Safety, Reliability and Risk Analysis: Beyond the Horizon – Steenbergen et al. (Eds)
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Simulation based comparison of predictive maintenance policies

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ABSTRACT: When an asset is operated in variable conditions, its operational efficiency can be improved significantly when the maintenance is performed in a dynamic manner. This means that variations in usage and operating environment are taken into account when deciding on the length of the maintenance intervals. Several predictive maintenance strategies, that enable such an approach, are nowadays being developed. However, demonstrating the benefits of these new maintenance concepts is generally difficult. As a result, implementation of the concepts is still rather limited. In this paper, a previously proposed modeling framework is used to quantify the performance of different maintenance policies for a navy frigate. A corrective policy will be used as a reference situation. Then the performance of a calendar time based, usage severity based and condition based maintenance policy will be calculated and compared to the reference policy. In all cases the performance of the policies is quantified through the total maintenance costs and the achieved system availability.

1 INTRODUCTION

The two most well-known and traditionally applied maintenance policies are corrective maintenance and calendar time based preventive maintenance. The former policy is normally applied to non-critical parts or systems for which the consequences of failure are small. In that case the component service life is fully utilized, which makes it an efficient policy.

However, for critical components or systems, failures are not allowed to happen. For these components the consequences of failure are too large, either in terms of costs (consequential damage, lost production) or in terms of safety or environmental effects (e.g. aircraft crashes, nuclear disasters). In that case, a preventive maintenance policy must be applied. The challenge is then to find the optimal moment of replacement. If components are replaced too early, failure is prevented effectively, but a large fraction of the service life still remains in the replaced parts, which makes it inefficient. On the other hand, when the replacement is too late, failure occurs. A good balance between the effectiveness (expressed in terms of availability) and efficiency (in terms of costs) must be found.

For systems that are used in a constant manner (i.e. time stationary behavior), experience from the past provides insight in the optimal interval length. Moreover, a fixed interval length provides the same maintenance performance over time, since the failure behavior of the system does not change.

When an asset is operated in variable conditions, it is much more difficult to determine the optimal maintenance interval. Moreover, the interval length that proves to be appropriate in a certain period of time, may not be suitable in another period with a completely different usage pattern. Therefore, the operational efficiency of an asset that is operated in variable conditions can be improved significantly when the maintenance is performed in a dynamic manner. This means that variations in usage and operating environment are taken into account when deciding on the length of the maintenance intervals.

Several predictive maintenance strategies, that enable such an approach, are nowadays being developed (Tinga, 2010, Byington et al., 2002). However, demonstrating the benefits of these new maintenance concepts is generally difficult. As a result, implementation of the concepts is still rather limited.

In this paper, a previously proposed modeling framework (Tinga and Janssen, 2013) is used to compare different maintenance policies. The traditional calendar time based policy will be used as a reference situation. Then the additional benefits of usage based maintenance, usage severity based maintenance and condition based maintenance will be calculated. Also a comparison with a corrective maintenance policy will be made. For each policy, the maintenance costs and the achieved system availability will be quantified.

Since the modeling framework considers a rather complex system, a navy frigate, with several subsystems (e.g. gas turbine, radar system), a realistic estimate of the benefits of an improved maintenance policy can be made. The effect of the reliability of any of the subsystems on the overall system reliability is automatically incorporated in the calculation. Moreover, the relation between (sub)system degradation and usage profile is explicitly modeled.

In the next section, the considered maintenance policies will be described shortly. Then, in section 3, the case study subject and the simulation model will be introduced and the simulations performed will be described. Section 4 presents the results and discusses the outcomes. Finally, section 5 contains the conclusion of this work.

2 MAINTENANCE POLICIES

2.1 *Corrective maintenance*

The most simple form of maintenance is to just wait for a part or system to fail, and then repair or replace it. As was mentioned in the introduction, this policy is very efficient for non-critical components, but cannot be applied to critical systems.

2.2 *Calendar time based maintenance*

The most basic form of preventive maintenance is Calendar Time Based Maintenance (CTBM), where the length of the intervals are defined in terms of calendar time, e.g. weeks or years. This policy does not account for any changes in usage of the system, and is therefore called a static policy.

If the number of operating hours varies in time, or the severity of the usage changes, e.g. due to changing environmental conditions, this policy is not very suitable. In that case failures will still occur every now and then (when unexpected usage conditions occur), or very conservative intervals must be adopted to account for the most severe usage profile. In the former case, the policy is not effective, in the latter case it is not efficient.

