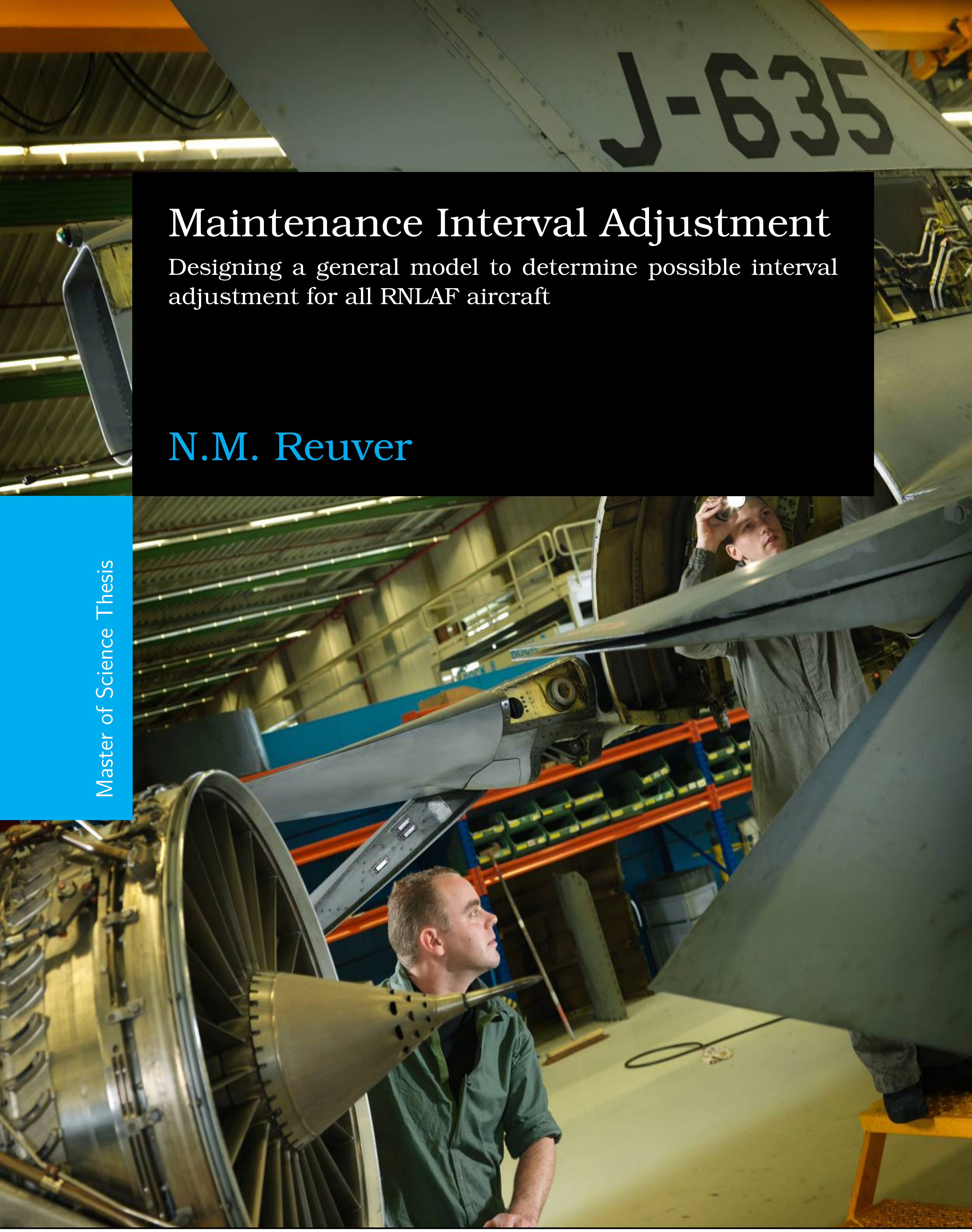

Maintenance Interval Adjustment

Designing a general model to determine possible interval adjustment for all RNLAF aircraft

N.M. Reuver

Master of Science Thesis

TU Delft Delft University of Technology

Faculty of Aerospace Engineering

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Master of Science Thesis

For the degree of Master of Science in Aerospace Engineering: Air Transport Performance & the Environment at Delft University of Technology

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Abstract

How does an organization that is mainly used to conduct maintenance to its aircraft according to manufacturers prescriptions adapt a method with which they can change and optimize their maintenance policies? This thesis report describes the state of the art in maintenance- and related reliability engineering that is used to obtain a step-by-step method for 'in house' Aircraft Maintenance Programme (AMP) alterations. A summary of the proposed method in a single figure can be found in fig. 5-1.

The method first contains a business part where organizational alterations and regulations are mirrored against some common Maintenance Steering Group (MSG) and Reliability Centered Maintenance (RCM) approaches to combine into a Maintenance Review Board (MRB)-cycle that can be applied to the Royal Netherlands Airforce (RNLAF).

Secondly, a reliability analysis part that uses RNLAF life data from all 8 types of aircraft is designed with use of Weibull and Failure Mode Effect and Criticality Analysis (FMECA) theory. This combines into a 11-step model that closely follows aviation regulations and that should give the associated reliability engineers within the RNLAF the necessary tools to start assessing the AMP of aircraft that fall under their responsibility.

Finally, the model is tested with two cases. The 125hrs lead-lag link inspection of the AH-64 Apache and the hydraulic pumps of the CH-47 Chinook proved to be sufficient examples to apply and verify the method. Life data is analyzed and all the steps of the model are performed, which has resulted in advice to change the 125hrs interval to 250hrs and to apply an inspection/replacement interval to the hydraulic pumps in order to proactively monitor the wear and preventively replace the pumps to reduce corrective downtime.

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Glossary

List of Acronyms

AMP	Aircraft Maintenance Programme
CM	Condition Monitoring
CMR	Certification Maintenance Requirements
DMO	Defense Material Organization
FMECA	Failure Mode Effect and Criticality Analysis
HT	Hard Time
HUMS	Health and Usage Monitoring System
I/R	Installs/Removals
MAA	Military Aviation Authority
MPD	Maintenance Planning Document
MRB	Maintenance Review Board
MSG	Maintenance Steering Group
MSG-3	Maintenance Steering Group guidelines version 3
MTBF	Mean Time Between Failures
MTBR	Mean Times Between Removals
MTCH	Military Type Certificate Holder
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
NLR	National Aerospace Center

OC	On Condition
OEM	Original Equipment Manufacturer
PM	Programme Management
RCM	Reliability Centered Maintenance
RNLAF	Royal Netherlands Airforce
TCH	Type Certificate Holder
TTF	Time To Failure

List of Symbols

$\bar{M}$	Mean Downtime
β	Weibull shape parameter
η	Weibull scale parameter
Γ	Gamma Function
ρ	Correlation coëfficient for fit of linear regression method, with estimator $\hat{\rho}$
σ_x	Standard deviation of x
σ_x	Standard deviation of y
σ_{xy}	Covariance of x and y
a	Straight line parameter for rank regression in Weibull fit, with its estimator $\hat{a}$
A_A	Achieved Availability
A_I	Inherent Availability
b	Straight line parameter for rank regression in Weibull fit, with its estimator $\hat{b}$
C	Confidence Level
F	Failure distribution as a function of time
i	Failure order number
M_{MF}	Acceptable Risk of Multiple Failure
M_{TED}	Protected System MTBF
M_{TIVE}	Protective System MTBF (backup system)
N	Total number of failures in the data set
N_{fail}	Number of failures during the data set
$P_{survival}$	Chance of survival at certain time of usage
t	Usage time from install in flight hours of calendar time
t_{tot}	Total number of flight hours during the data set
A(t)	Point Availability
FFI	Failure Finding Interval
MR	Median Rank
MTBF	Mean Time Between Failures

Preface

As employee of the RNLAF I have always been interested in improving maintenance concepts to gain in availability. It is clear, off course, that civil airlines are mostly profit oriented and operate a few types of (fixed wing) aircraft whereas the RNLAF has as main goal to ensure mission succes with 'mission ready' aircraft of 8 different types. The challenge came from the RNLAF central maintenance/logistics department Programme Management (PM) to create a model that contains both a business view and a technical view on changing the maintenance programme of all the aircraft types such that maintenance intervals could be extended. Such an approach turned out to be relatively new within the RNLAF but the involved departments seemed very motivated to incorporate the results.

I would like to thank Prof. dr. ir. R. Curran and Dr. ir. W.J.C. Verhagen for the clear guidance and comments during the research as well as embracing this purely external research within the faculty. Further gratitude goes out to all the RNLAF employees, in particular M.A.F.C. Michielsen MSc., that were involved in the execution and implementation of the method.

Finally, the close collaboration with the National Aerospace Center (NLR) in developing the official procedures that are proposed in the report and in providing advice, expertise and a good data analysis tool has made this research a great succes within the RNLAF.

Niels Reuver
Delft, April 29, 2016

Chapter 1

Introduction

The Royal Netherlands Airforce (RNLAF) uses a variety of military aircraft ranging from helicopters to transport- and fighter planes. The maintenance concepts and -intervals for all these aircraft are, of course, dependent on the type and what the Original Equipment Manufacturer (OEM) has prescribed for it. The RNLAF is therefore generally reluctant in determining it's own maintenance strategies that would provide a more efficient or effective use of maintenance resources and a higher availability for the entire fleet.

OEM's prescribe inspection and replacement moments dependent on time, cycles or flight hours but they take into account a certain usage pattern that is not necessarily applicable for the RNLAF. Moreover, these moments tend to be adapted very conservatively so change in usage patterns which happen in a matter of years are taken into account several years later or not at al. Also, spare parts-, maintenance- and financial resources are usually limited so replacing parts without notion of it's remaining reliability can lead to excessive maintenance.

As maintenance intervals tend to be on the 'far safe side' for the obvious reason of guaranteeing safety of the aircraft a lot of replacements (and inspections) are conducted before the end of a parts' lifetime. The RNLAF wants to know if, and how, it would be possible to adapt the maintenance intervals of it's aircraft while retaining current/sufficient reliability levels. In order to do so, a model needs to be created and tested where all factors, such as reliability, feasibility and necessity are taken into account.

Research question

This report describes a methodology that can be used by the RNLAF to assess the maintenance programme of their aircraft. The methodology described in this thesis will consist of a proposed business approach and the tested contents of a reliability report. As the main goal of the research is to develop this model, the central research question to be answered is:
How can the aircraft maintenance programmes of the RNLAF aircraft be adjusted to extend maintenance intervals and what will be the effect on reliability and availability of the components under investigation?

Hypotheses

This research originates from an assignment from the RNLAF to the researcher but as such, it depends on a few hypotheses that still have to be validated during the process. These hypotheses are:

- A model is required to be created within the RNLAF that describes a standard method for changing maintenance policies and -intervals.
- Availability can be improved (for all aircraft types) by changing maintenance policies and -intervals.
- The effects of changing intervals can be quantified.
- The effects can become visible within the duration of the research.
- Maintenance data can be analyzed for all aircraft types.

Academic value

As an addition to some common methods to analyze maintenance programmes and to existing reliability engineering standards found in literature, this research combines these methods into a single model/procedure that is applicable for all types of airlines but is specifically designed for the RNLAF. This requires an approach that is generic enough to be applicable for all 7 types of aircraft but specific enough that the output can in fact be a certifiable change in an Aircraft Maintenance Programme (AMP). Combining a great variety of data sources and using this information to comply to the aviations requirements is therefore of academic value as well.

Report content

Chapter 2 serves as s review of the literature that is used to form a basis of understanding of possible maintenance strategies, reliability analysis, interval determinations and already conducted research within this field of interest. This section also sets the requirements for a model or method that is subsequently developed in chapter 3. This chapter explains the research approach that is chosen and how the models are designed where the proposed company's processes and underlying calculations can be implemented and executed. The results of all manual test cases are presented in chapter 4, where the expansion to a general method and the implementation within the RNLAF are discussed as well. Finally, the conclusion, discussion and recommendations are found in chapter 5.

Chapter 2

Literature review

This literature review covers the part of reliability engineering that is required to answer the central question. This includes the design of maintenance programmes and how the Royal Netherlands Airforce (RNLAF) uses this knowledge. Also included is a basic understanding of the regulations and requirements and the reliability calculations to meet these requirements. This knowledge will be used in chapter 3 to compile a model.

2-1 Current state of the art from literature

2-1-1 Design and redesign of maintenance programmes

There are many examples found in literature where maintenance policies are adapted in order to gain in system availability and reduce maintenance costs. For the aviation sector, this is described in documents such as MSG-3 [Air Transport Association, 2007] which is internationally accepted or other forms of Reliability Centered Maintenance (RCM) reports [Spitler, 1990], [British Ministry of Defense, 2014] , [Aubin, 2004], [Nowlan and Heap, 1978]. The prescriptions that these reports present are used to design efficient and effective maintenance types and -intervals, based on classification of failure effects. MSG-3 is the current standard that many manufacturers (OEM's) use to design the maintenance programmes for their new aircraft as well.

These programmes usually come in the form of 'approved data' in which the maintainer and user find what to do (maintenance actions), when to do it (after a number of flight hours, calendar days or when a certain condition requires action) and with which parts and tools (approved parts list). However, according to [Tinga, 2013] and [Kinnison, 2004], a maintenance programme is often designed based on factory tests and a certain usage spectrum that users initially predict for their fleet while actual usage and wear are not continuously verified; especially with military aircraft [1] [Kiyak, 2012].

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[1] Of course, on new (commercial) aircraft, this is incorporated in the design much more elaborately than in the (usually older or more conservative) military aircraft design; mostly for operational reasons.

Approaches to assess current programmes

Because changing maintenance policies or -intervals may result in decreased reliability down to a level where it is no longer accepted or where flight safety is affected, knowledge of reliability and failure mechanisms is required to prevent this [EASA, 2012]. Also, some parts of the maintenance programme belong to the core of the safety components of an aircraft and do not allow change in intervals. When assessing the reliability of a component or a system, statistical distributions such as the Weibull distribution are generally used to find trends in maintenance- or failure data [Tinga, 2013], [Kiyak, 2012], [Jardine and Buzacott, 1985] (see section 2-2). These methods that use failure data are called experience based and use results from past experiences to predict reliability in the future. One advantage of these methods is that they rely on data that is usually available but some disadvantages are that there is no insight in the usage profile for the data and that they can only indirectly quantify the actual current- and future state of a component [Cohen and Poggio, 1979].

Another approach is the model based method where knowledge about the underlying failure mechanism (such as creep or fatigue) is used to predict the actual wear and tear. The failure parameter is an example found in literature to link the two methods. In any case, a combination of the two methods provides the most certainty [Lanza et al., 2009], [Delmas, 2013], [Heerink and Coorens, 2013], [Stuivenberg et al., 2013]. Both methods require modelling of the maintenance and linking failures to maintenance or inspection/replacement. Some examples are found in literature to achieve this mathematically [Dekker and Smeitink, 1994], [Scarf, 1997], [Wang and Pham, 2013].

All together, the researcher has found three major tracks in literature that, in combination, provide a well funded result to alter maintenance intervals:

1. Adapt maintenance policy through knowledge of how a maintenance programme is built and how regulations and stakeholders act in the process.
2. Model maintenance through analysis of maintenance- and failure data (experience based).
3. Model maintenance through knowledge of failure modes (model based).

Incorporation of adapted programmes

Examples and restrictions are given of changing maintenance policies to show what is needed to incorporate RCM and to model and adapt maintenance intervals. Figure 2-1 shows a combination of the previous points with all other factors that need to be accounted for, according to literature and previous knowledge of the researcher. Finally, some ideas arise where literature speaks about interval brackets and variable maintenance intervals instead of one (fixed) time [Percy and Kobbacy, 2000],[Cohen et al., 1979], [Raivio et al., 2001]. This is not (directly) applied for research but will be added in the possibilities in chapter 3.

In literature, several examples are found of how to implement this knowledge into an organization that has the task to guard and improve the maintenance programme for an airline. Most examples however, have great similarity to that of the Maintenance Review Board (MRB), presented by [Matteson, 1985] for example. This MRB contains members of the engineering department, planners, users and aviation authorities so a change in the maintenance programme is approved and accepted by all parties and is conducted several times a year to monitor these changes.

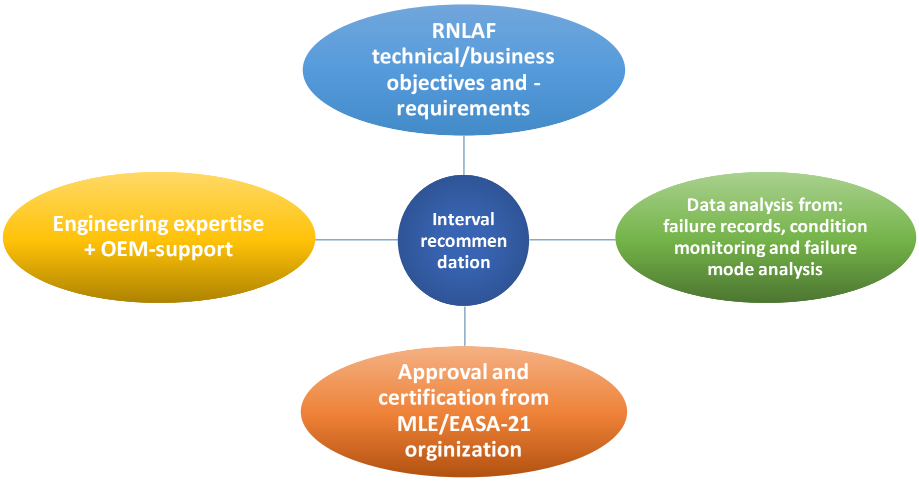

Figure 2-1: Combining different approaches appears to be the most effective and reliable method to change maintenance policies and -intervals.

2-1-2 Current state at the RNLAF

The engineering department of the RNLAF acts as the type certificate holder and is therefore allowed to change maintenance policies. The department (translated: Programme Management) for this research is the central department where logistics and spare-part management are combined with maintenance planning and operational ambitions on fleet level for all RNLAF aircraft. Programme Management is therefore a central link that can influence maintenance processes on a large scale.

