Maintenance of capital goods

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Inaugural lecture
prof.dr.ir. Geert-Jan
van Houtum
19 March 2010

/ Department of Industrial
Engineering & Innovation Sciences

TU/e Technische Universiteit
Eindhoven
University of Technology

Maintenance of capital goods

Where innovation starts

Inaugural lecture prof.dr.ir. Geert-Jan van Houtum

Maintenance of capital goods

Presented on 19 March 2010
at the Eindhoven University of Technology

Introduction

Capital goods are machines or products that are used by manufacturers to produce their end-products or by service organizations to deliver their services. For example:

- Lithography machines used by manufacturers of semiconductors
- Medical equipment used by hospitals to diagnose and treat patients
- Trains used by a service organization such as Dutch Railways to transport customers to their destinations
- Baggage handling systems used by airports to move baggage from passengers to airplanes and vice versa
- Chicken slaughtering lines used by slaughterhouses to process chickens into fillets, drumsticks etc.

Capital goods require maintenance. In general, maintenance can be defined as: ‘the combination of all the technical and associated administrative actions intended to retain an item in, or to restore it to, a state in which it can perform its required function’ (cf. the British Standards Institution). Capital goods are used in the primary processes of their users, and failure of a capital good may cause standstill of a complete factory, or in the case of public transportation can severely impact a large part of a country; as shown by the recent problems with rail transportation in the Netherlands caused by frozen points (called ‘*wissels*’ in Dutch) in the rail network.

Capital goods have a life cycle consisting of 5 phases; see figure 1 (cf. Dinesh Kumar et al. [2000]). In the first phase, needs and requirements are defined based on feedback from the market and knowledge of technical possibilities. Next, the system is completely designed. After that, multiple units of the system are produced. Then, in the exploitation phase, the systems are used, generally for extended periods (say 10-40 years). Finally, the system is disposed of.

figure 1

Life cycle of a capital good

What matters for the users of capital goods are the costs during the entire life cycle. These are known as the Total Cost of Ownership (TCO). The costs during the first three phases of the life cycle are reflected in the sales price for new systems. We call these costs the acquisition costs, which in many cases are high. The price of a lithography machine from ASML is 20-50 million euros, an MRI scanner costs 1-2 million euros, a baggage handling system at a major airport may range up to 300-400 million euros, and one Joint Strike Fighter will have a price of around 50 million euros.

The rest of the TCO occurs after the purchase of the new system. During the exploitation phase, costs of multiple types arise, with maintenance and downtime accounting for the largest proportion. Maintenance costs consist of all the resources needed for maintenance, which may be executed by the user itself or by the manufacturer or a third party. In any case, the items that have to be paid for include spare parts, service/maintenance engineers, infrastructure and management. Downtime costs may consist of direct costs, such as those caused by a reduction in the output of a factory, and indirect costs, such as those caused by loss of reputation and resulting loss of future revenues. Finally, in the disposal phase, there will be disposal costs. These may be significant if systems contain environmentally unfriendly materials. In many cases, the disposal costs are low. While in some cases, systems or parts of systems may be refurbished and can be re-used, so that disposal may even lead to a revenue instead of a cost.

To give an impression of how high the costs of a capital good may be after purchase, figure 2 shows how the TCO of an engineer-to-order system is divided over the acquisition, maintenance and downtime costs (cf. Öner et al. [2007]). Costs were determined for one particular system with an assumed lifetime of

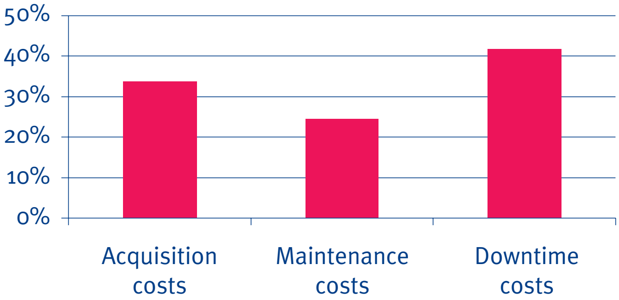

figure 2

Division of TCO for an engineer-to-order system

20 years, and all costs were discounted (with a discount rate of 5% per year). The system had already been in use for some years. This meant that the acquisition costs were known, and reliable estimates could be made of the maintenance and downtime costs. A conservative estimate was made of the downtime costs.