2.3 *Usage based maintenance*

A policy that is more dynamic than the previous policy is a Usage Based Maintenance (UBM) policy. In this policy, a suitable usage parameter is selected for the definition of the intervals. The usage parameter generally taken is the number of operating hours or kilometers (for vehicles). Variations in usage over time can then be accounted for, which makes the policy more effective and efficient than the CTBM policy.

However, operating hours is not always the best usage parameter. For example, for components failing due to fatigue, the number of stress cycles (e.g. number of starts/stops of the system) is a much better parameter to predict failure than operating hours. The selection of the most suitable usage parameter thus relies on knowledge of the (physical) failure mechanisms. But application of a relevant parameter enables to significantly reduce the amount of conservatism in the maintenance interval determination (Tinga, 2013).

2.4 *Usage severity based maintenance*

Even when a relevant usage parameter has been selected, the severity of every unit of this parameter may not be identical. For example, in a gas turbine the service life is strongly correlated to operating hours, but an hour at a high power setting causes much more damage than an hour at lower power. A Usage Severity Based Maintenance (USBM) policy takes this effect into account by quantifying the variations in usage. This policy requires rather detailed insight in the failure mechanisms and a proper registration of the usage conditions. However, when applied properly, it has the potential to accurately predict the component service life. Using that, the required length of the maintenance interval can also be assessed accurately.

2.5 *Condition based maintenance*

In some cases the condition of the system or part can be monitored, either directly through a dedicated sensor or indirectly by monitoring the system performance. Examples of direct condition monitoring are vibration monitoring and the application of crack length sensors. A performance related condition assessment is, for example, the monitoring of the flow through a pump. A measured reduction in flow is then an indication of a decreased system condition.

In a Condition Based Maintenance (CBM) policy the maintenance activities are triggered by the condition reaching a certain critical level. As in a corrective maintenance policy, the component service life is (almost) maximally utilized, but failure is prevented. Therefore, this policy is both efficient and effective with respect to the monitored part.

However, condition monitoring is not always feasible, either technically or economically. An example of the former is a rotating gas turbine blade, which cannot be monitored by a sensor due to the high temperature, rotational speed and inaccessibility of the blade inside the engine. Another reason not to apply CBM could be that the investments in sensors or data acquisition are higher than the potential benefits.

3 SIMULATION MODEL

In a previous paper (Tinga and Janssen, 2013) a model to simulate and optimize the maintenance process for a navy frigate has been proposed. That framework will be used in this work to compare different maintenance strategies, as will be described in this section.

3.1 *Case study: Navy frigate*

A navy frigate is a very complex system composed of many subsystems. Each subsystem has its own failure behavior and requires maintenance at a specific frequency to guarantee its availability. Moreover, the usage profile of a frigate is quite variable, since it performs different types of missions at various locations around the world. This means that all subsystems are subjected to a variable load sequence caused by changes in usage severity (e.g. number of operating hours per day, rotational speeds, operating temperatures) and environmental conditions (e.g. temperature, humidity). These variations make the failure behavior of the subsystems quite unpredictable.

Further, the more complex maintenance activities cannot be performed during an operational mission, but require the vessel to return to a harbor, where specialized maintenance personnel can be boarded. Such a maintenance period severely affects the availability of the frigate, and thus should be minimized in terms of duration and number of occurrences.

On the other hand, performing insufficient maintenance will lead to failures during operations, which also affects the availability and even might lead to abandoning the mission, with possibly severe security or safety consequences. And in addition to the operational issues, which are mainly related to system availability, also the costs of maintenance are important as there is a constant drive to increase maintenance efficiency and reduce costs.

3.2 *Simulation model details*

The simulation model contains four subsystems, i.e. the gas turbine, the diesel generator set, the refrigeration plant (water chiller) and the long-range search radar (SMART-L), see Figure 1. These installations are associated to different functions within the frigate, i.e. propulsion, energy generation, cooling and sensing, which are all quite essential for the continuation of an operational mission. The two gas turbines are always operated simultaneously, and are therefore modeled as one single system, which is also the case for the radar system. For the generators, four diesel engines are available on board, but only two of them are operated simultaneously. Also the water chillers have some redundancy: three chillers are available, and only in some specific situation all three systems are operated. In most cases, one or two chillers are sufficient to deliver the required amount of cooling to the active systems.