The RNLAF generally buys off-the-shelf aircraft including a fitting maintenance programme for the predicted usage pattern. For the RNLAF aircraft (fixed wing and helicopters), almost all maintenance policies and -intervals are prescribed by the OEM and adopted by the engineering department one-on-one. With increased insight in reliability and availability relations through new condition monitoring and failure statistics opportunities [2] comes the desire to understand the underlying theory and to use this for in-house adaptation of maintenance intervals.

Before the start of this research, only a few examples exist within the RNLAF of adapting pre-set maintenance intervals based on usage- or failure data; especially without consulting the OEM before doing so. As more of this data becomes available through years of experience with the aircraft, the question rises how to use this in favor of increased availability. This is the key performance parameter for the RNLAF because (a percentage of) the fleet is required to be available or 'mission capable' but no profit needs to be made in the process.

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[2] These opportunities are usually integrated by external research facilities such as the National Aerospace Laboratory (NLR) or by the OEM directly.

The RNLAF uses a maintenance/failure database with years of historic data and is currently testing a tool to extract a desired subset for further research. Actual causes of failure are generally scarcely monitored. In addition to fig. 2-1, all the available data sources (i.e. failure data, logistic data, shop reports, design data, etcetera) is available only separately and has never consistently been combined to serve as argumentation for Aircraft Maintenance Programme (AMP) alterations.

2-2 Contents of reliability analysis

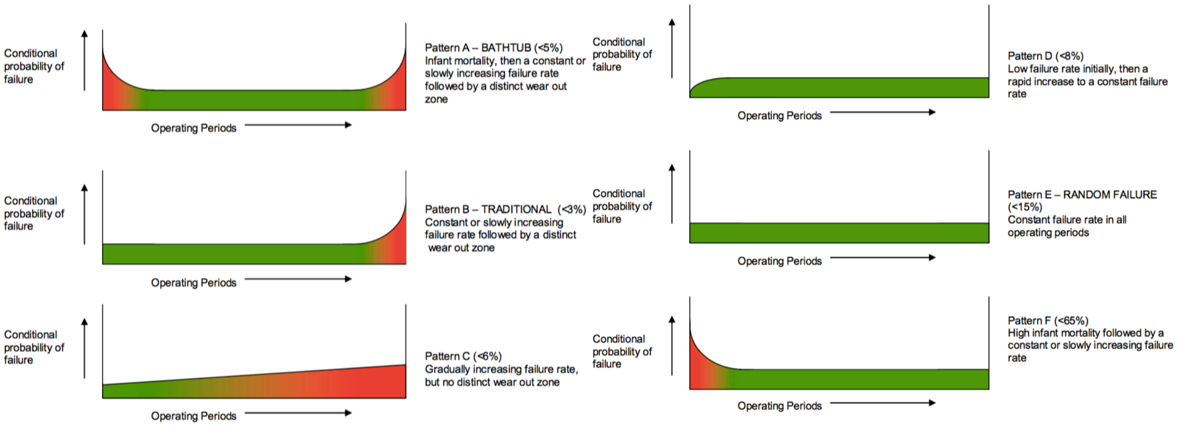
In this section, some theory to calculate reliability is explained. Both the fields of statistical analysis (of maintenance data) and physical/model based wear predictions are elaborate enough for a research on itself, therefore a summary of the most important parts of these theories are given and used further in this thesis. In the first subsection the requirements that are found in literature are explained while in the second subsection, the associated theory is explained.

For this report, the basics concerning calculation of reliability are assumed to be known to the reader; if this is not the case, [Tinga, 2013], [Kumar et al., 2000], [Nowlan and Heap, 1978] and [Dohi and Nakagawa, 2013] provide a well funded basis. This section aims at explaining the theory that is used for the calculations in section 3-3 and chapter 4

2-2-1 Requirements in relation to regulations

Both the trigger and the output for a MRB is a reliability report. This can come in many forms but the main goal is always to provide enough argumentation to review and improve some parts of an aircraft maintenance programme without compromising safety. The obligated contents of such a report have been standardised by the EASA and the US-army for example. According to [EASA, 2011], the report to optimize or escalate maintenance intervals should include:

1. Scheduled maintenance findings
    (a) Routine maintenance tasks that generate no findings. Tasks that generate no findings are as important as tasks that generate findings in determining failure-mode and life-cycle analysis.
    (b) Routine maintenance tasks that generate non-routine cards. These findings, which require corrective action involve structures, area/zonal, and aircraft systems categorized by ATA chapter.
2. Unscheduled maintenance findings, as applicable
3. Failure effect category considerations
4. Component Data (Shop Findings, No-Fault-Found Removals and Failures), as applicable.
5. Actual task interval
6. Four digit ATA code, if available



(a) Failure patterns with increasing failure rates

(b) Failure patterns without clearly increasing failure rates

Figure 2-2: The most common failure patterns with the percentage of occurrence. Design of maintenance programmes should be adapted accordingly.

2-2-2 Failure mode and criticality

Depending on the physical properties of a component, both the failure pattern and failure mode vary. For the failure pattern is important to bear in mind that that "the vast majority of complex assets exhibit no perceivable wear out zone" [Kumar et al., 2000]. This has important implications for maintenance because it then follows that unless the asset has a dominant failure mode that is age related, maintenance around an assumed age limit does little or nothing to improve overall reliability. In fig. 2-2 the most common failure patterns are displayed with a percentage of occurrence according to [British Ministry of Defense, 2012] and [EASA, 2012].

Criticality

Based on the failure mechanism (i.e. creep, fatigue, corrosion, etc.), the criticality of a component can be assessed that will also determine how extensive the agrumentation for redesign is required to be. A failure mode is the root cause (including human error) of a functional failure [Tinga, 2013]. According to [British Ministry of Defense, 2012] and [EASA, 2011], it may be sufficient to identify the failure of an asset as being the result of a single failure mode, even though it may have a number of internal failure modes at lower levels of functionality. Failure modes for assets with an existing service history may be determined from information stored on work recording databases, while failure mode identification on new designs is more difficult. "They have to be inferred from the hardware design, general knowledge of how things fail and experience from legacy systems in similar applications." [British Ministry of Defense, 2012]

According to [US Army, 2013] and [Nowlan and Heap, 1978],this process of Failure Mode Effect and Criticality Analysis (FMECA) is a series of reports that record the details of each stage in the process, i.e. functions, the possible functional failures, their causes and their outcome in terms of local effects, the effects at the next higher level of functionality and their effect on end item capability. "Included in the FMECA is a measure of how critical each failure mode is, based on the severity of the hazard they present and the probability of occurrence." [British Ministry of Defense, 2012] Each of the failure modes identified is subjected to the Maintenance Steering Group (MSG)/Reliability Centered Maintenance (RCM) decision logic to determine the most appropriate and cost effective maintenance actions [United States Airforce, 2009].

Task categorization

The consequence of a failure effect is determined by using the MSG/RCM methodology the general model for this can be found in appendix A. Based on this, the RCM or MSG strategy defines some different types of tasks that result from analysis of the failure mode and thus serve to prevent or detect failures (from [British Ministry of Defense, 2012] and [Air Transport Association, 2007]):

- *Lubrication and servicing* tasks are determined by the Original Equipment Manufacturer (OEM) or designer to meet functional requirements. They include the expected replenishment of consumables and simple preparation and recovery tasks.
- *On condition tasks* are those that enable the detection of a condition which indicates the imminent occurrence of a functional failure. The operating age when this identifiable condition occurs is shown as point P in fig. 2-3 and is known as the point of potential failure. The requirements for a On Condition (OC) tasks are:
    - Failure mode should be detectable.
    - P-Failure interval should be measurable but may have some variation.
    - P-F interval minus tasks interval should be long enough to take action.
    - On condition interval is shorter than shortest P-F interval
    - It must be feasible to do an OC task at the required interval.
    - On condition tasks can be crew/operator monitoring, general (visual) examinations, functional checks or condition monitoring with on-board sensors and analyzers than measure trens and thresholds.
- *Hard Time* tasks are those that restore a condition or replace a component at a specified life to prevent or reduce the probability of a functional failure. For a Hard Time (HT)-task the following holds for each failure mode:
    - There must be a clearly defined lifetime at which the probability of failure rapidly increases.
    - The probability of failure must be tolerable for both hidden and evident failures except for when the failure(s) affect safety; then the defined life must be one below which no failures are expected to occur
    - The HT interval must be less than the defined life of the item.

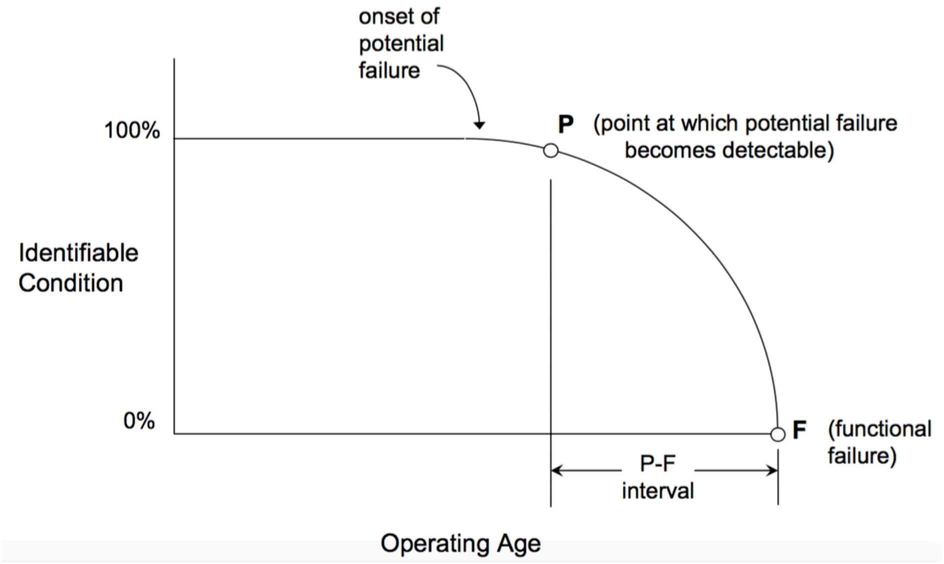


Figure 2-3: Sketch of a P-F interval; from the first point of possible notion of a failure during inspection to an actual failure.

Certification Maintenance Requirements (CMR)

As mentioned, the (required) content of a reliability analysis depends on the criticality of the part(s) under investigation. For certification and continued airworthiness, the CMRs are a subset of the instructions that contain the required scheduled maintenance tasks established during the design certification of the aircraft systems as an operating limitation of the type certificate (TC). This is fundamentally different part of the AMP (or approach) than the part that can easily be changed through application of a MRB cycle, see appendix A for a more detailed explaination. [Bahrami, 2011].

2-2-3 MTBF and MTTF

Two widely used methods for analyzing reliability and to use in interval adaptation are found in literature. Though on single component level, Mean Time Between Failures (MTBF) is used for repairable components and Mean Time To Failure (MTTF) for non-repairable, both are used for the same component on a fleet, with failure data available, as well. The information in this subsection is a combination of [British Ministry of Defense, 2012], [Nelson, 1982], [Tinga, 2013], [Ghosh and Roy, 2009] and [Kumar et al., 2000].

MTBF

The first method is to calculate the MTBF from failure registrations in data. This can be either failure during operation and failures found in an inspection or overhaul (hence the requirements of shop reports in section 2-2-1). Multiple sources use this relatively simple method because failure data is usually readily available and does not (necessarily) require additional data. The MTBF is displayed in eq. (2-1), where t_{tot} is the total number of flight hours for all aircraft of a certain type (during the data set) and N_{fail} is the total number of failures. This is also in accordance with [United States Department Of Defense, 1996], who states that "for a particular interval, the total functional life of a population of an item divided by the total number of failures within the population during the measurement interval."

$$MTBF = \frac{t_{tot}}{N_{fail}} \tag{2-1}$$

Unfortunately the MTBF is of limited use in determining when a particular component is likely to fail, as we have seen in section 2-2-2. It can, however, be used to determine if the current inspection/failure finding interval is still optimal.

One of two relatively simple formulae can be used for interval calculation; the first is known as a Risk-biased formula: FFI is failure finding interval (inspection).

$$FFI = \frac{2 \times M_{TIVE} \times M_{TED}}{M_{MF}} \tag{2-2}$$

where
M_{TED} is the Protected System MTBF
M_{TIVE} is the Protective System MTBF (of a backup function or safety device)
M_{MF} is the Acceptable Risk of Multiple Failure

The acceptable risk $(1 - R)$ is usually 10^{-6} for hidden failures on military aircraft and 10^{-3} for evident failure components so M_{MF} is then 10^6 or 10^3.

The second the the chance of survival at a certain interval. This chance ($P_{survival}$) can be calculated with the aid of MTBF by using equation

$$P_{survival} = e^{\frac{-t}{MTBF}} \tag{2-3}$$

where t is the usage time from install in flight hours or calendar time. This is graphically represented in fig. 2-4.

MTTF

Many literature discusses the use of a Weibull distribution as the most widely used tool to calculate the component MTTF. Where the most important limitation of using MTBF as a measure is that it assumes a constant failure rate, the Weibull method shows the distribution of failure times and the probability that the calculated MTTF is actually true (within 95% confidence bounds for example) [Azevedo, 2014]. An example of such a research within the RNLAF is that of [Roovers and Tinga, 2013], where the Mean Times Between Removals (MTBR) is assumed to represent the MTTF and after cleaning of this dataset, the MTTF is given with 90% probability. The main difference with the MTBF approach is that all failure/removal cases form an individual input for the result whereas MTBF is an average over the entire data set.

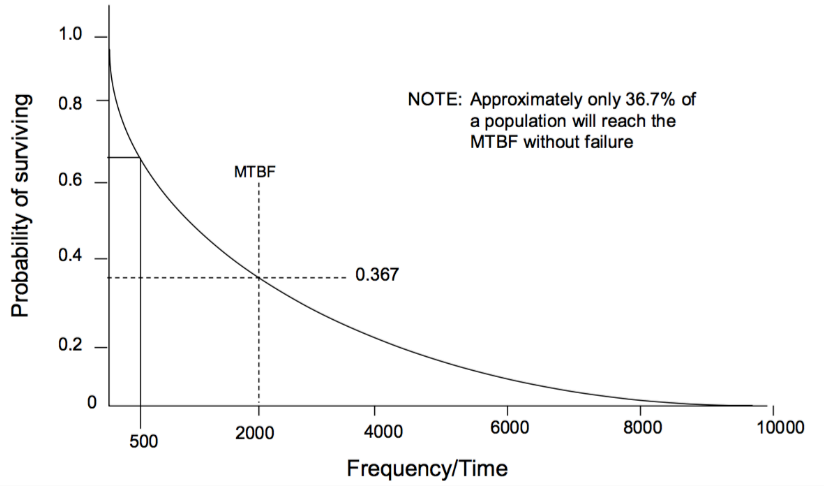


Figure 2-4: Exponential example of an age reliability relationship, from [British Ministry of Defense, 2012]

Weibull

For life data analysis, the most widely used distribution for non-repairables (or as good as new repairs) is the Weibull distribution. According to [Reliasoft corporation, 2014], the Weibull distribution is a general purpose reliability distribution used to model material strength, times-to-failure of electronic and mechanical components, equipment or systems. For the 2-parameter Weibull distribution, the probability density function $f(t)$ and the MTTF are [Nelson, 1982]:

$$\begin{aligned} f(t) &= \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \\ MTTF &= \eta \cdot \Gamma\left(\frac{1}{\beta}-1\right) \end{aligned} \tag{2-4}$$

In eq. (2-4), β is the shape parameter or slope of the graph and η is the scale parameter or characteristic life. When these two variables are known, both the Weibull plot with 95% confidence bounds and the MTTF can be calculated, with the latter making use of the Γ function that is explained in appendix B. This leaves the cumulative density function that is needed for the Weibull graphs:

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2-5}$$

It is clear that in any case the two parameters η and β are necessary for any part of the analysis. These parameters can be estimated from the Weibull plot that is created with the life data from the maintenance database. This procedure is relatively simple but not really accurate and it assumes an known plot line trough the data points. The preferred method for the thesis (Median Rank) is explained in appendix B-2 and can be used for both small datasets that consist of 10 data points for example and for large sets.[3]

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[3] Method is a combination of [Nelson, 1982], [Kececioglu, 1993] and [Reliasoft corporation, 2014]

2-2-4 Data censoring

As a set of life data can contain failure, no fault inspections and non-failure data, all these types need to be handled in the analysis. Data where all units under investigation have failed is called complete data, whereas data where some units have not yet failed is right-censored. Finally, interval censored data contains failures that have occurred somewhere between this and the previous inspection. Right censored data can readily be included in the failure records as suspensions but interval censored data needs assumption of a failure time somewhere between the previous an the current inspection time.

2-3 Trends and direction

It is clear that the main trends in choosing maintenance policy lie within the limits of MGS-3 and RCM approaches. Also the assessment of risk after failure is often performed through an FMECA method, which is in line with MSG-3 and also focusses on failure mode analysis. One approach that seems obvious but is not found within this literature list is a root-cause analysis. This is the translation of a failure trend [4] into using engineering knowledge to find the cause and eliminate this cause by changing it's maintenance policy or -interval. A part of the method should therefore be in line with MSG-3/FMECA but should leave room for root-cause engineering judgement.

In determining and calculating reliability a great part of the literature uses experience based approaches only, or the results are reviewed with mechanics/engineers knowledge. This is of course the most convenient method because all aviation maintenance companies have some sort of database with maintenance and failure information. A more reliable and accurate method is found in model-based approaches, as we have seen in this report. This can however be incorporated in a complete and general method only in the form of an option that will add extra certainty and insight because model-based wear calculations are very elaborate and are in principle performed by the manufacturer during the design process.

