MASTER

Optimising pro-active maintenance decisions for a multi-component system

Hoeks, J.A.J.

Award date:
2012

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
Optimising Pro-active Maintenance Decisions for a Multi-Component System

By J.A.J. Hoeks BSc.

J.A.J. Hoeks BSc (2009)
Student identity number 0596689

in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics

Supervisors:
Prof.dr. Ir. G.J. van Houtum, TU/e, OPAC
Dr. H. Peng, TU/e, OPAC
Ir. A. Huttinga, Project Manager at DAF Trucks N.V.
Ir. A. Knossen, Head Technical Information, Training & Diagnostics at DAF Trucks N.V.
Subject headings: Preventive Maintenance, Condition Based Maintenance, Age-based Maintenance, Time-Based Replacements
ABSTRACT

This master thesis describes a research project conducted within the after sales department at DAF Trucks N.V. in Eindhoven. The objective of the thesis is to gain insights into current maintenance practices at DAF and implementing a pro-active maintenance strategy. A framework is developed for implementation of a pro-active maintenance program. Within this framework, the criteria for the selection of a component, the process of developing a pro-active maintenance strategy and the integration with the existing maintenance practices are discussed. To support pro-active maintenance decisions for DAF, a tool is developed and evaluated.
This thesis represents the final assignment of the master program Operations Management & Logistics at Eindhoven University of Technology. The project is executed at the after sales department of DAF Trucks N.V. in Eindhoven.

This thesis is the last fulfilment of my educational program. During this period, I enjoyed the challenges both on the social level, as well as the academic level. I would like to thank a number of people who provided guidance during the research project.

First of all, I would like to thank my supervisors of Eindhoven University of Technology. Geert-Jan van Houtum for his feedback, tips and for helping me to keep a structured overview on the problem during the research project. Furthermore, I would like to thank Hao Peng and Qiushi Zhu for their ideas and contribution to the project.

I would like to thank DAF Trucks for providing me with an interesting research topic, and for the opportunity to graduate within the company. Especially, I thank Alex Huttinga for supervising my daily activities and Age Knossen for the constructive feedback during our meetings. I enjoyed the months I was working on my research at DAF, and during which I gained insights into the organizational ways of the company.

I enjoyed the time I spent at the after sales department but also at the reliability engineering department where I also spend a considerable amount of time. Therefore, I would like to thank all my colleagues for the pleasant atmosphere at the company and for providing me with valuable information for my research.

I end these acknowledgements by thanking my parents for giving me the opportunities to explore my talents, and my friends for the memories on the good times within and outside the academic life.

Jeroen Hoeks

Eindhoven, May 2012
DAF Trucks N.V. designs and manufactures commercial vehicles, its core activities are focused on the development, production, marketing and sales of medium and heavy-duty commercial vehicles. Typically in the truck industry repair and maintenance costs represent around 60% of the buying value of the truck.

In order to increase the reliability and availability of the trucks and lower the costs for repair and maintenance for the customer, DAF strives towards a more pro-active maintenance strategy instead of using corrective maintenance tactics. Before this research was conducted, the prescribed maintenance activities consisted of a limited set of tasks to be performed time- or usage-based.

This research investigated whether it could be profitable for DAF’s customers to introduce a more intensive pro-active maintenance strategy. Both a usage- or time-based strategy as well as Condition Based Maintenance (CBM) are considered as pro-active. CBM is a predictive maintenance technique focusing on performing maintenance actions based on the actual condition of a system. It is based on monitoring the underlying deterioration process of the equipment. By predicting the reliability of a component using either historical data or remote monitoring techniques, total costs of ownership for the customer can be reduced.

To identify the potential savings for such a strategy the following main research question has been investigated:

“To which extent and how can a pro-active maintenance strategy be used to decrease the Total Cost of Ownership for the customer?”

To help DAF in identifying these potential savings, a three step framework was designed to structure the process of introducing and maintaining a pro-active maintenance strategy. This framework consists of essential building blocks that help to structure the identification and implementation process and consists of answering three questions chronologically:

1. How to select candidate components for pro-active maintenance?
2. How to determine whether pro-active maintenance can be applied for a component?
3. How can pro-active maintenance be applied and integrated with the current maintenance practices at DAF?

To answer the first question, which aims at how to identify appropriate components to perform pro-active maintenance on, a Multi Criteria Decision Analysis tool was developed. The tool takes the most important characteristics for pro-active maintenance (e.g.
frequency, consequence and detect ability of the failures) into account, and it allows DAF to make a quick distinction between the appropriate and less appropriate components.

The second step of the model looks into the technical and economical details of a component and investigates the savings of pro-active maintenance quantitatively. To perform this analysis, an eight-steps model was designed based on a Failure Mode and Effect Analysis (FMEA) that has been expanded with some important aspects for pro-active maintenance. This step ends with stating for a component whether pro-active maintenance proves to be technically and economically feasible. The eight-steps model has been applied to six critical components on one of the main truck types at DAF.

The final step of the framework is integrating the pro-active strategy for a component with the existing maintenance practices. For this part a mathematical model has been developed that suggests preventive maintenance actions while taking the existing maintenance stops as a basis (combining replacement of components with planned maintenance stops as much as possible). This allows DAF to introduce pro-active maintenance gradually without disrupting the complete maintenance structure. To help DAF using this model, a tool was developed which suggests the optimal replacement interval based on the failure distribution and replacement costs of a component. An experiment shows that for four out of the six components investigated, savings ranging up to 19% can be achieved by basing maintenance decisions on this tool.

Furthermore a theoretical model was developed which also incorporates Condition Based Maintenance. A numerical example with realistic data was tested and it shows that potential savings with CBM can be even higher than the savings achieved via time- or usage-based maintenance based on historical data.

This report concludes with stating that DAF now has a framework to introduce pro-active maintenance. This framework has been applied to six components. The analysis has shown that for four out of the six components pro-active maintenance can lead to significant savings on the maintenance costs. Pro-active maintenance can be introduced for these components without having to change the structure of the current maintenance practices. Therefore, the environment in which DAF operates is suitable for a pro-active maintenance approach.
5.6.1. Input variables

5.6.2. Calculation of extra costs

6. Practical application; A Tool for DAF trucks

7. Conclusions and Recommendations

8. References

Appendix

A. Weibull fitted on failure data

B. Sensitivity Analysis

Eta varied

Beta Varied

Ratio Preventive vs. Corrective Costs varied

Mileage per year varied

C. Applications for DAF Trucks

1. Water pump (cooling system):

2. Compressor (air system):

3. Starter motor

4. Turbo

5. Alternator

6. Brake pads

7. Battery

8. Oil

D. Results MCDA Tool

E: Transformation of Weibull Distribution
<table>
<thead>
<tr>
<th>Term</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition Based Maintenance</td>
<td>a predictive maintenance technique focusing on performing maintenance actions based on the actual condition of a system.</td>
<td>Jardine (2006)</td>
</tr>
<tr>
<td>Corrective Maintenance</td>
<td>Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function</td>
<td>(SS-EN 13306, 2001)</td>
</tr>
<tr>
<td>Failure</td>
<td>Termination of the ability of an item to perform a required function</td>
<td>(SS-EN 13306, 2001)</td>
</tr>
<tr>
<td>Failure Effect</td>
<td>What happens when a failure mode occurs</td>
<td>(Moubray, 1997)</td>
</tr>
<tr>
<td>Failure Mode</td>
<td>A single event that causes a functional failure</td>
<td>(Moubray, 1997)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Combination of all technical, administrative, and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function</td>
<td>(SS-EN 13306, 2001)</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Activity, performed either manually or automatically, intended to observe the actual state of an item</td>
<td>(SS-EN 13306, 2001)</td>
</tr>
<tr>
<td>------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Pro-active Maintenance</td>
<td>Maintenance decisions carried out based on information, either historical failure data or condition information</td>
<td></td>
</tr>
<tr>
<td>Preventive Maintenance</td>
<td>Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item</td>
<td>(SS-EN 13306, 2001)</td>
</tr>
<tr>
<td>Prognosis</td>
<td>Prediction of when a failure may occur</td>
<td>(Lewis, S.A., Edwards, T.G., 2005)</td>
</tr>
</tbody>
</table>
Over the last few years the commercial vehicle industry has been slowly moving from product ownership to experience, the aftermarket network and processes are getting a more centric place. Availability and reliability are two very important factors for a customer of a truck manufacturer. Therefore, maintenance management becomes of more and more important. With trends as lean manufacturing and just-in-time production, the availability of capital goods is of increasing importance. Therefore, the management and optimization of maintenance processes are getting more important as well (Jardine et. al. 2006).

Technology is a major enabler in this process, with the increasing possibilities of obtaining information about the state or use of a system. This information can be used to predict failures and plan maintenance activities accordingly, preventing unplanned breakdowns. These methods can help manufacturers of capital goods to increase the availability of their products and therefore increasing customer satisfaction.