As we can see in figure 2, the acquisition costs constitute only one-third of the TCO, while the rest of the TCO consists of maintenance and downtime costs. For other systems, we may get different numbers, but generally the message is the same: the acquisition costs account for only a fraction of the TCO. So, when you buy a new system, you are implicitly making an investment that is 2-4 times as great as the acquisition costs alone. An intriguing example is the Joint Strike Fighter. The Netherlands wants to buy about 80 of these jet fighters, at a purchase cost of around 4 billion euros. Implicitly, we are then making a total investment over the life cycle of the aircraft of 8-16 billion euros.

The maintenance of capital goods is a major industry in itself, which is shown by different types of statistics. The Netherlands has a large industry that produces capital goods. In 2008, capital goods exports had a value of 117 billion euros (see the size of the exports of ‘*Machines en apparaten*’ [machines and equipment], ‘*Elektrotechnische machines en apparaten*’ [electrical machines and equipment], and ‘*Transportmiddelen*’ [means of transport] in Table 12.22 of the ‘*Statistisch Jaarboek*’ [statistics annual] [2009]). As already stated, the maintenance costs during the 10-40 years of the exploitation phase are often of the same order as the purchase price of a new system. In other words, the maintenance activities for the capital goods exports from the Netherlands in themselves add up to a market of a similar value! An important part of these maintenance activities is controlled and executed by central maintenance support organizations in the Netherlands. Imports of capital goods into the Netherlands are also around 117 billion euros (see Table 12.20 of the *Statistisch Jaarboek* [2009]). These goods are used in the Netherlands in factories, hospitals and so on, and their maintenance activities also form a market of a similar size. According to a study by AberdeenGroup [2003], global spending on after-sales services totaled more than 1500 billion US dollars annually; and spare parts sales and services in the United States accounted for 8% of the annual Gross Domestic Product. Deloitte [2006] carried out a study among a group of more than 120 large manufacturers in Europe, North America and the Asia-Pacific region with combined revenues of more than 1500 billion US dollars. They reported that 26% of these revenues (390 billion US dollars) came from services. Another interesting statistic was generated by Lam [1995].

He looked at the total costs of commercial airlines, and found that maintenance accounts for around 10% of the airlines’ total costs, which is about the same as fuel and travel agents’ commission. A similar percentage applies to many companies for which capital goods form the basis of their business.

Research themes

With respect to the maintenance of advanced capital goods, we see a shift of maintenance activities from the buyers/users to the manufacturers (see also Oliva and Kallenberg [2003] and Cohen et al. [2006]). This shift is caused by a number of factors that reinforce each other. First of all, systems are becoming more and more advanced, which means their maintenance is also becoming increasingly complex, especially for buyers/users with only limited numbers of systems. Secondly, the buyers/users of capital goods demand ever-higher system availability levels, which implies that the whole maintenance function has to be executed at a higher level. Thirdly, more and more buyers/users look explicitly at the TCO when they buy new systems, or equivalently at the cost of a capital good per produced product or the cost per serviced unit. In other words, they want both a high system availability and a low TCO (where TCO now excludes downtime costs). The best way to ensure that the promised availability level and TCO are achieved in practice is to enter into a so-called full service contract, under which the manufacturer is fully responsible for all the maintenance. The buyer/user then simply pays a fixed service cost per year, and it becomes the manufacturer’s task to manage everything. In the most extreme case the buyer/user does not even buy the system, but just buys the function of the system.

The above trend from a product-oriented to a function-oriented market (or industry) can be clearly seen for many types of capital goods. The speed of this trend and the current position of the market strongly depend on the technological complexity of the equipment, the importance of high system availability and the importance of a low TCO. Examples of capital goods for which the market is strongly function-oriented are aircraft engines, lithography machines and large-scale computer systems.

As I already said, achieving a high system availability level implies that maintenance has to be carried out at a highly professional level. Maintenance consists of preventive maintenance and corrective maintenance. Preventive maintenance is aimed at reducing the number of failures during the operational hours of the system. Corrective maintenance is aimed at getting the system up and running again as quickly as possible. In general, the higher the required system availability level, the higher the maintenance costs will be. Another way to increase the availability level is by making changes in the design of the capital good or in its maintenance concept, which lead to a change in the acquisition costs. In other words, there is a trade-off between availability on one hand and TCO, consisting of acquisition and maintenance costs, on the other; see figure 3.

