KEMA Maintenance Optimization Support System

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Abstract

In this article the basic principles of KEMA Maintenance Optimization Models are explained. The computer program KMOSS helps to find optimal maintenance and inspection interval based on costs and time dependent failure rates. The use of computer programs like KMOSS improves maintenance policies and it results in a more consistent maintenance program.

Keywords: Maintenance, Inspection, Optimization of Intervals, Probablistic Models, Time dependent failure rates, Preventive and Corrective Costs.

Introduction

Since 1985 the Risk and Reliability department of KEMA is developing maintenance optimization computer models.

Five models have been made. Together with a user friendly database management system the models form a complete computer program named "KMOSS" (KEMA Maintenance Optimization Support System).
The first model optimizes the maintenance intervals of a component that fails revealed. The second model is applicable to components which fail unrevealed. The third model concerns the conservation of technical systems. The fourth model optimizes inspection intervals and the last model harmonizes different maintenance intervals and produces an optimal maintenance plan for a whole system.

The models are based on a reliability concept and are applicable to all kinds of technical systems. The reliability concept in the models is the search for a balance of costs between preventive maintenance and corrective maintenance using a "simplified" bathtub curve as a mathematical model for the failure behaviour of a component.

This chapter explains the basic principles of the models. Furthermore the difference in the approach of components with revealed and unrevealed failures will be explained in more detail. An example of an application of KMOSS for the Dutch Ministry of Public Transport has been included: the structuring of the maintenance policy for the electrical mechanical part of the Van Brienenoord bridge at Rotterdam in Holland.

Model I (Revealed Failures)

This use based maintenance model optimizes the maintenance intervals of a production component. The property of a production component is that the component fails revealed (noticeable). The maintenance action is (or is equivalent to) replacement so the component is as good as new after the maintenance action (the renewal process).

The model needs cost and failure behaviour information in respect to a given maintenance interval, t:

1 Corrective (maintenance) costs, CC
2 Preventive (maintenance) costs, CP
3 Failure probability, $P\{F|t\}$

Corrective costs are the total costs incurred after the occurrence of a failure. It includes replacement costs, downtime costs and consequence costs (damage). If no failure occurs, a preventive maintenance action will take place. These costs include replacement costs and downtime costs, where the downtime costs of a preventive maintenance action will be smaller than or equal to the downtime cost of a corrective maintenance action.
Finding the failure probability in the form of a bathtub curve is often the most difficult part of maintenance optimization. Most of the time there isn't any bathtub curve at all. Still one needs to know the failure probability to optimize maintenance. The solution to this problem has been found in using expert opinions to obtain a so called simplified bathtub curve. To make a simplified bathtub curve one needs an estimation of the mean time to failure of a component $\mu(TF)$, the random failure period T_0 and the percentage of random failures per time period Z_0. These three parameters determine the simplified bathtub curve, which is based on a negative exponential distribution function in the random failure period T_0, and is based on a Weibull distribution function with shape parameter $\beta = 2$ in the period after T_0. See fig 1.

In formula:

For $t <= T_0$ the failure rate is constant:

$$Z(t) = Z_0$$

The failure distribution function is:

$$P\{F|t\} = 1 - \exp(-Z_0 \cdot t)$$

For $t >= T_0$ the failure rate becomes:

$$Z(t) = Z_0 + \alpha(t - T_0) \text{ and } \alpha > 0$$

The failure distribution function is:

$$P\{F|t\} = 1 - \exp(-Z_0 \cdot t - {}^1/_2\, \alpha(t - T_0)^2)$$

The Reliability $R(t) = 1 - P\{F|t\}$

a can be calculated by solving numerically:

$$\mu(TF) = \int_0^\infty R(t)\, dt$$

The total expected costs of a component $E(CT)$ is defined as the sum of the corrective costs CC times the failure probability $P\{F|t\}$ and the preventive costs CP times the reliability $R(t) = 1 - P\{F|t\}$. These expected costs are made in a cycle, $E(t)$ (the mean lifetime given the maintenance period t).
In formula:

$$E(CT|tr) = CC \cdot P\{F|tr\} + CP \cdot (1 - P\{F|tr\})$$

$$E(tr) = \int_0^{tr} R(t)\, dt$$

Minimizing the expected costs per cycle gives an optimal maintenance interval Tr. See fig 1.