In Chapter 2 the research environment and project approach is described.
2. RESEARCH ENVIRONMENT

This Chapter aims at describing the research environment and introduces DAF Trucks N.V. In the last part of this chapter the research environment and questions will be introduced.

2.1 DAF TRUCKS N.V.

DAF Trucks N.V. designs and manufactures commercial vehicles and is a fully owned subsidiary of the North-American Corporation PACCAR Inc. DAF Trucks’ core activities are focused on the development, production, marketing and sales of medium and heavy-duty commercial vehicles.

DAF works according to the ‘Build to Order’ principle. This means that all vehicles are built to satisfy each customer’s individual wishes, but production only starts after the order is received from the customer. Low costs per kilometer, high quality, driver comfort, low fuel consumption, minimal impact on the environment and high transport efficiency characterize all DAF products. The trucks produced are divided into three categories. The small LF series is designed for urban and regional distribution. For regional, national or international transport the CF series is developed. The CF can be used on smooth roads as well as rough terrain. The XF105 series is developed for long haul transportation.

DAF Trucks has production facilities in Eindhoven, Westerlo in Belgium and Leyland in the UK. In 2010 over 30.000 trucks were manufactured. In the heavy trucks segment DAF has achieved the third position considering market share (2010: 15.2%) in Europe. In the Netherlands, Belgium, Great Britain, Czech Republic, Poland and Hungary, DAF is market leader. In Germany and Italy, DAF is the largest import brand. Throughout Europe DAF has more than 7.000 employees of which almost 5.000 are based in Eindhoven. One of the goals of DAF is to achieve a 20% market share in the heavy truck segment in the nearby future, therefore, DAF has to make sure that the produced vehicles are meeting the ever increasing customer and legal requirements. To meet these requirements, DAF aims at manufacturing reliable trucks with a high availability and low total costs of ownership.

2.1.1 ORGANIZATIONAL STRUCTURE

DAF Trucks N.V. consists of six departments: Marketing and Sales, Product development, Operations, Information Technology Division, Purchasing and Finance. The headquarters and main production facility are situated in Eindhoven. This project is carried out at the after sales department which belongs to marketing & sales, this department manages all the after sales processes (e.g. it draws up and communicates the maintenance prescriptions). Other departments that are concerned with this project are: Multi support, which manages the Repair & Maintenance contracts with customers and reliability Engineering which aims at controlling the reliability of different components in the truck. The involved departments are depicted in Figure 1.
DAF operates in a highly competitive market; potential customers have the opportunity to compare the features of several big truck brands before buying a new commercial vehicle. Total cost of ownership (TCO) is, together with features as reliability and availability, one of the decisive factors in the customers’ consideration of several brands. DAF has set up a network of more than 1,000 dealers in Europe which are officially licensed to perform repair and maintenance action on DAF trucks (See Figure 4). These dealers make their money by performing maintenance actions on trucks and claiming back the incurred material and labour costs either from DAF or the customer.

Repair and maintenance costs and the acquisition value are factors that play a big role in the decision whether or not to buy a certain truck. Repair and maintenance costs form around 5.4% of the total costs of ownership of a commercial vehicle for the customer while the acquisition costs form about 8.4% of the TCO (Figure 2, Estimation made by DAF Trucks based on the average use of a XF105 Truck in Western Europe). A competitive advantage can be obtained if the costs involved in Repair and Maintenance can be reduced as compared to other truck brands.
2.1.3 CURRENT MAINTENANCE PRACTICE

The current maintenance carried out at DAF is based on two principles; time based and mileage based. The basic maintenance jobs are prescribed by DAF. The DAF dealers, who perform the maintenance, are obliged to follow these prescriptions. The different maintenance jobs are either included in the Y-service (yearly) or X-service (mileage based). To improve the planability of stops DAF tends to make more and more maintenance jobs time based. Another reason why trucks have to make planned stops is a stop for legal inspection, however the interval for these legal inspections varies widely from country to country. Maintenance jobs are combined with legal inspection as much as possible to avoid unnecessary stops and therefore increase the availability of a truck. Different maintenance jobs are defined for three usage classes: heavy duty work (for instance at construction sites), local and regional distribution and long haul transportation (see Figure 3).
Figure 3: Maintenance schedules for different usage classes

DAF distinguishes three different types of failure behaviour for components: components described as tasks that fit the regular maintenance schedule (this can be either time- or usage-based), components subject to wear and components which operate to failure. The way how to deal with parts which fit the maintenance schedule is documented in the maintenance prescriptions, these descriptions describe exactly at which moment a certain procedure has to be carried out (either time- or usage-based, this type of maintenance often does not incur the replacement of components but typically oil changes, filter replacements etc.). For the components that suffer from wear (DAFs definition of wear is: components with a limited lifetime influenced by the usage of the component and therefore the failure time cannot be accurately predicted, e.g. Braking Pads) DAF has inspection policies, during service stops the dealer inspects the status of a component and decides whether or not to change a part according to its findings. Parts which are not (known to be) subject to any form of wear are treated according to the run to failure principle.

These maintenance principles are only partly based on the state of a system at the time of service. Therefore parts are often changed when there is still a considerable useful life left. On the contrary some parts are operated to failure while this can lead to unplanned stops or even roadside breakdowns. This research investigates how the concept of Condition Based Maintenance (CBM) can be used to improve the service performance.
2.2 CONTEXT

DAF operates in an environment with several stakeholders, namely DAF, its Customers and the DAF Dealers. Each of these three stakeholders must be able to perform their activities in a profitable way to make sure that there is a sustainable market environment. The manufacturer, the dealer and the customer are in several ways independent of and dependant on each other. DAF depends on the dealer for most of the truck sales and besides that the dealer performs the service on the trucks on behalf of DAF. Therefore the dealer is often considered as the link between DAF and the customer. The Truck market is a highly competitive market and therefore it is important that the three parties in the playing field leave room for each other to operate in. The servicing of trucks is one of the main sources of income for the dealer, therefore it is important that DAF also looks after the interests of the dealer when making business decisions. When the customer decides to buy a maintenance contract on its truck, the customer will pay a monthly fee to DAF although he arranges the contract with the dealer. DAF then pays the dealer according to the maintenance actions the dealer performs according to an arranged discount tariff (Figure 5).
2.2.1 WARRANTY AND REPAIR & MAINTENANCE CONTRACTS

Currently DAF offers their customer a 1 year warranty on the complete truck and a warranty period of 2 years on the so called ‘driveline’ (i.e. all the components that are necessary to make a truck move). This means that all the repair and maintenance costs which are incurred in this period and are caused by normal use, are paid for by DAF. DAF often offers repair and maintenance contracts to its customers. These can either concern the driveline or the complete truck (full service R&M). The value of these contracts is based on the estimated usage of a truck. In such contracts the customer pays a monthly fee to DAF and the repairing dealer can claim the repair and maintenance costs from DAF. DAF currently applies a run to failure strategy on most of the crucial parts, however dealers often perform preventive maintenance on these parts based on their own insights and experience. This can lead to components not being utilised to their full potential. If the failure of a component can be predicted accurately customers can utilize the components as much as possible while not jeopardizing the reliability and availability of the truck.

2.2.2. PRO-ACTIVE MAINTENANCE IN THE AUTOMOTIVE SECTOR

Generally spoken companies in the automotive industry typically prescribe either time- or usage-based based maintenance or operate to failure strategies (Literature review, Hoeks 2011). An exception to this BMW, BMW introduced CBM (or as they call it Condition Based Service) quite some years ago. The concept of CBS, according to BMW (mr. de Vries, After Sales Manager BMW Nederland, 2011), is to create a flexible and economical maintenance schedule for all items that are subject to wear (the serviceable items). The system that BMW uses, censors the quality of the engine oil, the fuel filter, the filter for climate control and the brake pads. Besides these parts the wear of a number of other parts is calculated according
to several factors (e.g. mileage, speed, RPM). The on-board computer sends a notification to the driver when servicing is needed. This notification comes approximately one month before the part reaches a critical level. This goal of this system is to minimize the costs per driven kilometre while avoiding breakdowns. This means that it is possible that a car has to come in for the replacement of coolant fluids on a certain moment and when this service has been performed it has to come in for the replacement of the brake pads within two weeks after the previous service moment. BMW does not consider this a disadvantage of the system. In the truck market however the availability of the truck is much more important. Therefore, the clustering of maintenance activities is also important in this industry. According to BMW, the drivers behind introducing CBM were meeting ever more demanding customer requirements and cost reduction for the customer. The introduction of CBM lead to flexible and economical maintenance, the best use of serviceable items and therefore increased customer satisfaction.

This system differs from other car brands in the sense that normally factors as time and distance determine the service schedules. The CBM system continuously collects information from the vehicle allowing flexible intervals to be created and therefore preventing needless replacement of parts which still have considerable remaining useful life left. This approach however, if not designed properly can lead to an increased number of service points in time. Therefore it is essential to still cluster activities and perform them simultaneously. If this is not the case it can happen that a car has to be serviced for every monitored part separately.

