S.A.Stammes

Quality of the integral aircraft engine MRO chain

A case study on the Low and High Pressure Compressors at KLM Engineering & Maintenance Engine Services

TU Delft

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by

S. A. Stammes

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TU Delft

Preface

This report represents the results of my graduation project, needed to become a Mechanical Engineer with a specialization of Transportation Engineering and Logistics at the Delft University of Technology. This experience was full of challenges and it was my first of being a full-time intern in a corporate environment. The aim of this research was to create a control model for the quality of the Boeing 737 CFM56-7B engines within the MRO process.

First of all, I would like to thank KLM Engineering & Maintenance for the opportunity to conduct my graduation at them. Thank you Alex Gortenmulder and Guus Philips van Buren for the supervision and enthusiasm from the Lean Six Sigma office and a special thanks to Nienke Klinkhamer, Willem Brüggeman, Pui Chan and Govert Soeters for the input from Engine Services and for the opportunity to participate in the TAT45 taskforce. I would also like to thank my fellow graduating students Bart Belder and Stéphanie Hoekx for their advice and the mind stimulating table football sessions and gemba walks in the hangars.

Secondly, I would like to thank the graduation committee, Dingena Schott. Thank you for the critical questions, which helped me to structure my thesis and presentation. Wouter Beelaerts van Blokland, thank you for being my daily supervisor and sharing your amazing knowledge on the aircraft industry, Lean Six Sigma and for stimulating my critical thinking.

Thirdly, you never really get the time to say a proper thank you to everybody who supports you throughout your entire study period, that is why I would like to use this moment to thank everybody who has supported me throughout. I would like to start off by thanking Anne and Lennox McGregor, Brenda and Philip Harewood, Sheila and Bill Robbins and the rest of the family for helping me throughout the years. I would also like to thank my friends in alphabetical order Fabian, Joris, Maud, Miguel, Mike, Naphur, Robert and others for hearing my frustrations but also cheering with me in prosperity.

I would also like to thank everybody who worked with me during the last few years. I would like to thank you for the patience during my thesis period, now it's time to continue the good work and use the knowledge gained during this thesis in new projects and products.

Last but definitely not the least, the most important ones. Mam, Nigel, Jasmine, Krissy, Patty & Mila, thank you for the support and for being my go-to people and life rafts throughout the years!

Enjoy reading my thesis!

S. A. Stammes
Cambridge MA USA, April 2018

Abstract

This research presents a model to estimate the influence of the variance of the quality of repair steps on the EGT Margin within the serviceable limits of the overhauled modules. This model is created using literature and a single case study conducted at KLM Engineering & Maintenance Engine services (KLM E&M ES). The model is tested using a data set consisting of all the quality measurements registered during the repair process for two quality contributing modules within the engine. The main research question this thesis is attempting to answer is: *How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?*

This research begins with determining how the quality performance of the total engine is influenced. Then, the research is focussed on the gas flow path clearance. Each engine is built up out of sets of fanblades in the compressor and turbine modules. The quality of the engine is measured in degrees of EGT Margin (EGTM) and has a direct relationship to the Time On Wing (TOW) of the engine on the aircraft. Deterioration of the EGTM is mainly caused by increases of the fanblades tip clearances and deterioration of the seals that need to be matched to the casings for each individual set of fanblades. The researched is supported by the case study at KLM E&M ES and is scoped to investigate the CFM56-7B engine used in the Boeing 737 aircraft type and focusses only on the compressor part of the gas turbine consisting of two modules, the High Pressure Compressor (HPC) and Low Pressure Compressor (LPC).

In 2017, the quality performance of KLM E&M ES was 67%. For the current state at KLM E&M ES there is a high fluctuation in the delta contractual and actual EGT Margin. Hence, the match between EGT Margin that is agreed on and delivered is unstable. In 73% of the cases where a quality contract is made with the customer, there is an over performance in terms of degrees EGT Margin. The current state quality is controlled by the engineering department which creates a Bill of Work (BoW) where four types of repair possibilities are identified per engine module in order of EGT impact: Full overhaul, Performance restoration, Minimal overhaul or the part is serviceable removed and later assembled as whole. Since the BoW is the only type of quality control within the process, the contractual value cannot be set to a higher standard that can be monetized. This research helps to identify steps within the process where measurements take place that can help to estimate the total EGT Margin contribution value to the engine as a whole. This way, the EGT Margin level can be determined based on the in situ measurements and the goal is a closer match to the contractual EGT Margin values with the actual ones.

