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OPPORTUNISTIC MAINTENANCE MODELS: REVIEW AND DISCUSSION WITH A SPECIAL FOCUS ON THE TREATMENT OF UNCERTAINTY

SUMMARY

In this thesis, we review and discuss the area of opportunistic maintenance models. We want to examine if the existing models can be useful as decision-support to maintenance management, and focus especially on the treatment of uncertainty in the models.

A short introduction to opportunistic maintenance models has been given, and we have reviewed the treatment of uncertainty in existing models. Based on this review we have concluded that many assumptions and simplifications are taken in these models. Hence, they are not directly useful as decision-support without further assessment of the uncertainty related to these assumptions and simplifications. We present a method for assessing the uncertainty factors and rank their importance. With the information given by this assessment, we believe that the maintenance management has a better premise to use these models as decision-support.

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PREFACE

This thesis concludes my master's degree in Industrial Economics at the Faculty of Science and Technology at the University of Stavanger. The work has been carried out during the spring semester 2011.

I would like to express my sincere gratitude to my supervisor Professor Terje Aven at the University of Stavanger for his continuous support during the course of this work.

My gratitude also goes to Torgeir Jøssang for proofreading the thesis.

Last but not least, I wish to thank my dear Rita for her love, patience and support.

Stavanger, June 2011

Petter Furan

1 INTRODUCTION

1.1 Background

Opportunistic maintenance models basically refer to the situation where preventive maintenance is done at opportunities. An opportunity can for example be a system breakdown, quality inspections and other situations where the system is shut down. For many continuous operating systems such as power generators, processing plants and offshore oil installations the cost of a production stop can be very expensive, hence limiting the amount of stops by combining several maintenance tasks can reduce the total maintenance costs considerably.

Opportunistic maintenance models are a subgroup of multi-component maintenance models. For systems consisting of multiple components, three types of dependences can be classified (Thomas, 1986): Structural dependence, stochastic dependence and economic dependence. This thesis will focus on the latter – economic dependence – where savings due to economies of scale can be obtained when several components are jointly maintained instead of separately[1].

Many of the opportunistic maintenance models show their effectiveness in minimising maintenance costs, compared to other maintenance models (see for example Laggoune et al., 2009, Zhou et al., 2009). They can hence be beneficial to decision support systems where the main goal is minimising maintenance costs.

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[1] On structural and stochastic dependence, see Thomas (1986)

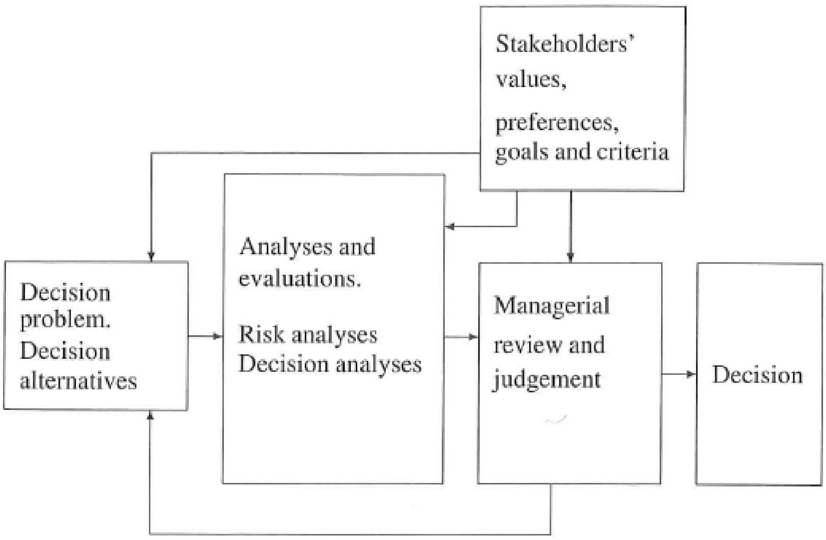

Figure 1 – A model for decision-making under uncertainty (Aven, 2003)

When a model is to be used as a decision tool, it is important to communicate enough information to make a sound decision for the decision makers. The manager needs to know the outcome of the different choices, and the benefits and potential uncertainty involved in choosing one solution over another. How certain are the different predictions of costs? What part of the system contributes the most to the total costs? Before a decision is taken, management reviews and evaluates the information given in the decision-support model (see Figure 1). We will therefore focus on the treatment of uncertainty in opportunistic maintenance models, in order to gain insight into these models' possible usefulness as decision-support.

It should be noted that many of the opportunistic maintenance models presented is limited to only a few components or only similar components. They are therefore not suited for being real decision support tools, but rather examples of ideas on how to solve opportunistic maintenance modelling questions.

A much cited review of multi-component maintenance models is Dekker et al. (1997). In their article they argue that "Only few papers deal with the situation where uncertainty is modelled or where new data collected in the course of maintenance is incorporated". They also outline that these few articles focus on single component systems, and that such models hardly exist for multi component models. This thesis will contribute to review the opportunistic maintenance area, and discuss the treatment of uncertainty in existing models.

1.2 Purpose

The main purpose of this thesis is to review and discuss the theory of opportunistic maintenance. More specifically the aim is to clarify how uncertainty is treated in existing models, and indicate how this treatment can be improved.

1.3 Content and thesis structure

This thesis is structured as follows: In chapter 2 we will give a short introduction to opportunistic maintenance theory and discuss existing models in this area. An opportunistic maintenance model is explained in more detail to give an example of the basics of this theory. Moreover the treatment of uncertainty in input variables and models are discussed. In chapter 3 we will propose a new method for uncertainty assessments in opportunistic maintenance models. Final remarks and conclusions are presented in chapter 4. Nomenclature and abbreviations are presented in appendix A, and another review of an opportunistic maintenance model is given in appendix B.

2 OPPORTUNISTIC MAINTENANCE MODELS

This chapter will give an overview of the opportunistic maintenance theory. We assume that the reader has basic knowledge about maintenance theory.

2.1 Opportunistic maintenance theory

The area of opportunistic maintenance has existed for almost 50 years. Based on the RAND project[2], a series of articles was published introducing this new view on maintenance modelling (see for example Radner and Jorgenson, 1963, McCall, 1963). Two reviews of this area are presented in Cho and Parlar (1991) and Dekker et al (1997).

Most maintenance actions incur a fixed cost. This might involve mobilising a repair crew, tools, transportation, safety provisions, disassembling and assembling of the system. Wildeman et al. (1997) describe this as the "set-up cost". See Figure 2 for an illustration of these costs. The set-up cost is incurred regardless of how many components are to be changed in the system. By combining several maintenance actions on the system, the set-up cost will be shared among these maintenance actions and the total maintenance costs can be reduced. This is done in for example block replacement models. However, the main difference between block replacement and opportunistic maintenance is that whereas block replacement is carried out at fixed time intervals, opportunistic maintenance is carried out at opportunities. The undesired failure of one unit can give an opportunity to preventively replace other degraded components as the system is in the failure state. Combining these activities can give rise to considerable cost savings.