### 2.3 PROJECT DESCRIPTION

This project will investigate whether pro-active maintenance actions can be used to lower the total costs of ownership for the customer. Pro-active maintenance decisions can be made based on the age of a component, the usage or the condition of a component. **Condition Based Maintenance (CBM)** is a maintenance program that recommends maintenance decisions based on the information collected through condition monitoring. It consists of three main steps: data acquisition, data processing and maintenance decision-making. Diagnostics and prognostics are two important aspects of a CBM program (Jardine et. al. 2006). This project aims at identifying the potential benefits of a pro-active maintenance policy for DAF and the customer.

#### 2.3.1 RESEARCH DESIGN

The aim of the project, as described in the previous paragraph, leads to the following main research question:

"**To which extent and how can a pro-active maintenance strategy be used to decrease the Total Cost of Ownership for the customer?**"
In the automotive industry the number of stops is very important for the customer, with a planned stop significantly less costs are incurred as compared to an unplanned stop. Furthermore, the number of service stops over time also has a big influence on the availability of a truck. Both of these subjects will be taken into account in this report as being relevant factors in determining the TCO.

Since DAF is interested in the concept of CBM particularly, the concept of Condition Based Maintenance will be assessed thoroughly.

### 2.3.2 DELIVERABLES

The first aim is to develop a method that supports DAF in selecting candidates that are of interest to perform pro-active maintenance on. When candidates are selected the next step is to develop an approach to successfully implement such a strategy for these components. Seven candidate components were investigated thoroughly to identify potential benefits of changing the maintenance strategy and a mathematical model is developed to investigate whether or not such a strategy can help to lower the total costs of ownership for the customer. The model integrates new maintenance decision making rules with the existing maintenance practices at DAF.

### 2.3.3 METHODOLOGY

For the time based and usage based maintenance strategy, basic renewal theory will be used to evaluate the opportunities. In the scientific literature, a substantial amount of research is conducted on these two kinds of pro-active maintenance. This is not the case for the research on Condition Based Maintenance; it is often based on solid, rigorous work, but sometimes difficult to implement in practical situations. There are nevertheless, some examples of very specific situations in which the theory has been put into practice, but it proves difficult to generalize the findings (Jardine and Tsang 2006). This research focuses on the development of a pro-active strategy, based on time, usage and condition, to improve the current maintenance situation.

According to Stadhouders (2011) a condition based maintenance design consists of four steps. This is depicted in Figure 6.
The framework is developed by integrating the available knowledge on CBM from literature, and consists of essential building blocks that help to structure the implementation process (Stadhouders 2011). The framework offers guidance within the process of unit selection, offering insights into the requirements of the condition indicator, and providing help within the prognostic model selection for the use in a CBM maintenance program. Based on an evaluation of the profitability of a unit under a CBM program, the unit(s) can be selected for implementation of a CBM policy.

This research is based on Stadhouders’ framework but adapted to fit the research environment at DAF, therefore it does not only consider CBM but also investigates the options to apply preventive maintenance based on historical data. This resulted in the following steps towards preventive maintenance in the automotive:

4. How to select candidate components for Pro-active maintenance?
5. How to determine if Pro-active maintenance can be applied for a component?
6. How can Pro-active maintenance be applied and integrated with the current maintenance practices at DAF?

1. HOW TO SELECT CANDIDATE COMPONENTS FOR PRO-ACTIVE MAINTENANCE?

The first step within framework is to identify interesting components to perform Pro-active maintenance on. This selection process should be based on the potential benefits of a Pro-active maintenance program for a specific unit, and the impact of the failure modes of this unit on the overall condition of a system. The criterion for unit selection can range from health, safety, environmental, customer-related, to financial related issues (Jardine and Tsang 2006). Multi Criteria Decision Making (MCDA) is a tool that is often used to investigate which components are interesting to investigate (Stadhouders 2011). In chapter 3, criteria to apply pro-active maintenance and a MCDA tool, which identifies CBM potential in a fast and easy way, is presented that is developed using both interviews and literature. Several
components were then assessed for suitability for Pro-active maintenance and CBM, and the most interesting ones were selected for further investigation.

2. HOW TO DETERMINE IF PRO-ACTIVE MAINTENANCE CAN BE APPLIED FOR A COMPONENT?

After the selection of interesting components, a detailed (technical) analysis on these components to identify the feasibility of a Pro-active program should be performed. The relation between the failure mode(s) of a specific unit and the related deterioration parameters has to be investigated. A failure mode can have a single, or multiple deterioration parameters to predict a failure (Jardine 2006). An important characteristic of the condition indicator is the failure trend. A very important criterion here is that the failure mode should be predictable either based on historical data or by monitoring. For a deterioration parameter, a threshold level should be defined. As the parameter reaches this threshold level, the unit is considered to be in a failed condition state. For the components chosen for the practical application possible condition indicators will be investigated. This analysis can be found in chapter 4.

3. HOW CAN PRO-ACTIVE MAINTENANCE BE APPLIED AND INTEGRATED WITH THE CURRENT MAINTENANCE PRACTICES AT DAF?

When a maintenance strategy for a component of a multi-item system is chosen it is key to find a way to find a way of incorporating this strategy into a maintenance strategy for the entire system, where in this situation availability and planability of stops is very important. Therefore the existing maintenance stops, which are based on legal inspections, are deliberately chosen as a starting point. A wide variety of prognostic models is available in the literature for prediction of the Remaining Useful Life (RUL) of a unit based on condition parameter(s) (literature review Hoeks 2011). The selection of an appropriate modeling technique is dependent on the available information on the failure threshold, whether subjective or objective condition indicator data is available or not, and the availability of failure data. For this research a mathematical model based on renewal theory and degradation modeling techniques, combining ‘regular’ maintenance with condition based maintenance, is developed. The description of this model can be found in chapter 5.

Given the output of the degradation modeling phase, relevant insights can be obtained into the maintenance decision making process. These insights can be the expected cost of replacing too early or too late, the expected costs for preventive- and corrective maintenance per unit time, the expected cost of downtime, and a quantification of the risk of failure at a specific moment in time (Stadhouders 2011). Based on these insights and a maintenance objective (e.g. maximize availability, or minimize total cost of maintenance), a
maintenance policy can be determined. Based on this knowledge, the unit(s) can be selected for implementation of a CBM policy.

In accordance with other research performed at the TU/e (Zhu 2011) the CBM model that will be presented is based on a fixed maintenance interval. This model is very suitable for this situation since obligatory legal inspections are often present in the automotive industry and customers value planability of maintenance stops. These prefixed moments where the truck already visits the workshop can be used to decide upon which maintenance actions to take against relatively low setup costs. The goal of the model will be to minimize the Total Costs of Ownership for the customer over a certain period. These opportunities are used to plan the maintenance actions according to the condition of components.

The decision model that is developed decides on predetermined time periods whether or not to preventively change a component. This decision will be an economical tradeoff based on the risk of failure in the upcoming maintenance interval and the potential costs of failure. The goal is to minimize the total costs of maintenance and repair actions (including penalty costs etc.) over the useful life of the truck.

In order for a CBM program to work, detailed insights need to be obtained on the interaction of components on one another, and the (multiple) causes of a failure mode of the system. Typically, the characteristics and relationships of all related components in a system and its environment can be too complicated to be modeled (Lee, 2007).

Decomposition of the system into lower level units (i.e. components) for which the failure modes and interactions are comprehensible is key at the start of a CBM program. Depending on the level of knowledge of these failure modes, analysis on the item, component, or system level is possible (Thomas 1986). For example, starter motor can be considered as a component, but also the entire steering mechanism (i.e. all components enabling the function of steering) can be considered to be the component for analysis. Depending on the
way of defining the unit, different failure modes will have different effects on the unit and will have different causes depending on the level of decomposition.

There are several research papers written on multi component CBM systems (e.g. Bouvard et. al. 2010) shows an approach to determine the condition of a complete truck from the condition monitoring information of the separate components). This research combines single unit degradation modeling with multi component CBM models to determine the right maintenance strategy. While availability is very important in the truck industry the issue of clustering maintenance actions is also assessed. The model that plans the multi component maintenance actions is based on fixed maintenance intervals (e.g. the legal inspection interval).

2.4. SCOPE

This research considers a new pro-active maintenance strategy. In the part of the research that considers maintenance decision making based on failure data, well known renewal theory principles are used. However for the CBM part a new approach is suggested. Bengtsson (2004) identified a need for organisations for a framework to implement CBM. A lot of examples of practical application of CBM are available in the literature (e.g. Lin et. al. (2004), Bouvard et. al. (2004), Jardine et. al. (1999, 2001), Willets et. al. (2001), Anderson et. al. (1982)). These models often describe very specific situations and therefore the results are difficult to generalize. However insights gained in these studies are used to define a general model for identifying the CBM opportunities in the automotive industry. Heng et. al. (2009) found that there are some general difficulties while implementing a CBM program. These difficulties can consist of complexity issues in real life systems, data collection and different operating conditions for different machines. This research focusses on identifying the difficulties and describing ways to overcome them in the commercial vehicle industry by providing a framework with which CBM can be introduced at DAF Trucks.
This Chapter describes a method on how candidate components can be selected for Pro-active maintenance. Firstly it elaborates on what issues are important when assessing Pro-active maintenance decisions in general. Afterwards it describes a situation where Condition Based Maintenance is assessed.