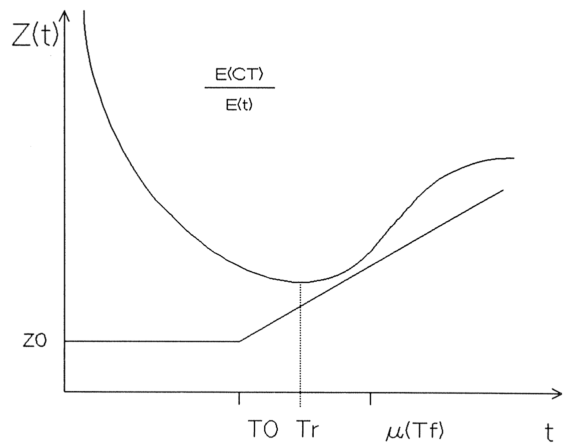

Fig. 1. Simplified bathtub curve and the total expected costs per cycle.

Model II (unrevealed failures)

This model is applicable for components which fail unrevealed, for instance safety devices. The model takes into account the possible unavailability of a standby component at the unpredictable moment of a process demand. If the component is not available due to an unrevealed failure, testing or maintenance, high consequence costs are made (explosion, very long downtime of the process).
The main difference between model I and II is that an optimal (model II) maintenance interval will be achieved only if the test interval is optimal. Because of the fact that an optimal test interval is dependent of the maintenance interval, finding the optimal maintenance interval is an iterative process. See fig 2.

The total expected costs of a model II component are divided into two parts, the standby part and the process part.

The standby part is equal to the total expected costs of model I. Only the test costs (if there are any) have to be added. This is $n \cdot C\text{test}$, where
- n is the mean number of tests per cycle
- Ctest are the costs of one test.

For the process part one has to make a difference between two situations. In the first situation the process will be stopped during testing or maintenance. In the second situation the process will be continued during testing or maintenance.

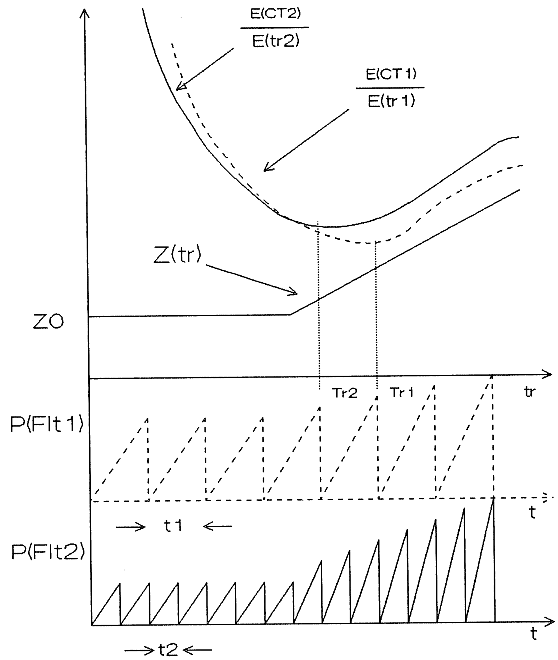

Fig. 2. An optimal test and maintenance interval.

If the process is stopped during a test, the contribution to the total risk due to testing will be $n \cdot \tau \cdot C\text{dtp}$, where
- n is the mean number of tests per cycle
- τ is the test duration and
- Cdtp are the downtime process costs per time period.

If the process is stopped during maintenance, the contribution to the total expected costs because of maintenance will be

$$[P\{F|tr\} \cdot Tc + (1 - P\{F|tr\}) * T\text{rev}] \cdot C\text{dtp}, \text{ where}$$

- $P\{F|tr\}$ is the failure probability
- Tc is the duration of the corrective maintenance action on the standby component
- Trev is the duration of the preventive maintenance action (revision) on the standby component
- Cdtp are the downtime process costs per time period.

If the process is not stopped, the downtime costs Cdtp become a risk $D \cdot CCp$, where
- D is the number of demands from the process per time unit
- CCp are the (high) consequence costs of the process if a failure occurs.

Whether the process is stopped or not the process part of the expected costs will always consist the risk due to an unrevealed failure $Uf \cdot D \cdot CCp$, where Uf is the mean time in which the standby component has an unrevealed failure.
Uf and n are functions of the testinterval t, so the total risk is a function of tr as well as t.

