IMPROVED REMAINING USEFUL LIFE ESTIMATIONS FOR ON-CONDITION PARTS IN AIRCRAFT ENGINES
LICENTIATE DISSERTATION

IMPROVED REMAINING USEFUL LIFE ESTIMATIONS FOR ON-CONDITION PARTS IN AIRCRAFT ENGINES

VERONICA FORNLÖF

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ABSTRACT

This thesis focuses on obtaining better estimates of remaining life for on-condition (OC) parts in aircraft engines. Aircraft engine components are commonly classified into three categories, life-limited parts (LLP), OC-parts and consumables. Engine maintenance typically accounts for 10% to 20% of aircraft-related operating cost. Current methods to estimate remaining life for OC parts have been found insufficient and this thesis aims to develop a method that obtains better life estimates of OC parts. Improved life estimates are essential to facilitate more reliable maintenance plans and lower maintenance costs. In the thesis, OC parts that need a better life estimates are identified and suitable prognosis methodologies for estimating the remaining life are presented.

Three papers are appended to the thesis. The first paper lays out the main principles of aircraft engine maintenance and identifies the potential for improving maintenance planning by improving the remaining life estimation for the OC parts. The paper concludes that research is needed to find better estimates so that the right amount of maintenance is performed at each maintenance occasion.

The second paper describes the aircraft and its engine from a system of system perspective. The aim of the paper is to show that no system is stronger than its weakest part and that there is a potential to increase the availability and readiness of the complete system, the aircraft engine, by introducing better life estimates for OC parts. Furthermore, a review of all engine parts, no matter if they are life-limited or on-condition, which needs to be incorporated in a replacement model for maintenance optimization, is given. The paper concludes that the reliability of the complete aircraft engine would be increased if better life estimates are presented also for the OC parts.

The third paper includes an evolved analysis of the subject and the analysis moves deeper in to a subsystem/module of the engine, the low pressure turbine. The specific subsystem/module is further analyzed to show the potential of increased reliability for the subsystem/module and the complete system, the aircraft engine, if better life estimates for the OC parts are obtained. Methods on how to estimate remaining life is discussed in this paper. It is stated that life estimates can be based on visual inspections, available testing methods (e.g. non destructive testing) or new techniques that may be need to be developed based on remaining useful life estimations. To estimate the remaining life for the OC parts well established prognostic techniques such as physic-based, data-driven, symbolic, hybrid, or context awareness approaches that combine contextual/situation information awareness will be considered.

Keywords: Aircraft engine maintenance, Reliability, Remaining useful life, On-condition parts, Prognosis.
SAMMANFATTNING


I den andra artikeln beskrivs flygplanet och dess motor från ett system av system perspektiv. Syftet är att påvisa ett inget system är starkare än sin svagaste punkt och att det finns en potential att höga hela systemets, flygmotorns, tillgänglighet om bättre livslängdsuppskattningar för OC komponenter erhålls. Vidare presenteras en redogörelse för alla komponenter, oavsett om det är OC komponenter eller livslängdsbegränsade, som ska inkluderas i den matematiska optimeringsmodellen och det konstateras att tillförlitligheten för hela flygmotorn ökar om bättre livslängdsuppskattningar för OC komponenterna tas fram.

Den tredje artikeln inkluderar en utökad analys av området och analysen går djupare in i ett delsystem/modul, lågtrycksturbinen, i flygmotorn. Det specifika delsystemet/modulen blir analyserad för att påvisa potentialen för ökad tillförlitlighet för dels delsystemet/modulen men också för hela systemet, flygmotorn, om bättre livslängdsuppskattningar för OC-komponenterna erhålls. Metoder för uppskattning av kvarvarande livslängd diskuteras i den här artikeln och det beskrivs att livslängdsuppskattningar kan baseras på visuella inspektioner, tillgängliga testmetoder eller nyutvecklade tekniker baserade på kvarvarande livslängdsuppskattningar. För att uppskatta kvarvarande livslängd för OC-
komponenterna kommer väletablerade metoder för prognostisering, som till exempel fysiska, datalogiska, symboliska, hybrid eller ett kombinerat angreppssätt, att övervägas.

**Nyckelord:** Flygmotorunderhåll, tillförlitlighet, kvarvarande livslängdsuppskattningar, On-condition komponenter, Prognostisering
GKN Aerospace Engine Systems (GKN) started this research project in January 2013 with a desire to improve its maintenance planning and to implement an algorithm for maintenance optimization. It did not want to be doing too much maintenance, but neither too little since safety cannot be compromised. One of the key elements in maintenance is knowing which components in an aircraft engine to exchange and when to do. It is thus important to know how much remaining life there is in specific engine components and to use this information as input to maintenance optimization.

The existing methodologies and knowledge within the area of remaining life estimation and prognosis were found to be insufficient. The research project is funded by GKN in cooperation with the Knowledge Foundation and the University of Skövde, and is also a part of the industrial research school within informatics called ApplyIT.

GKN is an original equipment manufacturer (OEM) and is responsible for all maintenance on the RM12 aircraft engine that powers the Swedish Gripen fighter. This research project will therefore only include the OC parts for the RM12 engine and exclude other aircraft engines.
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Veronica Fornlöf
Trollhättan, May 2016
PUBLICATIONS

This list of publications for which the author is responsible is divided into those that directly contributed (high relevance) to this research and those that indirectly supported (lower relevance) this research. The author is primarily responsible for the work on these papers, including developing ideas, performing research, and generating results and text.

PUBLICATIONS WITH HIGH RELEVANCE


PUBLICATIONS WITH LOWER RELEVANCE
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ABBREVIATIONS

ATA - Air transportation association
CM - Condition monitoring
D-level - Depot level
ECM - Engine condition monitoring
EHM - Engine health monitoring
FAA - Federal Aviation Administration
FMV - Swedish Defense Material
GKN - GKN Aerospace Engine Systems
HT - Hard-time
I-level - Intermediate level
LLP - Life-limited part
LRU - Line replaceable unit
LTS - Life tracking system
MRB - Maintenance review board
MRBR - Maintenance review board report
MSG-3 - Maintenance Steering Group 3rd Task Force
MTTF - Mean time to failure
OC - On-condition
OC part - On-condition part
OEM - Original equipment manufacturer
O-level - Operation level
PHM - Prognostics and health monitoring
RCM - Reliability-centered maintenance
SAF - Swedish Armed Forces
SRU - Shop replaceable unit
TBM - Time-based maintenance
CHAPTER 1
INTRODUCTION

This chapter aims to make the reader acquainted with the problem and present the structure of the thesis, background information, problem statement, purpose of the research, and research questions.

1.1 STRUCTURE OF THE THESIS

The thesis is divided into five chapters:

Chapter 1: Introduction – This chapter introduces the topic of estimating the remaining life of OC parts in aircraft engines and explains the problems related to this research area. It also sets out the purpose of the research, the research objectives, and the research questions.

Chapter 2: Literature review – This chapter presents state-of-the-art theories related to this research project, and specifically to maintenance, aviation maintenance, and aircraft engine maintenance. The theoretical framework lays the basis for understanding the research area.

Chapter 3: Research Methodology – This chapter describes the methodology used to find answers to the research questions.

Chapter 4: Summary of Appended Papers – This chapter provides summaries of the three papers appended to this thesis and highlights the most important aspects of each paper.

Chapter 5: Discussion and Conclusions – This chapter summarizes the completed research and suggests further research topics.

References: A list of references is provided.

Appended papers: Three papers are included in this thesis.

1.2 BACKGROUND

Maintenance of aircraft engines is expensive and time consuming; maintenance costs typically account for between ten and twenty per cent of aircraft-related operating costs (Maple, 2001). Thus GKN Aerospace Engine Systems (GKN) has decided to finance a research project to optimize maintenance and improve its competitive position.

GKN’s main business areas include maintenance of aircraft engines, both commercial and military. When an engine is removed for maintenance, it needs to be replaced by a spare as the operator normally requires access to an operational aircraft during the maintenance
period. The spare engine may be owned by the operator or the maintenance supplier, or it may be leased from a third party. The cost of the spare engine is always significant, regardless of how it is obtained. Every maintenance event is therefore associated with a more or less fixed cost in addition to variable costs such as material costs (Almgren et al., 2008).

GKN has been a supplier to the Swedish Armed Forces (SAF) since 1930 when the Swedish government and Nydquist & Holm workshops reached an agreement for the delivery of 40 Bristol aircraft engines (Fryklund and Widfeldt, 2005). This long collaboration has led to well-established contacts and customer relations with the SAF, and as result GKN has direct interfaces to SAF systems, including sharing data related to the engine systems. GKN also has daily contact with the SAF in regard to technical questions such as which engines to maintain. However, contracts and commercial questions are discussed with the Swedish Defense Materiel Administration (FMV). GKN’s contracts for maintenance and technical support are currently divided into two large, incentive-based contracts. Both parties thus benefit from more effective work processes and subsequent savings. Earlier contracts between GKN and FMV were divided into smaller parts, but shared experiences have led to the present contracts.

Efficient maintenance of an aircraft focuses on ensuring the realization of the inherent safety and reliability levels of the aircraft and restoring safety and reliability to their inherent levels when deterioration has occurred (Ahmadi et al., 2010). Such maintenance plays a key role in airline operation because it is essential to the safety of passengers and the reliability of airline schedules (Sinex, 2002). An unexpected failure that may lead to an aircraft crash must be avoided at all costs.

Aircraft maintenance involves actions intended to restore an item to an operational condition. These actions can be subdivided into inspection and determination of condition, overhaul, servicing, modification, and repair. The common goal of maintenance is to provide a fully serviceable aircraft when it is required by an airline at minimum cost (PeriyarSelvam et al., 2013). Effective and efficient maintenance is therefore a prerequisite for a successful aviation industry.

An aircraft engine is a complex and advanced system that has to meet high standards of safety and reliability. Regular maintenance with disassembling and replacement of parts is therefore required (Cottrell et al., 2009). Maintaining a fleet of aircraft also presents challenges from a business perspective since the goals of decreasing maintenance and operations costs may conflict with desired service levels and safety levels (Knotts, 1999, Wu et al., 2004). Maintenance and how it is performed is therefore of the utmost importance.

While an engine is being maintained, it is not available for operation. This can have serious consequences if the engine in question is needed for operation in, say, a combat situation. It is therefore very important to determine exactly what maintenance is needed and to avoid excessive maintenance.

Maintaining an aircraft engine is not only complex and time consuming but also very expensive. It may account for approximately 30% of the total maintenance cost for an aircraft (Dixon and Force, 2006). It is therefore of great importance to be time efficient and to decrease costs without jeopardizing safety. It is also very important to avoid performing excessive work and/or component replacement, which would both reduce engine availability and lead to the discarding of components with life remaining.

There are three different categories of components in an aircraft engine (Fig. 1): life-limited parts (LLPs), on-condition parts (OC parts), and consumables (Fig. 2). LLPs have a fixed lifespan and must be exchanged when they have reached that limit (Aragones et al., 2000) since they are safety critical (i.e. any failure of that part could cause an engine breakdown so serious that it would cause the aircraft to crash). OC parts are “stochastic” parts that are approved for further use as long as their condition is within approved limits (Fornlöf et al.,
It is also possible that a LLP that has not reached its life limit cannot be approved for continued service because of other life-limiting issues such as cracks or fretting. A LLP can thus also be evaluated as an OC part. The third group of components, “consumables”, represents a small group of components that are exchanged each time they are removed from the engine.

Aircraft engines are brought into the workshop for two reasons: unscheduled maintenance and routine/scheduled maintenance (Kleeman and Lamont, 2005). The main reason for taking an engine to the workshop for maintenance is that an LLP has reached its life limit and needs to be replaced or serviced. Scheduled maintenance occurs at predefined intervals when the engine components are still operational. It also includes periodic inspections of the engine while installed in the aircraft.

Unscheduled maintenance activities include troubleshooting, removal and replacement of defective parts, engine ground test runs, fan trim balancing, and repairs found to be necessary during inspections (Ashby and Byer, 2002). An engine may be taken to the workshop for other reasons as well if any indications of unresolved faults have been detected. In all cases, the workshop technicians must decide which components to maintain, including both LLPs and OC parts.

Deciding to change an LLP is comparatively uncomplicated since its remaining life is deterministic and defined by a numeric (quantified) life limit. There are well-defined rules for how many cycles are allowed before a particular LLP must be maintained or replaced. For an aircraft engine, a cycle can be defined as the period during which a particular engine parameter moves between two predefined limits. The number of cycles a LLP has consumed depends on the circumstances under which the engine has been used. For example, an engine that has been exposed to higher loads from air-to-air or air-to-surface missions is likely to have consumed more life than an engine on reconnaissance missions. Similarly, in an engine exposed to combat mode and higher loads, higher temperatures and pressures are likely to consume more cycles than an engine that is used for transportation. In the same
way, a commercial aircraft engine used in an area with many high mountains requiring it to climb rapidly to cruising altitude is likely to consume more life than an engine in a normal environment.

GKN, the original equipment manufacturer (OEM) for the RM12 engine that powers the Swedish Gripen fighter, has developed what is called a Life Tracking System (LTS) (Andersson, 2011). It calculates the life consumption of life-limited parts. The accuracy of the predictions has been improved by reducing one of the most significant uncertainties in the life analysis chain: uncertainty in regard to the loads experienced. The LTS uses the actual data for each mission flown rather than some a standard mission. The reduced uncertainty allows for reductions in safety margins without compromising airworthiness. As Fig. 3 shows, the life analysis models have reduced the costs associated with spare parts (Andersson, 2011). It has been found that the main source of the cost savings from using LTS are a result of components on average being used longer. The savings are especially significant when the life limit of some LLPs can be extended beyond the expected lifespan of the engines.

![Diagram](image)

Fig. 3. Reduced uncertainty with LTS allows for reductions in the safety factor (Andersson, 2011)

The life consumption calculations are important as the results influence the status of the LLPs. In the event that nothing unexpected and unforeseen occurs, the LTS calculation identifies the next maintenance interval. The calculations draw on engine parameters and data from each mission to determine how many life cycles have been consumed by each mission. However, although LTS reduces the uncertainty about the load situation for each individual component, the downside is that the variation in consumption rates between components increases. As a consequence it is no longer possible to give an exact estimate of how many flight hours that remain for an engine before the next maintenance is due, since its life cycle consumption is directly dependent on the circumstances in which it is used. This makes it much more difficult to predict when the next maintenance event will occur.

OC parts, the other category of components in an aircraft engine, are evaluated against their maintenance manual that contains approved deviations from OC-parts state when it is new. A component is either approved for continued operation or not. The remaining flight hours for OC parts are never estimated. Currently life length estimates are based on historical failure data (allowable flight hours) and the RM12 fleet leading program is primarily used to predict future demand for spare parts.