The criteria need to be formulated such that precious aspects as availability, maintenance costs and planability of stops are taken into account properly. The impact of a Pro-active maintenance program on the operational and technical costs can depend on numerous factors. Therefore, the identification of these factors and the related selection criteria for choosing a specific component are discussed.

3.1 CRITERIA ANALYSIS

Multiple criteria can be involved in maintenance decision making. Some customers can consider the component with the highest frequency of failures to be the most critical component while others consider the unit with the longest downtime to be the most critical one. Also, from a financial point of view, the cost involved with a corrective versus preventive maintenance can be considered to be a criterion for defining the criticality of a component. This implies that there is a need for a multi criteria decision approach (Labib et al., 1998). Ideally, these criteria should be analyzed in a quantitative manner. However, if no such quantitative information can be obtained from historical data, a qualitative approach can be used.

As discussed in (Labib et al., 1998) and (Scarf, 2007), important criteria for implementation of a CBM program are the average downtime per failure (downtime), and the number of failures per unit time (frequency). Other alternatives can be used according to company specific requirements.
In the figure above a general classification is made between different maintenance policies as a function of the average downtime per failure and the number of failures per unit time (Scarf, 2007). In case the average frequency of failures is high and the average downtime per failure is high, a redesign (design out maintenance) is advised. A CBM policy offers most potential when the average frequency of failures is low and the average downtime per failure is high. When design out maintenance or Condition Based Maintenance is not possible, time based maintenance is advised by Scarf. Time (or usage) based maintenance is therefore advised when the average downtime for a failure is high. When the average frequency of failures is low and the average downtime per failure is low, it is advised to use a run-to-failure (i.e. operate to failure) policy. Operator training (i.e. training of the servicer of a system) is recommended if the average frequency of failures is high and the average downtime per failure low.

In the truck industry components are designed for maximum availability. Generally this means that failure modes with a high frequency are not accepted by the customer and since the downtime of a failure is often high because most repairs can only be performed in the workshop. Therefore typically the failure types that occur in the truck industry can be categorized as to be handled with either ‘Time Based Maintenance’ or ‘Condition Based Maintenance’.

### 3.2 MULTI CRITERIA DECISION ANALYSIS SUPPORT TOOLS

As multiple conflicting aspects are to be handled within the organizational decision making process, the goal of making an optimal decision changes to making a decision that is satisfactory for the company. The Multi Criteria Decision Analysis (MCDA) methodology offers support in this situation. The solution to the problem might be considered to be best for the stakeholders who provided input in the process. It can be used as an aid for decision making to help organize data and predict the consequences (Belton and Stewart, 2002).

Different MCDA methods exist depending on the decision making situation, and the information available. This also includes different techniques for determining the criteria weights. The overall structural elements of a MCDA are criteria to compare different alternatives with, alternatives to decide upon, stakeholders and decision makers involved in the process, uncertainty in the decision making process which can be caused by external factors or a lack of knowledge on parameter influences, and the environment (i.e. time and place) at which the decision is made (Diakoulaki and Grafakos, 2004).

The stages of MCDA include (Diakoulaki and Grafakos, 2004):

1. **Problem structuring:** This crucial stage of MCDA, typically requiring the bulk of the effort, involves the identification of criteria and decision options and obtaining performance measures (Janssen, 2001).
2. Criteria weighting: This involves obtaining information from decision makers about the relative importance of criteria. Weights may be expressed at either an ordinal or cardinal measurement level.

3. Criteria transforming: As the criteria are in different components they need to be transformed into commensurate components prior to aggregation in the ranking or scoring function.

4. Option ranking and/or scoring: The weights and transformed performance measures are combined to determine the overall performance of each option, relative to other options.

Using the framework suggested by (Jardine 2006) as a basis combined with interviews with employees from reliability, commercial services and after sales departments important criteria for determining when a component is interesting for CBM are defined. First a meeting with employees was made to define the criteria and their weighing factors. Afterwards, following the guidelines of a Pareto analysis (20% of the failure modes cause 80% of the failures), a top 15 was made both based on the incurred costs for certain failures and the quantity with which they were present. All the failures in this analysis are by the definition of Scarf interesting to investigate for time based maintenance. For a CBM policy extra criteria to investigate the potential can be defined. These failures were weighed according to these criteria to select the six most interesting components to investigate for a CBM approach. The criteria used and their weight factor can be found in Figure 9. The complete procedure of defining the criteria and selecting the most interesting candidates can be found in the Appendix D.
<table>
<thead>
<tr>
<th>Weight</th>
<th>Criterion</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Are the failure modes detectable?</td>
<td>Is detectable <em>what</em> went wrong when a component fails (1 is not detectable – 10 is always detectable)</td>
</tr>
<tr>
<td>50</td>
<td>What are the effects of failure?</td>
<td>What <em>consequence</em> does a failure have</td>
</tr>
<tr>
<td></td>
<td>Does the failure cause a safety hazard? (30%)</td>
<td>Can the failure be considered as a major safety hazard (10) or not (1)</td>
</tr>
<tr>
<td></td>
<td>What are the repair costs? (20%)</td>
<td>What are the repair costs (excl. downtime costs) 1 is low 10 is high</td>
</tr>
<tr>
<td></td>
<td>What is the 'downtime' caused by failure and consequencial damage? (50%)</td>
<td>Can a failure be repaired by a planned stop (1), unplanned stop (4) or does it cause a breakdown (10)</td>
</tr>
<tr>
<td>20</td>
<td>How often does the failure occur?</td>
<td>1 being almost never, 10 a lot</td>
</tr>
<tr>
<td>10</td>
<td>Is ‘design out maintenance’ possible?</td>
<td>Is it possible to redesign a component to make it more reliable (1) or not (10)</td>
</tr>
<tr>
<td>25</td>
<td>Failure predictable (objective/ subjective)</td>
<td>Is the failure not (1), subjectively (5) or objectively (10) predictable</td>
</tr>
<tr>
<td>20</td>
<td>Monitor possibilities (not/ periodically/ continuous)</td>
<td>Is the parameter not (1) periodically (5) or continuously (10) monitorable</td>
</tr>
</tbody>
</table>

**Total: 150**

**Weighed total:**

*Figure 9: MCDA*
4. HOW TO DETERMINE WHETHER A PRO-ACTIVE STRATEGY CAN BE APPLIED FOR A COMPONENT?

This chapter describes a method to identify the possible savings achievable with pro-active maintenance. Time- and usage-based maintenance is described first. Afterwards, an eight step model towards CBM is presented to identify the CBM potential.

For a pro-active maintenance policy, the potential can be determined by looking at the following guidelines (Gits 1992):

- The failure of a component should be predictable, either by statistical analysis of historical data or by deducing the condition of a component based on other information.
- The failure rate of a component should be increasing over time; obviously when a failure rate of a component is decreasing or constant over time, a replacement of this component would not lead to an improved with a lower probability of failure. This can be investigated by analyzing the number of failures on a population of components over time or by analyzing the physical characteristics of a component.
- The replacement of the considered component should be done, without influencing the failure rate of other components in the system significantly.

When condition based maintenance is considered some extra steps have to be taken to investigate the potential for a pro-active maintenance strategy. It is key to determine the critical failure mode(s). This information can be obtained from historical failure event data with the related cause of failure. Also, expert opinion can be used for determining the relevant failure modes of a component. To obtain insights into the failure modes and criticality, several tools can be used. Some commonly used tools in the field of Root Cause Analysis (RCA) are Failure Mode & Effect Analysis (FMEA) and the Ishikawa diagram. The most commonly used method (which is also use at DAF Trucks) is the FMEA.

4.1 IDENTIFYING CBM OPPORTUNITIES

A Failure Mode & Effect Analysis (FMEA) can give valuable insights into the relation between a failure mode and the parameter to describe this specific mode of deterioration. This technique also supports the process of selecting the most critical failure modes of a specific component by evaluating the consequential damage related to it. Although FMEA is a subjective method, it is considered to be an effective way to relate the failures to a specific component as maintenance data often does not provide this information. Cross department involvement of expert opinion within the company can improve the validity of this technique. The result of the FMEA is a selection of the failure mode(s) to be monitored and insights into which deterioration parameter(s) should be selected to predict a specific failure mode. In FMEA, failures are prioritized according to how serious their consequences are,
how frequently they occur and how easily they can be detected. An FMEA also documents current knowledge and actions about the risks of failures for use in continuous improvement.

FMEA is a method that is already used within DAF. Findings in already existent reports and cooperation with the quality responsible of the investigated components lead to an overview of the CBM potential of the previous selected components. Through interviews and existing literature on CBM, we created an eight step flowchart to identify the CBM potential for a component. This method is mostly based on steps used in FMEA and the steps towards CBM as defined by Jardine (2006). These eight steps towards CBM determine whether or not it is technically and economically feasible to perform CBM on a component. These steps are shown in Figure 10. For one component (the compressor) these steps are briefly described in this chapter. The analysis for other components can be found in Appendix C.