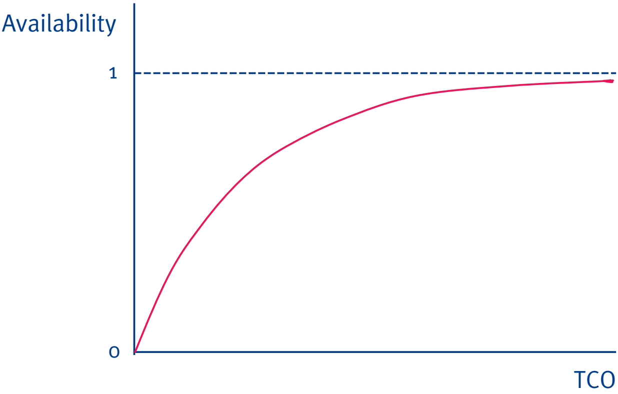

figure 3

System availability versus TCO

Let us now look in more detail at the factors that influence system availability. We assume a setting in which preventive maintenance can be performed during non-operational hours. System availability can then be defined as the fraction of time that a system is up and running during the normal operational hours. System availability is then given by the following formula:

$$\text{Availability} = 1 - DT \,/\, (\text{number of operational hours per year}), \tag{1}$$

where *DT* is the total number of hours per year that the system is down during the operational hours. Downtime starts when a failure occurs during the operational hours, and ends when the system is up and running again after a corrective maintenance action. Corrective maintenance starts with identifying the cause of the failure. Then, a spare part and/or a visit by a service engineer may possibly be needed. These two factors together lead to the so-called maintenance delay. Finally, the repair itself has to be executed. The formula for downtime is then as follows:

$$DT = FA \times (MD + RT), \tag{2}$$

where

FA = the number of failures per year;
MD = the average maintenance delay per corrective maintenance action;
RT = the repair time itself.

Note that the formulas for availability and downtime can be applied to both a single machine and a group of machines. Further maximizing availability is equivalent to minimizing downtime. From now on, we will focus on minimizing downtime. The trade-off between minimizing downtime and minimizing TCO is shown by the solid curve in figure 4.

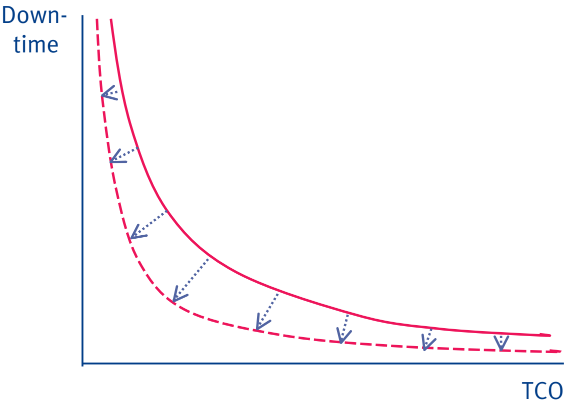

figure 4

Downtime versus TCO

Requiring ever-lower downtime leads to an exponential increase in TCO according to the solid curve in figure 4. Rather than accepting this solid curve, we would like to change the given concepts by bringing the solid curve to the position of the dashed curve in figure 4, in other words to a curve that is much closer to the axes. This is the mission of research within the chair of Reliability, Quality and Maintenance. We distinguish three research themes, all three of which are directly linked to Formula (2) for the downtime *DT* (see figure 5):

1. *Design and Control of Service Supply Chains*: Within this theme, we consider the worldwide networks in which spare parts and service engineers are positioned to support corrective maintenance actions. Through this theme, we influence the maintenance delay (*MD*).
2. *Maintenance Concepts*: Within this theme, we study the whole maintenance concept, which includes the trade-off between preventive and corrective maintenance, the monitoring of degradation behavior and the application of condition-based maintenance. Through this theme, we influence the number of failures (*FA*) and the maintenance delay (*MD*).
3. *Design for Availability*: Within this theme, we study the design of a capital good from the perspective of availability or downtime. We study design decisions such as the reliability levels of components, building-in redundancy, and a modular design, and we quantify their effect on downtime and TCO. Through this theme, we influence the number of failures (*FA*), the maintenance delay (*MD*) and the repair time (*RT*).

I will now describe each of these themes in more detail.

$$DT = \underbrace{\underbrace{FA \times (\underbrace{MD}_{\text{Theme 1}}}_{\text{Theme 2}} + RT)}_{\text{Theme 3}}$$

figure 5

Factors affected by the three research themes

Theme 1: Design and control of service supply chains

The first research theme is the service supply chain. We discuss this chain from the perspective of a manufacturer who has full service contracts with many customers for systems that are installed at different places in a continent or in the whole world. Another typical example is the network of a user of a fleet of capital goods which manages the entire maintenance process itself. The same principles apply in both these cases.