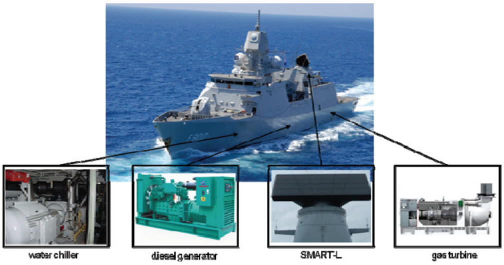

Figure 1. Navy frigate and the four modeled subsystems.

3.2.1 *Usage profiles*

The usage profile of the frigate is defined in terms of nine different mission types (e.g. anti-piracy), each consisting of a sequence of several mission phases, e.g. transit, anti-submarine warfare or surveillance. Also, for each mission the environment in which the vessel performs the mission (temperature, humidity) is defined.

Since not all subsystems on board are operating full-time during the mission, the fraction of time that each subsystem is active in each of the mission phases is specified. By selecting a specific mission and an associated mission duration, the total operating times for each subsystem can be calculated.

3.2.2 *Maintenance modeling*

It is assumed in this model that the ship is overhauled after a period of three years of operation. During the overhaul all subsystems are checked and, if required, parts or complete systems are repaired or replaced. But also during the operational period in between two overhauls, smaller maintenance activities will have to be executed, which in most cases requires the vessel to return to the base. In the present model it is assumed that intermediate maintenance is performed for 12 weeks during the three year operational period.

However, there are several ways to distribute the 12 weeks intermediate maintenance over the three years period, e.g. one period of 12 weeks or 6 periods of 2 weeks. Increasing the number of maintenance periods (n) yields a decrease of the time between two maintenance periods. Depending on the failure behavior of the subsystems and the usage profile, the optimal maintenance policy may consist of a different number of maintenance periods, where n ranges from 1 to 9.

In the model either corrective or preventive maintenance is performed on the subsystems, depending on whether failure has occurred in a certain period. For preventive maintenance it is possible to set a threshold value β. Preventive maintenance is executed when only a fraction β of the subsystem service life (T_{sl}) remains:

$$t_{active} \geq (1-\beta)T_{sl} \tag{1}$$

The larger the value of β, the more conservative the preventive maintenance policy becomes.

Note that both corrective and preventive maintenance can only be performed during intermediate maintenance periods. The condition in Equation 1 is thus only checked during these maintenance periods, and then the decision is taken whether or not preventive maintenance is to be performed. On the other hand, if a subsystem fails, it will be down for the time period until the next intermediate maintenance. For the single systems a failure also implies that the frigate as complete system is unavailable, for the redundant systems this is not the case.

3.2.3 *Cost function*

The model is used to optimize the maintenance process, which means that the costs are minimized, provided that the availability is higher than a certain minimal level (e.g. 80%). The maintenance costs are calculated using the following cost function

$$C = n_{corr}C_{corr} + n_{prev}C_{prev} + n_{per}C_{per} + C_{fix} \tag{2}$$

where n_{corr} and n_{prev} are the number of corrective and preventive maintenance activities, C_{corr} and C_{prev} the associated costs per activity (could be different per subsystem), n_{per} is the number of intermediate maintenance periods, C_{per} the associated costs per period (e.g. travel costs) and C_{fix} are the fixed costs. It is assumed that the cost of preventive maintenance is only a fraction $\alpha < 1$ of the cost of corrective maintenance, since residual damage to the failure of the subsystem can be prevented:

$$C_{prev} = \alpha C_{corr} \tag{3}$$

3.3 *Simulation approach*

For each subsystem in the frigate, the initial service life is defined in terms of operating hours. Then, subsequent missions are processed and the associated operating hours for each subsystem are subtracted from the remaining service life at the start of the mission. When for one of the subsystems no service life remains, failure will occur and, depending on the subsystem and mission type, the mission will have to be abandoned. Corrective maintenance can then be executed to restore the service life to its initial value. It is also possible to perform preventive maintenance at some earlier (and more convenient) moment in time, which restores the service life, but also prevents the failure to occur.

As the usage profile of each individual vessel in the fleet is different and also changes in time, the sequence of executed missions for the simulated frigate is obtained from a stochastic process, where a Markov matrix specifies the transition probabilities between the nine mission types. At this moment it is assumed that the mission types are completely independent, so the probability of occurrence for a certain mission type to be the next mission is just the relative number of times that this mission occurs, independent of the present mission type. However, in practice a real mission will always be preceded by a training mission, which in future work will be incorporated in the Markov matrix.