1. Describe failure modes and their criticality:
   Describe all the relevant failure modes in case of what happens and the effects of failure.

2. Describe the detectable failure modes in terms of what components fail and how:
   Investigate which failure modes are detectable, describe what happens technically with these components and what the monitoring possibilities are.

3. Describe failure modes in terms of all detectable phenomena (either the failures or the effects):
   Describe in what way(s) a failure mode can be detected. Can a components’ degradation level be measured directly or is there a possibility to deduct the level of degradation according to other measurable effects of the failure.

4. Distinguish failure modes using measurable effects:
   Identify whether the most important failure modes can be distinguished by their measurable effect. This is important since different failure modes often require different actions (either in how to deal with them technically or in the severeness of the consequence of the failure).

5. Determine accuracy of measurements and other possible causes for phenomena to show:
   In the next step it should be investigated how accurate the measurements and the deducted degradation estimations are in order to know how valid the conclusions are. Furthermore it should also be determined whether it is possible for other phenomena to produce the same measurement values. This is
important since one wants to be sure to draw the right conclusions when interpreting degradation signals.

Figure 10: 8 Steps towards CBM

1. Describe failure modes and their criticality
2. Describe the detectable failure modes in terms of what component(s) fail and how
3. Describe failure modes in terms of all detectable phenomena (either the failures or the effects)
4. Distinguish failure modes using measurable effects
5. Determine accuracy of measurements and other possible causes for phenomena to show
6. Determine which failure modes are most interesting to monitor
7. Determine whether it is economically feasible to initiate CBM
8. Determine thresholds and maintenance policy
6. Determine which failure modes are most interesting to monitor:

From the previous steps an overview can now be created to determine which failure modes have the best technical characteristics to apply CBM and are therefore the most interesting ones to apply CBM on.

7. Determine whether it is economically feasible to initiate CBM on this component:

A CBM program often requires investments to install monitoring systems, it should therefore be analyzed for the preferred failure modes, whether the potential savings are outweighing investment needed to determine the degradation level of a component.

8. Determine thresholds and maintenance policy.

The last step is to find a way to put CBM into practice by formulating a maintenance policy that fits the maintenance practices that are already used in the company. A way to deal with this with a multi-component system is described in Chapter 5.

4.2 EXAMPLE: COMPRESSOR

A good example of a is the air compressor in a truck (the brakes are air powered) it is possible to measure the time it takes for a system to come to pressure and the number of times the compressor has to turned on to maintain the braking function of a truck.

1. Describe failure modes and their criticality:
   Pump failure (leads to roadside breakdown) and leakages (lead to an unplanned stop) are the most frequent failure modes of the air system.

2. Describe the detectable failure modes in terms of what components fail and how:
   A Pump failure is a typical failure that is often due to wear. The compressor pump becomes less efficient over time and does not reach its efficiency target anymore to be able to bring the brakes up to pressure.
   Another failure mode is a leaking air system, there is an air leakage somewhere in the piping from the compressor towards the brakes.

3. Describe failure modes in terms of all detectable phenomena (either the failures or the effects):
   A pump failure can be detected by the air system not coming to the right pressure anymore or taking a longer than average time to come to the right pressure (long on-time).
   A leaking air system will also lead to a longer than average on-time of the compressor but this failure mode is also detectable in other ways; when the number of times that
the pump turns on increases this can be a sign of leakages. A difference in pressure between the moment of shutting down the engine and starting it later on can also be a sign of this failure mode. The time it takes for the air system to come to pressure can give a general indication whether or not the system is functioning properly.

4. Distinguish failure modes using measurable effects:

If it takes longer than average for a system to come to pressure this can be an indication for a leaking air system as well as a loss of function of the compressor. If the compressor has to be turned on more than usual (over a longer period of time) to reinstate the right pressure it can be due to a leaking system. A combination of these two symptoms can be used to perform remote diagnostics on the air system of a truck.

The failure mode pump failure can therefore be distinguished by a longer on-time of the compressor than average and an absence of the symptoms of an increased number of times the pump has to be turned on and pressure loss when the motor is turned off or the brakes are not used.

An air leakage in the system can be detected by a longer on-time of the compressor combined with other indicators as number of times the compressor has to bring the system to pressure and a loss of pressure while the system is not used.

5. Determine accuracy of measurements and other possible causes for phenomena to show:

The average on-time of the compressor depends on the axle configuration of the truck. But if this average on-time increases over a period of time it could be an indication of a deteriorating system. In the new (to be introduced) euro-6 trucks the on-time and the number of times the compressor is turned on can be measured directly and accurately. The pressure of the system is not measured but when the compressor turns on often directly after an engine start it could be a sign that there is a pressure loss in the system and therefore a possible leakage.

In the ideal situation it would be the case that every time there is a leaking system, several of the before mentioned phenomena show up. Nevertheless, it can also be the case that the only detectable effect of this failure mode is an increased on-time (e.g. when the brakes are used often also in a regular pattern, an increase in the number of times the compressor is turned on may be barely noticeable). Therefore, the overall functioning of the air system can be monitored, but distinguishing the different failure modes can be more complicated. This does not mean that CBM cannot be applied for this system. Only that when the efficiency of the compressor pump is decreasing, a signal can be processed to inspect the system at the next planned stop without exactly knowing which failure mode is apparent.
6. Determine which failure modes are most interesting to monitor:
   Based on the analysis performed above it can be concluded that both failure modes should be taken into account.

7. Determine whether it is economically feasible to initiate CBM on this component:
   Since both the number of times the compressor is turned on on average and the on-time can be measured in the new euro-6 trucks without any major extra investments, it is economically and technically feasible to perform CBM on this component.

8. Determine thresholds and maintenance policy:
   The previously stated information can be used to put a warning system in place for the air system. In current the maintenance practices prescribed by DAF (Service Rapido) it is stated that it should never take more than 5 minutes for an empty system to reach the right pressure. If the on-time of the compressor exceeds this number it is a signal that the air system is not working properly anymore. By monitoring the average on-time, an estimation can be made of when the on-time is going to exceed the critical level (5 minutes). According to this prediction a judgment can be made to either fix the problem at a regular maintenance stop or to wait. If the average on-time has been increasing significantly since the last service stop it can be an indication that system that will fail soon. However since this deterioration does not have to lead to an immediate failure this information can be used to perform preventive maintenance at the right times.
5. HOW TO INTEGRATE PRO-ACTIVE MAINTENANCE WITH THE CURRENT MAINTENANCE PRACTICES AT DAF?

This Chapter aims at incorporating Pro-Active Maintenance decisions into the regular maintenance practices at DAF. It consists of two parts: the first part represents a decision model based on a Weibull distribution fitted on actual failure data. The second part consists of a numeric example on how a Condition Based Maintenance model could look like, when fitted into the existing maintenance practices. As mentioned before, the number of maintenance stops has to be minimized as much as possible. Therefore, this model only allows performing maintenance at predetermined moments in time.

Consider a system with \( m \) different critical components: \( 1, 2, \ldots, m \).

The following premises hold:

- A Finite horizon (\( H \) in years) is assessed for calculating the total maintenance costs on a component.
- There are two types of components:
  - A: Failure distribution is given (Weibull distribution based on failure data).
  - B: Degradation parameter is given and continuously measured.
- Kilometers and time (in years) are proportionally related.
- Setup costs for planned maintenance stops and unplanned stops per failing component \( i \) are defined as \( S^p_i \) and \( S^u_i \) respectively.
- Per component the costs for a planned replacement and an unplanned replacement are given by \( C^p_i \) and \( C^u_i \) respectively.
- The degradation behavior of components of type B can be described with a stochastic process.
- Time to replace is negligible.

5.1 POLICY

- The visiting schedule of a truck to the workshop is predetermined and happens based on a fixed interval \( I \) (in months).
- \( I \) has a fixed number of possible values: through enumeration the optimal \( I \) will be determined per component.
- When a component fails in between two planned maintenance stops, the component will be replaced correctively.
- For components of category A an optimal replacement interval \( T \) (based on the fixed inspection intervals) will be calculated.
- For components of category B a prognostic modeling approach is chosen and integrated with the maintenance model to determine the optimal policy.
- Since the stops are determined on forehand and also include other activities, the setup costs will not be charged if a component is changed at a planned stop.
This model analyses the components separately, identifying the optimal maintenance interval for each one of them. Afterwards these components are linked to the schedule with the fixed schedule I. In the analysis below, all formulas apply to a single component and have to be read as such.