This research is concluded with a future state analysis where a Matlab model of the Low and High Pressure Compressors is created. The Matlab model is based on the Engine Service Manual and Workscope Planning Guide with the goal to simulate the impact of decreases in variance of the fanblades sets. The model is validated and tested using the KLM E&M ES case study with the actual handwritten quality performance registrations on piece part level. For the HPC, the limits of fanblades repairs has a bandwidth of 5 microinch in which the repair is considered serviceable. This 5 microinch influences the EGT Margin with 3,7 degrees EGT Margin potential for the HPC. When the lowest blades within a set are replaced, the maximum potential EGT margin that can be gained is 1.6 degrees EGTM. The Matlab model shows that the largest potential EGT gain is in stage 8 of the High Pressure Compressor. The variance at KLM E&M ES is the highest in stage 8 and 9. The decrease of the variance can result in a potential of 11 weeks Time on Wing.

This research ends with recommendations for further research. A similar study is needed on the quality contribution of the combustor and turbine assy's. Finally, this research can be continued in order to create a model for EGT Margin estimation for the CFM56-7B engine. A hypothesis for continuation of this research is formulated as follows:

The quality of the CFM56-7B engine in terms of EGT Margin can accurately be predicted using the repair step measurements of the combustor, compressors and turbines.

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List of Abbreviations

7B	General Electric CFM56-7B Engine	21
80C	General Electric CF6-80C Engine	21
80E	General Electric CF6-80E Engine	21
AFI	Air France Industries	22
BoW	Bill of Work	26
CC	Compliance Check	41
Combustor	Combustor module	26
CTQ	Critical To Quality	28
EGT	Exhaust Gas Temperature	5
ESM	Engine Service Manual	42
FAN	Fan module	26
FOCUS	Find, Organize, Clairfy, Understand, Select	8
GE	General Electric	1, 21
GEnx	General Electric GEnx Engine	22
HPC	High Pressure Compressor module	26
HPO	High Performance Organisation	2
HPT	High Pressure Turbine Module	26
IC	Incoming Check	41
KLM	Koninklijke Luchtvaart Maatschappij	2
KLM E&M	KLM Engineering & Maintenance	2
KLM E&M ES	KLM Engineering & Maintenance Engine Services	1
KPI	Key Performance Indicator	3
LPC	Low Pressure Compressor module	26
LPT	Low Pressure Turbine	26
MFI	Model for improvement	8
MRO	Maintenance, Repair and Overhaul	1, 2

MTBUR	Mean Time Between Unscheduled Removal	4
OEM	Original Equipment Manufacturer	23
OGSM	Objective, Goals, Strategies, Measurers	4
OTP	On Time Performance	4
PDCA	Plan-Do-Check-Act cycle	8
SIPOC	Supplier, Input, Process, Output, Customer	28
SPC	Statistical Process Control	17
SV	Shop Visit	2, 22
TAT	Turnaround Time	3, 22
TOC	Theory of constraints	11, 16
ToW	Time on Wing	4, 5, 40
TQM	Total Quality Management	13
WPG	Workscope Planning Guidel	43

Contents

1 Introduction

This chapter serves as in introduction to the research conducted in this thesis. It will describe the context of this research and will introduce the case study conducted at KLM Engineering & Maintenance Engine Services (KLM E&M ES). The central problem for KLM E&M ES is described and the scope and the objectives are defined. Furthermore, the main research question and sub-research questions are introduced. Finally, the approach and structure of this thesis are presented.