GKN, in cooperation with Chalmers University of Technology, has developed a mathematical model (Patriksson et al., 2007, Almgren et al., 2012) intended to help those responsible for engine maintenance determine which components should be replaced at an actual maintenance occasion. The model calculates the optimum balance between discarded component life and other maintenance associated costs (Patriksson et al., 2007, Almgren et al.,
The replacement model is designed to consider the cost of interrupted airplane use while minimizing the cost of maintenance. In practice this means that the model will strive to create a maintenance plan with as few maintenance occurrences as possible while maintaining sound use of replacement parts, including both new and used components (Patriksson et al., 2007). The input data consists of actual engine status; available new, used, and repaired components in stock; as well as all costs related to maintenance. The model calculates the optimum combination of components to replace at a particular maintenance occasion. The technician uses this optimization result as the basis for creating an action decision report.

1.3 PROBLEM STATEMENT

The present maintenance planning model handles components with a fixed remaining life limit, like LLPs, while the remaining life for OC parts is based on historical failure data. There is, therefore, a need for improved life estimates for the OC parts to better incorporate them in the maintenance planning model and to obtain more reliable outcomes.

LTS has resulted in much better information and control over the life consumption of the LLPs. As long as the customers continue to use their engines with the same flight profiles as before, it is possible to produce very detailed predictions on how many more cycles individual LLPs will survive. Better information regarding the life consumption for LLPs improves input data for the mathematical replacement model. This, in turn, leads to more reliable optimization.

LTS is, however, unable to calculate the life consumption for OC parts, and thus their remaining life has to be estimated. This is something that needs to be improved (Fig. 4), so that all necessary engine parts can be incorporated in the mathematical replacement model.

To increase the reliability of the optimization results, all components that influence the extent of the maintenance need to be incorporated, regardless of whether they are LLP or OC parts. Fig. 5 shows that almost all modules consist of a mix of LLPs and OC parts. Assuming that the reliability of the life estimation for the complete system is no better than its weakest point, it is easy to recognize the importance of increasing our knowledge on how to

![Fig. 4. Illustration of achieved information level for remaining life in aircraft engine parts. (Fornlöf et al., 2014)](image-url)
estimate the remaining life for OC parts in order to improve the predictions for the remaining life of the complete engine.

This is however not only a company specific problem for GKN, it is also relevant from a research perspective since a general solution for estimating remaining life for OC parts is missing. Better life estimation for OC parts would thus be of interest, not only for GKN, but for the whole aviation industry. Beyond aviation, other areas that would benefit from better life estimates area are the nuclear- and wind power industries. These are also industries with high demands on availability and safety where it is necessary that the correct amount of maintenance is performed at the right time.

This problem shares a common ground with other research projects. For example Jaw (2005) that presents a survey for engine health management that shares a common interest within the research questions and the problem statement. Another aspect within the research area is presented by Uckun et al. (2008) whom presents a review over current research methods within prognostics and health monitoring (PHM) with the aim of better life estimates for parts. PHM is a method that permits the assessment of the reliability of a product (or system) under its actual application conditions (Pecht, 2008). It is therefore identified that Uckun et al. (2008) share the objectives with this research project for analysis of prognosis methods to measure the impact in PHM. Furthermore is Engine Health Monitoring (EHM) also explored by Powrie and Fisher (1999) whom has a vision of a combined monitoring system that will enable the aircraft to report its own engine problems and thereby minimizing operational and support cost. All these research projects has in common that they are within in the aviation industry and that they aim to by prognostics and EHM aim to reduce direct costs for operating the aircraft engine.
1.4 PURPOSE OF THE RESEARCH
A simple “ok” or “not ok” has been found to be insufficient for utilizing the full potential of the mathematical replacement model and possible improvements have been identified. Better life estimates for OC parts would make it possible to lower maintenance costs without diminishing the availability and readiness of the aircraft fleet, maximizing the residual RUL and therefore minimizing the maintenance downtime. The main reason for performing this work is that existing theories and methodologies within this area have been found to be incomplete. The purpose of this research project is to contribute to knowledge of how to estimate the remaining life of OC parts in order to be able to predict how long they may remain in operation.

1.5 OBJECTIVES
The specific objectives of this research are to:

1. Identify which engine components that require better life length estimates in order to facilitate efficient use of the replacement model (i.e. find which components that should be included in the replacement model in addition to the LLP components).
2. Describe and evaluate methods of predicting the remaining life of the identified components.
3. Evaluate the resulting overall maintenance cost (as calculated by the replacement model as a function of resolution of the life length estimates) in relation to prediction accuracy and the length of the discrete time steps in the replacement model.
4. Choose, and if required adapt, life length estimation methods for the identified component types (i.e., create a framework for life length estimation).

1.6 RESEARCH QUESTIONS
The following research questions have been defined in order to fulfill the above objectives:

1. What OC parts need remaining life estimates to be incorporated in the model in order optimize the maintenance plan?
2. What prognosis methods should be used to estimate the remaining life for these components?
3. How should the prognosis methods be deployed?
4. What accuracy and confidence interval are required for remaining life estimates?

1.7 SCOPE AND DELIMITATIONS OF THE STUDY
This thesis focus on the aircraft industry specifically and aims to study how the maintenance of the aircraft engine can be improved by better life estimates for the OC parts. The thesis only includes OC parts for RM12 and excludes other engines and similar systems. The main reason for this is the differences in the cause-and-effect relationships of different engines due to the engines being exposed to different loads and usage. Furthermore, different engines have different structures and also different maintenance processes. However similarities in the applied methodologies are so obvious that validation with RM12 can be easily populated to other engines.

The thesis will make use of an existing mathematical replacement model described by (Almgren et al., 2012), but will not perform any further development of this model. New features to be implemented in the model can, however, be proposed.
CHAPTER 2
LITERATURE REVIEW

This chapter presents the theoretical framework and the basic concepts related to this research.

2.1 MAINTENANCE

The maintenance area has grown rapidly as technology has evolved over the last few decades. Maintenance is a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function (EN13306:2001). Maintenance can also be explained as a process that is triggered by equipment failure or planned repair (Duffuaa et al., 2001) and is the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function (Dhillon, 2002, Duffuaa et al., 1999). The goal of maintenance is mainly to minimize maintenance-related operating costs, not only to reduce failures or minimize breakdowns (Jardine et al., 1997). Maintenance can be divided into maintenance strategies such as preventive and corrective maintenance. Condition-based maintenance and predetermined maintenance are subsets of preventive maintenance, see Fig. 6.

![Taxonomy of maintenance philosophies](EN13306:2001)

Fig. 6. Taxonomy of maintenance philosophies, adapted from (EN13306:2001)
2.1.1 CORRECTIVE MAINTENANCE

Corrective maintenance is maintenance carried out after fault recognition. It is intended to return an item to a state in which it can perform a required function (EN13306:2001). The earliest maintenance technique was basically breakdown maintenance (also called unplanned maintenance, run-to-failure and reactive maintenance), which takes place only at breakdowns (Jardine et al., 2006). Corrective maintenance can be seen as a maintenance strategy that includes all unscheduled maintenance actions performed as a consequence of system or product failure and intended to restore the system to a specified condition (Blanchard et al., 1995, Wang, 2001). Corrective maintenance is a reactive approach to maintenance since the action is triggered by the unscheduled event of an equipment failure. This kind of maintenance strategy tends to lead to high maintenance costs due to the penalties associated with lost production and sudden failures (Tsang, 1995).

Run-to-failure is a reactive management technique that waits for machine or equipment failure before any maintenance action is taken. However, it is actually a “no-maintenance” management approach (i.e., no maintenance is performed as long as no breakdown has occurred). It is the most expensive method of maintenance management (Mobley, 2002).

Corrective maintenance is focused on regular, planned tasks that will maintain all critical plant machinery and systems in optimum operating condition. Maintenance effectiveness is based on the life cycle costs of critical plant machinery, equipment, and systems, not on how quickly a broken machine can be returned to service. The principal concept of corrective maintenance is that proper, complete repairs of all incipient problems are made on an as-needed basis. All repairs are well-planned, implemented by properly trained craftsmen, and verified before the machine or system is returned to service. Incipient problems are not restricted to electrical or mechanical problems. Rather, all deviations from optimum operating condition, that is, efficiency, production capacity, and product quality, are corrected when detected (Mobley et al., 2008).

2.1.2 PREVENTIVE MAINTENANCE

The application of preventive maintenance was based on a scientific approach presented in the 1950s (Ahmad and Kamaruddin, 2012). The main advantage of preventive maintenance based on a scientific approach is that decisions are based on real facts. In the literature, preventive maintenance can be divided into two techniques: comprehensive-based and specific-based techniques. The primary difference between corrective and preventive maintenance is that a problem must exist before corrective actions are taken. Preventive tasks are intended to prevent the occurrence of a problem. Corrective tasks correct existing problems (Mobley et al., 2008). Indeed, an alternative to corrective maintenance strategy is preventive maintenance strategy (also called planned maintenance) where maintenance is performed at periodic intervals regardless of the health status of the system (Jardine et al., 2006). Another description is that preventive maintenance is the maintenance that occurs when a system is operational (Wang, 2001). Preventive maintenance according to (EN13306:2001) is maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item. (MIL_STD_721C, Department of Defence,), on the other hand, defines preventive maintenance as all actions performed in an attempt to retain an item at a specified condition by providing systematic inspection, detection, and prevention of incipient failures. Even though there are a number of definitions of preventive maintenance, all preventive maintenance programs are time-driven. All maintenance tasks are therefore based on elapsed time or hours of operation (Mobley, 2002).

Maintenance concepts such as reliability-centered maintenance (RCM) and risk-based maintenance are variants of the comprehensive-based technique also known as mainte-
nance concept development (Ahmad and Kamaruddin, 2012). These maintenance concept developments are commonly called installation-specific maintenance techniques and are the embodiment of how a company thinks about maintenance as an operational function (Waeyenbergh and Pintelon, 2002). The specific-based technique, on the other hand, is a specific technique that has a unique principle for solving maintenance problems. Examples of specific-based technique are time-based maintenance and condition-based maintenance.

The concept of preventive maintenance has a multitude of meanings. A literal interpretation of the term is a maintenance program that is committed to the elimination or prevention of corrective and breakdown maintenance tasks, that is, maintenance should be performed before a failure occurs. A comprehensive preventive maintenance program will utilize regular evaluation of critical plant equipment, machinery, and systems to detect potential problems and immediately schedule maintenance tasks that will prevent any degradation in operating condition. In most plants, preventive maintenance is limited to periodic lubrication, adjustments, and other time-driven maintenance tasks. These programs are not true preventive programs. In fact, most plants continue to rely on breakdowns as the principal motivation for maintenance activities (Mobley et al., 2008).

Preventive maintenance strategies within the industry can either be performed based on the tactics and strategies in the industry or based on recommendations from the OEM and a scientific approach. If preventive maintenance is performed based on experience, it is in most cases performed at regular time intervals (Canfield, 1986, Sheu, 1995, Nakagawa, 1984). No standard procedures are normally followed when preventive maintenance intervals are determined through experience. Technicians and engineers instead base their decisions on knowledge and experience acquired from previous events. Abnormal machine conditions are identified by “intuition.” The main disadvantage of determining preventive maintenance intervals based on experience is that the company may face problems if the technicians and engineers with experience leave the company (Ahmad and Kamaruddin, 2012).

Performing preventive maintenance at predefined time intervals is not always appropriate (Labib, 2004):

1. Each machine works in a different environment and will therefore need different preventive maintenance.
2. Machine designers do not normally have the same experience of machine failures and the means of prevention as those who operate and maintain the machines.
3. Machine vendors may have a hidden agenda of maximizing spare parts replacements through frequent preventive maintenance.

The arguments presented by Labib (2004) are in first hand related to productions systems but can also be applied within the aircraft industry. An example from the aviation industry is when systems sometimes are delivered and deployed while they are still lacking reliability maturity. Subsystems and repairable items that are part of the maintenance plan of the entire aircraft can be delivered without enough testing and analysis of their functionality when integrated in the system. This could lead to a system that is exposed to a lot of corrective maintenance, unexpected costs and extra downtime.

With the rapid development of modern technology, products have become more and more complex, which requires better quality and higher reliability. This has gradually increased the costs of preventive maintenance, which has thus become a major expense of many industrial companies. Thus development has moved against condition-based maintenance.
2.1.2.1 PREDETERMINED MAINTENANCE

Predetermined maintenance is a newer maintenance technique that is defined as preventive maintenance carried out in accordance with established intervals of time or number of units of use, but without previous condition investigation (EN13306:2001). Predetermined maintenance (also called time-based maintenance, planned maintenance or periodic-based maintenance) uses a periodic interval to perform preventive maintenance regardless of the health status of the physical asset (Jardine et al., 2006). Predetermined maintenance, maintenance at predetermined time intervals, can bring the system to an as-good-as-new state (Chen and Trivedi, 2005). In predetermined maintenance, maintenance decisions are based on failure time analysis (Lee et al., 2006). Predetermined maintenance assumes that a component’s failure behavior is predictable, that is, a component must have a predictable wear-out stage to be eligible for predetermined maintenance. This assumption tends to be based on conclusions from the analysis of hazards or failure rate trends, also called bathtub curves (Ahmad and Kamaruddin, 2012), see Fig. 7.

![Bathtub curve](image)

Failure trends are normally divided into three identifiable regions. The first region refers to a burn-in period, also called the infant-mortality region, which is the period immediately after manufacture or overhaul in which there is a relatively high probability of failure. The second region exhibits a constant and relatively low failure probability; this period can be identified as useful life. The third region is a wear-out region, in which the probability of failure increases rapidly with age (Nowlan and Heap, 1978).

Fig. 7 depicts the classical bathtub curve. This is however not the only kind of conditional probability curve. In fact, United Airlines developed numerous conditional probability curves for aircraft components to ensure that longer overhaul intervals did not reduce the overall reliability. It was found that the conditional-probability curves fell into six basic patterns, shown in Fig. 8–Fig. 13. If the failure pattern of an item does not fit the bathtub curve, it is probably correct to conclude that the overall failure rate will be reduced if some action is taken just before this item enters the wear-out zone. When items are allowed to age well into the wear-out region, a significant increase in the failure rate will follow. These failures will, however, not have much effect on the overall failure rate unless there is a high probability that the item will survive to the age when wear-out appears (Nowlan and Heap, 1978).
The presence of a well-defined wear-out region is far from universal. Of the six curves in Fig. 8–Fig. 13, only two curves (Fig. 8 and Fig. 9) show wear-out characteristics. Examples of aircraft components that have a defined wear-out stage include tires, reciprocating engine-cylinders, brake pads, turbine-engine compressor blades, and all parts of the airplane structure. In some components without a wear-out stage, after a certain age the conditional probability of failure continues at a constant rate (Fig. 11–Fig. 13). Other types of components have no well-defined wear-out zone (Fig. 10), but do become steadily more likely to fail as age increases (Nowlan and Heap, 1978).