The main function of the service supply chain is to deliver the maintenance resources within specified time constraints when a system has failed and specific maintenance resources are needed to repair it. In general, spare parts and service engineers are the most important resources. These resources must be positioned at multiple places in the continent or around the world such that the specified downtime constraints are met at minimal costs. Here, two important principles have to be followed for design and planning decisions:

1. *Downtime constraints are formulated at the level of capital goods. Avoid decompositions into lower-level constraints and integrate decisions as far as possible*. In practice, it is common that maintenance delay constraints are translated into separate constraints for spare parts and service engineers, or that constraints at a machine level are translated into constraints for single items. While this may to some extent be necessary to manage the whole control or to allow optimization problems to be solved, it is in general better to avoid these decompositions as far as possible.
2. *Create as much pooling effect as possible for the maintenance resources*. Resources like spare parts and service engineers exist to meet demands. The demand processes are stochastic (volatile), and buffers need to be created in the spare parts stocks and numbers of service engineers to meet demand peaks. The more demands can be bundled before they are matched with resources, the less buffering is needed. In fact, this is something that applies to all supply chains. But special approaches are needed in service supply chains because of the low demand rates (for spare parts and repair capabilities) and the tight downtime constraints.

Research allows the importance of following these principles to be shown. However, doing so requires increasingly complex design and planning decisions, and these present another type of research challenge. Some more concrete research examples of the above principles will now be described.

Let us first describe a simple example to demonstrate the importance of the first principle, the formulation of downtime constraints at the level of capital goods. Consider a local stock point at a production site where multiple machines are installed. The machines have two critical components that are subject to failures. These components are called Component 1 and Component 2. For all machines together, there will be on average 6 failures per year of Component 1 and 0.6 failures of Component 2. These failures occur at random times (i.e. we assume that the underlying demand processes are Poisson). When a failure of a machine occurs, the component that has failed can quickly be identified. Next, the failed component is removed from the machine and replaced by a corresponding spare part. If this spare part is in stock, the replacement can be carried out immediately and the maintenance delay is zero. In that case, the failed part is sent to a repair shop and will be returned to the local stock point as a ready-for-use part after 2 months (on average). If there is no spare part on stock, then the failed part is sent to the repair shop for an emergency repair, and the part will be returned as a ready-for-use part after 3 days (on average). In that case, the maintenance delay is 3 days, and we also have to pay an extra-high price for the repair at the repair shop. Figure 6 shows a visualization of this example.

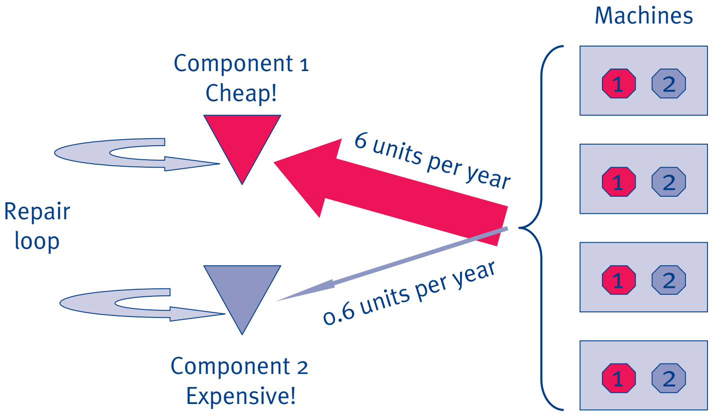

figure 6

Stocking of spare parts at a single production site

Let us assume that S_1 spare parts of Component 1 and S_2 spare parts of Component 2 are initially taken into stock. Then, under the assumptions I have described, we have a closed loop for the spare parts, and the stock on hand of Component i plus the number of parts in repair is always equal to S_i , $i = 1, 2$. The initial stock levels are our decision levels, and we want to optimize them such that the initial stock investment is minimized under a maintenance delay constraint.

The price per new spare part of Component i is denoted by c_i , $i = 1, 2$, where $c_1 = 100$ euros and $c_2 = 100$ euros. Let $\beta_i(S_i)$ be the probability that there is a ready-for-use part on stock when an arbitrary failure of a Component i occurs. The mean total maintenance delay per year is then equal to

$MD(S_1, S_2) = 6 \times \beta_1(S_1) \times 3 + 0.6 \times \beta_2(S_2) \times 3$ (in days).