**Components of Category A**

For Components $i$ of type A, a Weibull distribution is given with degradation parameters $\eta_i$ and $\beta_i$ (DAF uses parameters that are either time or mileage based). Where the $\beta_i$ indicates whether an increasing failure rate is present; if $0<\beta_i<1$ there is a decreasing failure rate over time, $\beta_i=1$ indicates a situation with a constant failure rate and $\beta_i>1$ describes a situation with an increasing failure rate over time. As stated in Chapter 4, for a component to be interesting for Pro-Active maintenance the failure rate should be increasing over time. The Reliability $R_i(t)$ of a component $i$ at time $t$ (the probability that a system will run without failure from the start ($t=0$) to time $t$) is then denoted as:

$$R_i(t) = e^{-\left(\frac{t}{\eta_i}\right)^{\beta_i}}$$

In this step the procedure of determining the optimal replacement interval for an age-based policy is described. If we let $T$ denote a preventive maintenance interval (the expected time between two replacements), the expected cycle length for component $i$ ($ECL_i$) at a certain service interval $T$ can be described as the probability that a component will survive for the entire interval multiplied by the length of the interval and the weighted average of the proportion that does not survive the entire interval:

$$ECL_i(T) = \int_0^T t \times f_i(t) \, dt + T \times R_i(T)$$

This is generally shorter than the preventive maintenance interval since there are always some components that will fail before time $T$ is reached.

To specify the total expected costs per time unit with a replacement interval of $T$, ($g_i(T)$), the expected costs per cycle ($ECC_i$) is divided by the expected cycle length. The Expected Cycle Costs are composed of the probability that a component will fail in a maintenance interval multiplied by the costs of corrective maintenance and the probability that it survives time the costs for preventive maintenance.

$$ECC_i(T) = (1 - R_i(T)) \times (S_i^m + C_i^m) + R_i(T) \times (S_i^p + C_i^p)$$

$$g_i(T) = \frac{ECC_i(T)}{ECL_i(T)} = \frac{(1 - R_i(T)) \times (S_i^m + C_i^m) + R_i(T) \times (S_i^p + C_i^p)}{\int_0^T t \times f_i(t) \, dt + T \times R_i(T)}$$
The next step is to incorporate that the maintenance actions are performed at predetermined intervals and that an interval can be either shortened or prolonged because of clustering of maintenance activities. This model considers a fixed maintenance interval $T$ where the replacement interval of separate components ($T$) equals $n*I$ (for $n = 1, 2, 3, ...$). To estimate the extra costs ($EEC_i$) if the actual replacement interval deviates from $T$ due to intermediate replacement, the following formula is used.

$$EEC_i(T,I) = \frac{1}{2}(ECC_i(T - \frac{I}{4}) + ECC_i(T + \frac{I}{4}))$$

Where the extra costs are composed of the costs of either replacing a certain component earlier or later than $T$. The decision on shortening or prolonging the replacement interval is made based on which of the two regular replacement moments is closest in time. Assuming that the moment the failure occurs is uniformly distributed between two planned replacements. The average time that a replacement will be shifted (either earlier or later in time) is $I/4$ with a 50% chance that it will be either earlier or later. The total expected costs per time unit then becomes:

$$TEC_i(T) = R_i(T) \cdot g_i(T) + (1 - R_i(T)) \cdot EEC_i$$

With this method the average maintenance costs per time unit for each component for all intervals. Through enumeration the optimal replacement interval as a multiplication of $I$ can be chosen.

**Components of Category B**

For components of Category B a degradation parameter and modeling approach has to be chosen. For this a model based on the framework defined by Lu and Meeker (1993), the general path model, is used. This model is further adapted by Zhu (2012) to fit to a maintenance model with a fixed maintenance interval. This model also calculates the expected costs per unit time based on the Expected Cycle Costs and Expected Cycle Length except the fact that these values are not calculated with only the Inspection Interval as a
decision variable but with the inspection interval and the warning level. A linear degradation path for component $i$ with a constant parameter, $\phi_i$, and one random parameter $\theta_i$ is assumed. The degradation function at time $t$ ($X_i(t)$) is stated as follows:

$$X_i(t) = \phi_i + \theta_i t, \quad \forall i \in I,$$

or

$$t = \frac{X_i(t) - \phi_i}{\theta_i}, \quad \forall i \in I,$$

where $t$ represents the time that a certain component is in use. This formula describes the situation where there is a standard level of degradation at the beginning of the experiment ($\phi_i$). Afterwards a linear term ($\theta_i$) is determined per component which from there determines the linear degradation path over time (Figure 11). N.B. in this model $\phi_i$ and $\theta_i$ cannot be observed separately; only values of the degradation function $X_i(t)$ can be observed.

Then the cumulative failure distribution function, $F_K(t)$, denoting the probability that the lifetime $K$ is smaller than or equal to $t$ can be transformed to a function of degradation above a certain threshold level, $H$:

$$F_K(t) = \Pr[K \leq t] = \Pr \{X_i(t) \geq H\}$$

When the distribution of $\theta_i$ is known, the failure distribution, $F_K(t)$, is also known.
Figure 12: Degradation Model

Figure 12 depicts the degradation behavior of an arbitrary component $i$, $H$ is the level at which a component actually fails and $K$ (and a corrective maintenance action is required) the time at which this occurs. $T_c$ represents the time at which the degradation stage reaches the control limit $C$. A preventive maintenance action is then performed at the next planned maintenance stop (N.B. if no corrective maintenance is performed in the meanwhile).

If the control limit $C$ is set too close to $H$ this will lead to relatively many corrective maintenance actions. However if the control limit is set too low, the maintenance costs increase due to a high number of preventive replacements. This model aims at optimizing the control limits for minimum average long-run costs. The probabilities of a preventive (PM) and corrective (CM) maintenance action can be written as:

\[
\Pr\{PM \text{ at } n\tau\} = \Pr\{n\tau \leq K, (n-1)\tau \leq T_c \leq n\tau\},
\]

\[
\Pr\{CM \text{ in interval } ((n-1)\tau, n\tau)\} = \Pr\{n\tau > K, T_c \leq (n-1)\tau\},
\]

where $\tau$ is a decision variable which represents a multiplication of $I$ ($\tau = n * I, \text{with } n = 1,2,3,\ldots$) the standard maintenance interval. Now the formulas to calculate the probability of a preventive maintenance action and a corrective maintenance action with a certain warning level $C$, the expected long run costs at a certain interval can still be calculated using the formula

\[
g(C) = \frac{ECC}{ECL},
\]

with
\[ \text{ECC} = \sum_{n \in \mathbb{N}} \left[ \Pr\{PM \text{ at } n\tau\} \ast \mathcal{C}_i^n + \Pr\{CM \text{ in interval } (n-1)\tau, n\tau\} \ast (S_i^n + C_i^n) \right], \]

and (ECL is the average time it takes to reach the control limits):

\[ \text{ECL} = \sum_{n=1}^{\infty} \left( \Pr\{PM \text{ at } n\tau\} \ast n\tau + \int_{(n-1)\tau}^{n\tau} f_K(t) \ast t \, dt \right) \]

\((f_K\text{ the probability distribution function of failure time } K)\). The model can then be optimized through:

\[ \min_{C_i} g(C) \quad \forall i \in I \]

The two decision parameters of this model are the value of the control limit and the maintenance interval \(\tau\). Below, a numerical study is performed to investigate the effect of these parameters for a single component.

5.3 DATA

The data used as input for this model was obtained from several databases within the company. To obtain an estimation of the planned replacement costs of certain component, the database of processed Repair and Maintenance and Warranty claims was used. Since this estimation covers only planned repairs, the repair actions that were performed at ‘home’ dealers were assessed. Looking at parts consumption and the claim description, standard replacement jobs were selected for the components including the involved labor costs. In all the analyses data was used from the most common type of truck sold, the DAF XF 105 FT in the German market.

For the calculation of the extra costs involved with a roadside breakdown, the number of claimed repairs from the repair and maintenance database was matched with the data of the ITS (International Truck Service of DAF). In this database the extra costs of a failure can be found (Unplanned dealer visit or a roadside breakdown). Replacement jobs that were not found in the ITS database are considered to be planned visits to the dealer. The majority of the trucks that end up in trouble contact ITS for support. But since there is no other way to investigate the consequence of failure this is only a conservative approximation of the consequence of failure in terms of lost production. Furthermore the average costs of the claims that are a consequence of failure is compared to the preventive replacement costs (the costs of replacement at a planned dealer visit) to determine the extra technical costs of failure.

For the time based maintenance components (Type A), information was used from DAFs Global reliability Database which registers failures of components, from this data Weibull curves are fitted on the data through the LSE method. For some parts the mileage of the truck was used as a predictor, for other parts the time since replacement. Since time and
mileage are proportionally related in the mathematical model the average mileage on trucks per year (120,000 km/year) was used to make the transformation between time and mileage of the truck. These Weibull distributions are corrected for the fact that they are censored.

All the data are used from the most sold truck the DAF XF 105 FT in the German market and is obtained over one complete year (from the 1st of November 2010 till the 31st of October 2011).