Fig. 8. Bathtub curve (Nowlan and Heap, 1978)

Fig. 9. Constant or gradually increasing failure probability followed by a pronounced wear-out region (Nowlan and Heap, 1978)

Fig. 10. Gradually increasing failure probability, but with no identifiable wear-out age (Nowlan and Heap, 1978)
Fig. 11. Low failure probability when the item is new, followed by a quick increase to a constant level (Nowlan and Heap, 1978)

Fig. 12. Constant probability of failure at all ages (exponential survival distribution) (Nowlan and Heap, 1978)

Fig. 13. Infant mortality, followed by a constant or very slowly increasing failure probability (Nowlan and Heap, 1978)

Failure data analysis is performed to define the intervals between each maintenance event. The basic purpose of this process is to statistically investigate the failure characteristics of the equipment based on the set of failure time data gathered. Ahmad and Kamaruddin (2012) present a detailed process of failure time data analysis, see Fig. 14.
The first step in a time-based maintenance (TBM) process is to analyze failure data to identify the failure characteristics of the equipment, including mean time to failure (MTTF) and the trend of the equipment failure rate based on a bathtub curve process. The next steps depend on the equipment failure rate. Only if a component has a distribution with increasing failure rate, and is located in the wear-out stage on the bathtub curve, is it of interest to move on to the next stage. This is because optimal preventive maintenance is only feasible in the wear-out stage. A component in its useful life phase has not yet started to deteriorate, and preventive maintenance is not useful until the component has reached the wear-out stage where preventive maintenance can be used to increase the wear-out stage.

The next step is then to determine the maintenance policy that provides optimum system reliability or availability and safety performance at the lowest possible maintenance cost.
(Pham and Wang, 1996). Another aspect is to determine whether it is possible to repair the equipment, or whether it is non-repairable and should be exchanged for a new one. If equipment is repaired, it might be called imperfect maintenance since the equipment is not returned to an as-good-as-new state but only becomes “younger” than before the repair (Pham and Wang, 1996).

2.1.2.2 CONDITION-BASED MAINTENANCE

Condition-based maintenance is defined as preventive maintenance based on performance and/or parameter monitoring and the subsequent actions (EN13306:2001). In 1974 condition-based maintenance was introduced in order to maximize the effectiveness of preventive maintenance decision making (Ahmad and Kamaruddin, 2012). It is a maintenance program that recommends maintenance actions based on the information collected through condition monitoring. Condition-based maintenance also attempts to avoid unnecessary maintenance tasks by taking maintenance actions only when there is evidence of abnormal behavior of a physical asset (Jardine et al., 2006) and is designed to detect the onset of a failure (Tsang, 1995).

Condition-based maintenance is commonly divided into two classes of tasks: diagnosis and prognosis (Jardine et al., 2006). Diagnosis is the process of finding the fault after or in the process of the fault occurring in the system. Prognosis is the process of predicting the future failure of a system by analyzing the current and previous history of the operating conditions of the system or by monitoring the deviation rate of the operation from the normal conditions (Prajapati et al., 2012).

The execution of condition-based maintenance normally consists of the four steps illustrated in Fig. 15:

1. **Data collection:** The relevant data are collected through the use of process control systems, vibration measurements, oil sampling, and other methods. The two most common types of data are failure data and process data (Veldman et al., 2011b). Failure data are related to such things as vibration acoustics and the amount, type and size of metal particles in lubrication oil, and are a direct expression of the failure mode of a component (Jardine et al., 2006). Process data relate to the output characteristics of the component (such as pressure, flow, and temperature) and can only be used indirectly to identify the failure mode (Tsang, 1995).

2. **Data analysis:** Depending on the situation, the data may need to be cleaned up. For example, during startups and shutdowns the engine may exhibit erratic behavior, which is not to be misinterpreted as failure. The data can be analyzed in several ways, for example by direct comparison with a threshold or by examining trends or unusual behavior. Two types of models are generally used for this purpose: analytical and statistical models (Jardine et al., 2006). Analytical models are cause-effect expressions of failure, whereas statistical models need historical data to calculate the probability of failure, along with the expected time to failure. Relating the process data–failure data dimension to the analytical model–statistical dimension yields a typology of condition-based maintenance types (see Fig. 16).
3. **Decision making:** Based on the data and the analysis, a decision is made. Such a decision may involve a change in operating routines or the direct execution of a maintenance task. It may also lead to additional data collection and analysis.

4. **Implementation:** Once a decision has been made, an intervention is planned. After the intervention, reports can be created and stored for future maintenance actions. Evaluations are conducted when deemed necessary (Veldman et al., 2011a).

Maintenance is planned dynamically on the basis of machine or system condition. Condition-based maintenance does have advantages compared to the other two strategies, since modern measurement and signal-processing methods are used to accurately diagnose item/equipment during operation. However, it requires a reliable condition monitoring method. One area within this type of maintenance is condition monitoring that aims to continuously observe wear-related variables throughout a system’s lifetime to determine its degree of deterioration (Maillart, 2006).

For condition-based maintenance, the action taken after each inspection depends on the state of the system. It may involve no action, minimal maintenance to return the system to the previous stage of degradation, or major maintenance to bring the system to an as-good-as-new state. For time-based preventive maintenance, the preventive maintenance is carried out at predetermined time intervals to bring the system to as-good-as-new state (Chen and Trivedi, 2005).

### 2.1.3 REMAINING USEFUL LIFE

The RUL of a system or a component is defined as the time period from present time to the end of its useful life and can be used to characterize current health status (Xiongzi et al., 2011). The concept of RUL is illustrated in Fig. 17.
There are several approaches for determining the RUL of subsystems or components. These are categorized as into different methodologies and techniques (Okoh et al., 2014) as illustrated in Fig. 18.

Fig. 17. Definition of remaining useful life, adapted from (Xiongzi et al., 2011)

Fig. 18. Classification of methodologies and techniques for RUL predictions, adapted from (Okoh et al., 2014)
2.1.3.1 PREDICTION METHODOLOGIES

- **Model based:** In this methodology, RUL predictions are based on statistics and approaches for computational intelligence. The models are derived from configuration, usage and historical run-to-failure data and are used in maintenance decision making. Components that are analyzed and documented in the literature include bearings and gear-plates from manufacturing industries. The model based methodology is commonly used to estimate RUL and thereby base the maintenance decision based upon failure threshold (Okoh et al., 2014).

- **Analytical based:** This approach for RUL prediction includes the physical failure technique and refers to an understanding of techniques which aid reliability estimates of the physics based model. Failure events such as crack by fatigue, wear, and corrosion of components are based on mathematical laws used to estimate RUL (Medjaher et al., 2012). Analytical based models require the combination of experiments, observations, geometry and condition monitoring of data to estimate any damage in a specific failure mechanism.

- **Knowledge based:** This model uses a combination of computational intelligence and experience to predict RUL and relies on the collection of stored information from domain experts and interpretation of rules set (Chen et al., 2012a).

- **Hybrid:** A hybrid model is a collection methodology and technique. A hybrid model uses several techniques for RUL estimations and can include both parametric and non-parametric data to improve accuracy (Okoh et al., 2014). The different parameters predicts RUL individually and methods based on probability theory facilitates the fusion of two or more RUL predictions results to achieve a new RUL (Medjaher et al., 2012).

2.1.3.2 PREDICTION TECHNIQUES

- **Statistics:** This technique is based on past and present data that is analyzed with methods such as auto regressive moving average and exponential smoothing for effective prediction of result (Okoh et al., 2014).

- **Experience:** This technique makes use of expert judgments and knowledge, either explicit (easily transferred to others) or tacit (difficult to transfer to another person by means of writing it down or verbalizing it), that is gained from domain experts.

- **Computational intelligence:** This method is also known as soft computing and includes fuzzy logic and neural networks that are parameter-based and therefore dependent on input data to generate the desired output (Okoh et al., 2014). An artificial neural network uses data from continuous monitoring systems and requires training samples. The artificial neural network is a “black-box” in the sense that it provides only little insight into the internal structures (Xiongzi et al., 2011).

- **Physics of failure:** This technique needs parametric data and is based on approaches such as continuum damage mechanics, linear damage rules, non-linear damage curves and two stage linearization (Okoh et al., 2014).

- **Fusion:** This technique is based on the merging of multiple data sets into a refined state. The technique extracts, pre-processes and fuses data for accurate and fast forecast of RUL (Okoh et al., 2014)
2.2 AVIATION MAINTENANCE

Efficient maintenance of an aircraft focuses on ensuring that the realization of the inherent safety and reliability levels of the aircraft are achieved, and also on restoring safety and reliability to their inherent levels when deterioration has occurred (Ahmadi et al., 2010). Aircraft maintenance has a key position in airline operation because maintenance is essential to the safety of the passengers and the reliability of airline schedules (Sinex, 2002). An unexpected failure that could lead to a crash must be avoided at all costs. Aircraft maintenance involves actions intended to restore an item to a serviceable condition and consists of servicing, repair, modification, overhaul, inspection and determination of condition. The common goal of maintenance is to provide a fully serviceable aircraft when it is required by an airline at minimum cost (PeriyarSelvam et al., 2013). Maintenance, and performing the correct maintenance, is therefore a prerequisite for a successful aviation industry.

The cost of maintaining a military jet aircraft is in the range of US $1.6 million per year. According to Kumar (1999), 10–20% of total operating cost for an aircraft is actually spent on maintenance (Fig. 19).

![Fig. 19. Maintenance cost related to total operation cost for an airplane](image)

There are two broad streams within the aviation industry, namely the civil (commercial) aircraft and military aircraft industries. The aircraft engines used in both are based on the same techniques and constructions. Military engines are, however, exposed to higher loads, and thus higher life consumptions, than engines in the civil aviation industry. For example, during a flight mission a military aircraft may vary its flight altitude many times, whereas a civil aircraft normally climbs to a specific altitude that it maintains until it descends to land.

2.2.1 AIRCRAFT ENGINE MAINTENANCE

Maintaining an aircraft engine is complex, time consuming and, above all, expensive. Direct engine maintenance costs actually account for approximately 30% of the total maintenance cost of an aircraft (Dixon and Force, 2006).

Aircraft engine maintenance was historically carried out with fixed time intervals between major overhauls. Later, maintenance changed to being carried out when needed, with no fixed time intervals (Ackert, 2010). Instead, a service plan was implemented to reduce the number of maintenance occasions, to avoid excessive maintenance and only maintain the engine when necessary.

There are three primary maintenance processes, called hard-time, on-condition, and condition monitoring. In general terms, both hard-time maintenance and on-condition maintenance involve actions directly concerned with preventing failure, whereas condition monitoring does not. The condition monitoring process is expected to lead to preventive action if needed. The categories of component maintenance are as follows:
**Hard-time (HT):** This is defined as a preventive process in which the known deterioration of an item is restored to an acceptable level by maintenance actions carried out at periods related to time in service. This time may be calendar time, number of cycles, or number of landings. The prescribed actions normally include servicing, full or partial overhaul, or replacement (Ghobbar and Friend, 2003).

**On-condition (OC):** This is a preventive primary maintenance process. It requires that an appliance or part be periodically inspected or checked against some appropriate physical standard to determine whether it can continue in service. The purpose of the standard is to remove the unit from service before failure during normal operation. These standards may be adjusted based on operating experience or tests, as appropriate, in accordance with a carrier’s approved reliability program or maintenance manual (Ghobbar and Friend, 2003).

**Condition monitoring (CM):** This is not a preventive process, having neither hard-time nor on-condition elements. Information on items obtained by taking relevant measurements on condition-related variables is analyzed and interpreted on a continuing basis in order to implement corrective procedures. Models of decision aspects of condition monitoring have concentrated on cases where a direct measure of wear is available, such as the thickness of a brake pad in a braking system (Christer and Wang, 1995). Those measurements are related stochastically to the condition of the component (Ghobbar and Friend, 2003).

In general, engines are subject to a consistent *lato sensu* on-condition program or, to be more precise, a condition-based maintenance philosophy that includes a designated engine condition monitoring (ECM) or EHM program. The monitoring program constantly monitors the condition of a number of engine operating parameters (such as turbine gas temperature, speed of rotors, vibration, and oil pressure) to ensure engine removal before in-service failure (Batalha, 2012). Statistically, only 60% of aircraft total failures can be found by ground inspection, while 40% of faults are exposed during flight (Chen et al., 2012b).

Under the condition-based maintenance concept, gas turbine engines are in fact subject to control by all three primary maintenance processes: HT, OC, and CM. GE and CFMI (2007) consider that those processes work hand-in-hand with one another and that they carry equal weight in a maintenance program. The time at which an engine is removed is generally dictated by the OC concept, but all three processes are equally important and their application priority depends only on the type of event that occurs first (Batalha, 2012).
Table. 1. Engine primary maintenance processes (Batalha, 2012)

<table>
<thead>
<tr>
<th>Primary Maintenance Processes</th>
<th>Method</th>
<th>Application Methodology</th>
<th>Action</th>
<th>Engine Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard Time</td>
<td>Preventive</td>
<td>Hour, Cycle or Calendar Limits</td>
<td>• Remove for shop visit</td>
<td>• Life Limited Parts: Turbine disks, Compressor disks, Airworthiness directives</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>o Discard LLP</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>o Overhaul</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>o Other maintenance task</td>
<td></td>
</tr>
<tr>
<td>On-Condition</td>
<td>Preventive</td>
<td>Inspect/Check/Verify against standard:</td>
<td>• Check/Correct defect:</td>
<td>• Oil consumption</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Hardware</td>
<td>o Replace component LRU</td>
<td>• Turbine boroscope inspection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Performance parameters</td>
<td>o Other line maintenance items; or</td>
<td>• Exhaust gas turbine margin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Remove engine for shop visit.</td>
<td>• Rotor vibration</td>
</tr>
<tr>
<td>Condition monitoring</td>
<td>Predictive</td>
<td>Engine Condition Monitoring:</td>
<td>• Check/identify causes of trend shifts</td>
<td>• Trend shift in takeoff exhaust gas turbine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Performance parameters trend/trend shifts evaluation</td>
<td>• Correct defects</td>
<td>• Take-off exhaust gas turbine margin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Check parameters against limits</td>
<td>• Cruise low pressure rotor</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>• Reliability data from OEM and operator</td>
</tr>
</tbody>
</table>

Aircraft engines are brought into the workshop for two reasons: unscheduled maintenance and routine/scheduled maintenance (Kleeman and Lamont, 2005). Scheduled maintenance occurs at predefined intervals when the engine components are still operational and includes periodic inspections of the engine while installed in the aircraft. Unscheduled maintenance activities include troubleshooting faults, removal and replacements of offending parts, engine ground test runs, fan trim balancing and repairs found necessary as a result of scheduled maintenance (Ashby and Byer, 2002). When an aircraft engine is removed from service for cause and shipped to the refurbishment shop, the engine and the performance of its individual modules are evaluated and the root cause of removal determined. If the engine is removed for performance or major part failure, the engine will, in most cases, be completely broken down into modules such as compressor, turbine and auxiliary gearbox (Zaretsky et al., 2002).