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[2] Today known as the RAND Corporation, a nonprofit institution that helps improve policy and decision making through research and analysis, Rand Corporation. 2011. Available: http://www.rand.org/about/history.html [Accessed 29.06.2011].

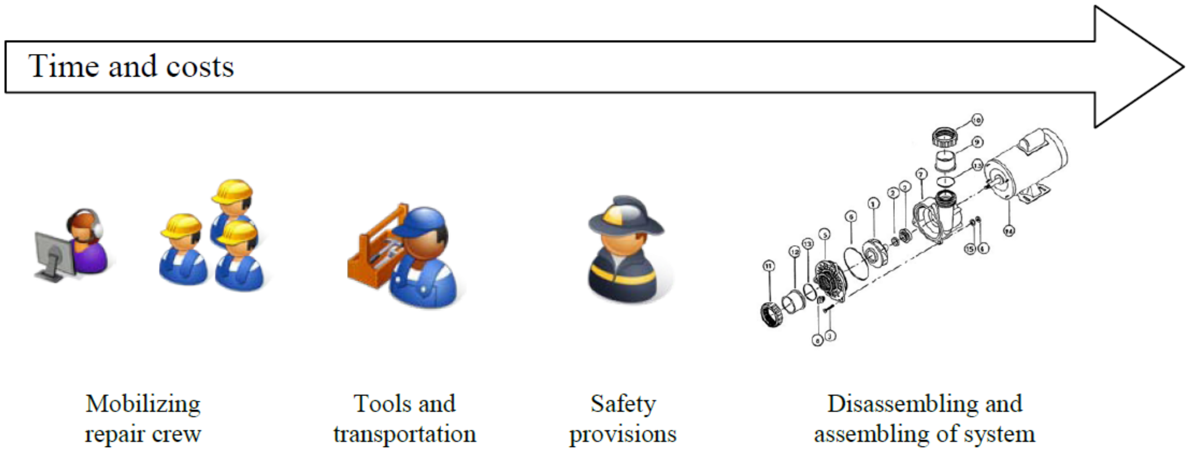


Figure 2 - Example of fixed costs for maintenance

An opportunity can, for example, be a breakdown of one unit, which causes the whole system to fail. By combining the corrective maintenance needed to get the machine running again with preventive maintenance on other parts of the machine, they share the same set-up cost and the total maintenance costs can be reduced.

> *Providing the opportunity to carry out preventive maintenance on some components along with replacement of failed components, leads to very small additional cost, compared to separate replacements.* (Laggoune et al., 2009 p 1500)

In Figure 3, the failure of component *i*, gives us the opportunity to replace component *j* at the same time. Doing so, will save us the set-up costs related to the forthcoming scheduled replacement of *j* (3), which will now be shared with component *i*. We also reduce the risk of component *j* failing before reaching the scheduled replacement (2). The downside of changing a non-failed component is that we lose the potential useful time left for the component (time difference between 3 and 1)

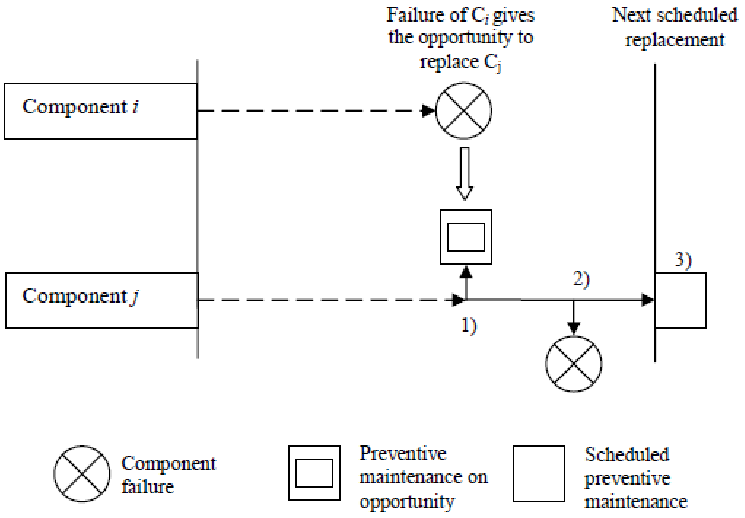


Figure 3 – Simple example of opportunistic maintenance on system failure

The challenging part of opportunistic maintenance models is that failures arrive unexpectedly. No planning or work preparation can be done, since we do not know when the next maintenance opportunity will occur. Some papers assume the opportunity generating process is independent of the failure process, occurring randomly and modelled through a renewal process (Dekker and Smeitink, 1991, Dekker and Smeitink, 1994).

There are two types of opportunistic maintenance: (i) the situations where the preventive maintenance can be advanced in case of an opportunity (e.g. system breakdown). This applies for non-redundant systems where the failure of a component must be corrected immediately. The other type (ii) is where the replacement of a failed component can be postponed to the next scheduled preventive maintenance. This applies for redundant systems (k-out-of-n systems). In this thesis we will focus on series systems, where if one component fails, the whole system fails. We will thus look at models using type (i).

Opportunistic maintenance is especially interesting in continuous operating units, such as offshore oil installations, power generators, petrochemical plants etc. as the cost of the production losses is often much higher than the maintenance costs of components (Rao and Bhadury, 2000, Volkanovski et al., 2008)

2.2 Definition of “opportunity”

Thomas et al. (2008) gives an overview of the understanding of opportunistic maintenance and the way it is practiced today. In their article, they claim that:

> *There are no norms, standards or consensual accepted meanings of 'opportunistic maintenance'. Instead this expression may refer to the 'right' instant to perform a given preventive maintenance action on a component, or to the environment of this component which could be favourable to an intervention.* (Thomas et al., 2008 p 245)

Berg (1978) and Dekker et al. (1997) for example restricts attention to the situation where preventive maintenance is carried out during corrective maintenance on failed parts. Jhang and Sheu (1999) on the other hand considers opportunities as idle moments of the system. The opportunity generating process is independent of the component failures, and appears according to a Poisson process.

Duncan and Scholnick (1973) give a general definition of opportunity, describing it as periods of time when no production loss arise due to the maintenance task. This can for example be: "Stock-out of work-pieces and other materials, parent machine breakdowns, quality control inspection during regular production and shift changes" (Duncan and Scholnick, 1973 p 271).