1.1. Research context

Every aircraft needs maintenance, repair and overhaul (MRO), this maintenance can be divided into three main sectors: airframe, engines and components. In terms of cost, engine maintenance is the most significant expenditure and will have a large contribution on the value of the entire aircraft [1], this is visualized in Figure 1.1. This research focuses on turbine engines that can be used on commercial jet aircraft, which are classified as *Turbofan Engines*.

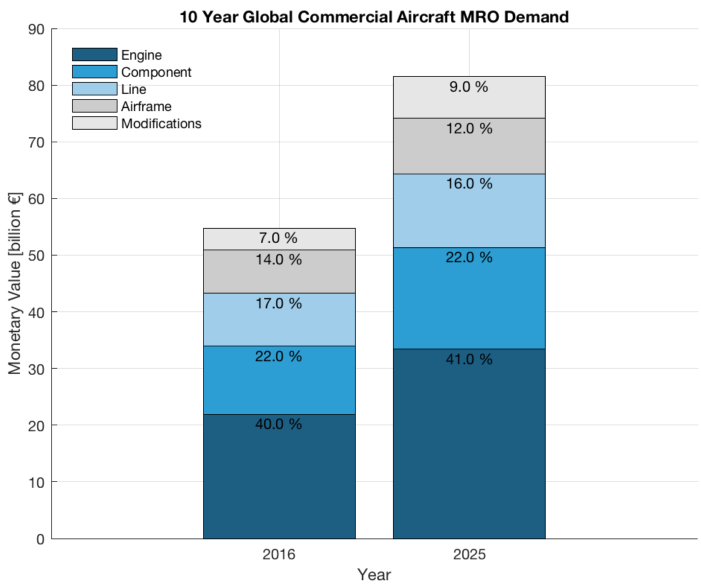


Figure 1.1: 2016 and 2025 prediction of global commercial aircraft MRO demand market value and build-up [1]

The aircraft engine market is dominated by General Electric, Rolls-Royce and Pratt & Whitney. General Electric (GE) and Safran Aircraft Engines form a joint venture called CFM International and Rolls Royce and

Pratt & Whitney form a joint venture called International Aero Engines [1]. In terms of market share, GE has the largest share with having its fully owned share of 21% and joint venture share with CFM of 37%. CFM is expected to remain the largest engine provider with the introduction of the CFM LEAP engine for narrow body jets [6].

The aircraft engine MRO market is worth around 22 billion Euro in 2016 and is expected to be worth around 34 billion Euro in 2025. The aircraft engine MRO market is divided into various MRO providers that can be categorised in the following three sectors [40]:

- Original Equipment Manufacturers (OEMs) (E.g. General Electric, Rolls Royce, Boeing)
- Airlines who provide MRO (E.g. KLM E&M, Delta TechOps, AFI E&M)
- Dedicated engine MRO providers (E.g. Vector Aerospace, GKN, SR Technics)

Aircraft engine MRO is a highly competitive market. Engine OEMs are currently busy changing their after-market strategies in order to get a larger market share in the MRO market. Engine OEMs are trying to leverage the Big Data coming from the engines, and have data contracts for preventative maintenance setup for their new generation of engines[10]. They are also embracing module swaps in order to reduce the workscope during a Shop Visit (SV) [25].

1.2. Research field

This research is conducted for the TU Delft, supported by a case study within the Lean Six Sigma office of KLM Engineering & Maintenance (KLM E&M). KLM E&M is a part of KLM, which is part of the Air France-KLM Group. The Air France-KLM Group flies with about 550 aircraft in total. More about the KLM aircraft can be found in Appendix B. Air France-KLM as a whole is under performing and needs to transform into a High Performance Organisation (HPO) in order to stay competitive. A framework for improvements, Perform 2020, has been created and consists of several transformation projects [14]. Perform 2020 covers four main themes: Customer focus, profitability and growth, competitive cost basis and a different way of working.