Aircraft engine maintenance can be carried out at three separate maintenance levels (Mattila et al., 2003). The operation level (O-level) is the lowest level activity and is carried out in the flight-line environment. An example of maintenance at this level is onboard engine performance monitoring using equipment to record engine and aircraft performance data in order to detect defects or the need for routine engine maintenance (Nguyen et al., 1999). At the O-level, the main focus of the maintenance is performing scheduled and unscheduled inspections of the engine while it still on the aircraft. This level also includes repairs, replacements, and services that can be performed while the engine is still installed in the aircraft. The next level of maintenance is the intermediate level (I-level) and the highest level is called Depot level (D-level) (Rau et al., 2011). The main focus of the I-level is scheduled and unscheduled maintenance to repair or perform service on line-replaceable units (LRUs) without sending the engine or LRUs to D-level. D-level is the level where larger overhauls and maintenance of LRUs can be carried out. Inspections, services, and replacement and repair of shop replaceable units (SRUs) are also performed at this level. Normally D-level is also responsible for spare parts distribution.
The typical process of a maintenance event can be explained by referring to Fig. 20. Basically the maintenance process can be divided into three cycles (Reményi and Staudacher, 2014):

- **Cycle 1**: Disassembly of the engine, cleaning/crack test, and inspection
- **Cycle 2**: Internal repair, external repair (outside supplier), and new and used parts provisioning
- **Cycle 3**: Assembly, test, and certification

![Fig. 20. Typical process of an engine maintenance event, based on Reményi and Staudacher (2014)](image)

Important milestones of the maintenance process are marked in Fig. 20, as well as the steps where important scheduling decisions have to be taken. Scheduling decisions have to be taken before starting disassembly, in the internal repair process, and before assembly (Reményi and Staudacher, 2014).

Once an engine is in the plant, it is disassembled for cleaning. Engines and engine components are often disassembled to their smallest components (or parts) in the overhaul and repair process. The components are then placed on a cart consisting of several containers or trays. Each component or part may follow a distinct route in the plant depending on the nature of the work to be done. They must converge for the assembly at some point in time in a synchronous manner. Expediting is supposed to be controlled by the planning process, but may be influenced by local decisions taken by operators depending on availability of parts (Ramudhin et al., 2008).

There exists a very limited amount of data on maintenance and flight operations in wartime for RM12. In crisis situations, the fleet operates under the threat of an enemy and the need of combat maintenance and aircraft battle damage repairs then arise. The most evident change in flight operations between normal conditions and crisis conditions is the engagements with enemy’s aircraft. The fleet may suffer losses in form of damaged or destroyed aircrafts, and the average flight intensity most likely increases during a crisis. Changes in the flight operations also add additional requirements of the maintenance system. Besides
battle damages, increased flight intensity increases the risk for failures and damage repairs. Furthermore, the pressure of restoring the aircraft, and the engine, to a mission capable condition as quickly as possible increases, and non-critical maintenance is often discarded in order to ease the workload of the repair shops.

In order to move from fixed maintenance intervals to maintaining the engine when required, an on-condition maintenance concept must be designed to guarantee reliability. This is one of the reasons that RCM was developed in the aircraft industry. The RCM process is designed to focus engineering attention on the component level in a formal and disciplined manner, leading logically to the formulation of a maintenance strategy plan. The benefits of RCM also include the development of high quality maintenance plans with decreased lead time and lower cost (Brauer and Brauer, 1987).

RCM methodology is used to generate and optimize a maintenance program, including inspection requirements, that focuses on preventive maintenance on the specific failure modes that are likely to occur. The methodology is based on the assumption that the inherent reliability of equipment is a function of the design and the built-in quality (Nowlan and Heap, 1978, Moubray, 1997, Dhillon, 2002, Vatn, 2007, Rausand, 1998). RCM theory requires that maintenance should not only be performed to avoid failures, but also to prevent or at least minimize consequences caused by failures. That is why RCM focuses on retaining function rather than on the hardware itself (Nowlan and Heap, 1978, Moubray, 1997). This means that RCM treats components differently depending on how important they are considered to be for the equipment and the system functions. It is also why components are divided into LLPs, OC parts and consumables. If there is a probability that an event could cause major consequences for the systems, like a breakdown, components related to this event are assigned higher importance. Preventive maintenance is used as a barrier to remove the consequences of failure, or at least to decrease them to an acceptable level.

The Air Transportation Association’s (ATAs) Maintenance Steering Group 3rd Task Force (MSG-3) is an implementation of RCM, and is the only process approved by the Federal Aviation Administration (FAA) for the development of a Maintenance Review Board Report (MRBR) for transport aircraft. MSG-3 was originally developed for the major airlines, and was later also adopted by regional aviation. MSG-3 outlines the general organization and decision process for determining the scheduled maintenance requirements initially projected for preserving the life of the aircraft, with the intent of maintaining the inherent safety and reliability levels of the aircraft (Ahmadi, 2010). MSG-3 is, however, expensive and time-consuming; for instance, an MSG-3 process for a propulsion system takes approximately 2000–2500 labor hours. Even though this is a significant amount of time, MSG-3 has been proven to provide significant payback to operators in minimizing preventive maintenance costs (Fantasia et al., 2004).

The decision process illustrated in Fig. 20 is used to evaluate and classify the failure modes into one of the three categories below (Tsang, 1995):

1. Safety related
2. Outage related, where the system do not fulfill all its requirements
3. Economics related

If a failure mode is found to be safety related, design modifications are mandatory. For failure modes in 2 and 3 above, the maintenance options can, for example, be time-directed tasks such as on-condition base maintenance, run-to-failure, and design modifications (Tsang, 1995).

As operational experience is accumulated, additional adjustments may be made by the operator to maintain an efficient maintenance schedule (ATA MSG-3 2007). This document
also states that the objectives of scheduled maintenance of aircraft are (Ahmadi et al., 2010):

- To ensure realization of the inherent safety and reliability levels of the aircraft.
- To restore safety and reliability to their inherent levels when deterioration has occurred.
- To obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate.
- To accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

Finally each aircraft, and thus also its engines, has its own maintenance requirements which are designed to keep the aircraft in an airworthy condition. These aircraft maintenance requirements typically originate from the aircraft manufacturer and can be revised throughout the life of the aircraft by the manufacturer, the FAA and/or the Maintenance Review Board (MRB) (Sinex, 2002).
CHAPTER 3
RESEARCH METHODOLOGY

The task of carrying out a research project is complicated (Robson, 2011). The overall reason for performing research is to understand why things happen as they do (Carey, 2011). It is necessary to have an appropriate research methodology to perform research. Research methodology refers to how a research problem is approached in order to find an answer to it (Taylor and Bogdan, 1984). Sumser (2001) on the other hand described research methodology as the link between thinking and evidence.

3.1 OVERALL RESEARCH APPROACH

There are in general three methods of performing research. The first way, called exploratory, focuses on exploring a new topic. The second method, descriptive, aims to describe a phenomenon. The third, explanatory, seeks to explain why something occurs. Table 2 describes this in more detail.

Table 2. Different approaches to research (Source: Neuman (2000))

<table>
<thead>
<tr>
<th>Descriptive</th>
<th>Explanatory</th>
<th>Exploratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Provide a detailed, highly accurate picture.</td>
<td>• Test a theory’s predictions or principle.</td>
<td>• Become familiar with the basic facts, setting, and concerns.</td>
</tr>
<tr>
<td>• Locate new data that contradict past data.</td>
<td>• Elaborate and enrich a theory’s explanation.</td>
<td>• Create a general mental picture of conditions.</td>
</tr>
<tr>
<td>• Create a set of categories or classifications.</td>
<td>• Extend a theory to new issues or topics.</td>
<td>• Formulate and focus questions for future research.</td>
</tr>
<tr>
<td>• Clarify a sequence of steps or stages.</td>
<td>• Support or refute an explanation or prediction.</td>
<td>• Generate new ideas, conjectures, or hypotheses.</td>
</tr>
<tr>
<td>• Document a causal process or mechanism.</td>
<td>• Link issues or topics with a general principle.</td>
<td>• Determine the feasibility of conducting research.</td>
</tr>
</tbody>
</table>
The aim of a descriptive study is to systematically describe a phenomenon, problem, situation, service, or program and to give information about the prevalent issue. An explanatory study goes beyond this. Its objective is to search for the reasons and the measurement of relationships between two or more aspects of a situation. Finally, an exploratory study consists of the exploration of a research area that is little is known and/or the determination of the feasibility of a particular study.

To fulfill the purpose of the present research project, a combined exploratory, descriptive, and explanatory approach was chosen. An exploratory approach was used at the start in order to become familiar with the topic and get a general idea of the research area. During this phase time was spent in GKN’s workshop to get familiar with engine maintenance. Furthermore, literature on aviation maintenance, especially aircraft engine maintenance, was studied to get acquainted with the research problem and the research area. Also the mathematical replacement model and previous work related to this were studied in this phase. A descriptive approach was then used to describe aircraft engine maintenance and how it is performed. Here information gathered during the exploratory phase was used to describe the research area and the problem. This ended up in the background information for the research and description for the statement of the problem. Finally, an explanatory approach was used to explain why better life estimates for OC parts are needed and to show how this could be of benefit for engine maintenance.

Research can be classified according to three different criteria: application, objectives, and enquiry mode (Kumar, 2010). This classification is schematically summarized in Fig. 21. From the application point of view, research can be either pure or applied. “Pure” research involves developing and testing theories and hypotheses that may not have application at the present time or in the future. “Applied” research is based on techniques, procedures, and methods for information collection to be used in policy formulation, administration and the enhancement of understanding of a phenomenon. From the objectives perspective, there are four kinds of research: descriptive, correlational, explanatory, and exploratory. The aim of a descriptive study is to describe a phenomenon, problem, situation, service or program systematically and identify the major issues. The purpose of a correlational study is to find the relationships between two or more aspects of a situation. An explanatory study goes beyond this and determines the reasons for relationships between two or more aspects of a situation, and measures the relationships. Finally, an exploratory study explores a research area that is little known, and/or determines the feasibility of a particular study. In the enquiry mode, research can be classified as either qualitative or quantitative. Qualitative research uses variables measured on nominal or ordinal scales, whereas quantitative research uses quantitative variables. Thus qualitative research establishes the variation of a phenomenon while quantitative research measures the magnitude of that variation.
The research reported here is classified as follows:

- **Applied**: This study aims to improve the maintenance program of aircraft engines.
- **Exploratory**: The four research questions lead to an analysis of the research topic and to study of a new way to improve these processes.
- **Quantitative**: The prognosis and its impact on maintenance processes need to estimate several variable parameters and their accuracy, which necessitates a quantitative approach.

### 3.2 DATA COLLECTION AND ANALYSIS

Data are a requirement for analysis and confirmation of results. Techniques for data collection can be classified into two different categories (Neuman and Kreuger, 2003). Data collection in the form of numbers is categorized as quantitative, whereas data collection in terms of words or pictures is qualitative.

During the research project three different methods of data collection were used: documents, observations, and interviews. All three methods were used at different times during the research, and they fulfill different purposes.

#### 3.2.1 DOCUMENTS

Documents supplied secondary data for literature reviews. Reading literature is a significant part of a research project and has been the base to gain knowledge related to the research topic. Company-related documents describing engine maintenance and the RM12 were also important for this project. For example to answer RQ1, documents such as engine maintenance plans, engine specifications and assembly instructions have been studied.

Moreover, this research project itself generated documents in the form of papers for conferences and journals and in the form of diagrams to support the research itself.

#### 3.2.2 OBSERVATIONS

Observations were conducted to gain a better understanding of the engine maintenance process at GKN. The observations were mainly overt, complete observer, and participant observations. To get familiar with the engine maintenance process at GKN, time has been spent in the workshop at numerous occasions. The author has been observing the complete...
maintenance process from when the engine is received, disassembled, inspected, repaired, assembled and tested to it is shipped back to the wing. The work with maintenance planning has also been observed. The organization that supports the maintenance from a technical perspective has also been continuously observed. This was natural considering that the author is employed within the customer support department at GKN which mainly focuses on technical issues for RM12 and also supports the end users of the engine.

3.2.3 INTERVIEWS
The interviews in this project were unstructured. They were conducted with persons working with engine maintenance and processes related to engine maintenance to gain a better understanding of engine maintenance and how this research project could improve the process. Interviews have been conducted continuously during the research project, often in combination with observations but also separately when the author needed to obtain information or validate information or results.

3.2.4 ANALYSIS TECHNIQUES
This research uses both quantitative and qualitative data analysis.

Data related to engine maintenance can be both numeric, suitable for quantitative data analysis, and non-numeric data that can be used for qualitative analysis. Quantitative data in aircraft engine maintenance include permitted life consumptions for LLPs and consumed flight time. Many constraints for evaluating OC parts in the maintenance manual are also expressed in numeric values that can be used for quantitative data analysis; for example the allowed length of cracks, or the number of rivets allowed to be missing. To answer RQ1, and present which components that need to be implemented in the maintenance replacement model, quantitative data in form of failure rates and engine parts replaced at GKNs workshop were studied. This data is available in systems that are used or administered by the department for customer support at GKN where the author is employed. Literature studies, interviews, and observations in the maintenance workshop resulted in data and information suitable for qualitative data analysis. Non-numeric, qualitative, data in form of the researcher’s notes were also commonly used to keep track of research work and to be used as a base for drawing conclusions from interviews, observations and findings in the literature. All this have been summarized and concluded to help finding better estimates of remaining life for OC parts.

3.3 IMPLEMENTATION OF THE RESEARCH PROJECT IN THE MAINTENANCE ORGANIZATION
The aim of this thesis is to achieve better life estimates for OC parts. These estimates are intended to be used as input data for the maintenance optimization, see Fig. 22. LTS is used to calculate the remaining life for LLPs based on actual flown missions, and this information is then simplified and transferred to the maintenance system. This remaining life data is in turn used as input for the maintenance optimization. Remaining life estimates for LLPs and OC parts will be estimated by separate methods, but the information of estimated remaining life will be used as input data for maintenance optimization no matter of component type.
Fig. 22. Incorporation of life length estimates for OC parts to the maintenance organization.
CHAPTER 4
SUMMARY OF APPENDED PAPERS

This chapter summarizes the three papers appended to the thesis and describes their contribution to answering the research questions.

4.1 PAPER 1

This paper describes the basics of aircraft engine maintenance and shows that an engine is an advanced system with high demands for safety and reliability. The aim of this paper is to describe the essence of aircraft engine maintenance and to point out the potential for improvement in maintenance planning by improving the remaining life estimates of OC parts. This paper lays the necessary foundation to be able to answer RQ1. It describes the current maintenance of aircraft engines and how aircraft engine maintenance has been carried out historically. Thereafter the paper explains the difference between different engine component categories and how it is decided when to maintain an engine. To further describe how engine maintenance has evolved from fixed maintenance intervals to maintenance as required, this paper reviews RCM and MSG-3. MSG-3 is commonly used as process to ensure that systems continue to do what their users require by defining required maintenance intervals. The paper concludes that aircraft engine maintenance is a complex and time-consuming procedure since an aircraft is an advanced system with extreme demands for availability, safety, and reliability. It is thus important to be as effective as possible at each maintenance occasion and to perform the correct amount of maintenance every time. The potential for improved maintenance planning was also identified, as well as the need for research to find better life estimates for OC parts.
4.2 PAPER II


This paper describes an aircraft and its engine from a system of systems perspective. The aim is to show that no system is stronger than its weakest point and that the reliability of the complete system can be increased by introducing better life estimates for OC parts.

An aircraft is commonly used to illustrate the concept of large-scale systems. It consists of a multitude of subsystems and components that have to be integrated. An aircraft engine is in itself a complex system for the propulsion of an aircraft exposed to high loads, temperatures, pressures, stress, and fatigue. The engine is also a part of a much larger system that is the complete aircraft, which is, in turn, part of a complete aviation system. However, the aircraft engine itself can also be described as a system of systems, since it can be broken down into separate modules/subsystems.

