assumes that the process lifetime is arbitrarily distributed with an increasing failure rate.

Furthermore, two maintenance actions are considered. The first is a perfect maintenance action, which restores the system to an as-good-as new condition if the process is in the in-control state. If however, the production process is in out-of-control state, it will be restored to the in-control state at a given restoration cost. Secondly, maintenance is always done at the end of a production cycle to ensure that the process is perfect at the beginning of each production cycle.

Wang and Sheu (2003) assume that the periodic inspections are imperfect. Two types of inspection errors are considered, namely (I) the process is declared out-of-control when it is in-control and (II) the process is declared in-control when it is out-of-control. They use a Markov chain to jointly determine the production cycle, process inspection intervals, and maintenance level. Wang (2006) derives some structural properties for the optimal production/preventive maintenance policy, under the assumption that the (sufficient) conditions for the optimality of the equal-interval PM schedule hold. This increases the efficiency of the solution procedure.

The quality characteristics of the product in a production process can be monitored by a $\overline{x}$-control chart. The economic design of the $\overline{x}$-control chart determines the sample size n, sampling interval h, and the control limit coefficient k such that the total cost is minimized.

Rahim (1994) develops an economic model for joint determination of production quantity, inspection schedule and control chart design for a production process which is subject to a non-Markovian random shock. In their model it is assumed that the in-control period follows a general probability distribution with an increasing failure rate and that production ceases only if the process is found to be out of control during inspection. However, if the alarm turns out to be false the time for searching an assignable cause was assumed to be zero. Rahim and Ben-Daya (1998) generalize the model of Rahim (1994) by assuming that the production stops for a fixed amount of time not only for a true alarm, but also whenever there is a false alarm during the in-control state. Rahim and Ben-Daya (2001) further extend the model of Rahim (1994) by looking at the effect of deteriorating products and a deteriorating production process on the optimal production quantity, inspection schedule and control chart design parameters. The deterioration times for both product and process are assumed to follow Weibull distributions. It is assumed that the process is stopped either at failure or at the mth inspection interval, whichever occurs first. Furthermore, the inventory is depleted to zero before a new cycle starts.

Tagaras (1988) develops an economic model that incorporates both process control and maintenance policies, and simultaneously optimizes their design parameters. Lam and Rahim (2002) present an integrated model for joint determination of economic design of $\overline{x}$-control charts, economic production quantity, production run length and maintenance schedules for a deteriorating production system. In the model of Ben-Daya and

Makhdoum (1998) PM activities are also coordinated with quality control inspections, but they are carried out only when a preset threshold of the shift rate of the production process is reached.

6.2.2 EMQ problems with failure aspects

A couple of articles study the EMQ model in the presence of random machine breakdowns or random failures of a bottleneck component For instance, Groenevelt et al. (1992b) consider the effects of stochastic machine breakdowns and corrective maintenance on economic lot sizing decisions. Maintenance of the machine is carried out after a failure or after a predetermined time interval, whichever occurs first. They consider two production control policies. Under the first policy when the machine breaks down the interrupted lot is not resumed and a new lot starts only when all available inventory is depleted. In the second policy, production is immediately resumed after a breakdown if the current on hand inventory is below a certain threshold level. They showed that under these policies the optimal lot size increases with the failure rate and assuming a constant failure rate and instantaneous repair times the optimal lot sizes are always larger than the EMQ. Nevertheless, Groenevelt et al. (1992b) propose to use the EMQ as an approximation to the optimal production lot size. Chung (2003) provides a better approximation to the optimal production lot size. Groenevelt et al. (1992a) study the problem of selecting the economic lot size for an unreliable manufacturing facility with a constant failure rate and general distributed repair times. The quantity of the safety stock that is used when the machine is being repaired is was derived based on the managerially prescribed service level.

Makis and Fung (1995) present a model for joint determination of the lot size, inspection interval and preventive replacement time for a production facility that is subject to random failure. The time that the process stays in the in-control state is exponentially distributed and once the process is in out-of-control state, a certain percentage of the items produced is defective or qualitatively not acceptable. Periodic inspections are undertaken to review the production process and the time to machine failure is generally distributed random variable. Preventive replacement of the production facility is based on operation time, i.e. after a certain number of production runs the production facility will be replaced.