For the Condition Based Model a Frechet or Reciprocal Weibull distribution \( F_K(t) \) is used as input for the model. Therefore the failure time data has to be fitted to this distribution, which is slightly different from the general Weibull distribution. In Appendix E the detailed transformation of this formula is shown as used by Lu and Meeker (1993).

\[
F_K(t) = e^{-\left(\frac{H-\phi_k}{\eta t}\right)^\beta}
\]

To show how such a model could work an example was calculated through using the costs figures and degradation rate of the battery since no degradation parameter is known for any of the components the hazard level \( H \) has been arbitrarily chosen to have the value of 25 with a corresponding \( \eta \) value of 1 (also arbitrarily chosen since the hazard level is also arbitrarily). Within these boundaries the optimal combination of Control limit \( C \) and maintenance interval \( \tau \) is calculated. The results of this numerical example are shown in Section 5.4.

### 5.4 RESULTS

Using data as described in the previous paragraph, the average costs for preventive and corrective repairs are estimated for the components that were chosen to investigate. These values can be found in Table 1 for this first analysis a yearly mileage of 120,000 km (10,000 km per month) was chosen and a standard maintenance interval of 12 months over a horizon of 10 years. The results consist of the minimum expected costs at a certain interval, the costs when the preventive action is linked to the regular maintenance interval and the costs if a corrective maintenance strategy is followed. The extra costs of corrective replacement consist of the extra technical costs of corrective replacement and the costs of non availability (the costs of non availability are calculated through taking into account the costs of the consequence of failure (unplanned stop or breakdown) according to the ratio of these consequences with the below mentioned penalty costs. These costs are estimations made by DAF for what the incurred costs are for the customers in different situations due to lost availability.

- An unplanned stop has a cost of [Blank]
- A roadside breakdown costs [Blank]

The results for the six investigated components can be found in Table 2 and Figure 13.
What can be seen is that for four of the six components an optimal replacement interval can be found with these input values, the achieved savings vary from 0 to more than 19%. The components for which no optimal interval is found could be components where CBM becomes more interesting since time or mileage does not seem to be an accurate failure predictor. However these results are still subject to interpretation. For instance if an optimal replacement interval of six years is given and you want to consider a lifetime of 10 years, it would be better to change the component halfway (at 5 years) since you are planning to incur these costs anyhow it is better to split the intervals in two equal parts of 5 years instead of one interval of 6 years and one of 4. This model gives DAF the opportunity to make maintenance decisions based on actual failure data and the expected costs of a repair.
It allows DAF to calculate whether preventive maintenance can lead to expected savings on the repair costs of a customer in different situations. Since the area around the minimum is relatively flat it is often not profitable to call a truck into the workshop for just that replacement action since set up costs for that stop must then be incurred. Linking it to the closest maintenance interval is therefore the most cost effective decision.

Figure 6: Graphical Representation of Results

What should be kept in mind that the savings are approximations and therefore the calculate savings cannot be guaranteed. Since these results are obtained by using the Weibull distribution as input for the model, the quality of the fitted Weibull distribution is essential to the success of the model. In Section 5.6 (Validation) this part of the analysis is further assessed.
For the CBM model the minimal costs at a maintenance interval $\tau$ of 1 time unit and with a control limit $C = 22.8$. The minimum costs then represent a value of 19.91. Although this does not prove a lot about the potential savings of a CBM program at DAF, results of this small numerical example show that with representative costs figures and failure rates. The minimum costs can be calculated if a proper condition parameter is defined and measured. To install and calculate the real potential savings, the technical details of one component should be thoroughly investigated. The graphical results of this numeric example are shown in Figure 14.

![Graphical results of CBM Model](image)

**5.5 SENSITIVITY ANALYSIS**

To investigate the influence of different factors a sensitivity analysis was conducted. As input the figures of the starter motor as used in the previous section are used. The complete figures of this analysis can be found in the appendix. The most interesting findings of the sensitivity analysis are that the relative savings seem not dependent on the mileage per year. This means that it looks like the amount of savings one reaches does not depend on the mileage per year. This means that the mileage per year only influences the replacement interval but not the maximum percentual savings as compared to corrective maintenance. What further meets the eye is the fact that as the Beta parameter of the Weibull distribution changes the percentual savings change as well. Where the $\beta$ indicates whether an increasing failure rate is present, $\beta=1$ indicates a situation with a constant failure rate and $\beta>1$
describes a situation with an increasing failure rate over time. This implies that when a component degrades faster the predictability of the failure and therefore the accuracy of the decision when to change a component becomes more reliable and therefore the optimal replacement interval can be more accurately predicted. Therefore, it seems that components of which the $\beta$ parameter of the Weibull distribution is relatively high, are more suitable for pro-active maintenance.

What also can be concluded is that there is a certain value of the ratio between preventive and corrective maintenance costs from which preventive maintenance becomes profitable compared to corrective maintenance (in this example that ratio is 1:2). If the difference between preventive and corrective maintenance costs is too small preventive maintenance will not be profitable. This means that the difference between preventive and corrective maintenance should be sufficient in order to make pro-active maintenance profitable.
5.6 VALIDATION

5.6.1. INPUT VARIABLES

The Weibull distribution is the backbone on the failure based part of the mathematical model. Therefore it is crucial that the underlying Weibull distribution represents the reality. The data on which the used Weibull distribution is fitted is reliability data on a monitored fleet of 500 trucks by the reliability department. To check whether this dataset is represents the reality well, the number of failures that the Weibull distribution would expect is checked with the warranty and repair & maintenance data. Because there is data available on every component about what is changed over 5 years. The Expected number of replacements per 100 vehicles was calculated using the Weibull distribution and compared to the actual number of replacements after 5 years per 100 vehicles. What can be concluded is that for all components the calculated and observed number of failures are in the same range of order. Differing from 0 to around 20% except for the alternator where the difference is bigger (37%). This difference can be explained by the fact that the reliability department only records failing components while in the repair and maintenance contracts also preventive replacements by the dealer are recorded. Generally it can be concluded that the Weibull distributions used are a fairly good approximation of the reality.

<table>
<thead>
<tr>
<th>Component</th>
<th>Calculated through Weibull distribution</th>
<th>Measured in Repair and Maintenance Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starter Motor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turbo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternator</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Compressor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Pump</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Validation
5.6.2. CALCULATION OF EXTRA COSTS

To keep the maintenance actions attached to a grid an extra costs term is introduced.

\[
\text{EEC} = \frac{1}{2} \left( \text{ECC} \left( T - \frac{T}{4} \right) + \text{ECC} \left( T + \frac{T}{4} \right) \right) - \frac{1}{2} \left( \text{ECL} \left( T - \frac{T}{4} \right) + \text{ECL} \left( T + \frac{T}{4} \right) \right)
\]

To investigate the correctness of this term a small simulation study is performed. In this study the EEC term was compared to the actual extra expected costs due to a shortened or prolonged maintenance interval when random failures are generated. For this example the input parameters of the turbocharger were used as presented before. 500 random failures were generated and the average expected costs for the changed maintenance interval were calculated with a maintenance interval of 1 year and 2 years. The results are presented in Table 4. What can be seen is that the costs calculated by the EEC term used in the model is generally slightly lower than the real extra costs incurred (although the two are close to each other). This is probably due to the fact that the assumption of the Uniformal distribution of the failures between two intervals in not entirely correct. Since the difference between the two terms is relatively small it can be assumed that the introduced term is a reasonably good approximation.

<table>
<thead>
<tr>
<th>Interval</th>
<th>EEC Term</th>
<th>Expected Extra Costs</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year interval</td>
<td>[\text{EEC}]</td>
<td>[\text{Simulation}]</td>
<td>[-0.065%]</td>
</tr>
<tr>
<td>2 year interval</td>
<td>[\text{EEC}]</td>
<td>[\text{Simulation}]</td>
<td>[-0.236%]</td>
</tr>
</tbody>
</table>

Table 4: Results Simulation Study

**Confidence interval:**

The standard deviation of the simulation performed with a one year maintenance interval is € 0.98764, for a 2 year maintenance interval this is € 3.5086. The formula of a 95% confidence interval can be characterized as follows.

\[
\text{Lower Bound CI: } \bar{x} - 1.96\sigma \\
\text{Upper Bound CI: } \bar{x} + 1.96\sigma
\]