On the basis of the system of systems approach and the description of how an engine is constructed, an analysis of all components that need to be incorporated in the mathematical replacement model for maintenance optimization is presented. It is shown that the reliability of the complete aircraft engine will be increased if better life estimates for the OC parts are available. All components that need to be included in the replacement model, no matter whether they are LLP or OC parts, are presented in this paper. Given the engine structure, how the engine is assembled and reassembled, analysis of failure rate data, maintenance plans, and unstructured interviews with personnel working with engine maintenance it was identified which parts, no matter if LLP or OC parts, that need to be implemented in the replacement model. In total 65 LLPs and OC parts were identified. The presentation of these components answers RQ 1.

4.3 PAPER III


This paper expands the work of the previous paper, which began with a system of systems focus for the aircraft engine. The aim is to further explore the research area and to move deeper into a module/subsystem to further point out the potential to increase the reliability of the complete system if better life estimates for OC parts are obtained. Current maintenance policies in aircraft engines are compared, and the differences between maintaining LLP and OC parts are described. The remaining lives of LLPs are calculated based on measured loads, whereas OC parts are evaluated against a component maintenance plan and either approved or not for continued operation at each maintenance occasion.

The next part of the paper discusses the predictions at component level for OC parts and presents a deeper analysis of the discussion in the previous paper. The analysis delves deeper in to a specific subsystem/module, the low pressure turbine. This subsystem/module is further analyzed to show the potential of increased reliability for the subsystem/module and the complete system, the aircraft engine, if better life estimates for the OC parts are obtained.

This paper further discusses the system of systems approach that was introduced in Paper II and the importance of performing the correct amount of maintenance at each individual maintenance event. A mathematical replacement model is used to ensure that the correct
maintenance is performed. The reliability of these results will be improved if there is a better way to estimate the life length for OC engine parts.

Methods of estimating remaining life are discussed in this paper. These estimates can be based on visual inspections, available testing methods, or new techniques that may be required or recommended based on RUL estimations. To estimate the remaining life of OC parts, well-established prognostic techniques such as physics-based, data-driven, symbolic, hybrid, or a context awareness approach that combines contextual/situational information awareness will be considered. The paper provides a summary of methods that can be used to estimate the remaining life of OC parts. The methods are related to answering RQ2 on defining what methods can be used to estimate the remaining life of OC parts.
CHAPTER 5
RESULTS, DISCUSSION AND CONCLUSION

In this chapter the results achieved so far are summarized and the work remaining is presented and discussed as future work.

5.1 RESEARCH CONTRIBUTION

The research area has now been explored and described. It has been shown that it is possible to improve maintenance planning and obtain more reliable results from the mathematical replacement model if better life estimates for OC parts are obtained. This knowledge lays the foundation for further work. Being able to estimate the remaining life of OC parts, rather than relying on only an approved / not approved decision for continued operation, will provide more detailed input data to the mathematical replacement model. This more detailed input will give more detailed, more reliable output data in the form of more reliable maintenance plans. Not only will the maintenance plans be more reliable, they will also optimize maintenance costs while maintaining the expected levels of availability of the complete aircraft.

The main contribution of this research project is the identification of the potential for improved maintenance planning and better results from the mathematical replacement model if better life estimates for OC parts are available providing a roadmap (prognosis selection and deployment) for this purpose.

To determine which OC parts need remaining life estimates, the RM12 engine was broken down into parts and modules. This method of dividing the aircraft engine or system into modules or subsystems in order to analyze each subsystem and its components could also be applied to other systems to identify which components need to be included in a mathematical replacement model.

This research project also identified available prognosis methodologies for estimating the remaining life of OC parts. Prognosis methods may be based on visual inspection, available testing methods, or new techniques that may be required or recommended based on RUL estimations. The research also identified methods to estimate the remaining life of OC parts such as physics-based, data-driven, symbolic, hybrid, or context awareness that combines contextual/situational information awareness.
5.2 FURTHER RESEARCH

In Paper II the answer to RQ1 was presented. RQ2 and RQ3 have also been addressed in this research project, but only partly answered. These research questions will be further explored and addressed in the upcoming phase of the research project.

The aim of RQ2 is to review what prognosis methods should be used to estimate remaining life. This research question has been addressed in the appended papers, but a detailed review of the actual prognosis methods has not yet been presented. More extensive literature studies within prognosis methods are required to create the review.

RQ3 will be further explored with the intention of providing guidelines for which prognosis methods to use for different OC parts. This will also include descriptions for combining methods for estimating remaining life for OC parts to actually perform life estimations and use them as input for the mathematical replacement model.

To answer RQ4 the mathematical replacement model will be used to perform a sensitivity analysis to find the balance between the effort to obtain remaining life estimates and what is required to derive reliable plans from the replacement model. The hypothesis is that the remaining life estimates do not need to be more accurate than a few (i.e. a discrete number as 25 or 50) flight hours to obtain a more reliable maintenance plan from the mathematical replacement model. It is nevertheless quite possible to produce very good life length estimates for OC parts by expending much time and cost, but without major impact on maintenance decisions. Thus the balance between the effort put into the analysis and the impact needs to be addressed in RQ4. This research question also raises the topic of the robustness of the replacement model, that is, its sensitivity to “errors” in estimates of remaining life for OC parts.
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PUBLICATIONS IN THE DISSERTATION SERIES
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PAPER 1
PAPER 1
On-Condition parts versus Life limited parts: A trade off in aircraft engines

Veronica Fornlöf  
University of Skövde  
SE- 461 81 Trollhättan  
+46 70 087 36 11  
veronica.fornlof@his.se

Diego Galar  
Luleå University of Technology  
SE-971 87 Luleå  
+46 920 492 437  
diego.galar@ltu.se

Anna Syberfeldt  
University of Skövde  
SE-541 28 Skövde  
+46 500 448 577  
anna.syberfeldt@his.se

Torgny Almgren  
GKN Aerospace Engine Systems  
SE-461 81 Trollhättan  
+46 70 087 22 62  
torgny.almgren@gknaerospace.com

ABSTRACT
Maintaining an aircraft engine is both complex and time consuming since an aircraft is an advanced system with high demands on safety and reliability. Each maintenance occasion must be as effective as possible and the maintenance need to be executed without performing excessive maintenance. The aim of this paper is to describe the essence of aircraft engine maintenance and to point out the potential for improvement within the maintenance planning by improving the remaining life predictions of the On-Condition parts, i.e. parts that are not given a fixed life limit.

Keywords
Aircraft engine maintenance, remaining useful life, reliability, On-Condition parts

1. INTRODUCTION
Aircraft engines are one of the most critical parts of an aircraft and are therefore where most of the maintenance efforts are allocated.

Efficient maintenance of an aircraft focus on how to ensure the realization of the inherent safety and reliability levels of the aircraft, and also to restore safety and reliability to their inherent levels when deterioration has occurred [1]. Aircraft maintenance does also occupy a key position in airline operation because maintenance is essential to the safety of the passengers and the reliability of airline schedules [2]. An unexpected failure that could lead to an aircraft crash must be avoided by all available means. Maintenance, and to perform correct maintenance, is therefore a prerequisite for a successful aviation industry.

Maintenance is the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. The goal is to prevent fatal damage for machine, human or environment and to prevent unexpected machine failure by using condition based maintenance planning to increase safety of production and quality control. Figure 1 below shows a breakdown of different maintenance strategies.

Figure 1: Breakdown into different maintenance strategies

Basically there are three different maintenance strategies [3]:

• **Run-to-break** is the most simple maintenance strategy that is often used for systems that are cheap and where damage does not cause other failures. The machine or system is used until it breaks. It is commonly used for consumer products.

• **Preventive Maintenance** is the most common maintenance method for industrial machines and systems. With this strategy maintenance is performed in fixed intervals. The intervals are often chosen so that only 1-2% of the machine will have a failure in that time.

• **Condition-Based Maintenance** is also called predictive maintenance. Maintenance is dynamical planned based on machine or system condition. Condition-Based Maintenance does have advantages compared to the other two strategies, since modern measurements and signal-processing methods are used to accurately diagnose item/equipment during operation. It though requires a reliable condition monitoring method. One area within this part of maintenance is condition monitoring which aims to continuously observe wear-related variables throughout a system’s lifetime to determine its degree of deterioration[4].
Maintaining an aircraft engine is not only complex and time consuming. It is, above all, expensive. Direct engine costs actually accounts for approximately 30% of the total maintenance cost for an aircraft [5]. Maintaining a fleet of aircrafts also means challenges from a business perspective since the goals of maintenance and operations costs may conflict with desired service levels and safety levels [6, 7]. It is therefore of importance that each maintenance event is as efficient as possible to lower the costs and to be time efficient without adventuring the safety issues. On the other hand, it is also of major importance not to perform excessive work and/or component replacements and thereby throw away components with remaining life or to reduce engine availability.

2. CURRENT MAINTENANCE OF ENGINES

Aircraft engine maintenance can be carried out at three separate maintenance levels [8]; the Operation level (O-level) is the lowest level activity and is carried out in the flight-line environment. For example are onboard engine performance monitoring equipment used to record engine and aircraft performance data at this level in order to detect defects or the need for routine engine maintenance [9]. At the O-level, the main focus for the maintenance is to perform scheduled and unscheduled inspections of the engine while it still is placed in the aircraft. This level also includes repairs, replacements and services which can be performed while the engine is still installed in the aircraft. The next level is the intermediate level (I-level) and the highest level is called Depot level (D-level) [10]. Main focus for the I-level is scheduled and unscheduled maintenance and to repair or perform service on line-replaceable units (LRUs) that can be performed without sending the engine or LRUs to D-level. D-level is the level where larger overhauls and maintenance of LRUs can be carried out. Also are inspections, services and replacements and repairs of shop-replaceable units (SRUs) are also performed at this level and normally D-level is additionally responsible for spare part distribution.

Aircraft engine maintenance has historically been carried out at fixed time intervals between major overhauls, but has then moved on to be carried out when needed, with no fixed time intervals [11]. Instead, services and controls of the engine system have been implemented according to a service plan to reduce the number of maintenance occasions to not perform excessive maintenance and only maintain the engine when needed.

In the aviation industry two main directions can be identified, the civil aircraft industry and the military aircraft industry. The aircraft engines used in both these specializations are based on the same techniques and constructions. The military engines are however exposed to higher loads, and thereby higher life consumptions, then the engines in the civil aviation industry. A military aircraft during a flight mission can for example vary its flight altitude many times, while a civil aircraft normally starts and climbs to a specific altitude until it descends to land.

Federal regulations govern all aircraft engine related matters. To maintain an aircraft mainly three sets of standards need to be fulfilled. First the standards in the manufacturer’s Federal Aviations Administrations (FAA)-approved maintenance manuals [12]. Next are the standards for the maintainers’ FAA-approved progressive inspection and maintenance program that must be met. Finally, the maintainer must meet the additional airworthiness standards from the Code of Federal Regulations (CFR) as well as the regulations concerning records, personnel and working conditions [13].

3. SELECTION OF MAINTENANCE TASKS

An aircraft engine consists of three different categories of components; Life Limited Parts (LLP), On-conditions Parts (OC-parts) and consumables (see Figure 2). LLPs are components with a fixed life limit and are exchanged when they have reached their life limits [12] since they are safety critical (i.e. a breakdown may cause an engine breakdown that are so serious that it would cause an aircraft crash). OC-parts are “stochastic” parts that are approved for further use as long as their condition is within approved limits. There can also be scenarios where a LLP has not reached its life limit, but cannot be approved for continued service due to other aspects as cracks, fretting or similar. It should be noted that an LLP also can be evaluated as an OC-part. The third group of components, “consumables”, is a small group of components that are exchanged each time they are removed from the engine.

![Figure 2: Component categories in an aircraft engine](image)

In order to move from fixed maintenance intervals to maintain the engine when required, an on-condition maintenance concept must be designed to guarantee reliability. This is one of the reasons that Reliability Centered Maintenance (RCM) was developed within the aircraft industry. The RCM process is designed to focus engineering attention on component level in a formal and disciplined manner, leading logically to the formulation of a maintenance strategy plan. Benefits with RCM also include the development of high quality maintenance plans with decreased lead time and at lower cost. [14]

RCM methodology is used to generate and optimize a maintenance program, including inspection requirements, that focuses on preventive maintenance on the specific failure modes that are likely to occur. The methodology is based on the assumption that the inherent reliability of equipment is a function of the design and the built-in quality [15-19]. Theories related to RCM mean that performing maintenance not only should be performed to avoid failures, but also to prevent or at least decrease consequences caused by failures. That is why RCM focuses on retaining functions instead of focusing on the hardware itself [15, 16]. This means that RCM treats components differently depending on how important they are considered to be for the equipment and the system functions. This is also the reason why the components are divided into LLPs, OC-parts and consumables. If the probability that an event could cause large consequences for the systems, like a breakdown, components related to this event are found to have higher importance. Preventive maintenance is then used to act as a barrier to remove...
the consequences of failure, or at least to lower them to an acceptable level.

An implementation of RCM, The Air Transportation Association’s (ATAs) Maintenance Steering Group 3rd Task Force (MSG-3) is the only process that is approved by the FAA for the development of a Maintenance Review Board Report (MRBR) for transport aircrafts. MSG-3 was originally developed for the Major Airlines, and was later also adopted by Regional Aviation Users. MSG-3 is however found to be an expensive and time-consuming process were a MSG-3 process for a propulsion system takes approximately 2000-2500 man hours. Even though this is a significant amount of time, MSG-3 has been proven to provide significant payback to operators in minimizing preventative maintenance costs [20]. MSG-3 outlines the general organization and decision process for determining the scheduled maintenance requirements initially projected for preserving the life of the aircraft, with the intent of maintain the inherent safety and reliability levels of the aircraft [21].

In order to evaluate and classify the failure modes into one of the three categories below, the decision process illustrated in Figure 3 is used [22].

1. Safety related
2. Outage related, were the system not will fulfill all its requirements
3. Economic related

If a failure mode is found to be safety related, design modifications are mandatory. For failure modes within bullet 2 and 3 above, the maintenance options can for example be time directed tasks as on-condition based maintenance, run-to-failure, and design modifications [22].

To ensure realization of the inherent safety and reliability levels of the aircraft.

- To restore safety and reliability to their inherent levels when deterioration has occurred.
- To obtain the information necessary for design improvement of those items whose inherent reliability proves to be inadequate.
- To accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures.

Finally each aircraft, and thereby also its engines, has its own maintenance requirements which are designed to keep the aircraft in an airworthy condition. These aircraft maintenance requirements typically originate from the aircrafts’ manufacturer and can be revised throughout the life of the aircraft by the manufacturer, the FAA and/or the Maintenance Review Board (MRB) [2].

4. THE NEED FOR ACCURACY IN THE REMAINING USEFUL LIFE (RUL) PREDICTION

The main drivers for the development of a failure prediction concept are the costs of a delay, or cancellations, of an aircraft departure or arrival. Delays can be caused by unscheduled maintenance between aircraft arrival and departure.