In the found literature, no clear distinction is made between intervals of HT replacement/inspection of individual parts and the 'hard time' intervals of inspections that include multiple different parts and tasks. Explained differently, most sources investigate parts reliability but only few relate this to aircraft reliability or availability and even fewer apply these analyses to inspections. One of the subquestions for this research is therefore how to relate parts reliability to (inspection) intervals and availability.

In terms of novelty, it would be unique to develop and apply a generalized model for AMP or interval alteration in military aviation. Moreover the combination of multiple data sources such as failure data, design data, shop reports and criticality data into a single report that acts as full argumentation for such alterations would be both novel and desirable.

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[4] Some part or set of parts fails very often or vice versa; it scarcely fails.

Chapter 3

Methodology Development

In order to create a method that can be used by Programme Management (PM) to assess the maintenance programmes for all the aircraft, a general business model needs to be established where the procedure is explained in steps so reliability- and optimal interval calculations can be applied next. These models (business and reliability) are explained in this chapter and validated in chapter 4.

3-1 Research approach

In chapter 2 we have seen that there is a general approach to assess a maintenance programme in a Maintenance Review Board (MRB) that mostly uses guidelines such as Maintenance Steering Group guidelines version 3 (MSG-3). Therefore, this will be the central link in the research approach for this thesis. In order to answer the central question, a plan is created wherein the requirements for a reliability report -as the basis for changes in the aircraft maintenance programme- are translated into a methodology that can be adopted by the Royal Netherlands Airforce (RNLAF). The first step therefore is to identify the requirements and how the organization can comply to them. Further, the specific possible solutions directions are compared between the theoretical perspective and from the organization perspective. This generates the set-up for the two models that are created (business and reliability) and validated trough test cases in chapter 4. The test cases offer material for recommendations on further research and introduction of the process into the organization of the RNLAF. In steps, the research approach that is applied during the thesis research is:

1. Identify requirements for R-report contents and interval adaptation
2. Investigate how the organization can comply to the requirements
3. Choose possible solution directions from literature that can be applied within the RNLAF

4. Create business model and calculations model/method to be used by reliability engineers from every aircrafts' PM team together with the MRB.
5. Validate and adjust models
6. Give recommendations for further research and introduction into the organization.

The first step is performed within the literature review and can be found in chapter 2 whereas the steps 2-4 are worked out in this chapter and the final two steps can be found in chapter 4 and chapter 5 respectively.

3-2 Business model

This section will describe the proposed methodology for the RNLAF to adopt the models into the organization and for the contents of a reliability report that could include the advice for interval extension.

3-2-1 Organizational process

Integrating a process within the RNLAF where the cycle for improvements in the maintenance programme is frequently completed, from a situation where mostly just changes from the Original Equipment Manufacturer (OEM) are implemented, requires design and definition of such a cycle. This is performed together with the National Aerospace Center (NLR) and has resulted in a (planned) trial period with dedicated reliability- and system engineers within the teams of PM. Figure 3-1 shows the general plan-do-check-act cycle that is applied for this process. The green Maintenance Planning Document (MPD) part is provided by the OEM and the translation of this MPD to a working version that the Type Certificate Holder (TCH) and operator use is called the Aircraft Maintenance Programme (AMP). The latter can be altered to an improved version by both the OEM and the operator/TCH by completing the cycle.

How this general cycle is integrated within the RNLAF is displayed in fig. 3-2. At the top of the figure the initial AMP is provided through the Military Type Certificate Holder (MTCH) and approved by the Military Aviation Authority (MAA) and then enters the cycle where (parts of) the AMP are reviewed to fit the current usage profile, maintenance profile, (experience based) optimal interval and alterations related to often occurring failures. This 'operator MRB-process' will be performed by PM first and then repeated/checked by the MRB that consists of at least: system engineering, maintainer, operator, MTCH and the MAA. For Certification Maintenance Requirements (CMR) and safety critical parts[1] the left loop from fig. 3-2 is followed in order to have the reliability report/advice checked before changes are made while the right loop can be followed for less critical parts that the operator (or in this case PM) is allowed to change.

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[1] These are generally called the chapter 4 parts of the maintenance programme because that is the case for many aircraft types.

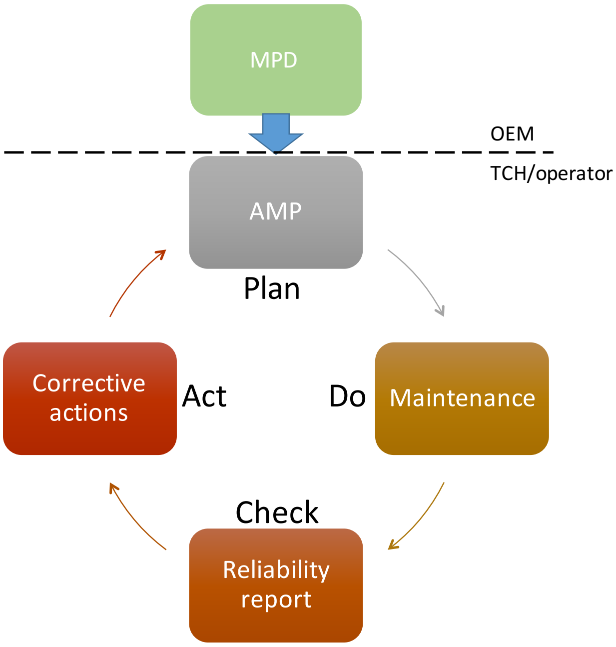

Figure 3-1: General plan-do-check-act circle for the MRB process

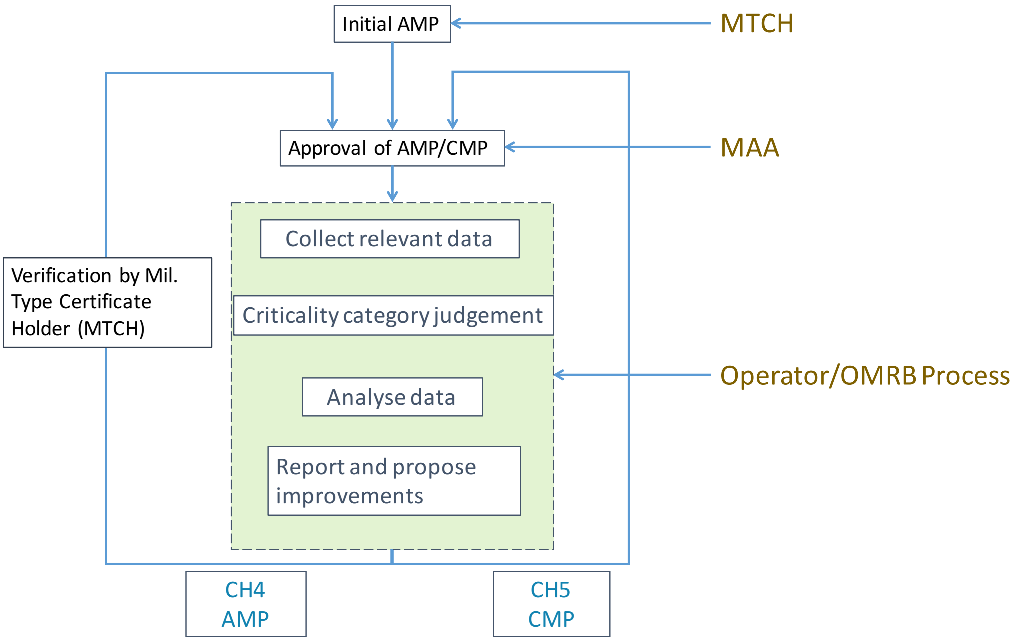

Figure 3-2: Implementation of MRB process into RNLAF organization: two paths can be followed after each operator MRB process, depending on the criticality category of the component. In case of a safety critical item, the left path is followed so the MTCH reviews the MRB advice first.

3-2-2 Proposed procedure for interval advice (MRB process)

The following procedure will be used a guideline for a reliability report contents. There are two slightly different approaches, depending on if the reliability engineer wants to investigate an inspection or a single part(number). Of course, in the latter case the inspection or replacement regime must be known for the part; especially if the part is overhauled at a fixed time interval. Shop reports are then required to complete the report. The following steps should be taken to provide a complete reliability report according to the EASA IP44 [EASA, 2011] and US Army ADS-79 [US Army, 2013] regulations. These steps are explained for RNLAF use only and will be further elaborated on in section 3-3.

1. Give an overview of the component or inspection that is under investigation. What does the inspection include? What are the main components that are inspected and what is their function in the aircraft? Is there a Hard Time (HT) removal schedule for the component(s) and are they discarded, repaired or overhauled after removal?

2. Collect all data including failure data, inspection data, shop reports, material orders and applicable shop manual; see also data requirements. Use can be made of the RAM-tool that is developed with the NLR.

3. Run calculations (NLR RAM-tool) to relate material orders to inspections. In order to be able to calculate how optimal an inspection or replacement interval is in relation to the in-service data from the RNLAF, we need to relate failures that occur both in between intervals and that are found through inspection tot the actual interval. In other words: how many failures have occurred in a specific system or in a group of systems that fall within one inspection and how does this relate to the current interval?

    (a) Investigate inspection: check all 'melding' [2] numbers that relate to that inspection check 'bestellingen' that relate to these numbers check for m2-type 'meldingen' and 'bestellingen' on all the parts that are inspected and check if they are unique for this part of the aircraft combine the two subsets of data.

    (b) Investigate specific part: check all 'meldingen' numbers for this part number or description and check 'bestellingen' that relate to these numbers and pick out those that are for a m4-type 'melding'.

    Alternative method: use mean time between removals as measure for reliabilty analysis. Such a data set needs to be free of records where components are temporarily removed or removed to install on another aircraft. This takes some time to perform but has the advantage that removals during inspections are registered as well, yet the disadvantage that on-aircraft repairs are not registered.

4. Use engineering judgement from mechanics and the (local) engineering departments to ensure that the tasks/parts within the inspection are not performed/inspected elsewhere in the maintenance programme and the part itself is not inspected or repaired through another unregistered method.

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[2] 'Melding' is a data record and 'bestelling' is a material order; these terms are explained in section 3-3

5. MTBF can be calculated simply by dividing the total number of flight hours that are flown during the data set period by the number of failures + the number of replacements during inspection (which are also failures in essence). This assumes a constant failure rate that needs to be made feasible with some of the following arguments:
    (a) Different scenarios/flight regimes do not directly lead to different wear of the part.
    (b) Parts are replaced preventively so no part reaches the wear-out phase of it's lifetime.
    (c) No 'child-deceases' are applicable to the parts because they are thoroughly tested are used throughout the world.
6. Perform a Weibull analysis where all failure times or all times between failures form the data points are examined. If a high probability is achieved for the MTBF (for example 80% or higher [EASA, 2011]), this MTBF/MTBR value can be accepted with certainty. Even more accurate is to use the least favorable 95% confidence bound. More information about these calculations is explained in the calculations model in section 3-3.
7. If the MTBF/MTBR is far greater (times 2 or higher for example) than the inspection or replacement interval, the advice can be to stretch the interval to a convenient new interval. In the case of an inspection it might be added to another inspection or a (sub)inspection can have a separate interval. Some possibilities are schematically represented in fig. 3-6, displayed later on in section 3-4.
8. A review needs to be presented of the usage spectrum that the incorporated aircraft have experienced during the time of the data set. If clear exceptions can be seen, these data entries need to be excluded from the analysis or a 'safety factor' can be applied by the review board to level these results.
9. Assess the criticality of the part(s): this is dependent on evidence of possible failure during flight and during inspection and on how directly the part is linked to flight safety. The MSG-3 approach (see appendix A) is the most common way to perform this assessment.
10. It is important to provide a clear description of the function of the investigated part(s) in relation to the effect of it's failure. Moreover, the possible failure modes/mechanisms need to be stated in the report. If an interval is to be extended it should be made physically feasible that the extended usage does not cause failure or that the failure can be accepted by the operator. The most common failure mechanisms are stated in fig. A-6 (appendix).
11. If all steps are performed, the maintenance review board can decide to approve the proposed changes in the maintenance programme, that of course should be more convenient, economical or safe that the old situation. According to the company process model, the next step is to provide the approved report to the Military Aviation Authorities for formal approval. Figure A-5 (appendix) shows a flow diagram that the reliability engineer can use for part-based investigation input in the advice for this final step.

3-3 Reliability model

This section describes the maintenance data appearance and -handling that is needed for the calculation/reliability parts of of the business model. First, the data appearance within the RNLAF is described, followed by the manual calculations sequence that is used in chapter 4 to create the input and output for this part of the model.

3-3-1 Maintenance data appearance

Both the current and the legacy maintenance databases of the RNLAF work with a preventive maintenance schedule that contains the inspections and maintenance actions that are required over time for a specific aircraft [United States Airforce, 2009]. This schedule generates records that mechanics automatically receive and have to perform to maintain the airworthiness of the aircraft. Some of these records are triggered through calendar time and some through flight hours.

When a mechanic starts his maintenance task, he creates a work-chart on which he describes the actions taken, the materials used and on which he can order parts. Notions have to be made each time a part is removed or installed from an aircraft and also if a failure is found during inspection. When the order is done, the record is set to ’zero’ and the timer starts counting for the next interval. It is also possible that an component fails during service and needs to be repaired or replaced. In this case the mechanic needs to create a failure record as well, that also needs creation of a work-chart when the task is performed. This process of interaction with the maintenance database is displayed in fig. 3-3.

In practice, there is no connection built in the database that relates failure to the inspection/maintenance regime. Moreover, mechanics often do not create a separate failure record (dashed line) when this failure is found during a regular inspection so this is often not visible directly. Of course, if a new part is ordered on the records of the (preventive) inspection task (or when a removal took place during inspection in the alternative approach), we may assume that the old part has failed so this coupling also needs to be created manually.

The standard method from the current maintenance database (SAP) requires the following steps, in relation the the required steps from section 2-2-1:

1. From M4 detailed information
    (a) Check M4 for related M1/M2 records and check the M4 text.
    (b) Are there M1/M2 records related to the M4 record, are there parts ordered during the inspection (M4) and are there parts removed/installed from the aircraft?
2. Collect all M1/M2 data from the related parts/equipments and inspections
3. Conduct MSG-3 analysis to find the failure effect category
4. Collect shop reports for components that require overhaul (as a result of inspection).
5. Assure current interval from preventive maintenance plan (PO-plan).

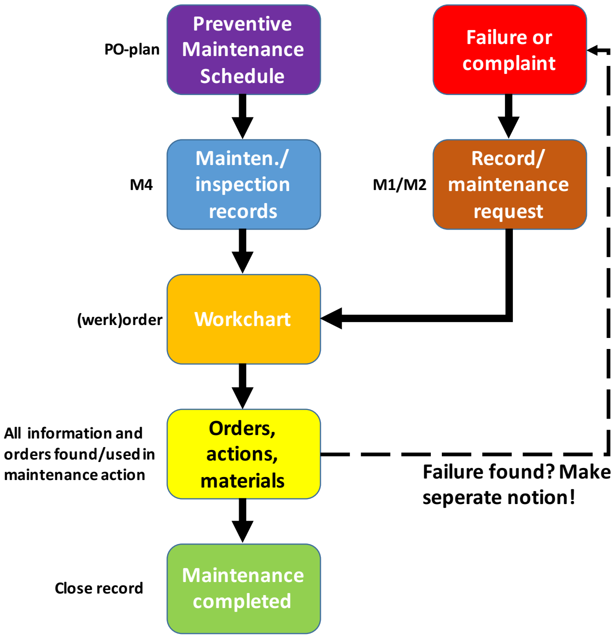

Figure 3-3: Schematic representation of data creation flow within the RNLAF maintenance database. Note the dashed line that represents the making of a separate record when a failure is found during inspection.

6. Look into 'functieplaats' in the data set and assure that the correct and precise ATA code relates to the inspection (parts).

When the combination of the legacy database (IMDS) and the current database (SAP) is used, a more general sequence of data cleaning and combining needs to be conducted. This relatively complex method is planned to be integrated in the RAM-tool that the NLR is developing for PM. However, the next subsection describes the manual sequence that is performed in chapter 4 as a validation of this method.

3-3-2 Manual calculations sequence

We have seen that two approaches are possible to use as data source; for the more simple MTBF calculations, the number of flight hours can be divided by the number of failures and for the more precise but time consuming MTBR the removals list needs to be cleaned up and can then be used for a Weibull analysis. Both approaches can be used in steps 5-7 of the MRB process from section 3-2-2 and even provide a more accurate result when combined. Therefore, both approaches were explained in the literature review and the application of (a combination of) this theory is shown in table 3-1.

When using the more elaborate and precise Installs/Removals (I/R) method, i.e. with the Mean Times Between Removals (MTBR) as data input, the schedule in fig. 3-4 needs to be followed. This schedule aims at generalizing the procedure for all different appearances of the data set. At the end, a number is acquired for the type of entry (row) that relates to the numbers in the next enumeration. This process is planned to be automated in the NLR

Table 3-1: There are two different methods to calculate the mean failure times with data from the current maintenance database, depending on which data is available and how precise the information from the results needs to be.

	MTBR with installs/removals	**MTBF with failure records and orders**
Data needed	Removals/Installs of part/equipment number	Failure records, preferable with parts' flight hours, parts orders
Data handling	Sort by serial number, Remove transfers to other aircraft, Remove parts that are still installed	Combine failure notifications with components order list, delete false or double entries, delete records that are not related to corrective or preventive maintenance (M2,M4)
Calculations	Substract flight hours at each removal with flight hours at installation for all serial numbers; this is MTTF data for Weibull analysis	Total number of flight hours divided by number of unique failures.
Results	MTTF division with probabililty and 95% confidence interval	MTBF of total serial number population together
Remarks	Clean dataset is more important here, not applicable for parts without flight hours counter	Assumes constant failure rate no possibility to exclude extremes. Records without components orders can be added.

RAM-tool but will be used for the manual calculation in this thesis report as well. This categorization leaves a clean and usable data set. The numbers in the next enumeration refer to the circled numbers in fig. 3-4.