Some other articles are concerned with PM policies for EMQ models. For instance, in Srinivasan and Lee (1996) an (S, s) policy is considered, i.e. as soon as the inventory level reaches S, a preventive maintenance operation is initiated and the machine becomes as good as new. After the preventive maintenance operation, production resumes as soon as the inventory level drops down to or below a prespecified value, s, and the facility continues to produce items until the inventory level is raised back to S. If the facility breaks down during operation, it is minimally repaired and put back into commission. Okamura et al. (2001) generalize the model of Srinivasan and Lee (1996) by assuming that both the demand as well as the production process is a continuous-time renewal counting process. Furthermore, they suppose that machine breakdown occurs according to a non-homogeneous Poisson process. In Lee and Srinivasan (2001) the demand and production rates are considered constant and a production run begins as soon as the inventory drops to zero. If the facility fails during operation, it is assumed to be repaired, but restoring the facility only to the condition it was in before the failure. Lee and Srinivasan (2001) consider an $(S,\ N)$ policy, where the control variable N specifies the number of production cycles the machine should go through before it is set aside for preventive maintenance overhaul, which restores the facility to its original condition.

Recently, Lin and Gong (2006) determined the effect of breakdowns on the decision of optimal production uptime for items subject to exponential deterioration under a no-resumption policy. Under this policy, a production run is executed for a predetermined period of time provided that no machine breakdown has occurred in this period. Otherwise, the production run is immediately aborted. The inventories are built up gradually during the production uptime and a new production run starts only when all on-hand inventories are depleted. If a breakdown occurs then corrective maintenance is carried out and this takes a fixed amount of time. If the inventory build-up during the production uptime is not enough to meet the demand during the entire period of the corrective maintenance, shortages (lost sales) will occur. Maintenance restores the production system to the same initial working conditions.

6.3 Deteriorating production system with buffer capacity

In order to reduce the negative effect of a machine breakdown on the production process, a buffer inventory may be built up during the production uptime (as it is done in the EMQ model). The role of this buffer inventory is that if an unexpected failure of the installation occurs then this inventory is used to satisfy the demand during the period that corrective maintenance is carried out. One of the earliest works on this subject is Van der Duyn Schouten and Vanneste (1995). In their model the demand rate is constant and equal to d (units/time) and as long as the fixed buffer capacity (K) is not reached the installation operates at a constant rate of p units/time $(p > d)$ and the excess output is stored in the buffer. When the buffer is full, the installation reduces its speed from p to d. Upon failure corrective maintenance starts and the installation becomes as good as new. It is possible to perform preventive maintenance, which takes less time than repair and it also brings the installation back into the as-good-as-new condition. The decision to start a preventive maintenance action is not only based on the condition of the installation, but also on the level of the buffer. The criterion is to minimize the average inventory level and the average number of backorders. Since the optimal policy is difficult to implement, the authors develop suboptimal (n, N, k) control-limit policies. Under this policy if the buffer is full, preventive maintenance is undertaken at age n. If the buffer is not full, but it has at least k items, preventive maintenance is undertaken at age N. Maintenance is never performed unless the system has at least k items. The objective is to obtain the best values for n, N and k.

Iravani and Duenyas (2002) extend the above model by assuming a stochastic demand and production process. Demand that cannot be met from the inventory is lost and a penalty is incurred. Moreover, it is assumed that the production characteristics of the system change with usage and the more the system deteriorates the more its production rate decreases and the more its maintenance operation becomes time-consuming and costly. In a recent article, Yao et al. (2005) assume that the production system can produce at any rate from 0 (idle) to its maximal rate if it is in working state. Upon failure corrective maintenance is performed immediately to restore the system to the working state. Preventive maintenance actions can be performed as well. Both the failure process and the times to complete corrective/preventive maintenance is assumed to be stochastic. Thus, in addition to the direct cost of performing corrective/preventive maintenance the non-negligible maintenance completion time leads to an indirect cost of lost production capacity due to system unavailability.

Kyriakidis and Dimitrakos (2006) study an infinite-state generalization of Van der Duyn Schouten and Vanneste (1995). The deterioration process of the installation is considered nonstationary, i.e. the transition probabilities depend not only on the working conditions of the installation but on its age and buffer level as well. Furthermore, the cost structure is more general than in Van der Duyn Schouten and Vanneste (1995) since it includes operating and maintenance costs of the installation as well as storage and shortage costs. It is assumed that the operating costs of the installation depend on both the working condition and the age of the installation.

Another way of maintaining the buffer inventory is according to an (S, s) policy, i.e. the system stops production when the buffer inventory reaches S and the production restarts when the inventory drops to s. This idea is used by Das and Sarkar (1999). They assume that exogenous demand for the product arrives according to a Poisson process. Back-orders are not allowed. The unit production time, the time between failures, and the repair and maintenance times are assumed to have general probability distributions. Preventive maintenance decisions are made only at the time that the buffer inventory reaches S, and they depend on both the current inventory level and the number of items produced since the last repair/maintenance operation. The objective is to determine when to perform preventive maintenance on the system in order to improve the system performance.