The purpose of failure prediction is to give the aircraft operator the opportunity to repair or replace a system during scheduled maintenance, if the system is not yet broken but are predicted to be before the next scheduled maintenance. The maintenance case is as follows:

1. A fault happens in flight.
2. Sensors detect the fault and report the fault to the cockpit.
3. The pilot/aircraft sends a maintenance request to the airport.
4. A maintenance mechanic checks the aircraft, when it is on ground.
5. The mechanic performs a fault search and a fault diagnosis.
6. Spare parts are ordered and a repair plan is made after the fault has been identified.
7. When the spare parts arrive, it is possible to carry through the repair.
8. The aircraft is ready again after the repair.

It is possible that the fault identification, diagnostics and spare parts management take too much time, so that the aircraft departure is delayed or even canceled. A cancellation or delay causes significant costs for an aircraft operator.

However the RUL prediction must match the opportunistic maintenance performed as a consequence of planned overhauls or similar actions. Indeed, when an aircraft engine is sent to D-level for overhaul, either a LLP has reached its fixed life limit or something indicates that something is wrong with the engine – in
which case the engine must be taken apart, further inspected and maintained. Oil supply to critical parts, such as bearings, is vital for a safe operation. For monitoring fuel and oil status, indicators for quantity, pressure, and temperature are used. In addition to these crucial parameters, vibration is constantly monitored during engine operation to detect possible unbalance from failure of rotating parts, or loss of a blade. Any of these parameters can serve as an early indicator to prevent component damage and/or catastrophic failure, and thus help reduce the number of incidents and the cost of maintaining aircraft engines [25].

A maintenance occasion were a specific component needs to be removed makes it however, often, necessary to remove other components to be able to removed the component that needs to be maintained. This creates an opportunity to perform additional maintenance which may be beneficial in a larger perspective. Each maintenance occasion is for example related to fixed costs as leasing a spare engine, transportsations, and administration. It can therefore be of interest to perform more maintenance at this specific maintenance occasion, so that this cost does not appear more often than necessary, i.e. to avoid sub-optimization by performing the right amount of maintenance at each maintenance occasion. To be able to calculate a correct maintenance schedule for what to repair, at a specific maintenance occasion, the estimated life limit for all relevant components must be available. At present is though not life estimated available for all components since only the LLPs have a fixed life limit defined, while the OC-parts instead are approved for continued operation as long as they fulfill their requirements. It would thus be beneficial, from a maintenance planning point of view, if estimates of the remaining life for the OC-parts would also be available when planning a maintenance event.

Research within this area has for example been addressed by Enright, Hudak [26] presented an approach for improving probabilistic life prediction estimated through the application of prediction methods. Actual F-16/100 usage data from flight data records were integrated with a probabilistic life prediction code to quantify the influence of usage on the probability of fracture for some engine component. Bolander, Qiu [27] on the other hand developed a method to predict the health of aircraft engine bearings, and their remaining useful lives, using spall detection.

Aircraft engines are maintained at D-level by companies specialized in aircraft engine maintenance. These companies’ benefit on how much maintenance and spare parts they are able to sell. It can therefore initially be difficult to see how performing too much maintenance could be unfavorable for them. But engine maintenance relationships are built on long term basis, where both the engine operators and maintainers benefits from doing the right amount of maintenance at the right time. It is therefore of interest to both parties to perform the right amount of maintenance since the engine operators’ goal is to maintain the engine with as low Life Cycle Cost (LCC) as possible without endanger the safety aspect. The maintainer, on the other hand, has an interest in performing the right amount of maintenance to ensure customer safety, but also to be able to attract new customers, make profit and to be competitive with other aircraft engine maintainers.

5. PROPOSED FRAMEWORK

A need for better life estimates for the OC-parts has been identified and a framework on how to estimate these life predictions will therefore be developed.

Large amount of historical data of failures and replacements of components and subsystems are available since aircraft engine maintenance if strictly registered. This data could be used to provide reliability analyses and reliability predictions for the components and subsystems. This would give more accurate predictions on how much longer the OC-parts could be kept in operation before being maintained and/or replaced.

In addition, the use of physical parameters that are monitored during the operation of the aircraft engine is of interest as well as parameters that are inspected during the maintenance. Both these kind of parameters could possibly by analyzed by using Proportional Hazard Models (PHM) from the aircraft engine operation and maintenance process as covariates.

This are two separate approaches on how to better estimate the life predictions for the OC-parts in aircraft engines, and this research aims to determine which approach that is the most suitable, or if they can be combined to reach better life predictions for the OC-parts. Independently of which approach that is used, the idea is to work with a hierarchy’s model, starting with an individual component up to a system level covering the maintenance process for a complete aircraft engine.

6. CONCLUSIONS

Aircraft engine maintenance can be both complex and time consuming since each aircraft is an advances system with excessive demands on safety and reliability. It is therefore important to be as effective as possible at each maintenance occasion and perform the right amount of maintenance every time.

This paper has described aircraft engine maintenance an identified a potential for improvement within the maintenance planning. A need for research within this topic has been identified to estimate the remaining life of the OC-parts so that their use can be optimized in correlation to maintenance cost. This should be done to keep the components in operation to an optimal level.

The current impression is that RAMS (Reliability, Availability, Maintainability, Safety) modeling seems to be an appropriate technique, and that this type of data eventually could increase the accuracy of the estimates of the remaining life for OC-parts.

7. REFERENCES


PAPER 2
Aircraft engines: A maintenance trade-off in a complex system

Veronica Fornlöf
GKN Aerospace Engine Systems
University of Skövde
Trollhättan, Sweden

Diego Galar, Anna Syberfeldt
University of Skövde
Skövde, Sweden

Torgny Almgren
GKN Aerospace Engine Systems
Trollhättan, Sweden

Abstract—An aircraft engine is a system of systems with several degrees of complexity. It is important to perform the correct amount of maintenance at each individual maintenance event. A mathematical replacement model is used to ensure that the correct amount of maintenance is performed. However, this paper shows that the reliability of this model could be improved if there were a better way to estimate the life length of on-condition maintained engine parts.

Keywords—aircraft engine maintenance; remaining useful life; reliability; on-conditions parts; prognosis

I. INTRODUCTION

An aircraft engine is a complex and advanced system that has to meet high standards of safety and reliability. Maintenance and how it is performed are of the utmost importance. However, while an engine is being maintained, it is not available for operation, which can have serious consequences if the engine is needed, for example, in a combat situation. It is therefore very important to determine exactly what maintenance is needed and to avoid excessive maintenance. When and to what extent maintenance is performed affects the availability of the system. Thus the maintenance should be performed in such way that the system is available for operation as much as possible. For example, in a combat situation a military engine must be maintained so that it can be back in operation as soon as possible.

II. SYSTEM OF SYSTEMS

A system is a set of interacting or interdependent parts that are components of a complex whole [1]. A system can itself be part of what is called a system of systems (SoS). While there is no clear, common definition of “system of systems” [2] the American Department of Defense defines it as a set or arrangement of systems resulting from the integration of independent and useful systems into a larger system that delivers unique capabilities. Both individual systems and a system of systems can meet the accepted definition of a system in that each consists of parts, relationships, and a whole that is greater than the sum of the parts. Although an SoS is a system, not all systems are SoS [3].

There are numerous systems that can be considered complex systems. Examples include a metropolitan light rail system or an aircraft carrier. However, both of these complex systems can also be subsystems within a larger SoS. For example, the light rail system is part of a metropolitan transportation SoS that includes private vehicles, air transport, buses, and other transportation systems. Thus complex systems that have been conceived, developed, and deployed as standalone systems to address a singular function can no longer be seen as operating in isolation [4].

III. THE AIRCRAFT ENGINE AS A SYSTEM OF SYSTEMS WITH SEVERAL DEGREES OF COMPLEXITY

Commercial aircraft, military aircraft, missiles, spacecraft, and launch vehicles are commonly used to illustrate the concept of large-scale systems. These vehicles consist of a multitude of subsystems and components that have to be integrated into a complex large-scale system. Designing and manufacturing these systems is not an easy task and requires large organizations of highly trained individuals [5]. These systems can then be part of a much larger system, such as an air force that consists of several systems that together form a SoS.

An aircraft engine is in itself a complex system for the propulsion of an aircraft. In doing so, it is exposed to high loads, temperatures, pressures, stresses, and fatigue. This engine is also a part of a much larger system that is the complete aircraft, which in its turn is a part of a complete aviation system that includes such elements as personal flight safety equipment, software applications for mission support, weapons, a system of air bases, and so forth (Fig. 1).

An aircraft engine itself may be seen as a system of systems. For example, the engine of a military aircraft can be subdivided into seven separate modules: fan module, compressor module, combustor module, high-pressure turbine module, low-pressure turbine module, afterburner module, and gearbox module. The modules are represented by the circles in Fig. 2. The fact that the engine is composed of modules improves availability: if a specific part fails and must be replaced, only the module of which it is a part needs to be removed for
repair, and not the whole engine [6]. The modules of the engine system shown in Fig. 2 can be separated at the lines between the circles. In order to remove a module, one must disassemble the system so that the module is released. For example to remove the high-pressure compressor module in Fig. 2, the fan and gearbox modules must first be removed so that the high-pressure compressor can be released from the combustor.

The modules in Fig. 3 are in turn built up from several components that must be assembled in a certain order. In addition there are several devices for the fuel system, electronics, and lubrication that are part of an aircraft engine. An aircraft cannot work without several peripheral systems. The concept of a module-based aircraft engine was chosen to ease engine maintenance. A module requiring maintenance can be replaced with a spare module either at the wing or in the workshop, and the engine can be returned to operation while only the module needing maintenance is kept in the workshop.

Maintaining an aircraft engine requires a complex balance between excessive maintenance and too little maintenance (which would send the engine back for repair too soon). The aviation industry is regulated by several safety constraints that tend to result in over-maintenance. In other words, maintenance is performed more often than necessary in order to fulfill safety regulations. An unexpected failure that could lead to an aircraft crash must be avoided at all costs. Maintenance, and in particular correct maintenance, is a prerequisite for a successful aviation industry.

Maintenance can be described as a combination of all the technical and administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. The goal of maintenance is to prevent fatal damage to the machine, human beings, and the environment. Unexpected machine failure can be prevented by using condition-based maintenance planning to increase the safety of production and quality control.

There are three main maintenance strategies [7]:

- Run-to-break
- Preventive maintenance
- Condition-based maintenance

All these maintenance strategies are important in aviation. Run-to-break maintenance can be used in specific cases, but not for the engine. Preventive maintenance fits the conservative approach and high safety factors that are important in the aviation industry. Condition-based maintenance is a natural evolution of preventive maintenance made possible by technological advances.

IV. CURRENT MAINTENANCE POLICIES IN AIRCRAFT ENGINES: OC PARTS VERSUS LLP

An engine consists of two types of components: life-limited parts (LLP) and on-condition parts (OC parts). The LLPs are safety critical parts with a fixed lifetime while the OC parts are engine components that are not safety critical. Components whose breakdown could cause an engine failure so serious that it could cause an aircraft crash are deemed to be LLPs. Examples of LLPs are fan blades and disks, whereas OC parts are components like the low-pressure turbine case and the exhaust frame assembly (Fig. 4).

Aircraft engines are brought into the workshop for two reasons: unscheduled maintenance and routine/scheduled maintenance [8]. The main reason for taking an engine to the workshop for maintenance is that an LLP has reached its life limit and needs to be replaced or serviced. An engine may also be taken to the workshop if any unresolved indications of faults have been detected. In both cases, the workshop technicians must decide which components to maintain including both LLPs and OC parts. Deciding to change an LLP is comparatively uncomplicated, for its remaining life is deterministic and has a formulated numeric life limit.
A. The accuracy of LLP remaining useful life prediction by means of measured loads

There are well-defined rules for how many cycles each LLPs is allowed before it must be maintained or replaced. One cycle for an aircraft engine can be defined as the period when a particular engine parameter has moved between two predefined limits. The number of cycles a life-limited part has consumed depends on the circumstances under which the engine has been used. For example, an engine that has been exposed to higher loads on air-to-air or air-to-surface missions is likely to have consumed more cycles than an engine used on reconnaissance missions. Similarly, for an engine exposed to combat mode and higher loads, higher temperatures and pressures are likely to consume more cycles than are used by an engine used for transportation. In the same way, a commercial aircraft engine used in an area with many high mountains and a requirement to climb rapidly to cruising altitude is likely to consume more life than an engine in a normal environment.

GKN Aerospace, the original equipment manufacturer for the RM12 engine that powers the Swedish Gripen fighter, has developed what is called a Life-Tracking System (LTS). It calculates the life consumption of life-limited parts [9]. The accuracy of the life predictions has been improved by reducing one of the most significant uncertainties in the life analysis chain: the uncertainty of the loads experienced. The actual data for each mission flown is used instead of a standard mission. The reduced uncertainty with LTS provides an opportunity to reduce safety margins without compromising airworthiness. As Fig. 5 shows, the life analysis models reduce the costs associated with spare parts [9]. It has been found that the main cost savings due to LTS occur because components can be used longer, and that the life limit of LLPs can often be extended beyond the expected lifetime of the engines.

The life consumption calculations are important to consider as the results influence the status of the LLPs. Providing nothing unexpected and unforeseen occurs, the LTS calculation will identify the next maintenance interval. The LTS method uses engine parameters and analyzes data from each mission flown to calculate how many life cycles have been consumed for each mission. LTS reduces the uncertainty about the load situation for each individual component, but at the same time increases the variation in consumption rates between components. Depending on how an engine is used, a component is exposed to more load or less load. Another effect of LTS is that it is no longer possible to give an exact estimate of how many flight hours remain for an engine before its next maintenance since its life cycle consumption is directly dependent on the circumstances in which it has been used. This makes it much more difficult to predict when the next maintenance interval will occur.

B. The challenge of OC parts

OC parts, the other category of components in an aircraft engine, are evaluated against their component maintenance plan (CMP). A component is either approved for continued operation or not. The remaining flight hours for an OC part are never estimated. At present the life length estimates based on historical failure data (allowable flight hours) is primarily used to predict future demand for spare parts.

GKN, in cooperation with Chalmers University of Technology, has developed a mathematical replacement model intended to help those responsible for engine maintenance determine which components should be replaced at an actual maintenance occasion. The model is able to calculate the optimum balance between the remaining life of engine components and the costs for each maintenance interval, versus the cost of components and their exchange[10, 11]. The replacement model is designed to consider the cost of interrupted aircraft use while minimizing the cost of maintenance. In practice this means that the model will strive to create a maintenance plan with as few maintenance events as possible while maintaining sound use of replacement parts, including both new and used components.
components[10]. Given input data consisting of actual engine status; available new, used, and repaired components in stock; as well as all costs related to maintenance; the model can calculate the optimum combination of components to replace at a particular maintenance interval. This optimization result is used as a basis for the technician to create an action decision report. The present maintenance planning model handles components with a fixed remaining life limit, like the LLPs, while the remaining life for OC parts is based on historical failure data. There is therefore a need for improved life estimates for the OC parts to better incorporate them in the maintenance planning model and obtain more reliable outcomes.