1. This case represents a clear data entry that can be used as failure data directly by subtracting the component flight hours at installation from that at removal.
2. Clearly some entries are missing here because the removal is from another aircraft than the installation. Experience teaches that installations are sometimes not registered correctly but removals due to a failed component are always correctly registered because no new component could be ordered otherwise. This installations' flight hours can be subtracted from that of the removal that is related to failure.
3. If the component flight hours are the same for both installations entries, one entry is double. Otherwise, only the second installation entry can be used.
4. Again, if two installations follow, but on an different aircraft, only the second installation can be used for the analysis.
5. When a removal entry is not preceded by an installation but by another removal, the assumption can be made that an installation entry should have preceded. Both removals can be used for the analysis. This may be the case for repairable components for example.

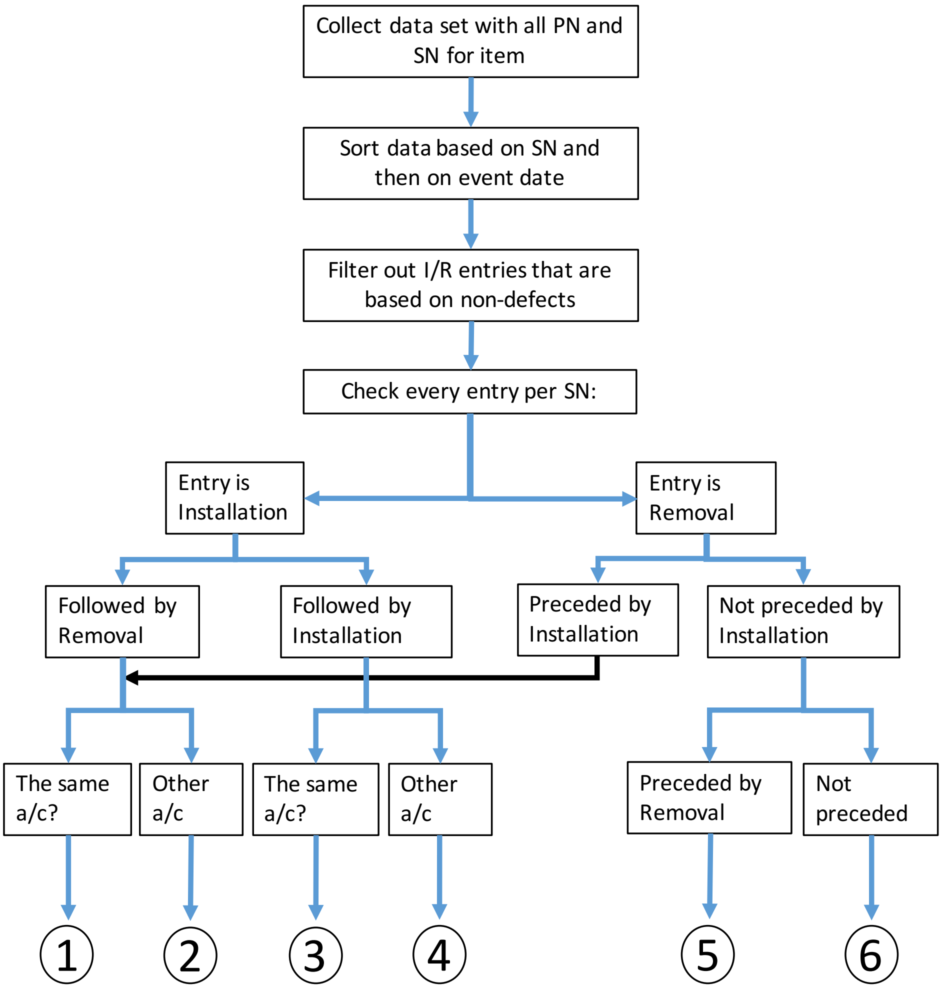

Figure 3-4: Data cleaning and handling process per entry/row of I/R of sorted data per serial number (SN) and date. The numbers 1-6 correspond to the enumeration that precedes this figure.

6. If no entry precedes the removal entry, engineering judgement is needed to assess whether the component has been installed on the aircraft since new (zero hours). These data can be added to the other failure data in a separate analysis.

Finally, a Weibull analysis can be performed with the failure data. The other data and the remaining information concerning failure cause for example, should be stored separately. A Weibull analysis is planned to be built into the RAM-tool but a simple and proven tool can be used as well (the latter is used for the test cases).

3-4 Input and output of models

3-4-1 Input/troughput

As the proposed business model implies, there is a variety of input data required for the reliability report, depending on the type of component or inspection that is under investigation. It is clear from fig. 3-5 that maintenance-, operational- and logistic data can be handled [3] to the correct format by the NLR RAM-tool to serve as input data for analyses within the reliability report such as Mean Time Between Failures (MTBF), Weibull and trend calculations. All this data needs to be analyzed by the reliability-/system engineers as a part of the MRB. Trends, availability, costs, material orders and occurrences are direct given data, as well as design data (though this requires interpretation). The other items on the list of fig. 3-5 need to be visualized or calculated with the method that was described in section 3-3.

3-4-2 Output

The different outcomes of a reliability report depend on what the initial goal was to start the analysis. If the goal was to extend an interval for example, fig. 3-6 shows some possibilities for what the advice/conclusion can be at the end. Another example is if an increasing failure trend is observed, the reliability engineer can propose a modification or root-cause analysis. In any case, the proposed method in this chapter serves as both the company procedure and the tool to accomplish the desired result, in accordance with (military) aviation regulations. A summary of the possible cases will be explained later in table 4-3.

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[3] This is planned to have been implemented by June 2016

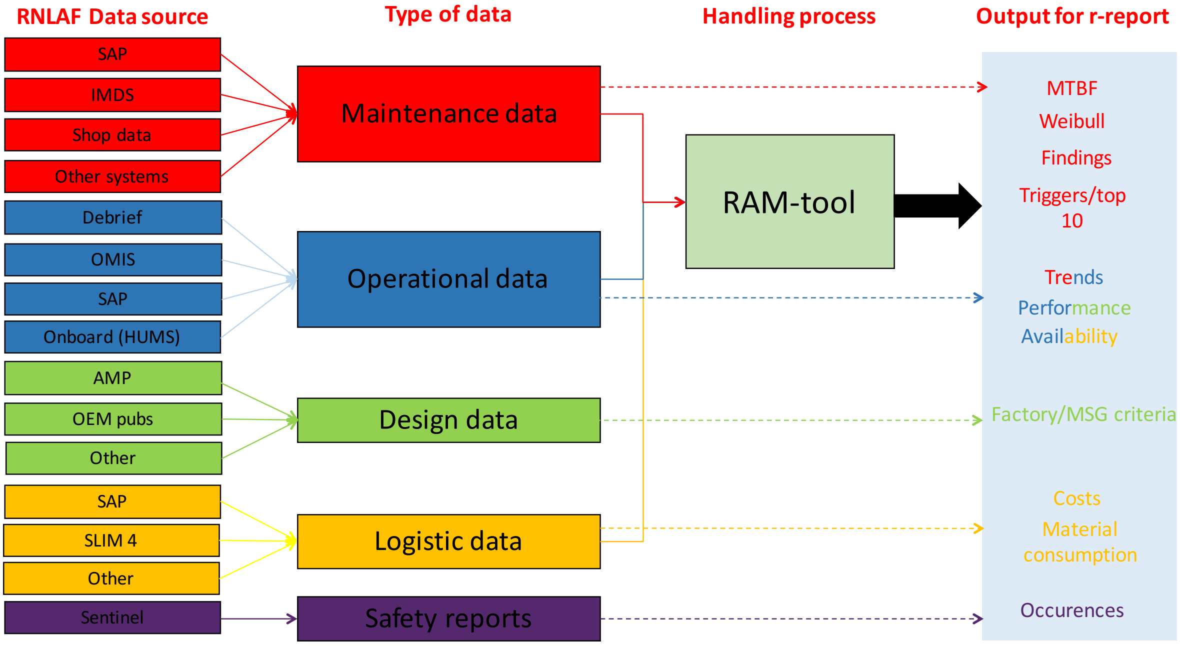

Figure 3-5: Dataflows for the RNLAF. From left to right are the different databases, the type of data that they generate, how this data is handled (dashed line depicts a more or less direct input for the r-report) and the actual input that can be used in a MRB reliability report.

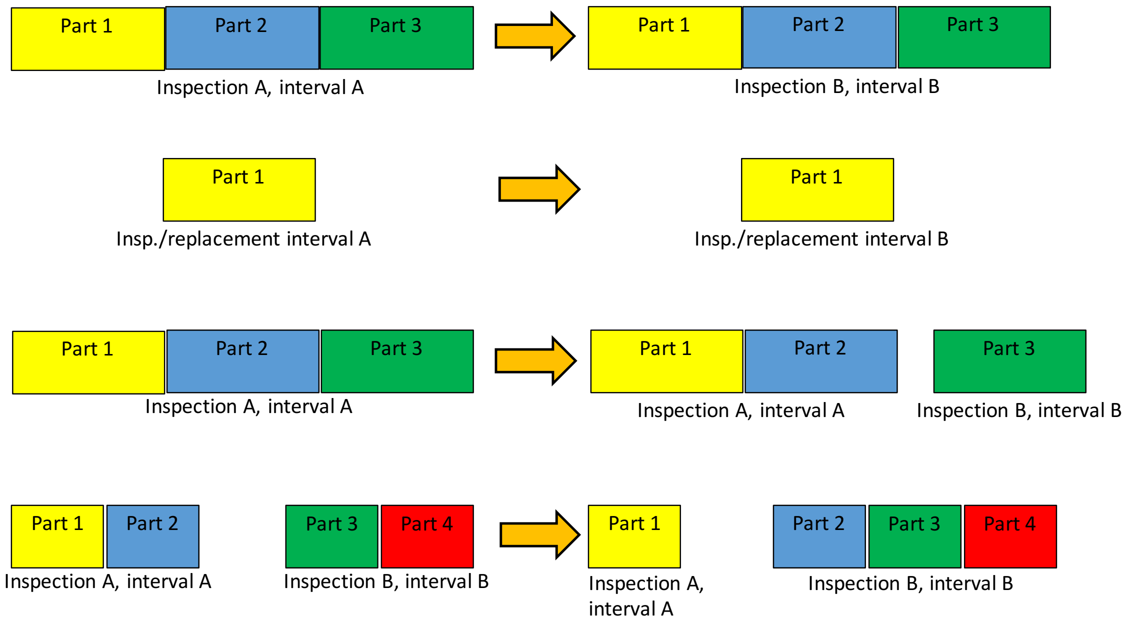

Figure 3-6: Schematic possibilities of transition from the old to a new situation/inspection protocol.

Chapter 4

Results

4-1 Results of manual testcases

The testcases are performed with inspections or parts that maintenance planners from the Royal Netherlands Airforce (RNLAF) have suggested to be of interest for a Maintenance Review Board (MRB).

4-1-1 Testcase lead lag link with teflon sleeve bearing AH-64

The first testcase concerns the lead-lag link hinge from a AH-64D Apache helicopter. An example of this link with its teflon sleeve bearing can be found in fig. 4-1. According to the maintenance planners, these links are often found intact at inspection so it may be possible that this interval is to short. To investigate this, the steps for the reliability report are performed.

1. In essence, these bearings are inspected every 125 flight hours because excessive wear could mean malfunction of the rotor which is critical for safety. The inspection of the lead-lag links encompasses the links (hinge pin), the bearing and the bushing that holds the hinge (of all four rotor blades). The former is inspected both visually and by non-destructive testing by a specialist and can be repaired if it is scratched within certain limits but discarded if the damage it too severe. The bearings have to be replaced if they are damaged (have failed); even if only the teflon liner is dented or worn. The same accounts for the bushing. Together these components form the hinge that makes blade motion possible in the direction of rotation so that flapping of one blade, and thus causing lead or lag in relation to the other blades as a side effect, does not cause severe vibrations that would occur if this was rigid instead of hinged.
2. The data that is collected for this case consists of all failure notifications and component orders that are related to the lead-lag link or the bearing that holds it and of all the

(a) The big bolt is the lead-lag hinge

(b) An example teflon sleeve bearing

Figure 4-1: The picture on the left shows the main rotorhead with the lead-lag hinge clearly visible. The right image is an example of a teflon sleeve bearing that is inspected every 125 flight hours.

Installs/Removals (I/R) data with the associated component flight hours[1]. The legacy database IMDS and the current database combine a total of 129 confirmed failure notifications and 37 material orders (during inspections) that leave 160 data entries to calculate the Mean Time Between Failures (MTBF). Separately, 150 removal/install entries can be related to the lead-lag link, of which 125 failures and 26 suspensions/censored. Finally, every serial number (so every individual link) provides 3 no-fault-found data entries on average, so this can be taken into account as well.

3. The inspection is for the entire link, including bearing, pin and sleeve all component orders and replacements and these items are combined in the data set, though a distinction will be made in step 10 between the different failure mechanisms. In steps 5 and 6 we will calculate the MTBF (and its distribution) with the two different approaches: I/R with components flight hours gives the Mean Time To Failure (MTTF) with a Weibull distribution and failure data/components orders gives an MTBF. In both cases, failed items that are found during inspection are included in the analysis; which is necessary because it is anticipated that most failure are discovered thought inspection. We can already see that the model from fig. 3-4 is not designed to cope with no-fault-found inspection removals and installs. This can easily be overcome by changing the filter that eliminated the no-failure entries after the failure analysis and include them afterwards.

4. This part of the rotor is inspected every 125 flight hours but a non-elaborate visual inspection is performed after every flight. This does not reveal faults in the bearings or in the link pin itself but it provides an overal view on the condition of the joint.

5. The MTBF is calculated by adding the failures and the times that components are ordered and dividing the total amount of flight hours during the data period. In this

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[1] at this stage there is no method to relate component flight hours to I/R notification in the new maintenance data system 'SAP', so for now only the legacy database is used

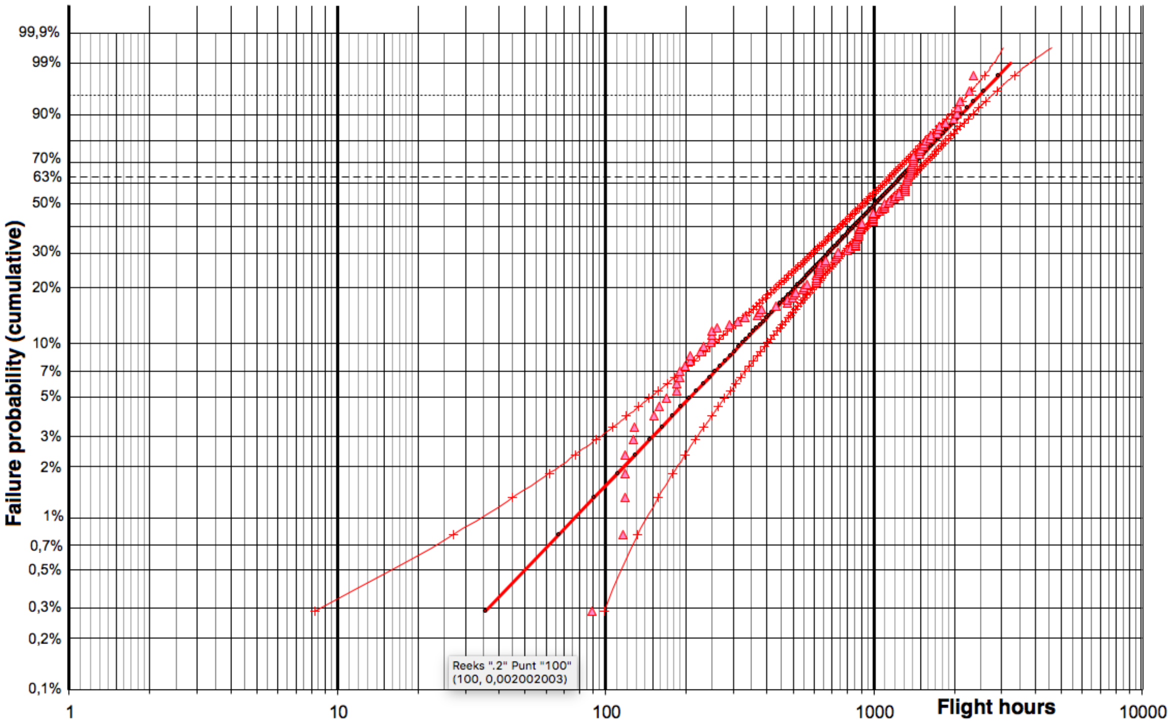

Figure 4-2: Weibull probability plot for AH-64 lead lag links life data, created with the reliability analysis tool of dr. Ross and dr. Tinga. The figure has the failure probability on the y-axis and the flight hours on the x-axis.

case the total amount of flight hours is 45000 so the MTBF is:

$$MTBF = \frac{56000}{160} = 350hrs \tag{4-1}$$

6. The Weibull distribution that comes forth from the I/R data is shown in fig. 4-2. From this we can conclude that the actual Time To Failure (TTF) is $1273 * \Gamma(\frac{1}{1.54} + 1) = 1139 \pm 11$ hours. In this analysis, the information of suspended/censored items, i.e. times at which a lead-lag link passes inspection, or is installed on another tail number in working order, is included. Though even without this information the TTF is still 997 hours. The reliability functions are:

$$\begin{aligned} R_1(t) &= e^{-\left(\frac{t}{1273}\right)^{1.64}} \\ R_2(t) &= e^{-\left(\frac{t}{1124}\right)^{1.51}} \end{aligned} \tag{4-2}$$

Performing this analysis with the (alternative) tool RAP++ from the National Aerospace Center (NLR) using the least squares fit as well, gives a very similar result. From this tool the Weibull parameters are $\eta = 1308$ and $\beta = 1.55$. This tool is also able to apply the method of maximum likelihood estimation, which is not described in this thesis report but can be found in [Nelson, 1982] for example. This gives as parameter result of $\eta = 1272$ and $\beta = 1.61$. Graphs from the RAP++ tool can be found in appendix A.