The model is implemented in Matlab. A time stepping procedure enables the simulation of a period of time representing 100 operational periods, i.e. 100 periods of three years. Although this is much longer than the actual service life of a frigate, it enables to simulate a usage profile that is representative for the complete fleet of ships. Moreover, the simulations have been performed 350 times with the same initial settings, which enables to calculate the confidence intervals for the results obtained. The mission duration is sampled from a triangular distribution function each time a new mission type is selected.

The model is then applied to compare the different maintenance strategies introduced in section 2. The aim of the present work is to quantify the differences between these strategies, both in terms of costs and availability. To achieve that, the model is used to determine, for each strategy, the optimal maintenance interval for the frigate (complete system), i.e. minimal costs at a prescribed availability, given the usage profile and the associated failure behavior of four important subsystems.

4 RESULTS

4.1 *Corrective maintenance*

A corrective maintenance policy can be simulated in the model by setting the value of the preventive maintenance threshold $\beta = 0$. This effectively means that preventive maintenance is performed only when the end of life has been reached, which implies that the subsystem has failed.

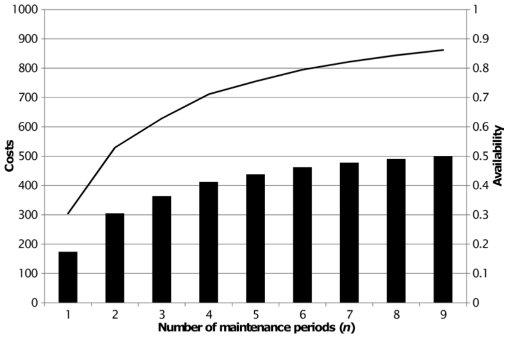

Figure 2. Costs (bars) and availability (line) for corrective maintenance at a range of interval lengths.

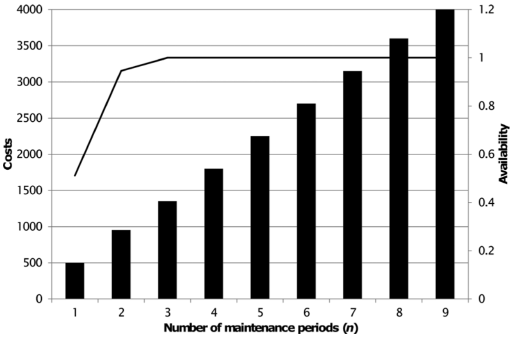

Figure 3. Costs (bars) and availability (line) for calendar time based maintenance at a range of interval lengths.

The resulting total maintenance costs for the frigate in the simulated period for different numbers of intermediate maintenance (n) are shown in Figure 2. In the same figure also the availability of the frigate in the simulated period is indicated. These results show that for $n = 1$ (only one intermediate maintenance period halfway the three years period) the costs are rather limited. However, the availability of the system is only 30%, which is much lower than the required 80%. This is explained by the fact that one or several subsystems fail before the maintenance period. The system is then down, but has to wait until the next maintenance period before the subsystems can be repaired or replaced. For $n = 1$ there is only one such opportunity, resulting in low costs and a low availability.

For increasing n the time between two maintenance periods decreases, the down-time is reduced and the availability is observed to increase. But at the same time, the maintenance costs increase considerably. The maximum achievable availability with this policy appears to be 86.2%. The optimal policy, with minimal costs and at least 80% availability, is the policy with $n = 7$. The availability is then 82.2% and the total costs are 478.

Note that the 95% confidence intervals for both the availability and costs are also obtained from the simulations. For the availability the interval is 82.1–82.3%, the total maintenance costs are in the range 477.2–478.5. It is clear from these numbers that the scatter in the results of individual simulations is rather limited.

4.2 *Calendar time based maintenance*

In a CTBM policy the subsystems are maintained at fixed moments in time. This can be simulated in the model by setting the value of the preventive maintenance threshold $\beta = 1$. In that case preventive maintenance is performed at each intermediate maintenance period, on each subsystem, since the remaining life of the subsystems is always less than 100%.

The resulting costs and availability for the range of maintenance intervals (n) is shown in Figure 3. It immediately becomes apparent that this is a very expensive policy, but also a policy that provides very high availability levels. From $n = 3$ the availability is a full 100%. This is due to the very conservative nature of the CTBM policy, in which subsystems are replaced at each opportunity, disregarding the age or condition of the subsystems. The optimal policy in this case would be $n = 2$, with a 94.6% availability and total costs of 951. The 95% confidence intervals for these results are 94.5–94.6% and 949.5–951.8.