2.3 Example of an opportunistic maintenance model

In this section we will illustrate the opportunistic maintenance theory by reviewing the paper "Opportunistic policy for optimal preventive maintenance of a multi-component system in continuous operation units" (Laggoune et al., 2009)

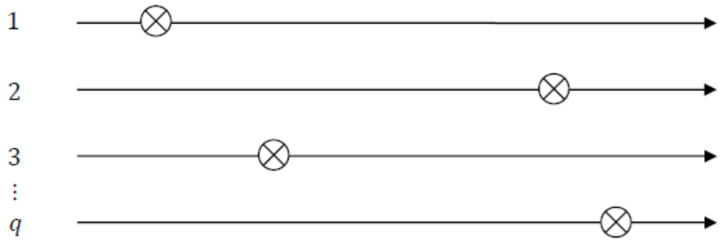
2.3.1 *System description*

The authors present a system composed of q components arranged in series. The failure of any component leads to the failure of the whole system. The main idea of the paper is to select a periodical replacement interval τ and find the optimal grouping policy for the components in the system, which gives the lowest maintenance costs per time unit.

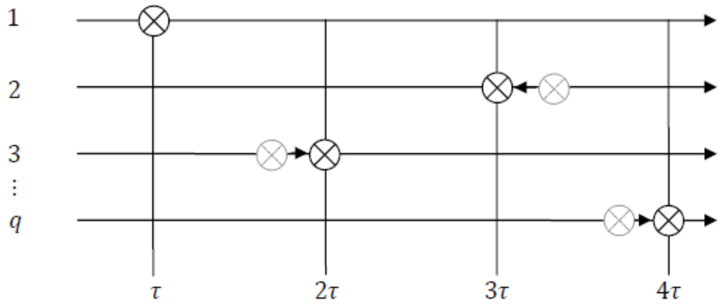
The optimal individual age-based replacement time for each component is used as a starting point in the search for optimal grouping policy. The optimal replacement time is given by the minimum of the cost function for age-based maintenance (Barlow and Hunter, 1960):

$$C_i(\tau_i) = \frac{C_i^c F_i(\tau_i) + C_i^p\left(1 - F_i(\tau_i)\right)}{\int_0^{\tau_i}\left(1 - F_i(t)\right) dt}$$

Where τ_i is the time for preventive replacement of component i and $F_i(\cdot)$ is the cumulative failure probability distribution for the component. C_i^c is the cost for corrective maintenance and C_i^p is the cost for preventive maintenance. An example of some individual optimal replacement times is given in Figure 4 a).



a) Individual optimal age-based replacement times for components 1,…,q



b) $\tau = \min_{i=1,\ldots,q} \tau_i$ (1 in this case). Shift to the nearest multiple of τ.

Figure 4 – Example of individual optimal age-based replacement times

The periodical replacement time τ is defined as the minimum replacement time of all components, $\tau = \min_{i=1,\ldots,q} \tau_i$. The other component's maintenance interval is then defined as a multiple of this maintenance interval $\tau_i = k_i \tau$, where k_i are integers satisfying $k_i \geq 1$ for $i = 1, 2, \ldots, q$. k_i is calculated by dividing the optimal replacement time for component i (τ_i^0) by the minimum optimal time in the system (τ_{min}^0) and rounding off to the nearest integer: $k_i^0 = Integer(\tau_i^0/\tau_{min}^0)$. Figure 4 b) shows that component 1 is the minimum individual optimal replacement time (τ), and that the other components' replacement times is shifted to the nearest integer multiple of this time. We can read out of this figure that $k_1 = 1,\ k_2 = 3$, $k_3 = 2$ and $k_q = 4$. Based on these calculations, the scheduled preventive maintenance plan for the system is presented in Figure 5.

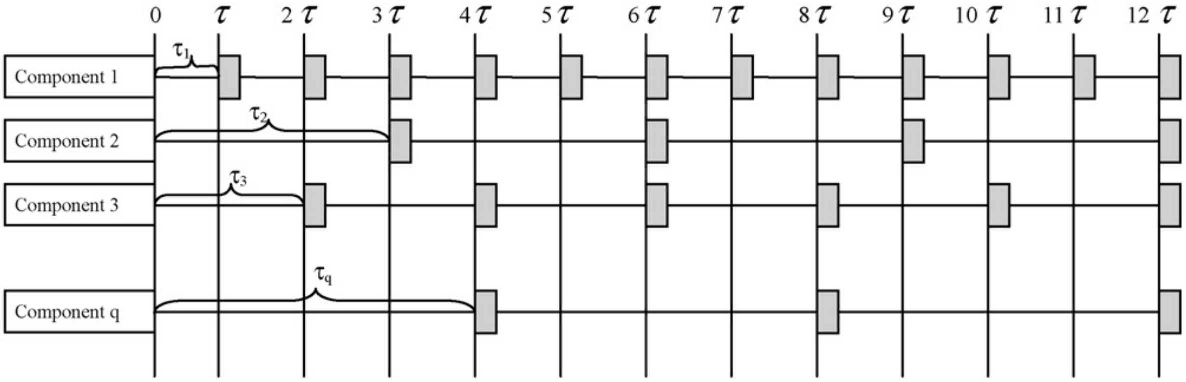


Figure 5 - Example of scheduled preventive maintenance plan (Laggoune et al., 2009 p 1501)

The authors defines both preventive and corrective maintenance as an opportunity to replace preventively non-failed components: On each time interval τ, and on all system failures, a decision will be made for each component whether it should be preventively replaced or left as is until the next scheduled replacement. This decision is based on “component degradation and risk undertaken if these components fail before reaching the following scheduled preventive time” (Laggoune et al., 2009). A component will be changed on an opportunity if the estimated cost of a system breakdown before the next scheduled replacement is larger than the cost of performing a preventive replacement at the opportunity (see Laggoune et al., 2009 p. 1504 for more details)

Each replacement, preventive and corrective, restores the component to “as good as new”. We also see that the system described in Figure 5 is completely renewed at 12τ. At this point, all the components are changed simultaneously, and the whole system becomes as good as new. This is described as the life cycle length of the system and is calculated using the least common multiple of the k_i-values: $K = lcm\{k_1, k_2, \dots, k_q\}$. The life cycle length $K\tau$ is used in the proposed solution as an upper time limit for the simulations.

2.3.2 *Calculating the optimal solution*

The cost structure of the model is as follows: The constant maintenance cost is related to mobilising repair crew, safety provisions, disassembling machine, transportation, tools and production loss directly related to these factors. The variable maintenance cost is related to spare part costs, manpower costs, specific tools, repair procedures and production loss related to the extraction and replacement the component itself.

The authors presents equations for preventive replacement and corrective replacement (we refer to the article for details), where the possibility for opportunistic maintenance is included.

These equations are then put together to calculate the total costs per time unit for the different combinations of τ and $k_1, k_2, \ldots, k_q$.