7. We can see that the MTBF is far greater than the inspection interval of 125 flight hours. However, at 125 hours many more components are inspected and (preventively) removing the rotor blades is more convenient when it is needed for other components as well. Therefore a viable opportunity is to separate this inspection from the rest of the 125 hours tasks and add it to the 250- or 500 hrs package or to look more closely to all other 125 hrs items and their failure behavior and design criteria.

8. Because the time span of available data is over a long period, all kinds of missions have been executed and no clear exceptions can be identified. Also, no clear difference in failure can be seen in periods where the Apache was on missions such as Afghanistan or Mali.

9. As the first level of the Maintenance Steering Group (MSG) schedule (see appendix A) leads to a hidden functional failure with safety effects because failure does not become visible to the crew during normal duties, except for when the link is severely damaged, but this does not change te category. In category 8, all questions from level 2 need to be answered and both the operational/visual check and inspection are applicable so this is performed correctly according to MSG-3. The operational check is during the rotor track-and-balance after maintenance at the rotorhead and during each daily inspection and the inspection is now every 125hrs. Though the Apache was not built (entirely) with MSG-3, the tasks that comply the inspection do in fact make the lead-lag link a candidate Certification Maintenance Requirements (CMR) item and changes in the inspection would take the left (H4) loop of fig. 3-2.

10. The lead-lag link is the central hinge pin that connects the rotor blades to the rotorhead. In the most severe case that it would break, the entire helicopter would fail. The most likely failure causes are sand and dust that come in to the bearings or on the link pin itself, corrosion of the bearing and the bushing and wear of the bearing that causes scratches on/in the link pin. The lead-lag link is therefore replaced due to the causes in table 4-1. Weibull plots that separate the different causes can be found in fig. A-7 (appendix). The table shows that for all the causes, the associated η, and thus the TTF differs only 100 hours from the combined data set without suspensions [2]; this implies

Table 4-1: Failure causes of lead-lag link from AH-64 Apache

Failure due to:	**# entries**	**Percentage of total**	β	η
Teflon bearing/liner worn	47	37%	1,59	1375
Bushing scratched or damaged	33	27%	1,80	1114
Link damaged (scratch/internal)	33	27%	1,47	1223
Corrosion on link	8	7%	1,82	1103
Unknown or no narrative	4	2%	-	-

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[2] The split data sets do not include components that have not yet failed because no failure cause is know

that combining failure mechanisms is allowed for analysis of the interval. The most common cause of failures is actually also the one with the largest TTF.

11. The data shows three mayor failure causes that generate a total of 125 failures with a MTBF/MTTF that are respectively 3 or 10 times larger than the inspection interval. Together with the fact that all failure causes are an important part of the inspection and 94% of the failures are noticed during the 125hrs inspection while no failures are known to have affected the flight(safety), this would provide sufficient argumentation for extension of the inspection interval. This is based on a combination of the theory, required elements for regulations and best engineering judgement. Another possibility arrises from the notion that most of the TTF entries are between 900-1200 hrs which could imply that it could be more efficient and effective to skip some inspections before 1000 hours or start the 125 regime only at 500 hours.

4-1-2 Testcase utility hydraulic pump CH-47

The second testcase concerns the hydraulic pump of the CH-47 Chinook helicopter. This item is only tested superficially during the 400 hrs phase inspection but has no fixed interval that can be adjusted though it does in fact fail regularly, so a reliability analysis can be used to assess the possibilities to cope with this component.

1. The hydraulic pumps are an essential part of the control system of the helicopter. Hydraulic pressure is needed to power the flight controls, start the engines, apply the brakes, control the ramp and many other tasks. Therefore, a set of four pumps is spread over the aircraft and is divided into flight and utility. One of the four pumps is different from the others because it is attached to the auxiliary power unit (APU), two are attached to the gearboxes of the front and aft rotors and one to the engine gearbox. This creates a redundant system, even when both engines fail. The pumps contain valves that control the flow of hydraulic fluid and have several other internal parts that can not be inspected other than in a shop, where the pumps can be overhauled.

2. Like the lead-lag link in section 4-1-1, the data consists of failure data and material orders for the global MTBF calculations and I/R for the Weibull analysis. The number of failures of the two databases combined is 49, with a total of 41 material orders to combine a failures dataset of 53 entries over 46000 flight hours. Separately, 38 I/R entries are found (in legacy system) that relate to failures. As no inspection protocol is applicable, no inspection findings are available. Also, no shop findings can be found at this stage.

3. No additional calculations are needed because only one (blackbox) item is under investigation so only a single part number is reviewed on failure data and material orders. The MTBF and its distributions are calculated in steps 5 and 6.

4. No inspection is applied to this item. Only during the 400hrs phase inspection, the pumps are removed for visual inspection. Failure of the pump can (indirectly) be seen in the cockpit or on the maintenance panel in the cabin; see step 9.

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then; hence the comparison with the uncensored set.

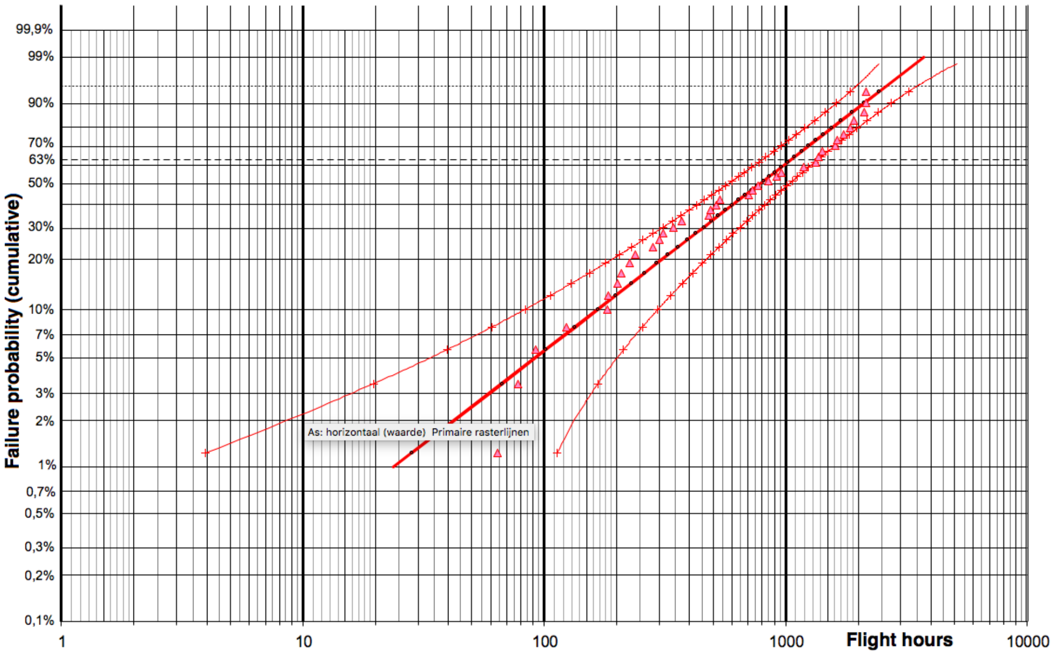

Figure 4-3: Weibull probability plot for CH-47 hydraulic pumps life data, with data entries that contain an initial install flight hours counter. The figure has the failure probability on the y-axis and the flight hours on the x-axis.

5. The MTBF is calculated by adding the failures and the times that the component is ordered during (phase) inspection, divided by the total number of flight hours of the data period. As the total flight hours add up to 47000, the MTBF is:

$$MTBF = \frac{47000}{53} = 887 \tag{4-3}$$

6. Again, the Weibull distribution from the I/R data shows a different result, see fig. 4-3. From this we can conclude that the TTF is $1059 * \Gamma(\frac{1}{1.23} + 1) = 993 \pm 19$ hours with the data where no installation flight hours are present, so zero hours is assumed. Without this data, the TTF is $1158 * \Gamma(\frac{1}{1.27} + 1) = 1054 \pm 21$ hours. The reliability functions to time (flight hrs) is:

$$\begin{aligned} R_1(t) &= e^{-\left(\frac{t}{1059}\right)^{1.23}} \\ R_2(t) &= e^{-\left(\frac{t}{1158}\right)^{1.27}} \end{aligned} \tag{4-4}$$

   Performing this analysis with the tool RAP++ from the NLR using the least squares fit as well, gives comparable result. From this tool the Weibull parameters are $\eta = 915$ and $\beta = 1.14$. This tool is also able to apply the method of maximum likelihood estimation, which is not described in this thesis report but can be found in [Nelson, 1982] for example. This gives as parameter result of $\eta = 914$ and $\beta = 1.22$. Graphs from the RAP++ tool can be found in appendix A.

7. As there is no clear inspection/replacement interval, even the 400hrs phase inspection seems 'too early' to inspect or preventively overhaul the pump. However, it can be

economical of effective to preventively replace/overhaul the pumps (Hard Time (HT)), at 400 hrs or 800 hrs for example, so unscheduled downtime can be reduced. Moreover, with a value > 1 for β, the pumps are in fact a candidate for preventive maintenance, as this means the failure rate is not constant.

8. The pumps have to generate a constant pressure in the hydraulic system so differences in usage do not directly lead to different failure behavior. However, both start-stop cycles and 'aggressive' use of flight controls can result in accelerated wear of the pumps. This can unfortunately not be related to a certain period in the data or to a specific type of missions at this time.

9. Failure of a hydraulic pump is an evident functional failure with safety and/or operational effects. This leaves us in MSG level 2 at category 5 or 6/7. Category 5 implicates that 'the functional failure or damage resulting from the failure has a direct adverse effect on operating safety'. Though this is true in a sense that failure of one pump causes (extra) wear on the backup system so a direct effect on operating safety is possible, the backup is, in fact, there to ensure operating safety when one pump fails. As failure of a pump does have an adverse effect op operating capability because return to base is required, category 6 is applicable in this case, implying 'operational effects with a task desirable if it reduces risk to an acceptable level'. As a functional check is performed before and during every flight, restoration/discard are the only possible tasks for this item; which is in fact the case (as it is overhauled). It would, however be economical/effective to do this at a (fixed) interval, because no other checks or inspections are possible.

10. The hydraulic pump is a redundant system with two pumps for flight and two for utility pressure. As seen in step 9, the failure of a pump becomes visible in the cockpit and the utility pumps can even be viewed from the cabin. The most severe case would be total failure of both pumps in a system, which would result in an uncontrollable helicopter. Also, if one pump fails, the other has to take over and generate the total pressure on its own. This would mean enhanced wear for the remaining pump, so returning to the (nearest) airfield is mandatory and the aircraft is not allowed to depart before the failed pump is replaced.

Table 4-2: Failure triggers for aircrew or maintenance personnel for CH-47 hydraulic pumps.

Failure found through:	**# entries**	**Percentage of total**
Fault or low pressure on panel	16	46%
Noise	10	29%
Oil leak	5	14%
Contamination	4	11%

11. No (clear) maintenance regime is in effect but both the failure rate β and the regular/frequent failures make it effective to apply a scheduled maintenance plan. The value of β also shows that the absence of preventive maintenance is not correct because failure rate is not constant; redesign or preventive replacement may be more efficient and effective. As it is close to the MTTF, the 800 hrs phase inspection is advised as a proper moment

to preventively replace/overhaul the pumps, so that corrective maintenance downtime can be minimized.

4-2 Expansion of results to general approach

In order to expand the results and methodology from the testcases to a general approach, an overview of all possible testcases that the model can handle are given in this section. Further, an estimation is made of the effect that changing intervals, or changing maintenance programmes in general, has on for example availability and safety. Only two test cases were performed during this thesis research but both represent a different starting point as to the (MSG) category and data availability and both have a different outcome. However, both cases also show that the methodology that is introduced is applicable for different types of cases. In section 4-2-1 peculiarities of the two cases will be discussed but in general these cases show applicability for all cases (except structures, see section 4-2-3), because of the common need for data, the common failure analyses, the common reliability analyses and the fact that the method includes all necessary elements according to civil and military regulations; so not only within the RNLAF.

4-2-1 Limitations and assumptions

The actual input, throughput and output data that will be used in all different cases was shown in fig. 3-5. Some comments or remarks on the test cases that are of influence on the expansion to a general approach are given in this section.

Remarks for both cases

- Both cases use I/R data from the legacy database and a combination of I/R, failure notifications and components orders from the current database because of the availability of data (see section 3-3-1). In general, this means that some failures that have no removal as a consequence are not taken into account in the legacy database. Although this does not seem to be an issue for the two test cases, as they can not be repaired on-aircraft, it could mean that some failures are not accounted for in other cases.
- At this point, no shop data was used so no overhaul/repair information is available, that is useful to finalize the report and apply the proposed changes.
- Approximately 15% of the data entries could not be used because some fields were empty, two removals followed without install, or the number of component flight hours was incorrect. Separating this is however a manual action that can not easily be included in a tool.

Remarks for lead-lag link

- It was clear from this case that it is possible to combine different failure causes/mechanisms into a single reliability analysis but this has to be made feasible through separate calculations.

- The 125hrs lead-lag link inspection is a part of the total 125hrs inspection package. Even more effective would be to research the possibilities to alter/extend the total inspection interval but this is left for further application.
- The case concerned an inspection that is performed every 125 hours for a directly flight critical, non redundant and failure-hidden system. The most common failure cause is in a less critical part of the component; the teflon cover of the bearing.
- Both analysis tool have provided very similar (2,7% difference) results, even when using the maximum likelihood estimation techniques.

Remarks for hydraulic pump

- Additional attention has to be paid to the fact that it is also possible for the two pumps in the 'flight' system could have a different replacement interval that the pumps in 'utility' so the failure time of the four pumps does not lie close together.
- Increase in availability must me calculated with a hypothetical Mean Time To Repair (MTTR) because the number of 486 hours that the RAM-tool has calculated is based on the ata-code and therefore only has two entries in the current database where technicians have filled in the ata-code.
- Probably because of β being closer to 1, the difference between the two calculation tools is a little greater than for the lead-lag link case (9% difference). This does not change the conclusion for the pumps because it is still within the range of the 400/800 hours inspection.

4-2-2 Effects of changing maintenance programmes: validation

The goal of a reliability programme is surely to enhance the effectivity and efficiency of the Aircraft Maintenance Programme (AMP) while ensuring the safety of the aircraft. One can imagine that extending maintenance intervals may have a positive effect on the overall availability of the fleet, simply because less maintenance means less downtime and thus more availability. However, it can have a negative effect on the safety or mission capability if the reliability analysis has not been performed correctly. This is why the criticality analysis and the failure effect analysis have to be conducted and approved by the authorities, especially for highly critical items.

The MTTR for the lead-lag link is acquired from both databases as 416 hours; which is (probably) the time for the total 125 hrs inspection, including waiting time for component orders. If the lead-lag link inspection would not take place at the 125 hrs interval, this would mean an average 4,8 days (or 115 hours) reduction of the inspection time because the rotor blades do not have to be dismounted (from maintenance man hours data). If the advice is applied to shift this inspection to be performed only at the 250 hrs intervals, this could result in 460 hours less maintenance downtime every 1000 flight hours. According to equation eq. (B-2) (appendix), the increase in possible inherent availability due to this inspection would be:

$$\Delta A_I = \frac{1139}{1139+301} - \frac{1139}{1139+419} = 6\%$$

with the decrease in reliability as:

$$\Delta R = e^{-\left(\frac{250}{1273}\right)^{1.64}} - e^{-\left(\frac{125}{1273}\right)^{1.64}} = -4,5\%$$

The hydraulic pump has a (hypothetical) MTTR of 468 hours that would mainly result from the duration of a 400 hrs phase inspection. A more realistic estimate is acquired from mechanics as 100 hrs, including waiting time for component orders. In the most beneficial case, this could almost be brought back to zero when no corrective maintenance is required because the pumps are preventively replaced. Let us assume a reduction to 10 hrs. This would give an increase in availability (only due to this component) of

$$\Delta A_I = \frac{1158}{1158+10} - \frac{1158}{1158+100} = 7\%$$

4-2-3 Possibilities for future cases

The possible cases with the associated outputs and remarks are given in table 4-3. However, only interval changes lie within the scope of this thesis. When the other types are investigated in future research or in practice by the reliability engineers, the required input typically stays the same by design of the method that is explained in chapter 3, though the output varies.

Table 4-3: Possible future cases

Case type	Output	Remarks
Large inspection interval	Escalation of interval, split inspection, redesign required	Requires very extensive r-report that contains analyses for all individual components.
Small inspection interval	Escalation of interval, split inspection, redesign required	Generally easier to alter and with short-term visible effect, analyze every single component separately.
Single component interval	New HT or inspection interval for component.	Requires only analysis for component and directly related components.
Redesign/modification of component	Redesign advice to OEM	This is normally the case if extensive or special failure behavior is noticed by the MRB.
Redesign/modification of a structure	Redesign advice to OEM	Has no data input from normal systems but is triggered by maintainer directly.
Addition of components or inspections	Direct change in manuals and/or notification to OEM	In (military) aviation, improvements and new components are frequently added to the configuration. Extra inspection is always allowed but extra components have to be certified.
Change in inspection/overhaul method	New method	Can be a result of inability to find failures during inspection as well as an improvement to do so.

4-3 Implementation within the RNLAF

To implement the methodology and models into the RNLAF, some important steps have already been taken at completion of this thesis. These steps are described in this section, together with a proposed plan for further implementation. Firstly, the validation of the method by experts within the field is explained briefly.

4-3-1 Expert validation

Though the method is based on industry standards and regulations for a great part, it is new within the RNLAF and no actual (military) examples were found of comparable methods. The research is therefore validated through experts in and around the RNLAF. This has been done during the research and has the effect that the MLE-21/design department Defense Material Organization (DMO), the Programme Management (PM) department and the NLR have agreed to use this proposed method as a standard operating procedure for the MRB of the RNLAF.