This leads to a 95% confidence interval for a one year interval of \([\ldots]\), and for a two year interval: \([\ldots]\). This shows that the results of the simulation are relatively close to the calculated Expected Extra Costs Term.
The mathematical model as presented before, was implemented into a Microsoft Excel Tool, this chapter describes its purpose. The tool allows DAF to make preventive maintenance decisions based on the Weibull Distribution of a component, the preventive and corrective maintenance costs, the maintenance interval and the mileage of the truck per year. The tool gives the optimal replacement interval for a certain component and the according expected yearly costs. Furthermore, it compares these costs to the expected costs when corrective maintenance is applied (see Figure 17 for screenshots). Weibull distributions are already well used within DAF to investigate the reliability of components, therefore, this tool offers DAF the opportunity to investigate the possible savings when applying Age-Based Pro-Active maintenance on components. The tool is automated and therefore usable for anyone who can obtain the right input parameters. Since the cost factor are input variables it can be used by different parties; for DAF internally (e.g. warranty and Repair & Maintenance contracts, which do not take into account costs due to lower availability) and externally (e.g. customers of DAF for which non-availability can also have a price). Another feature of the tool is to
support decision making on the improvement of components. When a component does not reach its reliability target, it either has to be improved or replaced more than expected. When one knows the distribution of the first component and can define a desired distribution for the improved component and one can make an estimation of how much the improved component will cost, the expected minimum yearly costs for each component can be compared. DAF adopted this tool as an official instrument to base preventive maintenance decisions on. The tool was presented to the maintenance group at DAF (a group with employees of all the departments relevant for maintenance (i.e. reliability Engineering, Technical Information, Commercial Services, Warranty) which will use this tool to support their decision making on maintenance issues. An example of this is that the tool was used by the R&M department to investigate the Turbocharger in the Spanish market. The costs incurred with a failure of the turbocharger are relatively high, often there is consequential damage because loose parts of the failed turbo end up in the catalyst which therefore has to be replaced as well. The department that handles the Repair & Maintenance contracts used the developed tool to decide whether or not to suggest a preventive maintenance action to the Spanish dealers since the turbocharger was failing more frequent than expected, especially in the Spanish market. From an analysis conducted with the model it was concluded that it would be cost effective to preventively replace 200 Turbochargers on the DAF X105 series in Spain.
7. CONCLUSIONS AND RECOMMENDATIONS

In this research a framework has been introduced for pro-active maintenance for an automotive system. It starts with the identification of appropriate components for pro-active maintenance and their possibilities. Furthermore, it provides a mathematical model that provides maintenance decisions based on both failure and condition data and integrates these decisions with the current maintenance practices. A practical test of this model proves that by introducing pro-active maintenance, potential savings can be obtained reaching up to almost 20% of the maintenance costs per component. Therefore, the research question as listed in Section 2.3.1 can be considered to be answered.

Conclusions:

- The developed three step framework offers insights into the potential value of using a pro-active maintenance strategy for a multi component system. It provides a step by step approach of evaluating the technical and economical potential of a pro-active maintenance strategy in a multi component system.

- This study shows that DAF operates in a suitable environment to introduce a pro-active maintenance strategy. This is due to the many components in a truck which are considered to be operating relatively independent from each other and the fact that a limited amount of components are causing the major part of the failures.

- The provided mathematical model offers the possibility to apply a pro-active (either age-based or condition based) maintenance strategy for separate components, based on the current maintenance practice. Therefore it is relatively easy to switch to a pro-active strategy for components one by one.

- As the mathematical model suggests it is possible for DAF and its customers to achieve savings of up to 19% on the maintenance costs (including costs for non availability) for trucks by incorporating failure data in the maintenance decision making.

- Although the optimal replacement interval could be in between two maintenance stops it is often profitable to cluster maintenance actions at the closest regular maintenance stop. Since the savings as compared to combining the replacement with a regular maintenance stop mostly do not justify an extra stop.

- This model provides DAF the opportunity to make preventive maintenance decisions based on historical data. For four of the six components investigated it proved to be profitable to apply pro-active maintenance. Since failure behavior of components can change over time, it is essential to keep on tracking crucial components to investigate whether preventive replacement of these components can be profitable.

- It is shown that with cost figures and a failure rate that are representative for the situation at DAF, a proper CBM strategy can be defined. However, since the proper technical information was absent, a complete example of how this could work could not
be given. To introduce such a strategy more research on the technical properties of the components is needed.

Recommendations:

- To take further steps towards CBM, DAF has to invest in monitoring equipment; this research provides suggestions for which components have the highest potential in this area and for the steps towards CBM could look like. Gathering condition data will offer insights into component degradation and enable statistical analysis and remaining useful life modeling. Gathering (more) data will result in more accurate maintenance decisions and will improve the accuracy of the CBM model. This will not only improve the insights into the degradation pattern of components and the physical behaviour of a component when it is in use, but will also help establish efficient warning threshold and trend characteristics when this condition data is linked to the already available condition data.

- In this research, failure data is used for gathering the input of the maintenance model. To further utilize the pro-active maintenance potential, reliable condition data at a significant scale has to be obtained. Therefore, additional sensory equipment needs to be installed at an extra cost charge per unit. This might influence the evaluation of the profitability of a CBM policy. DAF already developed a telematic system that will not only measure condition data but also provides other services (e.g. location tracking, driver monitoring etc.). Further research is needed in determining the influence of a shared cost structure for such equipment since maintenance costs are not the only benefits of this equipment.

- In this research, a predetermined static maintenance interval is used to determine the replacement moments of the investigated components. This approach guarantees that the replacement moments can be easily incorporated with the current maintenance plan. However, this approach does not guarantee an optimal solution for minimizing the maintenance costs. A recommendation is to investigate the extra savings that can be achieved with a dynamic maintenance interval.

- By comparing the deterioration characteristics of identical components across different trucks in different environments, specific profiles for deterioration can be built. This will obtain insights into the impact of customer usage and other factors on the deterioration of the components.
8. REFERENCES


Stadhouders H., 2011, “A Framework for implementing Condition Based Maintenance based on Operational Data”, *TU/e*


Zhu Q., 2011, *Research Proposal PhD Project TU/e*
APPENDIX

A. WEIBULL FITTED ON FAILURE DATA

The Weibull fitting procedure is performed with a commercial package (Weibull ©) which is specially designed to perform reliability analyses on components of a system. The fitting procedure follows a Least Squared Error approach and corrects the data for right side censoring (this means that it is taken into account that not all components have failed yet at the moment of generating the Weibull Curve).
## B. SENSITIVITY ANALYSIS

<table>
<thead>
<tr>
<th>Sensitivity Analysis Input</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck type</td>
<td>XF105 MX</td>
</tr>
<tr>
<td>Market</td>
<td>RDB Global</td>
</tr>
<tr>
<td>Component Name</td>
<td>Startermotor</td>
</tr>
<tr>
<td>Weibull Eta</td>
<td></td>
</tr>
<tr>
<td>Weibull Beta</td>
<td></td>
</tr>
<tr>
<td>Weibull Scale</td>
<td>Km</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td></td>
</tr>
<tr>
<td>EXTRA Costs Corrective Replacement</td>
<td></td>
</tr>
<tr>
<td>KM per year</td>
<td>150000</td>
</tr>
<tr>
<td>Standard Maintenance Interval (Months)</td>
<td>12</td>
</tr>
</tbody>
</table>
# Ratio Preventive vs. Corrective Costs Varied

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck type</td>
<td>XF105 MX</td>
</tr>
<tr>
<td>Market</td>
<td>RDB Global</td>
</tr>
<tr>
<td>Component Name</td>
<td>Startermotor</td>
</tr>
<tr>
<td>Weibull Eta</td>
<td></td>
</tr>
<tr>
<td>Weibull Beta</td>
<td></td>
</tr>
<tr>
<td>Weibull Scale</td>
<td>Km</td>
</tr>
<tr>
<td>Replacement Costs</td>
<td></td>
</tr>
<tr>
<td>KM per year</td>
<td>150000</td>
</tr>
<tr>
<td>Standard Maintenance Interval (Months)</td>
<td>12</td>
</tr>
</tbody>
</table>
MILEAGE PER YEAR VARIED
C. APPLICATIONS FOR DAF TRUCKS

In this section the eight step model towards CBM is applied to the indentified interesting components. All the steps that were possible to take are described (due to missing technical information on some components not all the steps are taken for all components). Mostly the threshold values here are determined through expert opinion, the physical limits that a component can endure or is determined through the prescribed norms a component must comply with. This norm can either be a safety norm or a performance norm. In this section the steps that have to be taken to perform CBM on several components are determined in accordance with the expert opinion from employees from the reliability and after sales department and prescribed safety norms as published in Service Rapido.
D. RESULTS MCDA TOOL
The parameter $\phi$ represents the common initial amount of degradation of the tested component and $\theta$ represents the degradation rate. For the critical level $H$, we can write:

$$H = \phi_i + \theta_i * K$$

Where $K$ is the variable that represents the failure time. This leads to the formula:

$$K = \frac{(H - \phi_i)}{\theta_i}$$

When the failure distribution is assumed to be Weibull distributed with shape parameter $\beta$ and scale parameter $\eta$, the cumulative failure distribution $G$ can be characterized as:

$$G(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}$$

The distribution function of the failure time $K$ becomes:

$$F_K = \Pr[K \leq t]$$

$$= \Pr\left\{\frac{H - \phi_i}{\theta_i} \leq t\right\}$$

$$= \Pr\left\{\theta_i \geq \frac{H - \phi_i}{t}\right\}$$

$$= 1 - G\left(\frac{H - \phi_i}{t}\right)$$

$$= e^{-\left(\frac{H-\phi_i}{\eta t}\right)^\beta}$$

The function $F_K(t)$ follows a reciprocal Weibull Distribution since $1/K$ follows a Weibull distribution.