In formula:

$$E(CT|tr, t) = E(CTst|tr, t) + E(CTpr|tr, t)$$

$$E(CTst|tr, t) = CC \cdot P\{F|tr\} + CP \cdot (1 - P\{F|tr\}) + n \cdot C\text{test}$$

$$E(CTpr|tr, t) = \begin{array}{l} Uf \cdot D \cdot CCp + \\ (n \cdot \tau + P\{F|tr\} \cdot Tc + (1 - P\{F|tr\}) \cdot T\text{rev}\,] \cdot \\ [X \cdot D \cdot CCp + (1 - X) \cdot C\text{dtp}] \end{array}$$

where

- $X = 0$ if the process is stopped and $X = 1$ if the process isn't stopped
- $Uf = \sum_{i=1}^{n} \int_{t_{i-1}}^{t_i} P\{F_i|\tau\}\, d\tau$ and $t_i = t_{i-1} + t$
- $\int_{t_{i-1}}^{\tau} Z(s)\, ds$
- $P\{F_i|\tau\} = 1 - e$

As in model I the total expected costs have been made in a cycle $E(tr)$. Minimizing the total expected cost per cycle gives an optimal maintenance interval Tr given a testinterval t.

Model III

Model III optimizes the conservation interval of a component and predicts when a replacement action has to be taken, given the conservation frequency.

The model needs cost and failure behaviour information.
1 Corrective replacement costs, *CC*
2 Preventive replacement costs, *CP*
3 Conservation costs per time unit, $Cp(tp)$
4 Failure probability, $P(F|t,tp)$
The corrective costs and preventive costs are defined in the same way as in model I. The conservation costs are incurred every time a conservation action takes place. Generally the conservation costs are not constant, but they are a function of the conservation frequency. The failure probability concerns the probability that the component will fail given a certain conservation frequency. So the failure probability is also a function of the conservation frequency. The impact of conservation on the shape of the simplified bath-tub curve is shown in figure 3. The impact of different conservation intervals on the parameter T_0 is shown in figure 4, and the possible relationship between Cp and tp is given in figure 5.

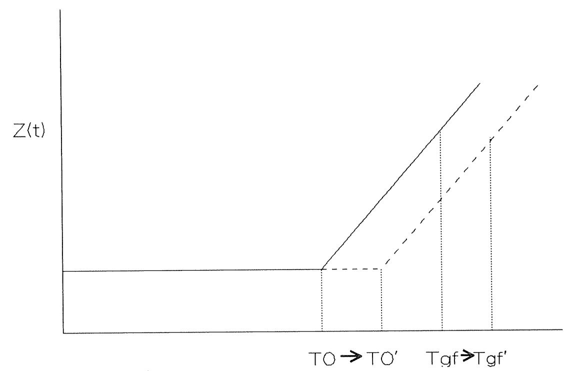

Fig. 3. Impact of conservation on the simplified bathtub curve.

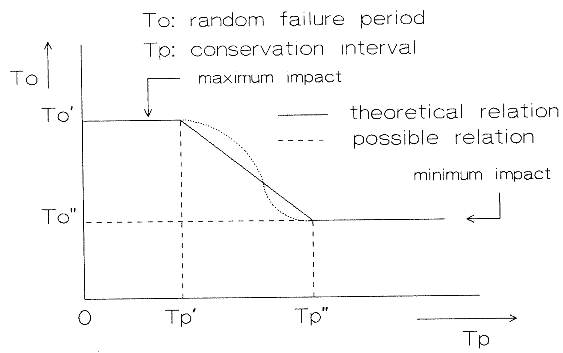

Fig. 4. Impact of the conservation interval on the random failure period T_0.

Again the total expected costs of a component is defined as the sum of the corrective costs times the failure probability and the preventive costs times the reliability. This total expected costs are made in a cycle $E(\tau|tr,tp)$ (the mean lifetime given the maintenance period τr and the conservation interval tp). Minimizing the expected costs per cycle plus the conservation costs per time unit $Cp(tp)$ gives an optimal maintenance interval τr given the conservation interval tp. Comparing the minimum total expected costs per cycle for every conservation interval tp gives the optimal conservation interval Tp and the optimal replacement interval Tr.

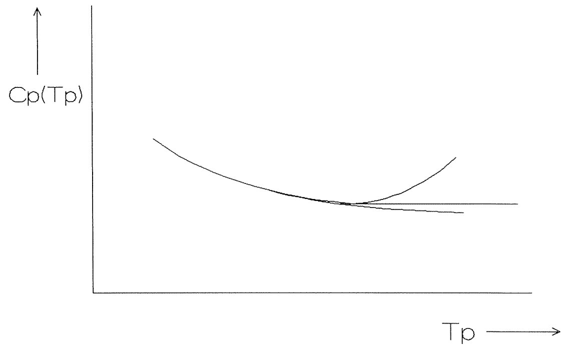

Fig. 5 Possible relation between the conservation interval and the costs.

Model IV

Model IV is a condition based maintenance model which optimizes the inspection intervals of a component and predicts when a replacement action has to be taken, given the mean residual lifetime.