Due to economic dependence, the optimal maintenance schedule for the system might be different than the optimal individual maintenance schedule presented in Figure 5. Changing several components at the same time saves set-up costs, and can be beneficial for the system as a whole. Since the possible combinations of $k_1, k_2, \ldots, k_q$ increases with the factorial of the number of components, the authors propose to limit the search range for each component to ± 1 of its k-value, meaning that the preventive replacement interval for component i can be advanced or postponed by one period (τ) if this is better for the system optimal solution. The total possible combinations of $(k_1, k_2, \ldots, k_q)$ are then reduced to three times the number of components, instead of the factorial. This strongly increases the effectiveness of the computation, especially when we have a large number of components.

An algorithm for finding the best set of maintenance times $(\tau, k_1, k_2 \cdots, k_q)$ is presented in Figure 6. Since the cost model consists of both discrete and continuous variables, the algorithm is based on Monte Carlo simulation which can handle both variables. Random samples of the components' lifetimes are generated, and used to simulate the total maintenance cost for different combinations of $(\tau, k_1, k_2 \cdots, k_q)$. The authors show that the mean cost estimate converges towards the optimum as the number of samples increases.

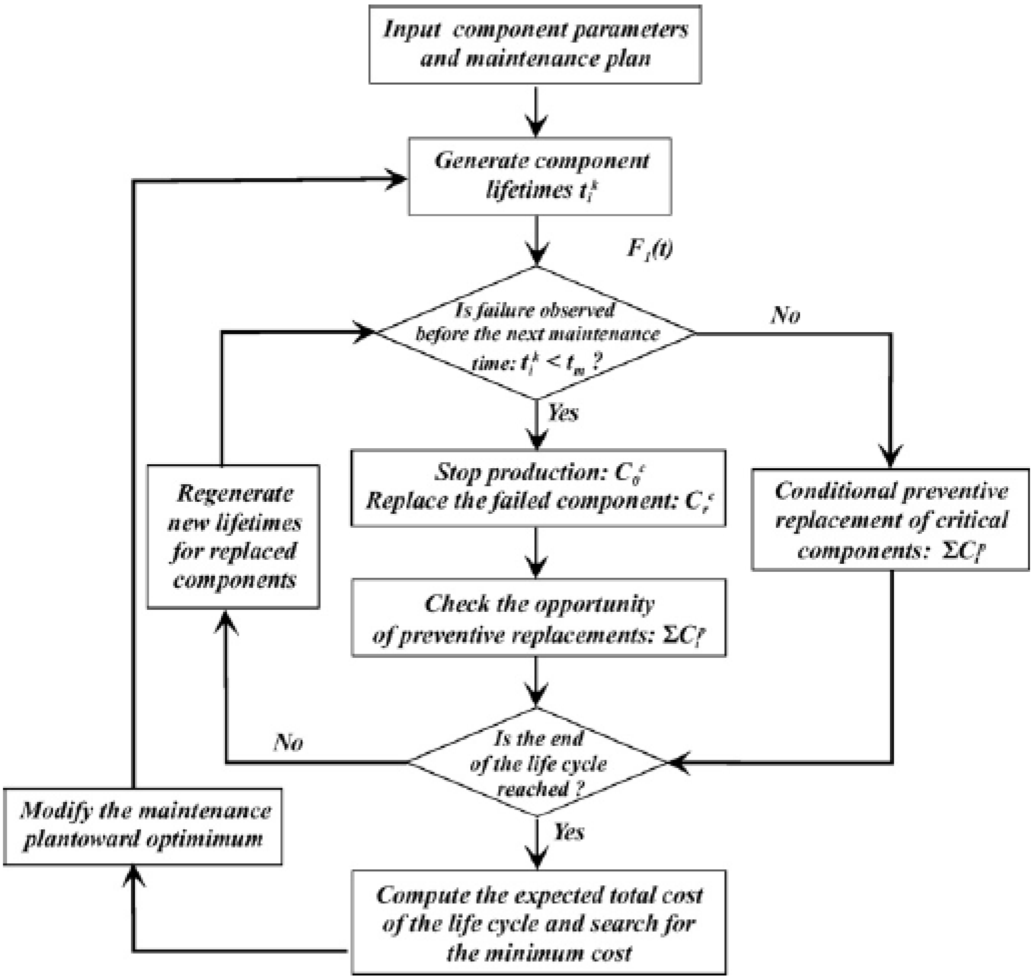


Figure 6 – Flowchart of algorithm for finding the optimum replacement time and grouping strategy (Laggoune et al., 2009 p 1503)

2.4 Overall considerations of treatment of uncertainty in the models

Scarf (1997) examines the application of mathematical models in maintenance. He points out that the challenge for opportunistic maintenance models is to make the models “simple enough to be both tractable an accessible to practitioners” (Scarf, 1997 p 496). Perhaps the focus on simplicity has been prioritised at the expense of treatment of uncertainty? Many of the models reviewed use strong simplifications to show the concept of the model and to prove the model’s supremacy compared to other models. These simplifications and their influence on the model output are seldom analysed.

Most of the articles do not discuss the uncertainty aspect of neither the input variables, nor the model itself. The scope of these articles is to provide a model for maintenance. To make the models as clear and concise as possible, many assumptions and simplifications are made. The uncertainty related to these assumptions and simplifications need to be assessed. More examples of such assumptions are presented in the following chapters.

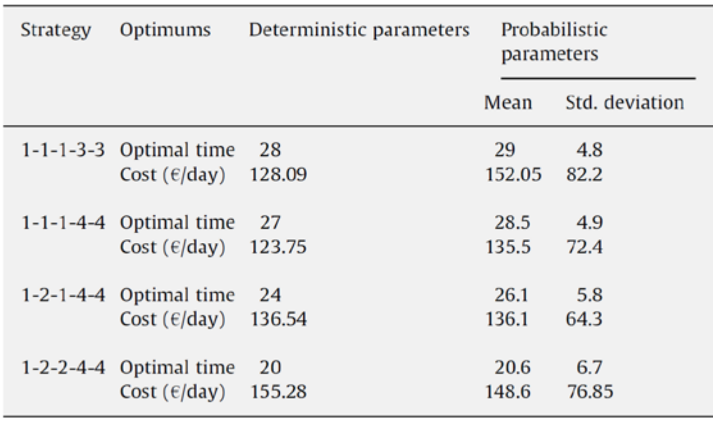
2.5 Uncertainty in the input variables

In most of the reviewed papers, the authors simplify the cost structure in the models, by only allowing for estimated values of the costs. (for example Laggoune et al., 2009, Scarf and Deara, 2003, Zhou et al., 2009). Deterministic costs will make the model easier to calculate and present, but the model output will not reflect the uncertainty related to the input parameter values. Use of point estimates is less critical if we have derived it from large samples and calculate the long term average costs of the model, because the long term average will converge to the optimal value. However, for opportunistic maintenance models, the information is only available during a short period of time. And the model sensitivity for deviations of the input parameters will be higher in a short-term perspective than for a long-term perspective. When simulation is used in the models, the simulation of the cost probability distributions can easily be implemented. The challenge is to provide good probability distributions for the cost function.