4-3-2 Steps that are taken

At this point, several steps have been taken towards implementation of the proposed methodology within the RNLAF: The reliability report and its contents are now used as as basis for reliability engineering at all different departments at PM. At each department (per aircraft type), at least one reliability engineer is appointed, as well as a system engineer that is the expert in the field of OEM design analyses. These engineers differ highly in experience with reliability analyses and thus they need the knowledge of this thesis, combined with some specific knowledge to be able to start conducting analyses on their 'own' aircraft type. Therefore, two workshops are planned in april 2016 where the engineers are trained and educated on the required know-how. Finally, the regulations (as well as the knowledge dat AMP alterations are allowed within the RNLAF itself) are planned to be implemented in the Airforce/PM company manuals.

4-3-3 Steps to be taken

An important part of the MRB process is the actual organization of an MRB, including all its members. Without this being present, no alterations can take place and there would be no standard control loop for the effects of the alteration. This needs to be implemented as soon as possible. Because the r-engineers and other members of the MRB are not actively conducting these analyses, no real AMP alteration case has been performed to verify the method in practice. These results are essential to test and modify the method, as well as trend results to assess the effects of alteration. Further, not all of the data sources from fig. 3-5 were used here because the two test cases did not require trend analysis for example, which will be the goal for further implementation. Combination of this variety of data sources is a novelty for the RNLAF in any case and can be an example in other companies/airlines as well.

Chapter 5

Conclusions and recommendations

5-1 Conclusion

5-1-1 Methodology and business approach

The methodology that is applied throughout the research has proven to be a viable combination of existing methods in reliability engineering/Aircraft Maintenance Programme (AMP) adaptation and new ideas that are taylor-made for the Royal Netherlands Airforce (RNLAF). There are some requirements to the contents of a reliability report in order for it to be sufficient as a basis to alter maintenance intervals and other elements in an AMP. These requirements are met through the combination of steps in the proposed content of the r-report.

It is because of the fact that these requirements have to be met so strictly (which is logical and necessary for safety reasons), that the input data -that is readily available- does not always suffice. For example, shop reports provide important knowledge for Hard Time (HT) overhaul or inspection components that is not in the most common RNLAF databases but has to be acquired separately. In both the lead-lag link and the hydraulic pumps testcase, this is in fact information that would complete the report.

5-1-2 Reliability analysis and -advice

In the two testcases, two different changes in the AMP were proposed. The lead-lag link case concerned an inspection that is performed every 125 hours for a directly flight critical, non redundant and failure-hidden system. However, when looking at the failure mechanisms that are inspected, the most common failure cause is in a less critical part of the component. This knowledge, combined with the high Mean Time To Failure (MTTF) relative to the interval, has led to the advice to extend the interval to 250 hrs for example. For the hydraulic pumps, no (clear) maintenance regime was in effect but both the failure rate and the regular failures make it effective to apply a scheduled maintenance plan. As it is close to the MTTF, the 800 hrs phase inspection is advised as a proper moment to preventively replace/overhaul the pumps, so that corrective maintenance downtime can be minimized.

The two tools that were used to verify the results from chapter 4 have provided very similar results when the cases included censored data (of non-failures) but deviated slightly in the case of the hydraulic pump, where only failures are present in the data set and where β is closer to 1.

5-1-3 How can the AMP of the RNLAF aircraft be adjusted to extend maintenance intervals and what will be the effect on reliability and availability?

This report shows the work that has been performed in order to provide the RNLAF with a method that can be used to change a situation where alterations in the AMP are reserved for manufacturers to a situation where the different departments have a role to proactively contribute to optimization of intervals and maintenance policies. This is mainly the effect of the 'business model', in which all required steps are described for AMP alteration and tools are given to execute these steps.

Moreover, a combination of data analysis, failure effect/criticality analysis and reliability calculations define the second part of the method that is needed to assess the optimality of current maintenance policies and -intervals and to calculate the effects of the proposed changes. The combination of these two parts of the models is specific enough for accurate analysis but general enough to be applied to nearly all aircraft parts of all RNLAF aircraft and, because civil demands are incorporated, for civil aviation companies as well.

Therefore, the answer to the central question is simply 'by applying the proposed method', that has proven to work for the two testcases and has been made plausible for all other cases for the RNLAF with the exception of aircraft structures by means of generalization of the model and of the data(base) analysis. The effects on reliability and availability have been quantified for the two test cases but clear guidelines on the limitations are not defined by the RNLAF and are dependent on the criticality and thus different per case. A total summary of the research, with the method where the Maintenance Review Board (MRB) is the central link and where an AMP alteration is the product, can be found in fig. 5-1.

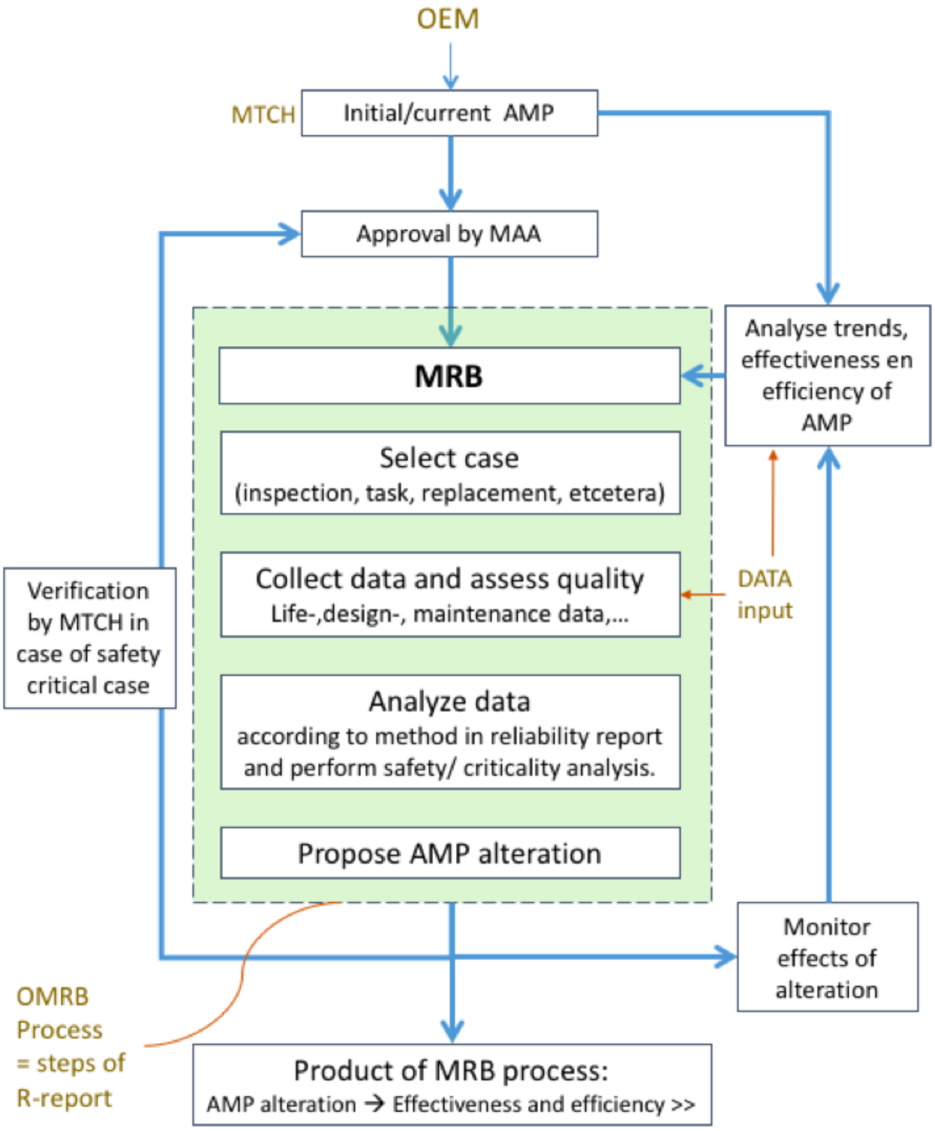

Figure 5-1: The executive summary of the method with the MRB as the central link in continuously analyzing and monitoring the effectiveness an efficiency of the AMP for the different aircraft types. Notice the loop on the left of the figure, where the proposed changes are 'fed back', through verification by the MTCH if needed for safety critical cases, before approval by the MAA. Also notice the loop on the right, that represents the monitoring of the effects of an alteration trough trend analysis; which can be performed with the aid of the NLR RAM-tool for example.

5-2 Discussion

Novelty

The state of the art as described in the literature review is mainly focussed on separate analyses of (series of) components or inspection policies and on RCM/MSG applications on individual cases whereas this model combines all necessary argumentation and calculations into a step-by-step plan, that is conducted by RNLAF employees and effected in the MRB cycle.

The concept of a MRB is not new on itself but the application within an organization that both operates the different types of aircraft and is the type certificate holder seems quite unique in (military) aviation. This is why a general method that prescribes all required steps for AMP alteration, including reliability life data analysis, is a novelty within the field. Elements that could improve or add to this method are described in section 5-4. The last novelty, that is mentioned in section 4-3, is that this method facilitates combination of a possible 15 data sources into a single reliability report. This has great advantages for the RNLAF but can be an example for other airlines as well.

Feasibility

Section 4-2-3 has shows the possible future cases that can be handled with the method that is presented in this thesis report. Additionally, the fact that the method is based on a combination of EASA, USAF, RAF and Dutch military aviation regulations, the general applicability of the method and the theory that is used for reliability calculations anticipate feasibility of the model. Together with the already mentioned limitations, the results from the test cases and the fact that the RNLAF is already implementing a great part of the method, the model seems feasible for an organization such as the RNLAF.

5-3 Recommendations for the RNLAF

Succes factors

As mentioned in section 4-3, many parts of the method have been implemented during this research. However, for the method to succeed, Programme Management (PM) does need to continue educating the reliability engineers and to actually perform an AMP alteration. Before this, the workshops that are planned should result in a test scenario in which all involved engineers from the different aircraft types can get used to their proactive roll in the process. The step from the test scenario to the real case will be crucial and therefore requires guidance from the staff, the National Aerospace Center (NLR) and from a working RAM-tool.

Continued application

Because a change in company procedures is being made in order to fit the new tasks for the reliability engineers and to maintain a frequent gathering of the MRB, all the procedures have to be documented in a handbook or in the standard operating procedures of PM or the RNLAF. Finally, the shop reports for all overhaul/repair components need to be made readily available for the MRB so they can add this information to the r-report.

5-4 Recommendations for further research

There are some parts that are not included in this method and therefore leave room for further research:

1. Though for example [Tinga, 2013] and [Stuivenberg et al., 2013] have researched the link between usage (severity) and required maintenance, there is great potential in adding a full usage spectrum to the reliability report and correlating this with certain maintenance actions or wear patterns. Especially the interpretation of Health and Usage Monitoring System (HUMS) -like systems in this context would be of great added value for critical components.

2. The effect of inspections and repairs is not included specifically in this research. Not only perfect inspections and as-new repairs need to be considered; decline in MTTF after several repairs is usually more realistic. Further research could investigate the effect of inspections/repairs on the MTTF of (a set of) components.

3. More elaborate quantification of the effects of changing intervals on availability could prove the effectiveness of this method even more. Though most of the effects can be observed only after implementation, the RNLAF could benefit from optimization on quantitative availability.

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Appendix A

Additional tables and figures

A-1 Properties of repairable and non repairable components

Table A-1: Properties of repairable and non-repairable components

Properties	Non-repairable	Repairable
Actions after failure	Discard (and replace)	Repair to functional state
State after maintenance	New	As good as new or as good as before
Failure records	Only time of failure is recorded	Time between failures and number of failures are recorded.
Reliability method	MTTF	MTBF
Statistic distribution	TTF with exponential, normal, Weibull	Stochastic Point Process (/data analysis)
Failures per system	One failure per system, so one random variable	Multiple failure per system are possible, thus multiple RV's
Multiple copies of system	Can assumed to have identically distributed failure times	Have different times between failure, dependent on usage and maintenance quality.

A-2 Data example from lead-lag link data

Table A-2: Small fragment of AH-64 lead-lag link data set with columns: Removal/Install, Serial number, flight hours component, event number, event date, event narrative, tail number, flight hours tail number and how-malfunction code.

R/I	S/N	HOURS	EVENT NR	EVENT DATE	EVENT NARRATIVE	TAILN	FLT HRS TAIL NR	DDR HMF
R	0000000202	1733	R031130318	23-04-2003	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ15	379,60	800
I	0000000202	1733	R031130318	23-04-2003	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ15	379,60	800
R	0000000202	1979	J042010277	19-07-2004	P/301SQN 125HRS STRAP PACK OUTB.	APQ04	628,00	799
I	0000000202	1979	J042010277	19-07-2004	P/301SQN 125HRS STRAP PACK OUTB.	APQ04	628,00	799
R	0000000202	2105	R043360133	01-12-2004	I/125H/STRAP PACK OUTB.BOLTS NDO INSP. FREQ 000125 DUE 750.0HR	APQ04	754,60	804
R	0000000202	2105	R043360133	01-12-2004	I/125H/STRAP PACK OUTB.BOLTS NDO INSP. FREQ 000125 DUE 750.0HR	APQ04	754,60	804
R	0000000202	2105	R043360133	01-12-2004	I/125H/STRAP PACK OUTB.BOLTS NDO INSP. FREQ 000125 DUE 750.0HR	APQ04	754,60	804
R	0000000202	2105	R043360133	01-12-2004	I/125H/STRAP PACK OUTB.BOLTS NDO INSP. FREQ 000125 DUE 750.0HR	APQ04	754,60	804
I	0000000202	2105	R043360133	01-12-2004	I/125H/STRAP PACK OUTB.BOLTS NDO INSP. FREQ 000125 DUE 750.0HR	APQ04	754,60	799
I	0000000202	2250	R071860214	05-07-2007	REPLACE ALL 4 CORRODED LEAD LAG LINKS	APQ09	863,20	170
R	0000000202	2751	A100915030	01-04-2010	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ09	1364,10	800
I	0000000202	2751	A100915030	01-04-2010	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ09	1364,10	799
I	0000000202	2751	A100965027	06-04-2010	**** NO NARRATIVE INSERTED ***	APQ09	1364,10	799
R	0000000699	2048	U043340611	29-11-2004	#4 LEADLAG LINK BUSHING WORN.	APQ07	611,50	116
I	0000000713	1676	J080420309	11-02-2008	REMOVE AND REPLACE LEAD-LAG LINK #2 AND #4	APQ30	1376,00	20
R	0000001075	1357	J041370059	16-05-2004	P/301SQN 125HRS STRAP PACK OUTB.	APQ17	624,30	800
I	0000001075	1357	J041370059	16-05-2004	P/301SQN 125HRS STRAP PACK OUTB.	APQ17	624,30	799
R	0000001075	1484	R042600145	16-09-2004	REMOVE LEAD LAG LINK #4 TO FACILITATE OTHER MAINTENANCE	APQ17	751,60	800
I	0000001075	1484	R042600145	16-09-2004	REMOVE LEAD LAG LINK #4 TO FACILITATE OTHER MAINTENANCE	APQ17	751,60	799
R	0000001075	1610	J050650089	06-03-2005	P/301SQN 125HRS STRAP PACK OUTB.	APQ17	877,60	800
R	0000001075	1610	J050650089	06-03-2005	P/301SQN 125HRS STRAP PACK OUTB.	APQ17	877,60	20
R	0000001075	1731	R061040307	14-04-2006	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ26	876,20	804
I	0000001075	1731	R061040307	14-04-2006	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ26	876,20	799
R	0000001075	2096	J080690147	09-03-2008	KS. DURING 250H INSPECTION FOUND WORN BUSHINGS ON 2 LEAD-LAG LIN	APQ24	1236,30	20
I	0000001075	2096	J083450023	10-12-2008	NSPECTION PREPERATION OF AIRCRAFT FOR 270 D STRAPPACK OUTER BOLT NDI I	APQ24	1420,60	425
R	0000001098	2346	R07294B063	21-10-2007	REMOVE CORROSION BY REAMING BUSHINGS IN ALL 4 LEAD-LAG LINKS	APQ17	1496,60	127
I	0000001098	2346	J083450023	10-12-2008	NSPECTION PREPERATION OF AIRCRAFT FOR 270 D STRAPPACK OUTER BOLT NDI I	APQ24	1420,60	425
R	0000001155	1180	A092710005	28-09-2009	**** NO NARRATIVE INSERTED ***	APQ07	1330,10	20
R	0000001236	1499	R023170572	13-11-2002	C/E LEAD LAG LINK FOR APQ20 CANNIBALIZATION FOR UNIT: R JCN 022830074001	APQ13	247,90	799
R	0000001236	1622	R031320044	12-05-2003	P/301SQN 125HRS STRAP PACK OUTB. BOLTS INSP.	APQ20	377,80	799

A-3 MSG decision logic

When (re)designing an Aircraft Maintenance Programme (AMP), the most common method is to use Maintenance Steering Group (MSG) decision logic. For most tasks, the flow diagram from figures fig. A-1 through fig. A-3 suffices. The tasks are then explained in table A-3. In addition to those tasks and intervals established through MSG-3 analysis, scheduled maintenance tasks may arise within the FAR 25.1309 certification process [Air Transport Association, 2007]. These tasks are called Certification Maintenance Requirements (CMR) is a required periodic task, established during the design certification of the airplane as an operating limitation of the type certificate. CMRs are a subset of the tasks identified during the type certification process. CMRs usually result from a formal, numerical analysis conducted to show compliance with catastrophic and hazardous failure conditions. A CMR is intended to detect safety significant latent failures that would, in combination with one or more other specific failures or events, result in a hazardous or catastrophic failure condition. The process that distinguishes CMRs is displayed in fig. A-4. All figures in the section are complementary to the theory from chapter 2, and can be used by the reliability engineer to categorize the components or inspections.