The model needs cost and failure behaviour information in respect to a given lifetime T.
1 Corrective (maintenance) costs, CC
2 Preventive (maintenance) costs, CP
3 Inspection costs, Ci
4 Failure probability, $P(F|ti,T)$

The corrective costs and preventive costs are defined in the same way as in model I. The inspection costs are incurred every time the component is inspected. The failure probability concerns the probability that the failure prediction property reaches a limit during the next inspection period, given the present lifetime of the component. So condition based maintenance is only applicable if such a failure prediction property consists. Furthermore neither the preventive costs nor the difference between the corrective and preventive costs are allowed to be higher then the inspection costs.

The inspection risk of a component IR is defined as the sum of the difference between corrective and preventive costs CC-CP times the failure probability and the inspection costs *Ci* times the reliability. This risk is incurred in a cycle $E(t|ti,T)$ (the mean lifetime given the inspection period *ti* and the present lifetime *T*). Minimizing the risk per cycle gives an optimal inspection interval *Ti*. A replacement action has to be taken when the inspection risk becomes too high or when the inspection interval becomes too small.

Model V

Model V harmonizes maintenance intervals. In the first place all the possible combinations of maintenance actions have to be definied. Furthermore the benefits of all the combinations have to be known. The computerprogram gives the maintenance intervals for every combination. The total risk of the combined maintenance action will be greater then the cumulative risk of the maintenance actions without harmonization. But if the benefit of the combined maintenance action is greater then the difference between the combined risk and the cumulative risk, harmonization is worthwhile. See figure 6.

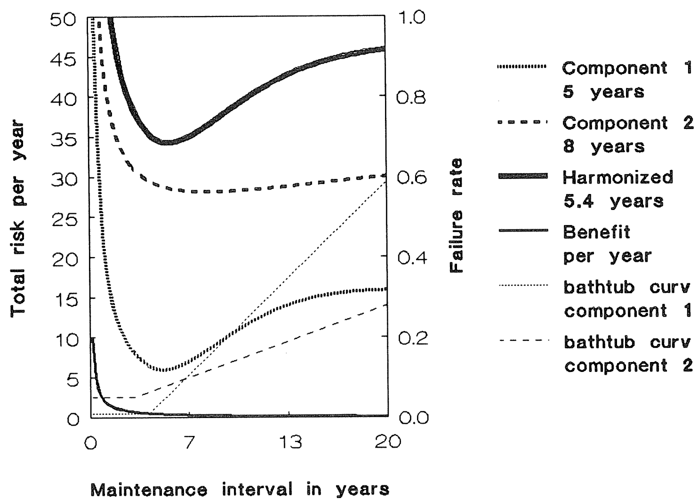

Fig. 6. Harmonization of two components

Comp 1:

Cost parameters	CP_1	$= 5,\ CC1 = 40$
Failure parameters	Z_{01}	$= 1\%,\ T_{01} = 4,\ \mu(TF)1 = 10$
Maintenance int.	Tr_1	$= 5$
Total costs	$C(Tr_1)$	$= 1.5$

Comp 2:

Cost parameters	CP_2	$= 10,\ CC_2 = 250$
Failure parameters	Z_{02}	$= 5\%,\ T_{02} = 3,\ \mu(TF)2 = 15$
Maintenance int.	Tr_2	$= 8$
Total costs	$C(Tr_2)$	$= 14.1$

Benefit per maintenance action		= 5 (= CP_1)
New maintenance interval	Th	= 5.2
Total costs without harmonization		= 15.6
Total costs with harmonization		= 14.9 (incl. benefit)

The Van Brienenoord bridge

In theory one has to determine a maintenance (or inspection) interval for every component of the bridge. It takes a lot of time applying the models to all the components of a complete system, so a method had to be found to reduce the work.

The method contains seven steps.

Step one is:
Dividing the total bridge system into subsystems based on their functions. Such a subsystem is the electrical mechanical part of the bridge containing 114 components.

Step two is:
Forming four groups of components based on the applicability of the models 1 to 4.

Step three is:
Forming subgroups of components with equal failure consequences. There are five different failure consequences (combinations are possible):
1 a total system failure
2 a total system failure due to a failure of a combination of components
3 no effect to the system
4 a failure of a subset of the system due to a failure of a component
5 unsafe situation or system damage

Step four is:
Searching for the most important components in the subgroups. The importance depends on the mean life time and the difference between the planned and unplanned repair time. The result is a list of only five components namely:
- The main electromotor (Model 1,3 or 4, consequence 2)
- The brake (Model 4, consequence 1 & 5)
- The reduction gearing (Model 4, consequence 1)
- The auxiliary motor (Model 2, consequence 1)
- The main bearing (Model 3, consequence 1)

Components with consequence 3 or 3 and 4 like an oil pump or a pressure indicator are maintained corrective.