The maintenance costs are closely related to the maintenance duration times, due to the cost of system downtime and labour costs. However, the duration of maintenance action is often considered neglectable for the simplicity of the model. Rao and Bhadury (2000) take into account that extra downtime incurred due to opportunistic maintenance is neither neglectable nor constant. They define probability distributions to both failure times and repair times for the simulation of the model.

Most of the papers also require complete knowledge of the failure distribution of the components (see for example Laggoune et al., 2009, Scarf and Deara, 2003). In many practical situations, this will not be the case and we will have few or sparse failure data to rely on. Laggoune et al. (2010) proposes to use the Bootstrap technique for dealing with this problem. Resampling methods such as the Bootstrap technique provides clear advantages when we have small data samples from non-normal distributions. The resampling in this article provides insight into the variation of the scale and shape parameters of the Weibull distributions. In the model simulation, the scale and shape parameters are drawn randomly based on the scale and shape probability distributions, and the output of the model is presented with the mean and standard deviation of the different maintenance strategies.

The authors show that the optimal maintenance strategy based on deterministic parameters is no longer the optimal solution (see Table 1, strategy 1-1-1-4-4); The strategy previously ranked as number three (1-2-1-4-4), now turns out to be the most robust solution, with a mean cost close to the minimum value, but with a smaller standard deviation.



Strategy	Optimums	Deterministic parameters	Probabilistic parameters	
			Mean	Std. deviation
1-1-1-3-3	Optimal time	28	29	4.8
	Cost (€/day)	128.09	152.05	82.2
1-1-1-4-4	Optimal time	27	28.5	4.9
	Cost (€/day)	123.75	135.5	72.4
1-2-1-4-4	Optimal time	24	26.1	5.8
	Cost (€/day)	136.54	136.1	64.3
1-2-2-4-4	Optimal time	20	20.6	6.7
	Cost (€/day)	155.28	148.6	76.85

Table 1 – Opportunistic policy under deterministic and probabilistic parameters (Laggoune et al., 2010)

In Laggoune et al.’s (2010) article, uncertainty is measured as a probability distribution of the input variables. But it is important to note that the resampling itself does not increase the information in the original data. It merely estimates the accuracy of the estimators (such as the mean or variance) and produces a probability distribution of them instead of a point estimate. In addition, while the Bootstrap technique is used to quantify the uncertainty of the input parameters, the use of the Bootstrap technique itself can lead to uncertainties, for example when important assumptions such as independence of samples are made. These assumptions have to be addressed in an uncertainty assessment of the model.

Even if we have a large number of data samples and a robust mean value, other uncertainties of the input parameters can be addressed: Are the data samples relevant for this component? Are the conditions for this component similar to the ones in the data samples? Are the components properly tested before and after installation? These and similar questions are all important to unveil uncertainties regarding data samples, and a solution to this assessment is proposed in chapter 3.

2.6 Uncertainty in the model

Limitations are often included to reduce the complexity of the models, and increase the efficiency of the calculation of the results. For example, in the search for the optimal grouping strategy, Laggoune et al. (2010, 2009) include a search limitation of ±1 maintenance period relative to the individual component’s optimum. They thereby reduce the number of combinations to three times the number of components instead of the factorial. The authors claim that this limitation gives “convenient bounds for optimal search”, but this is not documented in the article. The uncertainty factor of this limitation has to be analysed.

Many opportunistic maintenance models have a long-term basis for the models with infinite horizon. This leads to problems incorporating short-term information such as opportunities or varying use of components. Moreover, the infinite horizon makes the calculated values converge towards the optimum value, while a more realistic finite horizon model would have increased the uncertainty in the model. Wildeman et al. (1997) proposes a ‘rolling horizon’ approach, where a long-term tentative plan is used as a basis for adaption of dynamically changing information.

Several articles assume that the replacement of components restore them to an “as good as new” condition (Laggoune et al., 2009, Rao and Bhadury, 2000). In practice, however, this assumption does not hold, as the cumulative tear and wear on adjacent components may not be noticed, and thus worsen the condition of the actual component and the system (Zhou et al., 2009). Zhou et al. (2009) implement this imperfect replacement and take into account that systems deteriorates over time.

3 SUGGESTION FOR AN UNCERTAINTY ASSESSMENT METHOD FOR OPPORTUNISTIC MAINTENANCE MODELS

Based on the review in chapter 2, we have found that many assumptions and simplifications are made in the existing opportunistic maintenance models. The potential consequences of these assumptions and simplifications are not throughout discussed in the models, and need a special focus if these models shall be used as decision-support.

In this chapter, we will propose a new method for assessment of uncertainty in opportunistic maintenance models. An application of this method is presented to show its usefulness.

3.1 Framework for assessment of uncertainty

The assessment of uncertainty considers both input parameters and the opportunistic model itself. The framework presented in this chapter is based on Selvik and Aven (2011). While the article of Selvik and Aven has no direct comparison to the work presented in this thesis, the uncertainty assessments in their article is used as an inspiration in our development of a model for uncertainty assessment.

Our specialised model is presented in Figure 7. The opportunistic maintenance model is used to calculate the optimal maintenance strategy in step 1 (and step 2 where applicable). The model, with its assumptions and simplifications, in addition to the input parameters forms our background knowledge for the uncertainty analysis performed in step 3. The evaluation of the uncertainties and decisions on how much information to be presented for the management is performed in step 4. On the basis of the information presented in the previous step, a decision is taken by the management in step 5.

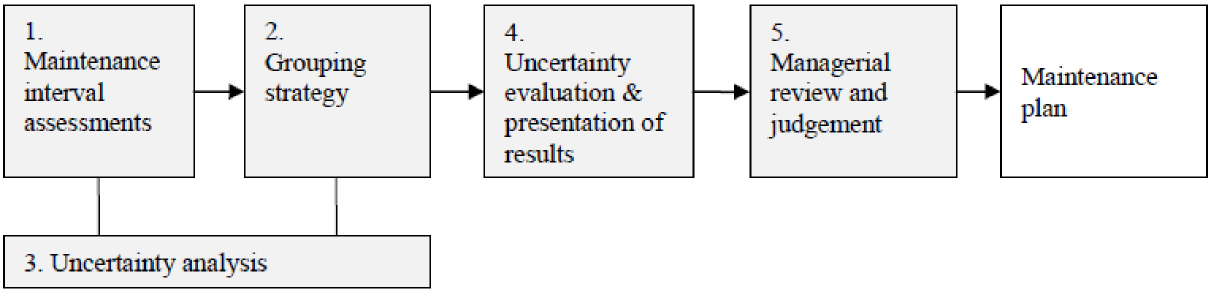


Figure 7 – Uncertainty analysis of maintenance strategies (inspired by Selvik and Aven (2011))

When the management has more information on how the results are calculated and the assumptions taken in the model, they will have a broader decision basis.