V. PROGNOSIS IN COMPONENT/SUBSYSTEM LEVEL FOR OC ITEMS

Maintenance for OC parts is a preventive primary maintenance process. It requires that an item of equipment or a component be periodically inspected and checked against some appropriate physical standard to determine whether it can continue in service. The purpose of the standard is to remove the unit from service before failure during normal operation. These standards may be adjusted based on operating experience or tests, as appropriate, in accordance with an operator’s approved reliability program or maintenance manual [12, 13]. For an aircraft engine installed in an aircraft, the standard referred to is the Aircraft Maintenance Manual (AMM), a formal document that details the way in which all maintenance tasks are to be carried out on an aircraft. It includes items such as the lubrication system functional checks, and servicing of the airplane, but usually excludes structural repairs and modifications [13].

An OC part is changed when needed. The decision to change it is based on several factors such as cracks, discoloration, and other fault modes that indicate the health of each component. The size of allowed cracks and other allowed fault modes can be found in the Component Maintenance Manual (CMM), a formal document that details the way in which off-aircraft maintenance tasks on specified components are to be done. The maintenance tasks contained in these manuals include procedures for restoring a component to a serviceable state. Reworking and refinishing procedures are often provided in the appropriate CMM [14]. Based on their experience and using the information available from inspections and the data in the CMM, technicians must estimate whether an approved component will function adequately until the next maintenance occasion. A prognosis method based on thresholds or technical criteria would contribute to increasing the accuracy of the prognosis as well as avoiding different decisions due to different technicians with differing skills and experience.

VI. UNCERTAINTY MANAGEMENT IN DETERMINING REMAINING USEFUL LIFE AT A SYSTEM LEVEL: BENEFITS OF OC PROGNOSIS

In the current maintenance process the actual status of OC parts can only be identified and detected through inspection and nondestructive testing. This status evaluation could, however, be improved. Estimation of the remaining life for OC parts could also be improved if the parts could be divided into different life length groups using some classification method. The method would allocate the OC parts to groups depending on detected and identified fault modes, component status, and an estimate of the remaining life for each component. The estimated remaining life could then be used to indicate how much longer each component could fulfill its requirements and be kept in operation.

A replacement model that uses classified OC parts as input would also make it easier for a technician to ensure that the correct maintenance activities are performed at each maintenance interval. A possible outcome would naturally be that a replacement model using classified OC parts might change the way in which maintenance is performed. One possible change would be longer intervals between maintenance events because the replacement schedule is based on more reliable input data.

VII. PROGNOSTICS AND DIAGNOSTICS

There are three mains ways to model how faults develop using symbols, data, or mathematical formulations based on physical principles, as shown in Fig. 6.

“Diagnostics” is the investigation or analysis of the cause or nature of a condition, situation, or problem, whereas “prognostics” are concerned with calculating or predicting the future as a result of rational study and analysis of available pertinent data. In terms of the relationship between prognostics and diagnostics, the latter is the process of
detecting and identifying a failure mode within a system or subsystem [15].

Prognosis is defined by the International Organization for Standardization (ISO) as “the estimation of time to failure and risk for one or more existing and future failure modes” [16]. In this understanding, prognostics is also called the “prediction of a system’s lifetime” as it is a process whose objective is to predict the remaining useful life (RUL) before a failure occurs, given the current machine condition and past operating profile [7].

Several methods exist to monitor the condition of rotary machinery. However, the most common are the model-based and data-driven approaches for diagnosis and prognosis. Each has its own advantages and disadvantages, and they are therefore often used in combination [15].

VIII. PROGNOSIS AGGREGATION FROM COMPONENT TO SYSTEM LEVEL AND FUTURE WORK

LTS has resulted in much better information about and control over the life consumption of the LLPs. As customers will continue to use their engines with the same flight profiles as before, it is also possible to get very detailed prognostics over how many more cycles individual LLPs will survive. Using better information regarding life consumption for the LLPs will improve input data for the mathematical replacement model. In turn, this will breed more reliable optimization results due to more reliable input data.

LTS is, however, unable to calculate the life consumption for OC parts, so it is still necessary to estimate the remaining life for these parts. This is something that needs to be improved (Fig. 7), so that all necessary engine components can be incorporated in the mathematical replacement model.

To increase the reliability of the optimization results, all components exposed to maintenance in the engine need to be incorporated, independent of whether they are LLP or OC parts. Fig. 8 shows that almost all modules consist of a mix of LLPs and OC parts. With a simple assumption that the reliability of the life estimations for the complete system is no better than its weakest point, it is easy to realize the importance of increasing knowledge on how to estimate the remaining life for OC parts in order to increase the knowledge of the remaining life for the complete engine.

The aim of our research is to develop better life length estimations for OC parts. Several factors need to be taken into consideration. First of all, the engine components must be analyzed to generate a list of which engine components should be included in the maintenance optimization. This will focus on aggregation of information on prognosis and the relevant OC parts (Fig. 8). The list of engine components will then be analyzed in more detail to identify the need for maintenance and/or the influence of the extent of the maintenance.

The next step is to find the balance between the remaining life estimated and what is required to obtain reliable plans from previous maintenance optimization models. This step evaluates prognosis uncertainty and determines how good the estimates are. Thus it is also necessary to evaluate the costs of reasonable effort to determine the lead time, labor hours, and resources required to classify components and their remaining life. It is probably possible to produce very good estimates with high time consumption and cost, but in some cases there may be no impact on maintenance decisions. Thus the balance between analysis effort and impact needs to be analyzed. It is also necessary to evaluate the robustness of the replacement model, i.e., how sensitive the model is to “errors” in the estimates of remaining life.

These methods need to be investigated to obtain an overview of what has already been done within the field of life estimation, prognosis, and remaining useful life. The most relevant methods for aircraft engines should then be described and methods suggested for further study. This review should include whether the life estimated should be based on visual inspections, currently available testing methods, or new techniques that may be required or recommended. This part of the investigation will therefore address the area of context awareness in prognosis.

It is most important that the remaining life estimation for OC parts should lead to an estimation of the remaining life for each component that can be incorporated into the replacement model. Life estimates for OC parts could be binary (“ok/not ok”), a few possible values, a continuous variable in a specified range, or even data in an algorithm. This will

![Fig. 6. Diagnosis and prognosis approaches, adapted from [17]](Image)

![Fig. 7. Illustration of achieved information level for remaining life in aircraft engine components](Image)
Red arrow indicates that both superjacent component must be removed to unmount the component.
Green arrow indicates the addition of a cost to remove an extra component on the same level.

Fig. 8. Engine structure diagram indicating the location of each component, LLP or OC part probably vary from component to component, but these are questions that should be focused on to resolve the problem of developing better life estimates for the OC-parts in an aircraft engine.

References

PAPER 3
Abstract—An aircraft engine is a system of systems with several degrees of complexity. It is important to perform the correct amount of maintenance at each individual maintenance event. A mathematical replacement model is used to ensure that the correct maintenance is performed. The reliability of these results will be improved if there is a better way to estimate the life length for on-condition engine parts.

Keywords—aircraft engine maintenance; remaining useful life; reliability; on-conditions parts; prognosis

I. INTRODUCTION

Efficient maintenance of an aircraft focuses on ensuring that the required safety and reliability levels are met and to restore safety and reliability to the required levels when deterioration has occurred [1]. Aircraft maintenance is vital to airline operations because it affects the safety of passengers and the reliability of airline schedules [2]. Unexpected failures that could lead to a crash must be avoided.

Aircraft maintenance is defined as actions that can restore an item to a serviceable condition. It involves determination of condition, servicing, modification, overhaul, inspection, and repair. The common goal of maintenance is to provide a fully serviceable aircraft when it is required by an airline at minimum cost [3]. Maintenance, and carrying out correct maintenance, is a prerequisite for a successful aviation industry.

Maintaining a fleet of aircraft does, however, present challenges from a business perspective since the goals and costs of maintenance conflict with desired service and safety levels [4, 5]. When, how, and to what extent maintenance is performed is of the utmost importance. While an engine is being maintained, it is not available for operation, which may have serious consequences if the engine in question is needed. (For example a military engine in a combat situation must be returned to operation as soon as possible.) It is therefore very important to determine exactly what maintenance is needed and to avoid excessive maintenance.

Maintaining an aircraft engine is not only complex and time-consuming, but also very expensive. Direct engine costs account for approximately 30% of the total maintenance cost of an aircraft [6]. It is therefore important that each maintenance event is as efficient as possible to lower the costs and to be time efficient without putting safety at risk. Care must also be taken not to perform unnecessary work that reduces engine availability and not to discard components that still have remaining life.

There are three separate levels of aircraft engine maintenance [7]. Maintenance at the operation level (O-level) is the lowest level and is carried out in the flight-line environment. For example, onboard engine performance monitoring equipment is used to record engine and aircraft performance data in order to detect defects or the need for routine engine maintenance [8]. At the O-level, the main focus is on performing scheduled and unscheduled inspections of the engine while it still in position on the aircraft. This level also includes repairs, replacements, and services that can be performed while the engine is still installed. The next level of maintenance is the intermediate level (I-level), where the focus is on scheduled and unscheduled maintenance and to repair or service line-replaceable units (LRUs) without sending the engine or LRUs to the depot level (D-level), which is the highest level of maintenance [9]. The D-level is the level where larger overhauls and maintenance of LRUs are performed. Inspection, servicing, replacement, and repair of shop-replaceable units (SRUs) are also performed at this level. The D-level is also normally responsible for spare part distribution.

The typical process of a maintenance event is shown in Fig. 1. Basically the maintenance process can be divided into three phases [10]:

- Phase 1: Disassembly of the engine, cleaning /crack test, and inspection
- Phase 2: Internal repair, external repair (outside vendor), and new and used parts provisioning
- Phase 3: Assembly, test, and certification

Aircraft engine maintenance has historically been carried out at fixed time intervals between major overhauls, but has then moved on to be carried out when needed, with no fixed time intervals [11]. Instead, services and controls of the engine system have been implemented according to a service plan. This to reduce the number of maintenance occasions and to not perform excessive maintenance and only maintain the engine when needed.
Rules for military aviation (RML) govern all aircraft engine related matters. It applies to organizations and person, who supervise, carry out ground and air operations including command and control, aerodromes and aviation MET services, design and produce aeronautical products, maintain such products and carry out training and education within the Swedish Military Aviation System. The Rules for Military Aviation are under constant development. Therefore it is the responsibility of operators and providers, and other entities within the military aviation system, to constantly review the current issues of RML, in order to be up to date with changes made [12].

Figure 1. Typical process of an engine maintenance event.

II. SYSTEM OF SYSTEMS

An aircraft engine consists of thousands of components, ranging from fan blades, nozzles, and cables to nuts and bolts. All these components together form a system that is used to power an aircraft system. A system is a set of interrelated elements [13], also described as a set of interacting or interdependent parts that are components of a complex whole [14]. A system can itself be part of what is called a system of systems (SoS). While there is no clear, common definition of “system of systems” [15], the American Department of Defense defines it as a set or arrangement of systems resulting from the integration of independent and useful systems into a larger system that delivers unique capabilities. Both individual systems and a system of systems can meet the accepted definition of a system in that each consists of parts, relationships, and a whole that is greater than the sum of the parts. Although a SoS is a system, not all systems are SoS.

Numerous systems can be considered complex systems. Examples include a metropolitan light-rail system or an aircraft carrier. However, these complex systems can also be subsystems within a larger SoS. For example, the light-rail system is part of a metropolitan transportation SoS that includes private vehicles, air transport, buses, and other transportation systems. Thus complex systems that have been conceived, developed, and deployed as stand-alone systems to address a singular function cannot be seen as operating in isolation [16].

A. The aircraft engine as a system of systems with several degrees of complexity

Commercial aircraft, military aircraft, missiles, spacecraft, and launch vehicles are commonly used to illustrate the concept of large-scale systems. These vehicles consist of a multitude of subsystems and components that have to be integrated into a complex large-scale system. Designing and manufacturing these systems is not an easy task and requires large organizations of highly trained individuals [17]. These systems can then be part of a much larger system, such as an air force that consists of several systems that together form a SoS.

An aircraft engine (Fig. 2) is in itself a complex system for the propulsion of an aircraft. In doing so, it is exposed to high loads, temperatures, pressures, stresses, and fatigue. The engine is also a part of a much larger system that is the complete aircraft, which in its turn is a part of a complete aviation system that includes such elements as personal flight safety equipment,
software applications for mission support, weapons, a system of air bases, and so forth (Fig. 3).

An aircraft engine itself may be seen as a system of systems. For example, the engine of a military aircraft can be subdivided into seven separate modules:

- Fan module
- Compressor module
- Combustor module
- High pressure turbine module
- Low pressure turbine module
- Afterburner module
- Gearbox module

The modules are shown in Fig. 4.

The fact that the engine is composed of modules improves availability: if a specific part fails and must be replaced, only the module of which it is a part needs to be removed for repair, and not the whole engine [18]. The modules of the engine system shown in Fig. 4 can be separated at the lines between the rectangles. In order to remove a module, one must separate the system so that the module is released. For example to remove the high-pressure compressor module in Fig. 4, the fan and gearbox modules must first be removed so that the high-pressure compressor can be released from the combustor.

The modules in Fig. 4 are in turn built up of several components that must be assembled in a certain order. In addition the engine is linked to other components such as the fuel, electronics, and lubrication systems. An aircraft cannot operate without several peripheral systems. The concept of a module-based aircraft engine was chosen to ease engine maintenance. A module requiring maintenance can now be replaced with a spare module either on the aircraft or in the workshop, and the engine can then be returned to operation while only the module needing maintenance is kept in the workshop.

Maintenance is defined as a combination of all technical, administrative, and managerial actions during the lifecycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function [19]. The goal of maintenance is to prevent fatal damage to the machine, human beings, and the environment. Unexpected machine failure can be prevented by using condition-based maintenance planning to increase the safety of production and quality control.

There are three main maintenance strategies (Jardine et al., 2006):

- Run-to-break is the simplest maintenance strategy. It is used for systems that are cheap and where damage does not cause other failures. The machine or system is used until it breaks. This strategy is commonly used for consumer products but is never used on aircraft engines due to safety regulations.

- Preventive maintenance is the most common strategy for industrial machines and systems. It is maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of functioning of an item [19]. In this strategy, maintenance is performed at fixed intervals, which are often chosen so that only 1% to 2% of the machines in use will experience a failure during the interval. This maintenance strategy is commonly used for aircraft engines. Historically, aircraft engines were maintained at predetermined times. However, engine maintenance has now progressed so that it is only performed when a component has reached its life limit or when indications show that the engine is malfunctioning.

- Condition-based maintenance is preventive maintenance based on performance and/or parameter monitoring and the subsequent actions [19]. Maintenance is thus planned dynamically based on the condition of the machine or system condition. Modern measurements and signal-processing methods can be used to accurately diagnose items/equipment during operation. However, reliable condition monitoring methods are needed, for instance to continuously observe wear-related variables throughout the system lifetime to determine its degree of deterioration [21]. In aircraft engines condition-based maintenance is for instance used by detecting contaminants in the oil system. The oil is continuously analyzed, and the oil system is also equipped with chip detectors to detect whether the oil is contaminated with metal particles, which may indicate that components have begun to break down.