A different approach of dealing with integrated maintenance/production scheduling with buffer capacity is presented in Chelbi and Ait-Kadi (2004). They assume the preventive maintenance actions are regularly (after each T time periods) performed and the duration of corrective and preventive maintenance actions is random. The proposed strategy consists in building up a buffer stock whose size S covers at least the average consumption during the repair periods following breakdowns within the period of length T. When the production unit has to be stopped to undertake the planned preventive maintenance actions, a certain level of buffer stock must still be available in order to avoid stoppage of the subsequent assembly line. The two decision variables are: the period T at which preventive maintenance must be performed, and the level S of the buffer stock.

A recent article of Kenne et al. (2006) considers the effects of both preventive maintenance policies and machine age on optimal safety stock levels. Significant stock levels, as the machine age increases, hedge against more frequent random failures. The objective of the study is to determine when to perform preventive maintenance on the machine and to find the level of the safety stock to be maintained.

6.4 Production and maintenance rate optimization

An integrated production and maintenance planning can also be made by optimizing the production and maintenance rates of the machines under consideration. In this line of research we mention the work of Gharbi and Kenne (2000), Kenne and Boukas (2003), Kenne et al. (2003) and Gharbi and Kenne (2005). In these articles a multiple-identical-machine manufacturing system with random breakdowns, repairs and preventive maintenance activities is studied. The objective of the control problem is to find the production and the preventive maintenance rates of the machines so as to minimize the total cost of inventory/backlog, repair and preventive maintenance.

6.5 Miscellaneous

Finally, we list some articles that are dealing with integrated maintenance and production planning, but their approaches for modelling or the problem settings are different than in the articles presented in the previous categories. For instance, the model presented in Ashayeri et al. (1996) deals with the scheduling of production and preventive maintenance jobs on multiple production lines, where each line has one bottleneck machine. The model indicates whether or not to produce a certain item in a certain period on a certain production line. In Kianfar (2005) the manufacturing system is composed of one machine that produces a single product. The failure rate of the machine is a function of its age and the demand of the manufacturing product is time-dependent. Its rate depends on the level of advertisement on that product. The objective is to maximize the expected discounted total profit of the firm over an infinite time horizon. Sarper (1993) considers the following problem. Given a fixed repair/maintenance capacity, how many of each of the low demand large items (LDLIs) should be started so that there are no incomplete jobs at the end of the production period? The goal is to ensure that the portion of the total demand started will be completed regardless of the amount by which some machines may stay idle due to insufficient work. A mixed-integer model is presented to determine what portion of the demand for each LDLI type should be rejected as lost sales so that the remaining portion can be finished completely.

7 Trends & Open areas

Initial publications on models in the production and maintenance area date from the end of the eighties (Lee and Rosenblatt (1987)). Since that time many papers have been published with the majority dating from the nineties and the new millennium. This may be due to a search bias, because those papers are most likely to be found electronically. The most popular area in this review is also the oldest one, i.e. on integrated models for maintenance and production. However, still many papers appear in that area and the models become more and more complex, with more decision parameters and more aspects.

The areas on opportunity maintenance and scheduling maintenance in line with production have also been popular, but maybe more in the past than today. We did expect to find more studies on specific business sectors, but could only find many for the airline sector. That sector seems to be the most popular as it has both a lot of interaction between maintenance and production as well as high costs involved. In the other sectors, we do see the interaction, but perhaps more papers will be published in the future. The other sections are interesting but small in terms of papers published.

In general, the demands on maintenance become higher as public and companies are less likely to accept failures, bad quality products or non-performance. Yet at the same time society's inventory of capital goods is increasing as well as ageing in the western societies. This is very much the case for roads, railways, electric power generation and transport and aircrafts. As there are continuous pressures on maintenance budgets we do foresee the need for research supporting maintenance and production decisions, also because decision support software is gaining in popularity and more data becomes electronically available. The theory is therefore needed in these decision support systems. As several case studies have taught us that practical problems have many complex aspects, there is a high need for more theory that can help us to understand and improve complex maintenance decision making.

8 Conclusions

The review in this article discusses the interaction between maintenance and production in several categories, viz. costing of downtime, opportunity maintenance, and it deals with several specific sectors, viz. railways, roads, airlines and electric power generators. These categories were not treated in an earlier review by Ben-Daya and Rahim (2001). We also distinguish between articles focusing on maintenance aspects in line with production requirements, studies dealing with the production planning of maintenance and finally with articles integrating production and maintenance decisions.

We have observed a non-stop attention for integrated production and maintenance models, which nowadays deal with quality and failure aspects. In comparison with other specific sectors, much work has been done on modelling maintenance for the airline sector. Although many articles have been written on the interaction between production and maintenance, a careful reader will detect several open issues in this review. The theory developed thus far, is far from complete and any real application, is likely to reveal many more open issues.

Acknowledgements

The authors would like to thank Khairy Kobbacy, Pra Murthy, Georgios Nenes and Sophia Panagiotidou for their helpful suggestions and comments.

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