Step five is:
Determining the maintenance intervals of the (5) dominating components.

Step six is:
Allocating the maintenance intervals to the non dominating components based on expert judgement.

Step seven is:
Harmonization of the maintenance intervals to get a practical maintenance plan.
The results of step five and seven are now presented in more detail.

Step Five

Results for the main electromotor:
Input failure behaviour:
Mean life time: 30 y.
Random failures: 1% /y.

Input relative costs:

Inspection	: Preventive	: Corrective
1	: 1000	: 2000

The inspection intervals are rounded off 0.5 y.

Model I gives an optimal replacement interval of 50 years. This means that because the ratio between the corrective costs and the preventive costs is small, a failure of the main motor is accepted.
Model III gives an optimal conservation interval of 0.5 years.
(Conservation costs : Preventive costs = 1 : 1000)
These conservation actions improve the failure behaviour of the electromotor. Nevertheless the optimal maintenance interval becomes 48 years, because at that time the conservation costs per cycle are higher than the benefits.
Model IV gives an optimal inspection strategy based on the fact that all the inspection results won't change the estimated mean life time of 30 years.
Until 3 years the inspection interval is 1.5 year.
From 3 to 13 years the inspection interval becomes 1 year.
From 13 to 27.5 years the inspection interval is 0.5 year.
One has to replace the motor if the mean residual lifetime becomes less than 2.5 years.

Results for the brake:
Input failure behaviour:
Mean life time: 10 y.
Random failures: neglectible

Input relative costs:

Inspection	: Preventive	: Corrective
1	: 100	: 1000

The inspection intervals are rounded off 2 months.

Model IV gives an optimal inspection strategy based on the fact that all the inspection results won't change the estimated mean life time of 10 years.
Until 4 years the inspection interval is 4 months.
From 4 to 8 years the inspection interval becomes 2 months.
One has to replace the brake if the mean residual lifetime becomes less than 2 years.

Results for the reduction gearing:
Input failure behaviour:
Mean life time: 50 y.
Random failures: 0.1% /y.

Input relative costs:

Inspection	Preventive	Corrective
1	1000	5000

The inspection intervals are rounded off 0.5 y.

Model IV gives an optimal inspection strategy based on the fact that all the inspection results won't change the estimated mean life time of 50 years.
Until 12 years the inspection interval is 1 year.
From 12 to 44 years the inspection interval is 0.5 year.
One has to replace the brake if the mean residual lifetime becomes less than 6 years.

Results for the auxiliary electromotor:
Input failure behaviour:
Mean life time: 30 y.
Random failures: 0.1% /y.

Input system behaviour:
Mean number of demands: 0.25 / y.

Input relative costs:

Testing	Preventive	Corrective	Consequence
1	100	200	500

The testintervals are rounded off 0.1 y.

Model II gives an optimal testinterval of 1.5 year. The optimal replacement interval becomes 49.5 years, if no bad testresults are found. This means that before 49.5 years the mean unavailability of the auxiliary motor during a testinterval of 1.5 year is acceptable. After the 49.5 years the mean unavailability becomes too high and the total expected costs per cycle will increase.

Results for the main bearing:
Input failure behaviour:
Mean life time: 10 y.
Random failures: 0.1% /y.

Input relative costs:

Conservation	:	Preventive	:	Corrective
1	:	1000	:	5000

The conservation intervals are rounded off 1 month.

Model III gives an optimal conservation interval of 10 months. The optimal replacement interval becomes 30 years. These conservation actions improve the failure behaviour of the bearing. The mean life time becomes 40 years (was 10 years). Without conservation the replacement was every 3.8 years.

Step seven (Harmonization results):

Model III components with a total system failure consequence become a conservation interval of 1 year (was 10 months). This implies increasing costs of 0.5% per cycle.
Model IV components with an unsafe or system damage failure consequence get an inspection interval of 3 or 6 months (was 2 and 4 months) depending on the residual life time. This implies an increased risk in the first interval of 3.4%.

Conclusions

Probabilistic models prove to be a powerful tool to control inspection and maintenance intervals. This was not only shown by the case study of the Van Brienenoord bridge, but this was also shown by a case study of concrete carbonation. Clear distinction could be made between foundations produced by different contractors. Inspection intervals of 17 and 4 years were calculated.

Developing maintenance optimization support systems like KMOSS is a necessity to improve maintenance policies.
Applying the computermodels is the most difficult part. The reason for this is not the data in the first place but the acceptance of probabilistic decision making.