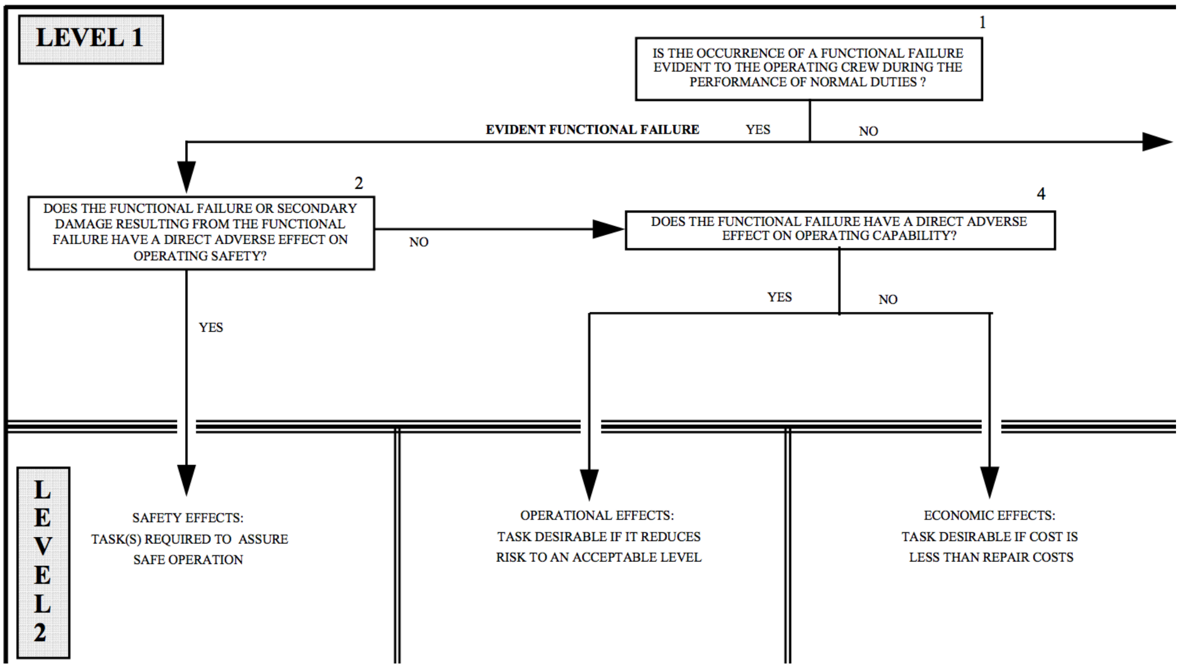


Figure A-1: Left side of MSG3 level 1 decision logic, from [Air Transport Association, 2007]

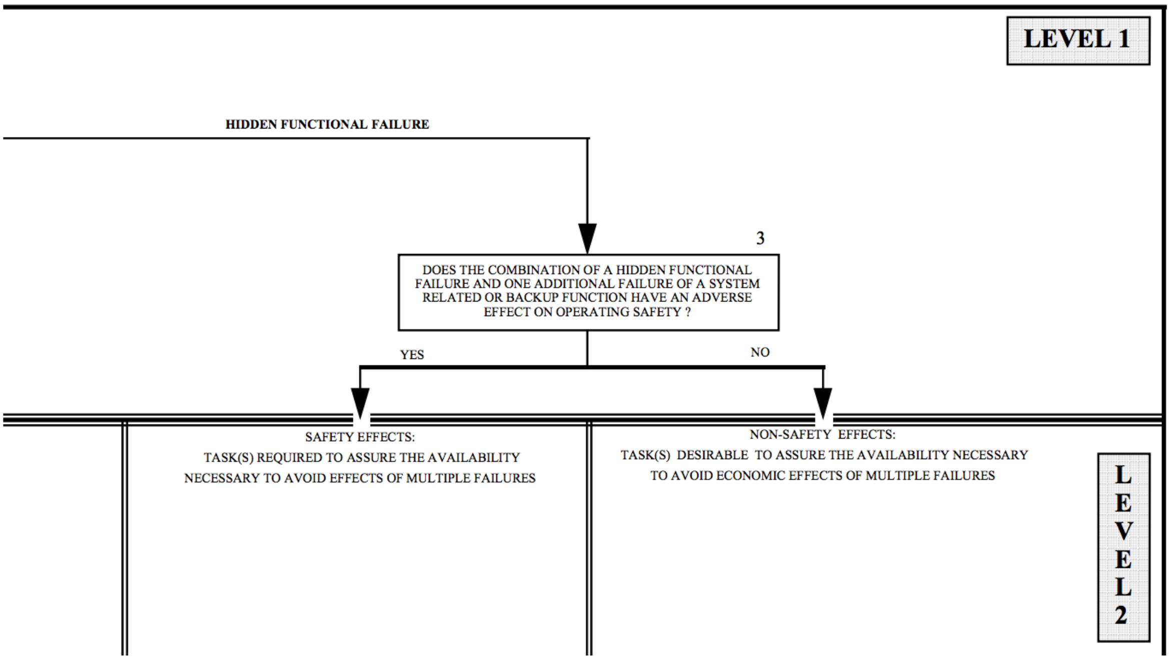


Figure A-2: Right side of MSG3 level 1 decision logic, from [Air Transport Association, 2007]

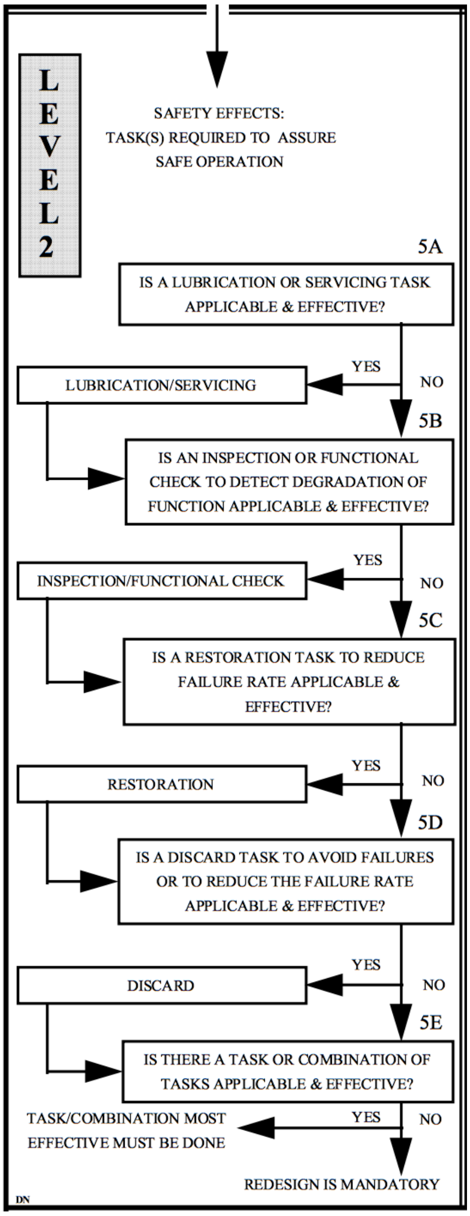


Figure A-3: MSG3 level 2 decision logic, from [Air Transport Association, 2007]

Table A-3: MSG-3 task classification from [Air Transport Association, 2007]

TASK	APPLICABILITY	SAFETY EFFECTIVENESS	OPERATIONAL EFFECTIVENESS	ECONOMIC EFFECTIVENESS
LUBRICATION OR SERVICING	The replenishment of the consumable must reduce the rate of functional deterioration.	The task must reduce the risk of failure.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective.
OPERATIONAL OR VISUAL CHECK	Identification of failure must be possible.	The task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure.	Not applicable.	The task must ensure adequate availability of the hidden function in order to avoid economic effects of multiple failures.
INSPECTION OR FUNCTIONAL CHECK	Reduced resistance to failure must be detectable, and reasonably consistent interval between a deterioration condition and functional failure.	The task must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective; i. e., the cost of the task must be less than the cost of the failure prevented.
RESTORATION	Functional degradation at identifiable age; large proportion of units must survive to that age. It must be possible to restore the item.	The task must reduce the risk of failure.	The task must reduce the risk of failure to an acceptable level.	The task must be cost effective; i.e., the cost of the task must be less than the cost of the failure prevented.
DISCARD	The item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive to that age.	The safe life limit must reduce the risk of failure to assure safe operation.	The task must reduce the risk of failure to an acceptable level.	An economic life limit must be cost effective; i.e., the cost of the task must be less than the cost of the failure prevented.

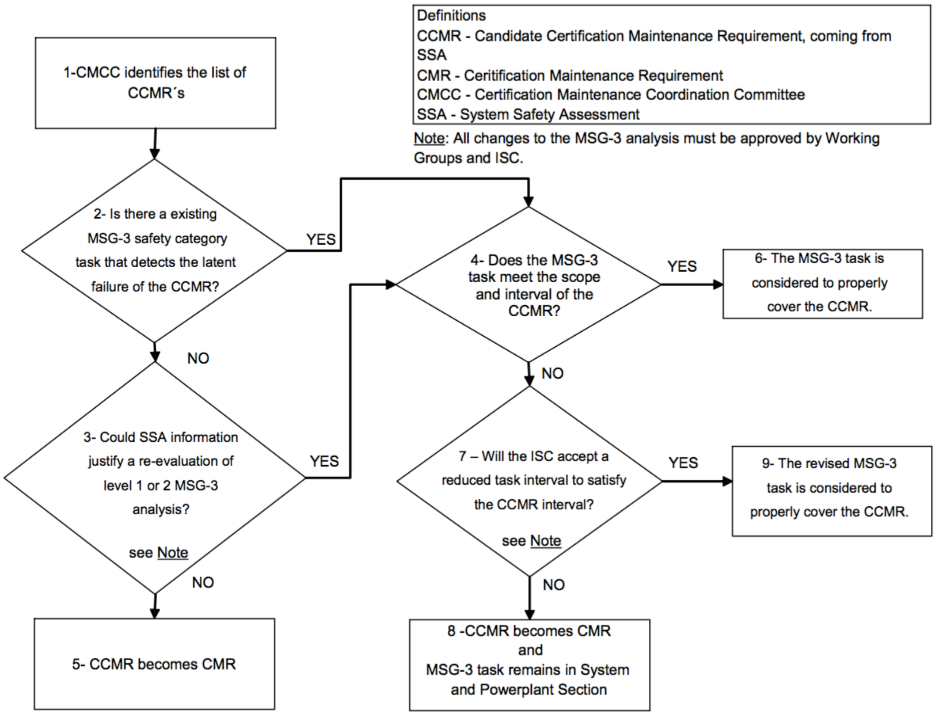


Figure A-4: MSG3 decision logic for CMR's, from [Air Transport Association, 2007]

A-4 Maintenance regimes with R-report categories

Observing the diagram of fig. A-5, we can see the four different maintenance regimes that have been explained in chapter 2 are used to distinguish the types of parts:

1. Hard Time (HT) replacement parts are not inspected or overhauled so only failure data (and failure mode off course) is relevant to assess the interval. There is a step added where the criticality is reviewed. This is required to evaluate the safety effects from failure of the part and it determines how elaborate the argumentation should be for interval extension. The same step is required for the other categories, though not displayed in the figure.

2. The second category encompasses parts that have a hard-time replacement interval as far a the maintainer is concerned, but are overhauled within the Royal Netherlands Airforce (RNLAF) back-shops or at an external party. In this case, shop reports from the overhaul can provide valuable information on hidden failures or components that have wear that is only detected through this overhaul. If the latter is the case, the overhaul interval is on time whereas many failures implicates that the overhaul is too late. Finally, few findings and few failures could mean that the interval could be extended.

3. If the part is under an inspection or Condition Monitoring (CM) regime, where parts are often serviced or even repaired, the inspection findings need to be analyzed together with the failures in between inspections and the material orders during inspection. Again, if most failures are found during inspections, the inspection is conducted on time but

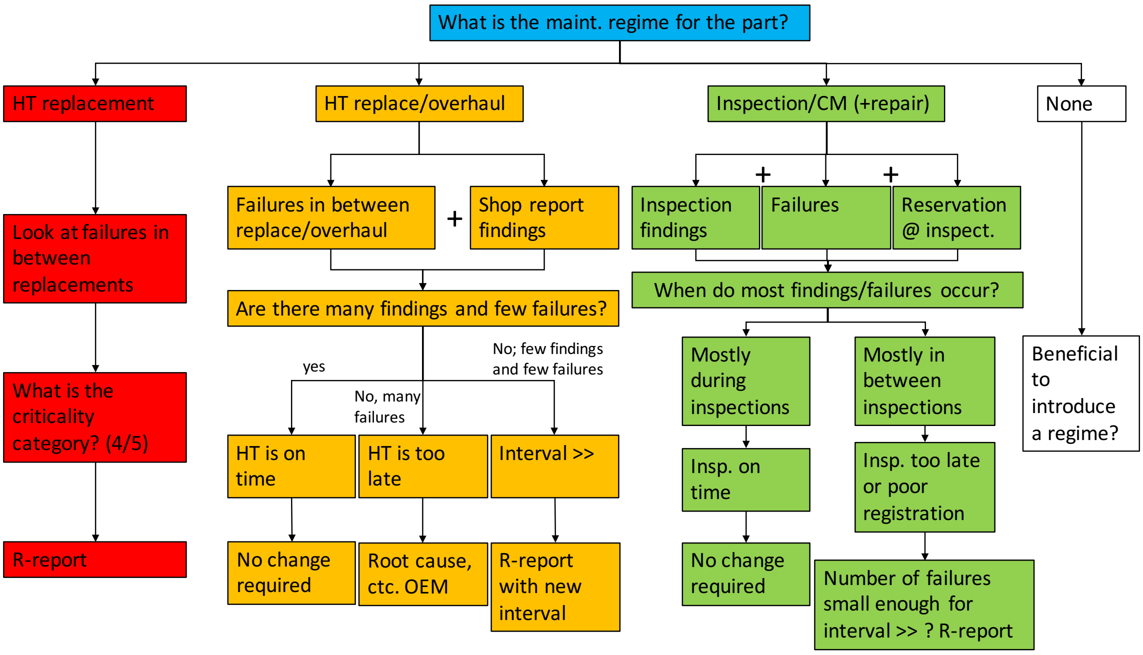


Figure A-5: Flow diagram with distinction between maintenance regimes. Depending on the type of part, a different approach for the reliability report needs to be followed.

if most failures occur during operational periods, the inspection is not timely and the number of failures determines if the interval can become greater of smaller.

4. The final category is parts that are operate-to-failure. If these parts do fail regularly (but not very often) it may be beneficial/economical to apply an inspection (interval) to have a more pro-active method of ordering new or replacement parts.

A-5 Failure mechanisms

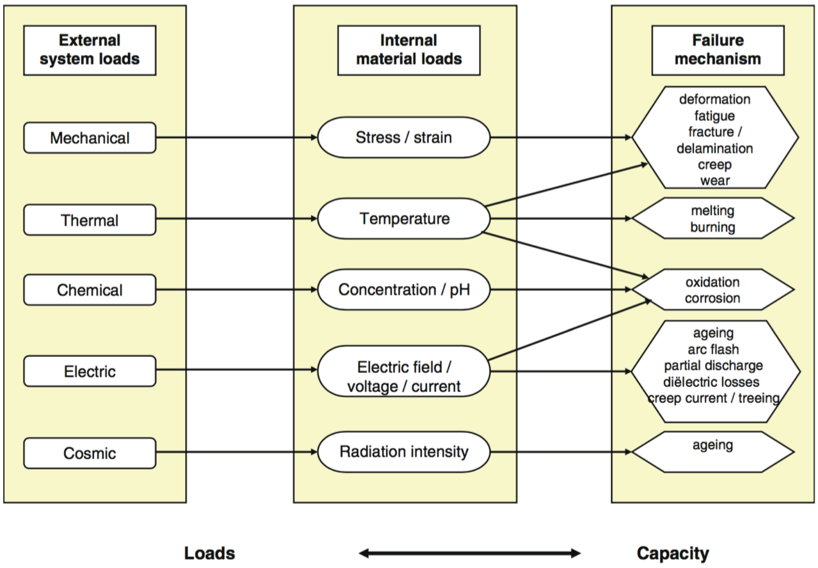
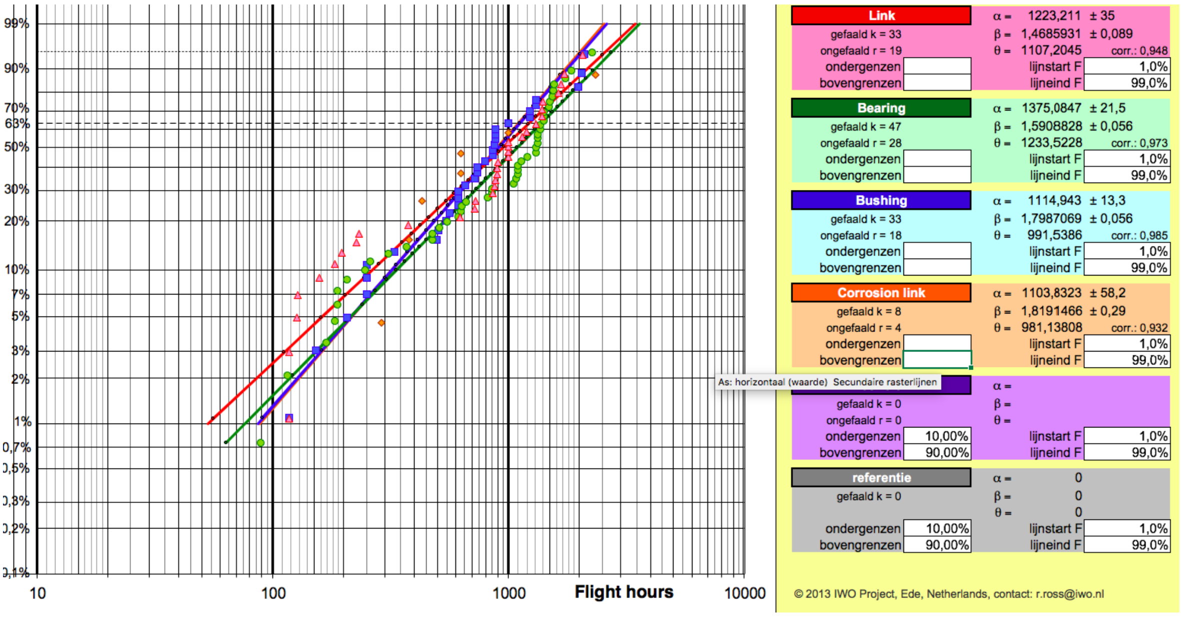


Figure A-6: Failure mechanisms and the external/internal loads they result from; from [Tinga, 2013].