We are particularly interested in steps 3 and 4, which deal with uncertainty analysis, uncertainty evaluation and presentation of these results for managerial review and judgement.

The uncertainty analysis cover the following main tasks (Selvik and Aven, 2011):

1. Identification of uncertainty factors
2. Assessment and categorisation of the uncertainty factors with respect to degree of uncertainty
3. Assessment and categorisation of the uncertainty factors with respect to degree of sensitivity
4. Summarisation of the uncertainty factors' importance

The categorisation of uncertainty in tasks 2 and 3 are subjective judgements based on the score chart presented in Table 2. The importance rating is an average of the uncertainty and sensitivity score, and can take the values L, M, H, as well as combinations of these, for example H/M or L/M.

Aspect	Score	Interpretation
Uncertainty	Low (L)	One or more of the following conditions are met: • The assumptions made are seen as very reasonable • Much reliable data are available • There is broad agreement/ consensus among experts • The phenomena involved are well understood: the models used are known to give predictions with the required accuracy
	Medium (M)	Conditions between those characterising low and high uncertainty
	High (H)	One or more of the following conditions are met: • The assumptions made represent strong simplifications • Data are not available, or are unreliable • There is lack of agreement/ consensus among experts • The phenomena involved are not well understood: models are non-existent or known/ believed to give poor predictions
Sensitivity	L	Unrealistically large changes in base case values needed to bring about altered conclusions
	M	Relatively large changes in base case values needed to bring about altered conclusion
	H	Relatively small changes in base case values needed to bring about altered conclusions
Importance	L, M or H	Average of the other two aspect scores

Table 2 – Uncertainty assessment score interpretation (Selvik and Aven, 2011 p. 328)

Selvik and Aven (2011) also present a worksheet for the assessment of uncertainty. Relevant fields to incorporate in the analysis of opportunistic maintenance models are:

- *Maintenance interval determination:* Description of how the maintenance interval assessment is performed; type of optimisation model used and relevant constraints.
- *Recommended maintenance interval:* Result from the maintenance interval assessment
- *Uncertainty factors for maintenance interval assessments:* List the relevant uncertainty factors identified related to the maintenance interval assessment
- *Uncertainty factor score:* For the uncertainty factors identified, give a qualitative score on degree of uncertainty, sensitivity and importance (Table 2)
- *Sensitivity of maintenance interval recommendation:* Check if an uncertainty factor has the potential to produce a significant change in the maintenance interval compared with the one recommended. List the adjusted intervals and the corresponding uncertainty factors

These fields will be used to analyse the model uncertainty later in this chapter. A worksheet for this analysis is presented in Table 3. The first row is used to describe how the results are calculated in the model. All assumptions and constraints are to be identified. Then the recommended maintenance interval is presented. All the uncertainty factors will be listed in the next field, and given a degree of uncertainty, -sensitivity and -importance. These values are subjective probabilities based on our background knowledge about the parameters and the model, and are assessed based on the information in Table 2. The uncertainty factors with the highest importance are communicated to managerial review and judgement. The uncertainty factors are then tested if they have the potential to produce a significant change in the maintenance strategy. If they do so, they will also be communicated to managerial review.

<table>
<tr><td colspan="2">Maintenance interval determination:

Description of how the maintenance interval assessment is performed; optimisation model, constraints.</td><td colspan="3"></td></tr>
<tr><td colspan="2">Recommended maintenance interval:</td><td colspan="3"></td></tr>
<tr><td colspan="2">Uncertainty factors for maintenance interval assessments:</td><td colspan="3">Uncertainty factor score:</td></tr>
<tr><td>No</td><td>Assumption</td><td>Degree of uncertainty</td><td>Degree of sensitivity</td><td>Degree of importance</td></tr>
<tr><td>1</td><td></td><td></td><td></td><td></td></tr>
<tr><td>2</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3</td><td></td><td></td><td></td><td></td></tr>
<tr><td>4</td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="5">Sensitivity of maintenance interval recommendation: Check if an uncertainty factor has the potential to produce a significant change in the maintenance interval compared with the one recommended. List the adjusted intervals and the corresponding uncertainty factors below</td></tr>
<tr><td>No</td><td colspan="4">Adjusted intervals</td></tr>
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</table>

Table 3 – Worksheet for analysing uncertainty in maintenance models (inspired by Selvik and Aven, 2011)

3.2 Communication of uncertainty

One of the most important aspects of the uncertainty evaluation and presentation (Figure 7, step 4) is how this information is communicated to the management function in step 5. When information is aggregated to the next decision level, it is important to have focus on the factors that have the possibility to produce different maintenance strategies than the recommended. The degree of importance in the uncertainty assessment highlights which uncertainty factors to be prioritised in the presentation of the results to managerial review and judgement.

3.3 Application of the method

To prove the usefulness of the proposed method, we will analyse the industrial application from Laggoune et al. (2009) where they calculate the optimal maintenance strategy for a centrifugal compressor in a refinery. We use the worksheet presented in Table 3 to analyse the possible uncertainties in the model and the input parameters. The results are presented in Table 4.

Maintenance interval determination: Description of how the maintenance interval assessment is performed; optimisation model, constraints.	• Use of opportunistic maintenance model for calculating optimal periodical preventive maintenance and optimal grouping. • Uses historical failure data to generate Weibull lifetime distributions through "Statistica" software which uses the maximum likelihood method and allows censored data • Use mean cost values, as the cost assessment is very hard and complex • Only allowing the advancement or postponing of one period relative to the individual optimum in the search for optimal grouping strategy			
Recommended maintenance interval:	Maintenance interval: $\tau = 124$, grouping strategy: 2-2-2-2-3-3-6-6			
Uncertainty factors for maintenance interval assessments:		**Uncertainty factor score:**		
No	Assumption	Degree of uncertainty	Degree of sensitivity	Degree of importance
1	Historical data is not relevant for the component	L	M	L/M
2	Few observed failures in the historical data	H	H	H
3	Use of mean cost estimates	H	M	H/M
4	Limitation of ± 1 period in the search for optimal grouping	M	M	M
Sensitivity of maintenance interval recommendation: Check if an uncertainty factor has the potential to produce a significant change in the maintenance interval compared with the one recommended. List the adjusted intervals and the corresponding uncertainty factors				
No	Adjusted intervals			
	N/A			

Table 4 – Application of the uncertainty assessment worksheet

Since we do not have access to the model and the simulations, the sensitivity of maintenance interval recommendation cannot be tested. However, the most important factors to report from this uncertainty analysis are that few observed failures in the historical data, can lead to a change in the recommended maintenance interval. The use of mean cost estimates can also influence on the recommended interval.