The policy to replace all the subsystems at all periods is extremely conservative, especially when not all subsystem are equally critical to the system availability. For the presently assumed service life times and usage profile of the frigate, the gas turbine appears to fail much more frequently than the other subsystems. Therefore, another variant of the CTBM policy would be to replace the gas turbine each period, at the previously determined optimum of $n = 2$, but only replace the other subsystems at $n = 1$. The simulation shows that the system availability stays on 94.6%, but the total costs are reduced to 571. This demonstrates that it sometimes pays off to tune the intervals to the different subsystems within a certain policy.

4.3 *Condition/usage severity based maintenance*

For both the USBM and CBM policy the actual degradation of the subsystems is assessed. The difference is that in CBM the assessment is based on sensors experimentally determining the condition, while in USBM a physical (numerical) model is applied. In the present simulation these two

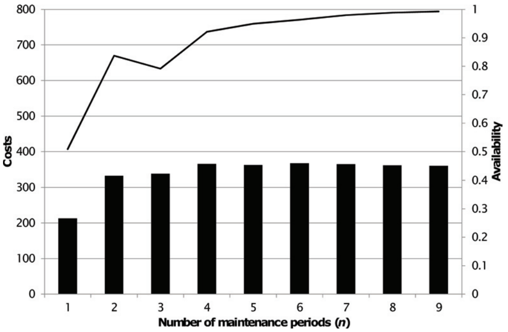

Figure 4. Costs (bars) and availability (line) for condition based maintenance at a range of interval lengths.

policies are identical: in both cases the subsystem degradation is described by the consumption of the remaining service life. Since this quantity is known in the simulation, also the maintenance decisions can be based on this information.

The optimization in this case is somewhat more complex, since the optimal combination of the number of maintenance intervals n and the value of the threshold β must be determined, as is presented in (Tinga and Janssen, 2013). Assuming a ratio between preventive and corrective maintenance costs $\alpha = 0.5$, and a threshold value $\beta = 0.2$, the costs and availability are shown in Figure 4.

The results show that this advanced maintenance policy yields high availability levels for most interval lengths at quite low cost levels. The optimal policy in this case is $n = 2$, with a 83.7% availability and 333 total costs. Note that the policy with $n = 9$ only has slightly higher costs (360), but a considerably higher availability (99.3%). So for a slight cost increase, a much better performance is obtained.

The explanation for the very good performance of this policy is the fact that subsystems are only (preventively) replaced when their condition indicates that it is necessary. This means that unnecessary maintenance is avoided, resulting in low maintenance costs. At the same time, this policy is very effective in preventing failures, which explains the high availability levels.

4.4 *Comparison of policies*

The costs and availabilities of the three analyzed policies are summarized in Table 1.

The results show that corrective maintenance in this case is a rather cost-effective policy, but the maximum achievable availability is 82%. Calendar time based maintenance is extremely conservative and safe, but therefore also very expensive. Condition based maintenance appears to be the most attractive policy for this application, with high availability at quite a low cost level. However, as was mentioned before, application of CBM or USBM requires more detailed insight in the failure behavior and may possibly require an investment in sensors or data acquisition hardware and software.

Table 1. Comparison of maintenance policies.

Policy	Availability	Total costs
Corrective	82.2%	478
Calendar time	94.6%	951
Calendar time (smart)	94.6%	571
Condition based	83.7%	333
	99.3%	360

Note that many approaches have been developed for quantifying the costs of maintenance, e.g. Life Cycle Costing (Blanchard, 1998). Also many maintenance modeling approaches have been presented to optimize the maintenance strategy (van Noortwijk, 2009; Nicolai et al., 2009). However, all these approaches start with an assumed failure distribution or random failure process, not taking into account the actual usage of the system. The present work has demonstrated how these effects can be incorporated and how they affect the effectiveness and efficiency of various maintenance strategies.

5 CONCLUSIONS

In this paper a simulation model for a rather complex system containing several subsystems with different failure behavior was applied to compare a number of maintenance policies. The model enabled to quantify the total maintenance costs of the various policies, as well as the achieved system availability. A simulation model has therefore demonstrated to be a suitable method to quantitatively compare different scenarios, which is a requirement when new and innovative maintenance concepts are developed and proposed. Such new concepts will only be adopted in practice when their benefit can be quantified.

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