Let us assume that the mean total maintenance delay must be no more than 2.0 days. Then, our decision problem is as follows:

(P) Min. $c_1 S_1 + c_2 S_2$
such that $MD(S_1, S_2) \leq 2.0$

The optimal solution appears to be $\hat{S}_1 = 5$ and $\hat{S}_2 = 0$. The corresponding performance is then as follows:

Initial stock investment = $100 \times 5 + 10{,}000 \times 0 = 500$ euros
$MD(\hat{S}_1, \hat{S}_2) = 6 \times \beta_1(\hat{S}_1) \times 3 + 0.6 \times \beta_2(\hat{S}_2) \times 3 = 1.86$ days

Using the above problem (P), the maintenance delay constraint is modeled at machine level, and we have integrated the decisions for the initial stock levels S_1 and S_2. Now suppose that, for some reason, we want to model the maintenance delay constraint at component level so that both initial stock levels can be optimized individually. Then the ‘budget’ of 2.0 days for the mean total maintenance delay first has to be divided over the two components. We can do this proportionally to their demand rates, which gives a budget of $(6/6.6) \times 2.0 = 1.82$ days for Component 1 and a budget of $(0.6/6.6) \times 2.0 = 0.18$ days for Component 2. The problem to be solved for Component 1 is as follows:

(P_1) Min. $c_1 S_1$
such that $6 \times \beta_1(S_1) \times 3 \leq 1.82$

and a similar problem is obtained for Component 2. We then obtain $\hat{S}_1 = 3$ as optimal solution for Component 1 and $\hat{S}_2 = 1$ for Component 2. The resulting performance at machine level is then equal to:

Initial stock investment = $100 \times 3 + 10{,}000 \times 1 = 10{,}300$ euros
$MD(\hat{S}_1, \hat{S}_2) = 6 \times \beta_1(\hat{S}_1) \times 3 + 0.6 \times \beta_2(\hat{S}_2) \times 3 = 1.62$ days

This nicely meets the maintenance delay constraint, but at an initial stock investment that is 20 times as high (10,300 vs. 500 euros)! This is purely due to the unnecessary decomposition of problem (P) into single-component problems.

The property that multi-item models for spare parts planning lead to much lower costs than single-item models has also been supported on the basis of real-life data for problems with many items and in multi-echelon settings; see Sherbrooke [2004], Rustenburg [2000], and Thonemann et al. [2002].

Integrated planning can also be applied to multiple types of maintenance resources. In collaboration with ASML, we carried out a research project on integrated planning of spare parts and service tools, and showed that large benefits are possible in comparison with a separated planning (see Vliegen [2009]).

The second principle, the creation of pooling for maintenance resources, has been studied extensively for spare parts (see Wong et al. [2006] and Paterson et al. [2009]). Under tight maintenance delay constraints, spare parts have to be stocked at short distances from the installed machines. At the same time failure rates are low, which means we have low to very low demand rates at the local warehouses. Excessively high spare parts stocks at the local stock points can be avoided by allowing so-called lateral transshipments between local warehouses. A lateral transshipment can take place when a local stock point is out of stock and receives a demand. That demand can then be met by a neighboring stock point that has the required part in stock. This leads to a maintenance delay that can be much lower than for an emergency shipment from a central stock point. In fact, with lateral transshipments local stock points start to behave as if they are one large, virtual stock point. This creates the same demand pooling effect as with a single, large stock point, while the spare parts are still kept at a short distance from the installed machines.

In a joint research project with ASML, we developed a partial pooling concept and we showed by a case study that both downtime and costs could be reduced drastically. This concept has since been implemented by them, and has had the predicted impact; see Kranenburg [2006] and Kranenburg and Van Houtum [2009]. Based on the concept developed for ASML, Rijk [2007] developed a similar concept for the car stocks and quick response stocks at Océ Technologies, and also found large improvement opportunities. This study was followed by a successful pilot in France, and is currently being implemented in other countries.

In the current PhD projects of Reijnen, Van Wijk and Karsten, we are respectively investigating more general forms of partial pooling: exactly when lateral transshipments should be applied and when not, and the pooling of spare parts owned by different companies; see also Reijnen et al. [2009], Van Wijk et al. [2009], and Karsten et al. [2009]. The project of Reijnen is part of the SLF Research project, a collaboration with Erasmus University, the University of Twente and a group of 15 companies. The project of Van Wijk is being carried out in collaboration with the Department of Mathematics and Computer Science. The project of Karsten is currently focusing on fundamental theoretical questions, but the topic is promising from a practical point of view, and we plan to explore the ideas in Master's thesis projects carried out at companies. At present, the pooling of parts owned by different companies, or belonging to different business units or service contracts, hardly happens in practice, but it constitutes a great opportunity for companies to reduce both spare parts investments and downtime. The key issues to be investigated are the conditions under which companies benefit most from collaboration, and allocation rules that ensure that all parties benefit from collaboration.