A-6 Additional Weibull plots from chapter 4

.



Link
gefaald k = 33
ongefaald r = 19
ondergenzen
bovengrenzen
α = 1223,211 ± 35
β = 1,4685931 ± 0,089
θ = 1107,2045 corr.: 0,948
lijnstart F 1,0%
lijneind F 99,0%

Bearing
gefaald k = 47
ongefaald r = 28
ondergenzen
bovengrenzen
α = 1375,0847 ± 21,5
β = 1,5908828 ± 0,056
θ = 1233,5228 corr.: 0,973
lijnstart F 1,0%
lijneind F 99,0%

Bushing
gefaald k = 33
ongefaald r = 18
ondergenzen
bovengrenzen
α = 1114,943 ± 13,3
β = 1,7987069 ± 0,056
θ = 991,5386 corr.: 0,985
lijnstart F 1,0%
lijneind F 99,0%

Corrosion link
gefaald k = 8
ongefaald r = 4
ondergenzen
bovengrenzen
α = 1103,8323 ± 58,2
β = 1,8191466 ± 0,29
θ = 981,13808 corr.: 0,932
lijnstart F 1,0%
lijneind F 99,0%

gefaald k = 0
ongefaald r = 0
ondergenzen 10,00%
bovengrenzen 90,00%
α =
β =
θ =
lijnstart F 1,0%
lijneind F 99,0%

referentie
gefaald k = 0
ondergenzen 10,00%
bovengrenzen 90,00%
α = 0
β = 0
θ = 0
lijnstart F 1,0%
lijneind F 99,0%

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Figure A-7: Weibull plot for separated failure mechanisms of the AH-64 lead-lag link test case.

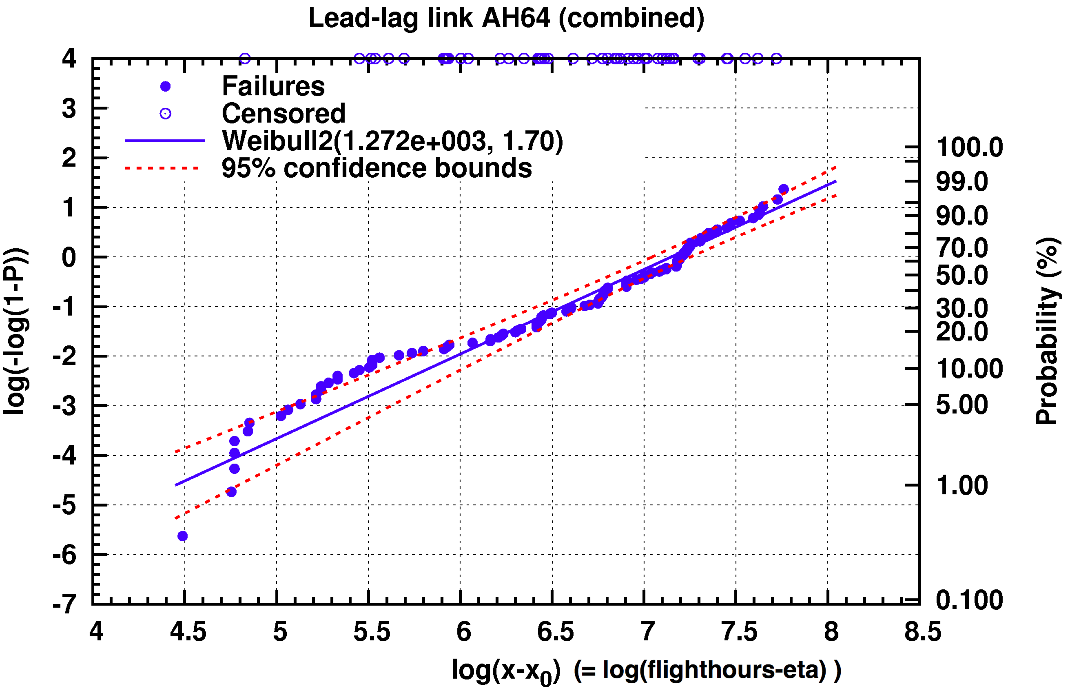

Figure A-8: RAP++ Weibull plot for combined failure mechanisms of the AH-64 lead-lag link test case using maximum likelihood estimation

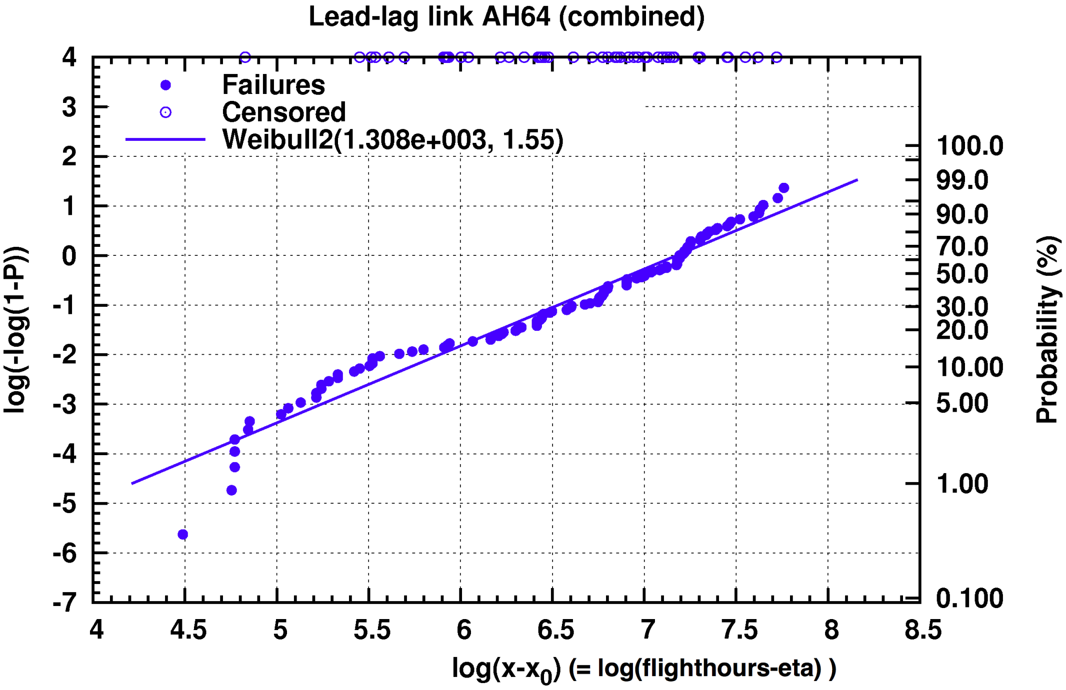

Figure A-9: RAP++ Weibull plot for combined failure mechanisms of the AH-64 lead-lag link test case using least squares estimation.

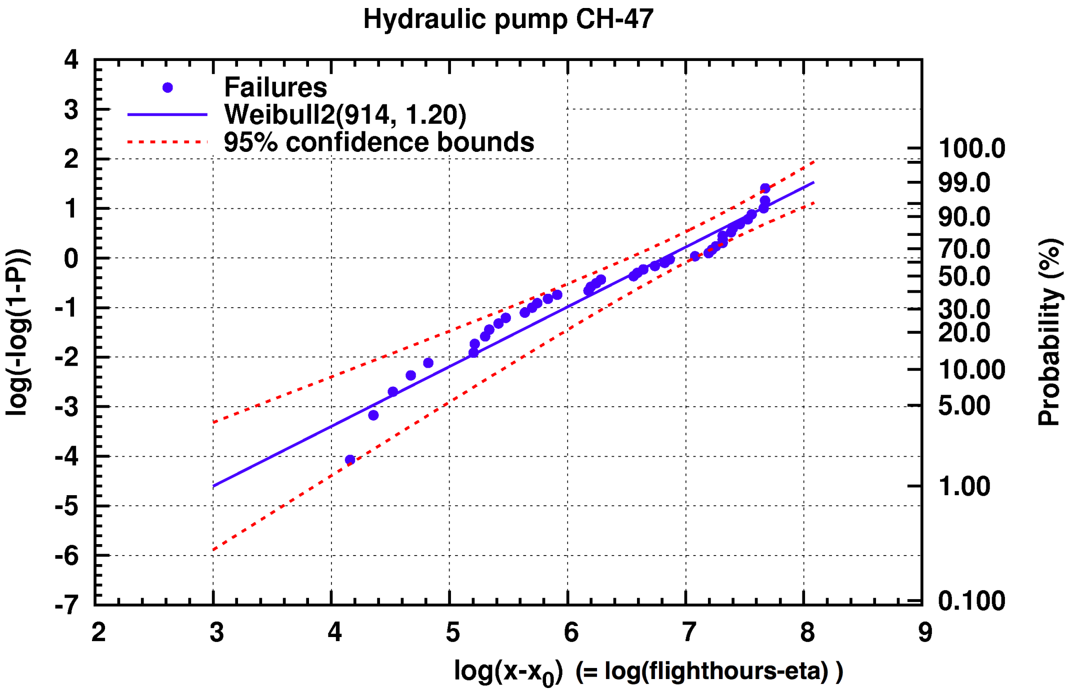

Figure A-10: RAP++ Weibull plot for the CH-47 hydraulic pump test case using maxmimum likelihood estimation.

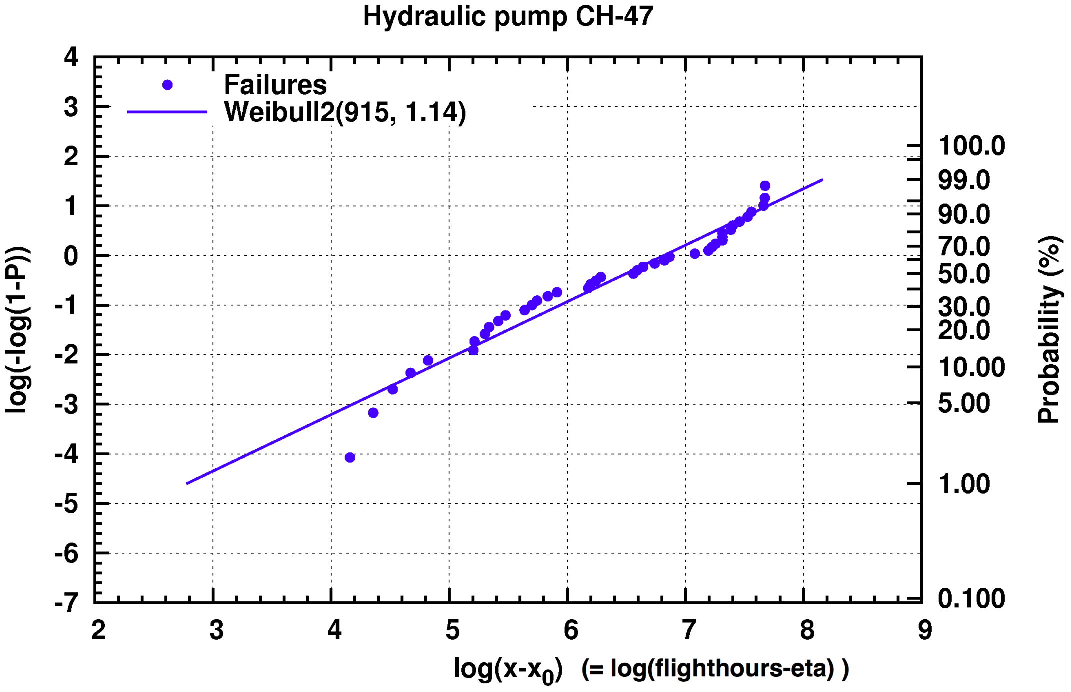

Figure A-11: RAP++ Weibull plot for the CH-47 hydraulic pump test case using least squares estimation.

Appendix B

Equations and derivations

This appendix shows some derivations for the equations that are used throughout the report as well as some additional equations that can be used for the calculations section of the r-report.

B-1 Weibull equations

This section explaines some equations that are used in the reliability analysis, as anaddition to the equations from section 2-2-3.

B-1-1 Gamma-function

The first equation that is explained in this appendix is the Γ function, which is defined as:

$$\Gamma(n) = \int_0^{\infty} e^{-x} x^{n-1} dx \tag{B-1}$$

B-1-2 Availability

The point availability A(t) can be calculated with eq. (B-2), such that a change in availability is obtained by estimating the change in downtime, for example as a result of interval extension.

$$A(t) = R(t) + \int_0^{t} R(t-u) m(u) du \tag{B-2}$$

The point availability is defined as the sum of the probability that the system is functional at time t (since $t = 0$) and the probability that the system is functional since last repair with $m(u)$ is the renewal density function [Nelson, 1982]. A more convenient approach is to use the inherent availability (A_I), that is given for a single component and for a system respectively in eq. (B-3) or the achieved availability (A_A), where preventive maintenance downtime is included as well (eq. (B-4)).

$$
\begin{aligned}
A_I &= \frac{MTTF}{MTTF + MTTR} \\
A_I &= \frac{MTBF}{MTBF + MTTR}
\end{aligned}
\tag{B-3}
$$

$$
A_A = \frac{MTBM}{MTBM + \bar{M}} \tag{B-4}
$$

where
MTTF is the calculated mean time to failure
MTBF = uptime/# of failures
MTTR = corrective maintenance (CM) downtime/# of failures
MTBM = uptime/# of failures + # of preventive maintenance (PM) entries
$\bar{M}$ = (CM downtime + PM downtime) / (# of failures + # of PM entries)

B-2 Parameter estimation

B-2-1 Median Rank and confidence bounds

Median Rank

To estimate the two parameters for the Weibull equations, a best-fit line equation is plotted for the data points first. From this, two methods for estimation will be explained. First, obtain the median rank MR plotting positions of the data points. Median rank positions are used instead of other ranking methods (such as the Kaplan-Meijer method for example) because median ranks are at a specific confidence level (50%). This done with eq. (B-5), that is displayed in the original and simplified form (Benard's approximation).

$$
\begin{aligned}
50\% &= \sum_{k=i}^{N} \binom{N}{p} MR^k (1 - MR)^{N-k} \\
MR &\sim \frac{i - 0.3}{N + 0.4} \cdot 100
\end{aligned}
\tag{B-5}
$$

In which i is the failure order number of a data set that is ordered from the smallest time to failure to the largest and N is the total number of failures. When the MR is plotted and a line is drawn through these points, a Weibull graph will be acquired. A vertical line from the point where F (on the y-axis) is 63,2% represents $t = \eta$ so $F(t = \eta) = 1 - e^{-1} = 0,632$.

Confidence bounds

With the same method, the confidence bounds for a specific confidence level can be obtained. In reliability engineering, usually two sided 95% confidence bounds are used. This means that eq. (B-6) needs to be solved for both confidence levels (C) 0.975 and 0.025. The ranks are then plotted in a smooth curve as the confidence bounds [Kececioglu, 1993].

$$C = 0.025; 0.975 = \sum_{k=i}^{N} \binom{N}{p} MR^k (1 - MR)^{N-k} \tag{B-6}$$

B-2-2 Weibull parameters β and η

Some exact methods to estimate the parameters are rank regression (least squares) or maximum likelihood estimation that works with minimization of the two maximum likelihood functions. The latter method is more difficult to program into Excel for example so for this thesis the rank regression on the y-axis is used. The goal is in any case to find the best-fit line to use the slope as an estimate for β and the 63,2% value for $F(t = \eta)$. Rank regression on Y is performed by minimizing the following equation for a straight line [Nelson, 1982]:

$$min \sum_{i=1}^{n} (a + bx_i - y_i)^2 = \sum_{i=1}^{n} (\hat{a} + \hat{b}x_i - y_i)^2 \tag{B-7}$$

where $\hat{a}$ and $\hat{b}$ are the least squares estimates of a and b, and N is the number of data points. The values for $\hat{a}$ and $\hat{b}$ are then obtained by

$$\begin{aligned} \hat{a} &= \frac{\sum_{i=1}^{n} y_i}{N} - \hat{b} \frac{\sum_{i=1}^{n} x_i}{N} \\ \hat{b} &= \frac{\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{N}}{\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{N}} \end{aligned} \tag{B-8}$$

Finally, by using the slope $\hat{b}$ as β and $0,632 = \hat{a} + \hat{b}x_i$ for $\eta = x_i$, the parameters are known. Further derivations of these formulas can be found in [Nelson, 1982] and [Reliasoft corporation, 2014].

B-2-3 Correlation

The correlation coefficient is a measure of how well the linear regression model fits the data and is usually denoted by ρ [Kececioglu, 1993]. In the case of life data analysis, the correlation is a measure for quality of the linear relation between the median ranks and the data. The correlation coefficient is given in eq. (B-9), where a resemblance can be observed with the previous equations.

$$\begin{aligned} \rho &= \frac{\sigma_{xy}}{\sigma_x \sigma_y}, so \\ \hat{\rho} &= \frac{\sum_{i=1}^{n} x_i y_i - \frac{\sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{N}}{\sqrt{\left(\sum_{i=1}^{n} x_i^2 - \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{N}\right)\left(\sum_{i=1}^{n} y_i^2 - \frac{\left(\sum_{i=1}^{n} y_i\right)^2}{N}\right)}} \end{aligned} \tag{B-9}$$

where
σ_{xy} is the covariance of x and y,
σ_x is the standard deviation of x,
σ_x is the standard deviation of y and
$\hat{\rho}$ is the estimator of ρ with a range of $-1 < \hat{\rho} < 1$