All these maintenance strategies are important in aviation. Run-to-break maintenance can be used in specific cases, but not for the engine. Preventive maintenance is used with a conservative approach using the high safety factors that are required in the aviation industry. Condition-based maintenance is a natural evolution of preventive maintenance made possible by technological advances.
To determine the initial maintenance schedule for a new aircraft system and its subsystems, the system is analyzed according to Maintenance Steering Group standards (MSG-3). For a new aircraft and its subsystems, for example the engine, there is a lack of historical data to determine maintenance intervals. However, there are historical data on the performance of similar components and systems used in earlier designs, as well as test data from manufacturers and component vendors [11].

III. CURRENT MAINTENANCE POLICIES IN AIRCRAFT ENGINES: OC VERSUS LLP

An aircraft engine has three different categories of components: life-limited parts (LLP), on-condition parts (OC parts), and consumables (Fig. 5). LLPs are components with a fixed life limit and are exchanged when they have reached that limit [23] since they are safety critical (i.e., a failure of that part might cause an engine failure so serious that it could cause an aircraft crash). OC parts are “stochastic” parts that are approved for further use as long as their condition is within approved limits [24]. It should be noted that an LLP also can be evaluated as an OC part – for example, the LLP may not have reached its life limit but cannot be approved for continued service due to other problems such as cracks or fretting. The third group of components, “consumables,” is a small group of components that are exchanged each time they are removed from the engine.

Aircraft engines are brought into the workshop for two reasons: unscheduled maintenance and routine/scheduled maintenance [25]. The main reason for taking an engine to the workshop for maintenance is that an LLP has reached its life limit and needs to be replaced or serviced. Scheduled maintenance occurs at predefined intervals when the engine components are still operational and also includes periodic inspections of the engine while installed in the aircraft. Unscheduled maintenance activities include troubleshooting faults, removal and replacements of offending parts, engine ground test runs, fan trim balancing, and repairs found necessary as a result of scheduled maintenance [26]. An engine may be taken to the workshop for other reasons as well, if any unresolved indications of faults have been detected. In both cases, the workshop technicians must decide which components to maintain, including both LLPs and OC parts. Deciding to change an LLP is a comparatively uncomplicated since its remaining life is deterministic and it has a defined numeric life limit.
A. Using measured loads to predict remaining useful life

All LLPs have well-defined rules regarding how many cycles that are allowed before the component must be maintained or replaced. One cycle for an aircraft engine can be defined as the period in which a particular engine parameter moves between two predefined limits. The number of cycles an LLP has consumed depends on the circumstances under which the engine has been used. For example, an engine that has been exposed to high loads during air-to-air to surface missions is likely to have consumed more cycles than an engine used on reconnaissance missions. Similarly, the higher loads, temperatures, and pressures on an engine used in combat mode are likely to consume more cycles than would be used by an engine used for transportation. In the same way, a commercial aircraft engine used in an area with high mountains and a requirement to climb rapidly to cruising altitude is likely to consume more life than an engine in a normal environment.

GKN Aerospace, the original equipment manufacturer for the RM12 engine that powers the Swedish Gripen fighter, has developed what is called a Life-Tracking System (LTS) [27]. It calculates the life consumption of LLPs. The accuracy of the life predictions has been improved by reducing one of the most significant uncertainties in the life analysis chain: uncertainty about the loads experienced. The actual data for each mission flown is used instead of standard data. The reduced uncertainty with LTS provides an opportunity to reduce safety margins without compromising airworthiness. As Fig. 7 shows, life analysis models reduce the costs associated with spare parts [27]. It has been found that the main cost savings due to LTS occur because components can be used longer, and that the life limit of LLPs can often be extended beyond the expected lifetime of the engines.

The life consumption calculations are important to consider as the results influence the status of the LLPs. The LTS calculation will identify the next maintenance interval provided nothing unforeseen occurs. The LTS method uses engine parameters, and analyzes data from each mission flown, to calculate how many life cycles have been consumed for each mission. LTS reduces the uncertainty about the load situation for each individual component, but at the same time increases the variation in consumption rates between components. Depending on how an engine is used, a component is exposed to more or less load. Another effect of LTS is that it is no longer possible to give an exact estimate of how many flight hours remain for an engine before its next maintenance since its life cycle consumption is directly dependent on the circumstances in which it has been used. This makes it much more difficult to predict when the next maintenance interval will occur.
B. The challenge of OC parts

OC parts, the other category of components in an aircraft engine, are evaluated against their component maintenance plan (CMP). A component is either approved for continued operation or not. The remaining flight hours for an OC part are never estimated. At present life length estimates based on historical failure data (allowable flight hours) are used primarily to predict future demand for spare parts.

GKN, in cooperation with Chalmers University of Technology, has developed a mathematical replacement model [28, 29] intended to help those responsible for engine maintenance by suggesting which components should be replaced at the time of the actual maintenance. The model is able to calculate the optimum balance between the remaining life of engine components and the costs for each maintenance interval versus the cost of components and their replacement [28, 29]. The replacement model is designed to consider the cost of interrupted engine use while minimizing the cost of maintenance. In practice this means that the model will strive to create a maintenance plan with as few maintenance events as possible while maintaining sound use replacement parts, including both new and used components [28]. Given input data consisting of actual engine status; available new, used, and repaired components in stock; as well as all costs related to the maintenance; the model calculates the optimum combination of components to replace at a particular maintenance interval. This optimization result is used as a basis for the technician to create an action decision report.

The present maintenance planning model includes components with a fixed remaining life limit, like the LLPs, while the remaining life for OC parts is based on historical failure data. There is therefore a need for improved life estimates for the OC parts to better incorporate them in the maintenance planning model and obtain more reliable outcomes.

IV. PROGNOSIS AT COMPONENT/SUBSYSTEM LEVEL FOR OC ITEMS

Maintenance for OC parts is a preventive primary maintenance process. It requires that an item of equipment, or a component, is periodically inspected and checked against some appropriate physical standard to determine whether it can continue in service. The goal is to remove the unit from service before failure during normal operation. These standards may be adjusted based on operating experience or tests, as appropriate, in accordance with an operator’s approved reliability program or maintenance manual [30, 31]. For an aircraft engine installed in an aircraft, the standard referred to is the Aircraft Maintenance Manual (AMM), a formal document that details the way in which all maintenance tasks will be carried out on the aircraft. It includes items such as the lubrication system functional checks and servicing of the airplane, but usually excludes structural repairs and modifications [31].

An OC part is changed when needed. The decision is based on several factors, such as cracks, discoloration, and other fault modes that indicate the health of each component. The size of allowed cracks and other allowed fault modes can be found in the Component Maintenance Manual (CMM), a formal document that details the way in which off-aircraft maintenance tasks on specified components are carried through. The maintenance tasks contained in these manuals include procedures for restoring a structural component to a serviceable state. Reworking and refinishing procedures are often provided in the appropriate CMM [32]. Based on their experience and using the information available from inspections and the data in the CMM, technicians must estimate whether an approved component will function adequately until the next maintenance event. The nature of OC parts makes it necessary to evaluate different prognostic techniques that can be data-driven, physical models, symbolic, or thresholds based on technical criteria. A prognostic method based on thresholds or technical criteria will contribute to increasing the accuracy of the prognosis as well as avoiding different decisions being made by different technicians with differing skills and experience.

V. UNCERTAINTY MANAGEMENT IN REMAINING USEFUL LIFE AT A SYSTEM LEVEL: BENEFITS OF OC PROGNOSIS

In the current maintenance process the actual status of OC parts can only be identified through inspection and non-destructive testing. This status evaluation could, however, be improved. The estimation of the remaining life for OC parts could also be improved if they could be divided into different life length groups using a more classification method. The method would allocate the OC parts to groups depending on detected and classified fault modes, component status, and an estimate of the remaining life for each component. The estimated remaining life can then be used to indicate how much longer each component could fulfill its requirements and be kept in operation.

A replacement model that uses better life estimates for OC parts would also make it easier for technicians to ensure that the correct maintenance activities are performed at each maintenance interval. A replacement model including better life estimates for OC parts might allow a more reliable replacement schedule to be calculated, as well as providing a better support system for technicians. Another advantage of a better model would be that knowledge could be shared by a group and not limited to only one individual. A possible outcome would be that a replacement model using better life estimates for OC parts might change the way in which maintenance is performed. One possible change might be longer intervals between maintenance events because the replacement schedule is based on more reliable input data. A desirable effect would be to eliminate at least one maintenance service due to longer intervals between maintenance events.

Another outcome of developing and implementing a method to estimate the remaining life of the OC parts would be that the working process of inspection and testing of OC parts could be more standardized less complicated to perform, and be supported by improved routines in order to maintain and use knowledge.
VI. PROGNOSTICS AND DIAGNOSTICS

There are three mains ways to model how faults develop using symbols, data, or mathematical formulations based on physical principles, as shown in Fig. 8.

![Diagram of Diagnosis and prognosis approaches](image)

Fig. 8. Diagnosis and prognosis approaches, adapted from [33]

Diagnostics are actions taken for fault recognition, fault localization, and cause identification [19]. Diagnostics can also be said to refer to the investigation or analysis of the cause or nature of a condition, situation, or problem. Prognostics are concerned with calculating or predicting the future as a result of rational study and analysis of available pertinent data. In terms of the relationship between prognostics and diagnostics, the latter is the process of detecting and identifying a failure mode within a system or subsystem [34].

Prognosis is defined by the International Organization for Standardization (ISO) as “the estimation of time to failure and risk for one or more existing and future failure modes” [35]. In this understanding, prognostics is also called the “prediction of a system’s lifetime” as it is a process whose objective is to predict the remaining useful life (RUL) before a failure occurs, given the current machine condition and past operating profile [20].

There are several methods of monitoring the condition of rotary machinery. The most common are the model-based and data-driven approaches for diagnosis and prognosis. Each has its own advantages and disadvantages, and they are therefore often used in combination in many applications [34].

This research project concentrates on prognosis to better estimate when OC parts will break. Diagnosis is outside its scope, since it is clear that OC parts can and will break if not maintained properly.

VII. PROGNOSIS AGGREGATION FROM COMPONENT TO SYSTEM LEVEL AND FUTURE WORK

The Life Tracking System (LTS) has resulted in much better information about, and control over, the life consumption of the LLPs. As customers will continue to use their engines with the same flight profiles as before, it is also possible to get very detailed predictions over how many more cycles individual LLPs will survive. Better information regarding life consumption for the LLPs improves the input data for the mathematical replacement model, leading to more reliable optimization results.

LTS is, however, not able to calculate the life consumption for OC parts, so it is still necessary to estimate their remaining life. This needs to be improved (Fig. 9), so that all necessary engine components can be incorporated in the mathematical replacement model.

To increase the reliability of the optimization results, all components liable to maintenance in the engine need to be incorporated, independent of whether they are LLP or OC parts. Fig. 10 shows that almost all modules consist of a mix of LLPs and OC parts. With a simple assumption that the reliability of the life estimations for the complete system is no better than its weakest point, it is easy to realize the importance of increasing knowledge on how to estimate the remaining life for OC parts in order to increase the knowledge of the remaining life for the entire engine.

To show the impact better life estimates for OC parts will have on a subsystem, the low pressure turbine in Fig. 10 is selected for further analysis. The low pressure turbine consists of thirteen components, LLPs as well as OC parts (Fig. 11). The components are divided between the stator (marked “x”) and rotor (marked “y”), to which most of the components are related.

Both LLP and OC parts are required for engine operation. A reliability block diagram for the low pressure turbine is shown in Fig. 12. During maintenance the low pressure turbine will only be approved for continued operation if all components are functioning and approved within given limits. If this information is transferred into the reliability block diagram, all components will be in a serial structure. The system will only work as long as there is a connection between the end points a and b through all the blocks representing the components.

The reliability block diagram in Fig. 12 shows that LLPs and OC parts are equally important if the system is to be approved for continued operation at a maintenance event. Improving the remaining life estimation for an OC part will help to improve the reliability of the complete subsystem (module), as an improvement affecting any component will improve the planning for the complete subsystem. By extension, this argument also applies to the complete engine system. Thus better life estimates for the OC parts will help to improve the reliability of the complete engine system.

LTS calculates the remaining life for LLPs based on actual flown missions. This information is then simplified and transferred to the maintenance system. Remaining life data is later used as the basis for calculating which components to maintain at each individual maintenance event. Better life length estimations can in turn be used as input to maintenance optimizations (Fig. 13).
Fig. 9. Illustration of achieved information level for remaining life predictions in aircraft engine components [36]

Fig. 10. Engine structure diagram indicating the location of each LLP or OC part
Fig. 11. Low pressure turbine structure diagram indicating the location of each LLP or OC part

Fig. 12. Engine structure diagram indicating the location of each LLP or OC part

Fig. 13. Addition of life length estimations for OC parts to the maintenance organization
The aim of this research is to develop better life length estimates for OC parts. Several factors need to be taken into consideration. First of all, the engine needs to be broken down into the subsystems and components to be included in the maintenance optimization. At this time the focus will be on aggregation of the prognostic information for the relevant OC parts (Fig. 10). The result of this prognostic information and further aggregation will result in more detailed criteria to help maintainers identify the need for maintenance and/or the influence the extent of the maintenance.

The next step is to find a balance between the effort to obtain remaining life estimates and what is required to derive reliable plans from previous maintenance optimization models. This step evaluates prognostic uncertainty and determines how good the estimates are. Uncertainties regarding the mechanical properties of each component combine with uncertainties regarding the future use of the engine. Thus it is also necessary to evaluate the costs associated with reasonable efforts to determine the lead time, labor hours, and resources required to better estimate the remaining life of OC parts. It is probably possible to produce very good estimates with high time consumption and cost, but in some cases there may be no impact on the maintenance decisions. Thus the balance between the effort put into the analysis effort and the impact needs to be assessed. It is also important to evaluate the robustness of the replacement model (i.e. how sensitive the model is to “errors” in the estimates of remaining life).

It is important that the remaining life estimation for OC parts leads to estimates of the remaining lives for each component and incorporated into the replacement model. Life estimates for OC parts can be binary (“ok/not ok”), a few possible values, a continuous variable in a specified range, or even data in an algorithm. This will probably vary from component to component, but these are key issues in resolving the problem of developing better life estimates for the OC parts in an aircraft engine.

Prognosis has been popular in the aircraft field and much work has already been done in the fields of life estimation, prognosis, and remaining useful life. The most relevant prognostic methods for aircraft engine parts should be described and selected according to the different types of OC parts and the desired certainty of the outcome.

This research should result in a clear proposal indicating whether life estimates should be based on visual inspections, currently available testing methods, or new techniques that may be required or recommended based on RUL estimations. Well-established prognostic techniques such as physics-based, data-driven, symbolic, hybrid, or a context awareness approach that combines contextual/situation information awareness will be considered.

REFERENCES


[37]
Veronica Fornlöf is a industrial PhD student at GKN Aerospace Engine System and the University of Skövde. She has received her Master of Science in Mechanical Engineering from the Linköping University in 2009. Her research topic is related to maintenance within aviation and aircraft engines.