4 FINAL REMARKS AND CONCLUSIONS

In the beginning of this thesis, we asked if the existing opportunistic maintenance models could be useful as decision-support for maintenance management. After reviewing the area of opportunistic maintenance models, it is clear that the models reviewed have strong limitations and simplifications that need to be analysed before we can make decisions on basis of their output.

Based on the review, we suggested a method for uncertainty assessment for opportunistic maintenance models. The purpose of this assessment was to analyse the uncertainty factors of the input variables and the model. The degree of uncertainty and sensitivity give the factors an importance ranking, which are communicated to management review and judgement in addition to the model output.

On the basis of the information given by this assessment, we believe that the maintenance management has a better premise to make a sound decision on the maintenance strategy.

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APPENDIX A – NOMENCLATURE AND DENOMINATION

Nomenclature and denomination used in this thesis is given in the table below.

CDF	Cumulative distribution failure
$F_i(\cdot)$	Cumulative distribution failure (CDF) of component *i*.
i	Subscripts, indicating component nr 1, 2, …, q
LCM	Least Common Multiplier
MSI	Maintenance Significant Items
OM	Opportunistic Maintenance
PM	Preventive Maintenance
RCM	Reliability Centred Maintenance
$RRCM$	Reliability and Risk Centred Maintenance
τ	Basic preventive maintenance interval

APPENDIX B – REVIEW OF ZHOU ET AL. (2009)

The review of Zhou et al. (2009) is presented here to give the reader insight into the area of opportunistic maintenance.

Description of the model

In Zhou et al. (2009) the authors implement the imperfect effect into the opportunistic preventive maintenance (PM) action. The imperfect effect takes into account that every system as a whole will degrade over time. Despite all the components in the system being preventively replaced to a state as good as new, the "cumulative wear on adjacent components may go unnoticed and worsen the condition of the relative parts, and the system as a whole." (Zhou et al., 2009). This is in line with most practical maintenance planning, when systems need shorter intervals between maintenance actions as the system gets older.

The motivation for the authors of incorporating this imperfect effect is that many articles dealing with multi-unit systems assume that maintenance will restore the system to as good as new (see p 362 for a list of articles). This has proven to be far from the real world. Second, many articles focus on the long-run average maintenance costs, while information usually is only available over a short term. This article focus on maximising the short-term cumulative opportunistic maintenance (OM) cost savings.

A reliability threshold is established for each unit. Whenever one of the units reaches this threshold, the system has to stop and the unit is replaced. This gives an opportunity to simultaneously replace the other units and hence share the set-up cost. If the unit fails before the scheduled PM, a minimal repair is performed.

The authors refer to Pham and Wang (1996) for a review of the field of imperfect maintenance. Out of eight methods listed in this article, they choose the improvement factor method for modelling imperfect PM action in their article. The improvement factor basically implement a time shift in the hazard rate function: If T_{ij} is the PM interval and $h_{ij}(t)$ the hazard rate function for unit j, the hazard rate function after the ith PM ($h_{(i+1)j}(t)$) becomes $h_{ij}(t + a_{ij}T_{ij})$ for $t \in (0, T_{(i+1)j})$ where $0 < a_{ij} < 1$ is the age reduction factor due to the imperfect PM action. This means that after each imperfect PM the initial hazard rate is moved to the right (elder) to $h_{ij}(a_{ij}T_{ij})$. a_{ij} beeing larger than zero means that the system is not as good as new. See an illustration of this shift in Figure 8.

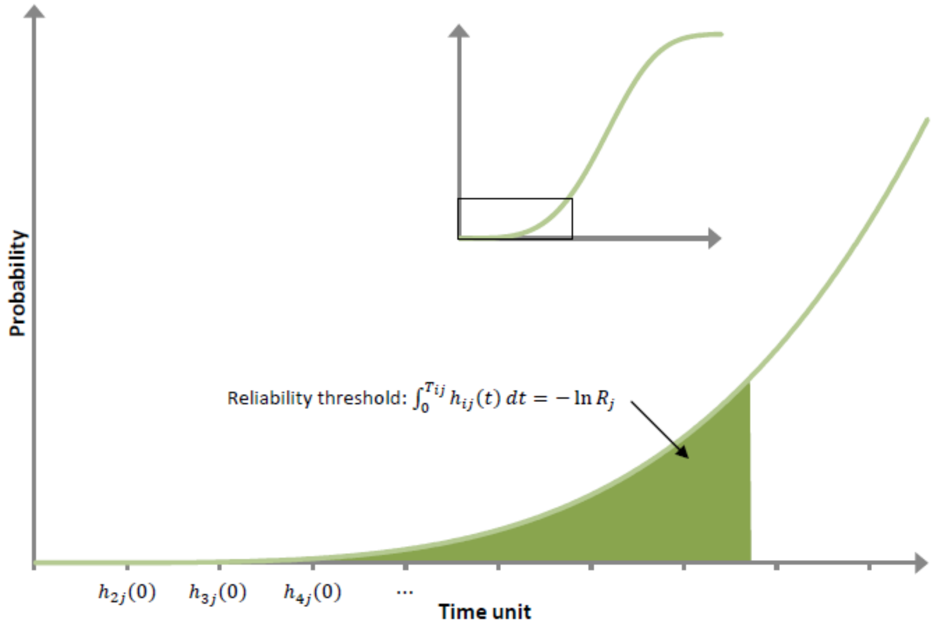

Figure 8 – Illustration of the effect of the improvement factor method

PM is performed whenever the reliability of unit j reaches its threshold value R_j. The authors present an equation for calculation of this value:

$$\int_0^{T_{1j}} h_{1j}(t)dt = \int_0^{T_{2j}} h_{2j}(t)dt = \cdots = \int_0^{T_{ij}} h_{ij}(t)dt = -\ln R_j$$

where $\int_0^{T_{ij}} h_{ij}(t)dt$ represents the cumulative failure risk in maintenance cycle i. The expected number of failures (and minimal repairs) is equal to $-\ln R_j$. As we know the reliability threshold and the failure rate distribution, we can calculate the time intervals between preventive maintenance for component j, $T_{1j}, T_{2j}, \ldots T_{ij}$.

At a mission time T we can assume the number of PM actions to be N_j. The total cost per unit time for j is then:

$$CE_j = \frac{\sum_{i=1}^{N_j}\left(C_{mj}(-\ln R_j) + (c_{pj} + c_{dj})\tau_{pj}\right)}{\sum_{i=1}^{N_j}\left(T_{ij} + \tau_{pj}\right)}$$

where C_{mj} is the cost for minimal repair, including repair cost and the downtime cost during repair. c_{pj} and c_{dj} is the maintenance cost and downtime cost per unit time for a PM action. τ_{pj} is the duration of the PM. By minimising CE_j, the optimal reliability threshold R_j can be found.