Three new projects that have been started up recently are the PhD projects of Arts and Driessen, and the postdoc project of Basten. The project of Arts is part of an innovation program of NedTrain on 'Rolling Stock Life Cycle Analysis'. This program is built around 4 PhD research projects in total, and involves a multidisciplinary group of researchers from Delft and Eindhoven universities of technology and the University of Twente. In the research of Arts, we will focus on the control of the closed loop of all repairables, which includes the control of the repair shops. The project of Driessen focuses on the role of material planners in companies that own a fleet of capital goods and organize their own maintenance, and how they can be supported by quantitative models. This project is led by Gordian Logistic Experts, and in total involves a group of 6 companies. The postdoc project of Basten is part of the One Logistics project. This project was initiated by parties involved in the World Class Maintenance consortium. Its aim is to develop a business concept for a central support organization for the maintenance of military systems of European defense organizations.

Theme 2: Maintenance concepts

The maintenance concept of a capital good is defined during the design phase. Later, adaptations are made based on empirical data collected during the exploitation phase. This may be done by either the OEM, the users or a third party, and depends on who is leading with respect to the maintenance.

Maintenance concepts involve a basic trade-off between preventive and corrective maintenance. Preventive maintenance leads to scheduled downtime, while corrective maintenance leads to unscheduled downtime. Unscheduled downtime occurs in the middle of the operating hours of a capital good, and leads to inconvenience and significant downtime costs. The consequences of scheduled downtime will be much lower if it can be planned outside the normal operational hours. However, in an increasing number of environments the time available outside operational hours is either non-existent or very limited. And if there is any time, then it is during the nights or at weekends, and carrying out maintenance at those times may be hard to organize or it may be expensive.

A first research topic that we want to study is the trade-off between preventive and corrective maintenance, with downtime constraints during operational hours. We may study this for both an individual capital good and a fleet of capital goods, such as a fleet of trains operated by the Dutch Railways or a fleet of trucks operated by a transportation company. Directly related to this topic is the question of how many systems you need to buy to make sure you always have a given number of systems available during operational hours. To answer this question the trade-off between preventive and corrective maintenance has to be made at the moment that new systems are bought, i.e. before the start of the exploitation phase.

The other main research topic is condition-based maintenance, based on information about the degradation states of components and systems.
The underlying degradation state of many systems can be monitored periodically or continuously by manual inspections, event logs and sensor measurements.
The aim is to monitor quantifiable measures by which the health of critical components can be assessed. Examples of such measures include vibration,

temperature and the percentage success rate of scanners in mail sorting systems. Based on the measurements, we can predict when a certain threshold level at which the component is likely to fail is exceeded, and we can then decide to replace the component preventively at a somewhat earlier time, which is preferably outside the operational hours of the system; see also figure 7 (taken from Elwany and Gebraeel [2008]), which gives an example of a graph showing the degradation behavior of a component and its failure threshold.

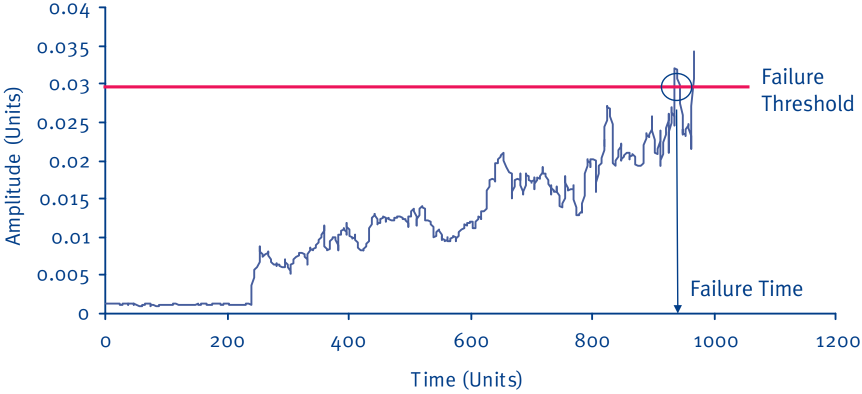

figure 7

Degradation behavior of a critical component

A factor that strongly facilitates the above approach is that nowadays many systems in geographically remote locations are connected to communication networks, which allows the degradation behavior to be monitored remotely and analyzed by specialists at a central hub. This reduces inspection costs and leads to better predictions of failures.