The authors present a multi-unit series system consisting of n units. Whenever unit j ($j \in \{1, \cdots n\}$) reaches its reliability threshold, the whole system has to stop and unit j is preventively replaced. This leads to opportunities for the other units in the system to be preventively replaced simultaneously with unit j. The decision of whether a unit shall be preventively replaced or not depends on the OM cost saving described below. "Since the unit's degradation information is only available in he short-term, it is assumed that only one PM action for each unit is considered in one decision cycle.". The process is described in the following steps:

1. Reliability threshold calculation
2. Determining OM cost saving
3. PM activities grouping and decision making

The authors presents a mission time T, and the individual reliability threshold R_j for all the units and the corresponding maintenance cost per unit time is calculated based on the imperfect PM model described above. Since the units are in series, the authors assume that all the units have the same downtime cost C_d during PM activities ($C_{d1} = \cdots = C_{dn} = C_d$). They also assume that all the units have the same duration of PM ($\tau_{p1} = \cdots = \tau_{pn} = \tau_p$).

The determination of OM cost saving is determined by comparing different possible scenarios of opportunities for the different components. For a n unit system, assume the time is t_{k1} and the different scenarios for component j described in Figure 9 are the following:

1. Component j can be changed at the opportunity created by component k at time t_{k2} ($t_l < t_{k2} \leq t_j$)
2. Component j can be changed at the opportunity created by component l at time t_l ($t_l \geq t_{k1}, l \neq j$)
3. Component j is to be changed at it's scheduled preventive maintenance time t_j

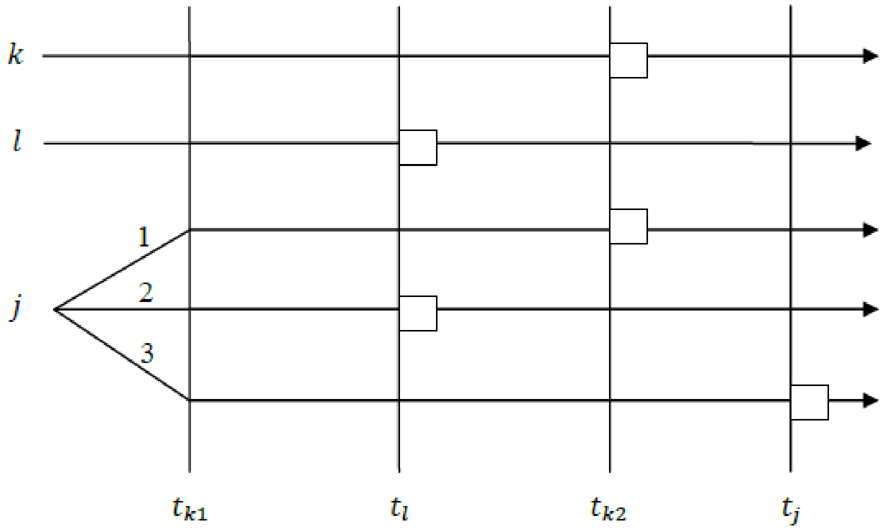

Figure 9 – Different scenarios for component j

For scenario 2, the cost saving can be defined as:

$$CostSave_{jl} = DC_{jl} + MC_{jl} - PC_{jl}$$

where DC_{jl} is the downtime cost saving, MC_{jl} is the maintenance cost saving and PC_{jl} is the penalty cost incurred for advancing the scheduled maintenance time.

Downtime cost saving can be defined as:

$$DC_{jl} = c_d \tau_p$$

Since unit j now shares the set-up cost (downtime cost) with unit l. The maintenance cost saving MC_{jl} can be defined as the reduction of risk for minimal repairs. The scheduled replacement of unit j has a cummulative risk $-\ln R_j$ whereas the cummulative risk when unit j is maintained with l is assumed to be $-\ln R_{jl}$. The maintenance cost saving is

$$MC_{jl} = \left[\left(-\ln R_j\right) - \left(-\ln R_{jl}\right)\right] C_{mj}$$

Because of the advancement of PM, all of the scheduled PM times will change. The cumulative time shift is then calculated as

$$\delta T_{jl} = \sum_{i=1}^{M} \left(T_{ijo} - T_{ijn}\right) \quad for \quad M \in \{1, 2, 3, \dots\}$$

where T_{ijo} is the original PM schedule, T_{ijn} is the new PM schedule and M is the remaining cycles in mission time T with the new schedule T_{ijn}.

T_{ijo} satisfies the same criteria as T_{ij} in the introduction, while T_{ijn} satisfies

$$\int_0^{T_{1jn}} h_{1jn}(t)dt = -\ln R_{jl}$$

and

$$\int_0^{T_{2jn}} h_{2jn}(t)dt = \cdots = \int_0^{T_{ijn}} h_{ijn}(t)dt = -\ln R_j$$

The penalty cost for unit j to advance the PM is:

$$PC_{jl} = CE_j * \delta T_{jl} = CE_j \sum_{i=1}^{M} (T_{ijo} - T_{ijn})$$

The interpretation of the CostSave function is then: If the sum of the downtime cost saving and the maintenance cost saving is larger than the penalty cost, the total cost savings are positive, and the OM action is recommended. But:

If unit j is maintained with unit l, it will loose the opportunity to be maintained with unit k at time T_{k2} (see Figure 9 scenario 1). We calculate the CostSave function for j beeing maintained with k in the same way as above. The total OM cost savings for unit j is then:

$$OC_{jl} = CostSave_{jl} - CostSave_{jk2}$$

where, as a consequence of the boundaries of scenario 1:

$$CostSave_{jk2} = \begin{cases} DC_{jk2} + MC_{jk2} - PC_{jk2} & for \ \ t_l < t_{k2} \leq t_j \\ 0 & for \ \ t_{k2} \leq t_l \ or \ t_{k2} > t_j \end{cases}$$

The last step in the process is grouping maintenance actions:

The authors present an n-unit system, and it is assumed that only one PM action is considered for each unit in one decision cycle. The combination of units $G_1, \dots, G_m$ beeing a subset of $\{1, 2, \dots, n\}$ are mutually exclusive and satisfies:

$$\begin{cases} G_p \cap G_q = \emptyset, \quad \forall p \neq q \\ G_1 \cup \cdots \cup G_m = \{1, 2, \dots, n\} \end{cases}$$

All PM activities within each group is executed at the same time

The cumulative OM cost savings for any combination G is:

$$OC_{\{1,2,\dots,n\}} = \sum_{p=1}^{m} OC_{G_p}$$

The optimal combination G^*, with the largest OC savings, is found by maximising $OC_{\{1,2,\dots,n\}}$.