The use of condition-based maintenance has multiple advantages:

(i) it leads to less downtime during operational hours

(ii) unlike age-based preventive maintenance, it hardly reduces the used lifetime of a component

(iii) it facilitates a planned supply of maintenance resources; e.g. there is sufficient time to send a required spare part from a central warehouse, and it may no longer be necessary to stock such parts in local warehouses

(iv) replacement takes place before the actual failure, which by itself leads to lower replacement costs (e.g. less risk of damage of other parts).

A current research project within the ‘Maintenance concepts’ theme is a project on basic models for condition-based maintenance, in which components are first assumed to show a defect, with real failure only occurring after a certain delay (cf. Christer and Waller [1984]; see also Stein [2009]). For first results on this research, see Çelebi et al. [2010]. Further, we plan to start up two PhD research projects on condition-based maintenance and remote monitoring and diagnostics in the course of this year. We also plan to collaborate with data mining specialists for the analysis of event logs and other data that are automatically collected for high-tech systems.

Theme 3: Design for availability

As already argued, users of several types of capital goods want to maximize availability (minimize downtime) and minimize TCO. The customer support organizations of many OEMs are aware of these customer interests. Surprisingly, many R&D departments still seem to focus primarily on reliability and cost price. What seems to be lacking is a form of real availability management, and a 'design for availability' attitude (cf. Smets et al. [2010]). Managing availability is like quality management. All departments have to participate, and it starts with the definition of aims and purposes at top management level (see e.g. Mitra [2008] for the principles of quality management).

One of the tasks at top management level is to set the right targets for the design of new systems. The design phase has a strong impact on TCO and downtime levels. Factors that play an important role are the reliability levels of components, building-in redundancy, building-in sensors to facilitate condition-based maintenance, a strongly modular design structure, and the use of common components in different machine types. We aim to model and quantify the effect of these factors.

In the PhD project of Öner, the effect of reliability levels and redundancy has been investigated; see Öner et al. [2010a, 2010b]. Let us illustrate the effect of the reliability level of a critical component. Assume that a new capital good has been designed, and that the OEM expects to sell 1000 units of this capital good. These units will be used during an exploitation period of say 20 years. We consider the reliability level of a specific component, which is measured as the Mean Time Between Failures (MTBF) and denoted by τ. There is a minimal MTBF level, denoted by τ_l, which represents the standard reliability level for the component as reached by competitors and expected by the market. There is also a maximal reliability level τ_u, which is regarded as the highest possible reliability level. It is generally known that the design costs and the production costs for all 1000 units together are increasing and convex as a function of τ. These costs are denoted by $A(\tau)$. The maintenance costs for all 1000 units during the entire exploitation phase will decrease as a function of τ, and these costs are denoted by $M(\tau)$. Finally, the total downtime will also decrease as a function of τ and is denoted by $D(\tau)$.

The curves for $A(\tau)$, $M(\tau)$, and $D(\tau)$ are shown in figure 8.

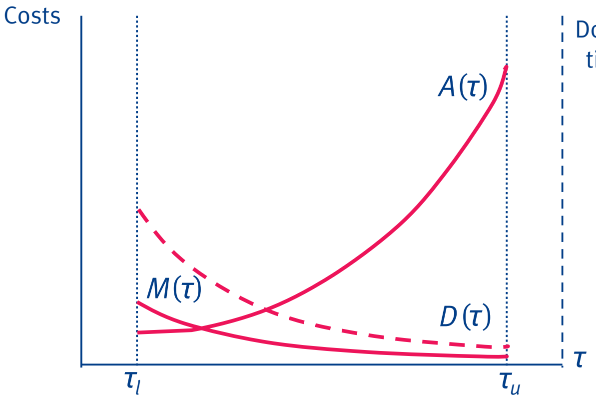

figure 8

The effect of reliability level on downtime and TCO

If we now want to optimize τ, we have to translate the downtime $D(\tau)$ into costs. This may be done by multiplying the total downtime $D(\tau)$ by a Lagrange parameter λ (i.e. a shadow price) which is connected to a budget for downtime for all critical components together (or for even a broader scope). The Lagrange parameter gives a virtual value to each time unit by which the downtime of the component is reduced. The higher the budget, the higher λ will be, and therefore the higher the incentive to go for a higher reliability level τ than if the effect on downtime was ignored. For a given λ, we get total costs

$$\pi(\tau) = A(\tau) + M(\tau) + \lambda D(\tau) .$$

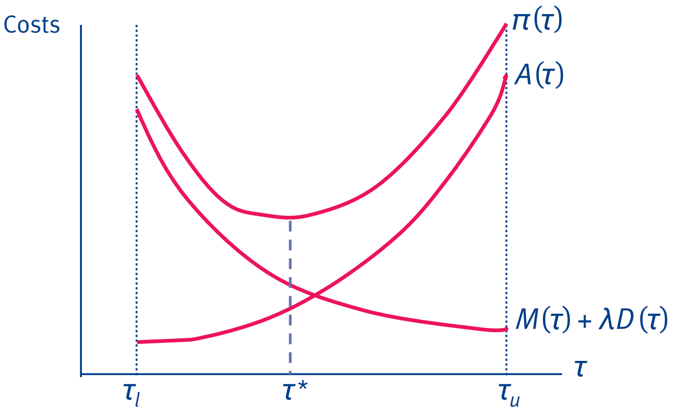

figure 9

Total costs and optimal reliability level

The function $\pi(\tau)$ typically has a convex shape and a unique minimizer τ^*; see figure 9. If downtime is taken into account, the optimal reliability level τ^* may be significantly higher and the optimal costs $\pi(\tau^*)$ may be significantly lower than when the effect on downtime is ignored.

While it is generally believed that the design and production costs $A(\tau)$ are increasing and convex, in practice it appears to be hard to get good estimates of these costs. This prevents the translation of the above approach into easily usable decision support tools. However the situation is different when a component in a new system has to be chosen from different components available on the market. In this situation prices are known, and generally information on reliability levels is available, so an analysis as described can be made. Similarly, it is possible and practical to evaluate redundancy choices. An environment in which the above approach is also applicable is the engineer-to-order environment, in which each new system for a customer is designed from existing building blocks; see Vlasblom [2009] who, during a project at Vanderlande, built a prototype decision support tool to make a downtime and TCO evaluation of alternative designs of baggage handling systems.

The PhD project of Öner is part of the IOP-IPCR project on ‘Service-Oriented Design of Capital Goods’, a collaboration with the University of Twente and a group of 16 companies. This project will be completed in the course of this year, and we aim to start up new research projects in the near future. Apart from availability and TCO, we can also study the effect of design decisions on sustainability. We can do this by a similar approach as in the current PhD project of Hoen on green supply chains.

Research collaboration

The dominant research methodology within the chair of Reliability, Quality and Maintenance is quantitative modeling research. That is, for various types of maintenance issues, we build appropriate mathematical models, and next we generate insights on trade-offs or develop efficient solution algorithms to support specific decisions. Technical data are taken as given. In our research, we aim to have both a high scientific impact and a high practical impact. To achieve both these research aims, collaboration with industry and other research groups is important.

We are currently part of multiple large research projects: the SLF research project, the NedTrain innovation program, the ‘materials planners’ project led by Gordian, the IOP-IPCR project on ‘Service-Oriented Design of Capital Goods’, and the One Logistics project. At a higher level, we participate in the Service Logistics Forum, the logistics top institute Dinalog (which has a separate research program on service logistics), and the World Class Maintenance consortium. These forms of collaboration are useful and will be continued in the future. It would be even better if all the involved organizations and large projects could join forces in one institute in the near future. They fit together well, and this would further strengthen the innovation in maintenance.

Acknowledgments

I have given you an outline of my research plans in the area of maintenance of capital goods. I would like to conclude by expressing my gratitude to a number of people.

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Curriculum vitae

Geert-Jan van Houtum (1967) studied Applied Mathematics in the department of Mathematics and Computer Science of TU/e. He worked in the same department on his PhD research on multi-dimensional queueing systems. After gaining his PhD in 1995, he worked for four years in the Production and Operations Management group of the Mechanical Engineering department at the University of Twente. There he worked on production and inventory systems, and on spare parts management within a joint maintenance management project at the Royal Netherlands Navy. In 1999, he moved to the department of Technology Management (now Industrial Engineering & Innovation Sciences) at TU/e, where his research gradually moved to the area of maintenance management for capital goods. This research is carried out in close collaboration with both producers and users of capital goods. In 2001, he worked at Carnegie Mellon University as visiting associate professor. In 2008, he was appointed as full professor to the chair of Reliability, Quality, and Maintenance.

Prof. Van Houtum is scientific director of the Beta research school on Operations Management and Logistics. He is associate editor of OR Spectrum, the Flexible Services and Manufacturing journal, and Mathematical Methods of Operations Research. He is also scientific advisor to EURANDOM for the Queueing and Performance Analysis research area, and he is a board member of the European Supply Chain Forum and the Service Logistics Forum.

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