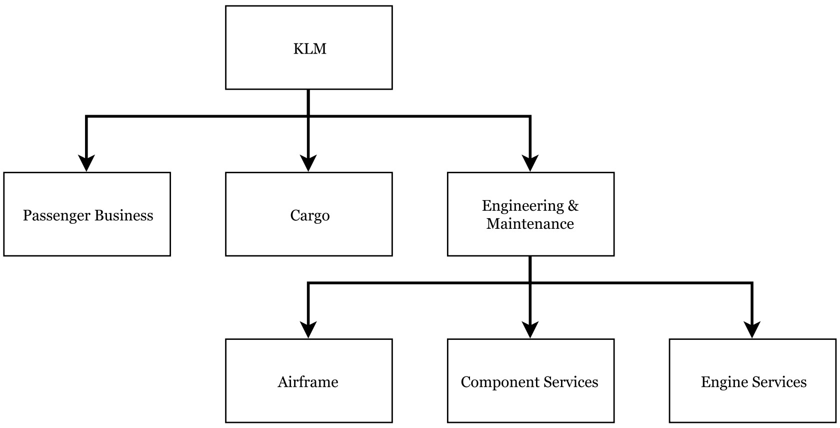


Figure 1.2: KLM E&M and its maintenance units

As shown in Figure 1.2, KLM has three main divisions, Passenger Business, Cargo and Engineering & Maintenance. This thesis focuses on KLM Engineering & Maintenance, which has the main goal to provide Maintenance, Repair and Overhaul (MRO), in order to continue airworthiness of the aircraft for its customers.

KLM Engineering & Maintenance consists of three departments: Airframe, Component Services and Engine Services. Each department has its own strategy in order to improve its performance guided by Perform 2020. More about the Air France-KLM Group and its organisational structure, as well as the aircraft MRO market can be read in the company profile in Appendix C.

This research focuses on Engine Services, a very important key component in the growth strategy of Air France-KLM. In the first half financial report of 2017 [15], it was stated that the aeronautics maintenance industry has a growth forecast of 4.1% in the next decade. Air France - KLM states that the growth will be driven in particular by the engine and component support businesses. Engine Services has three main processes on a strategic level:

1. To organize Engine Availability
2. To provide Engine MRO
3. To provide Parts Repair & Engine Accessories MRO

These three KLM EM ES processes can be subdivided into the different process steps on operational level as seen in Figure 1.3. This figure can be seen in detail in Appendix C.

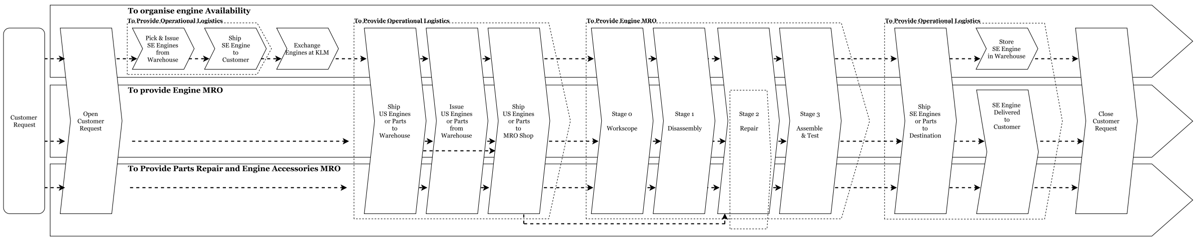


Figure 1.3: KLM E&M ES overall process chain

From this overall process chain a dashboard is created with several result Key Performance Indicator's (KPI's) that are used to optimize the process. The KPI's that are used for steering the process are divided into availability and MRO based KPI's. The availability based KPI is the amount of *Serviceable Spare Engines*. The MRO based KPI's are the *On Time Performance*, *Product Quality EGT*, *Test Cell Yield* and the *Productivity*.

Previous research has been conducted in the form of TU Delft students graduating at KLM E&M ES through the KLM Lean Six Sigma Office. The following students have conducted their thesis at KLM E&M ES in chronological order:

1. 03/2016 - Willemijn Mogendorff: Aircraft Engine Combustor Maintenance - A model to measure MRO turnaround time [28]
2. 04/2016 - Pien Meijs: Reducing the turnaround time of in house repairs of aircraft engine MRO services [26]
3. 11/2016 - Amber Rozenberg: Designing a comprehensive framework to analyse and improve engine MRO processes from an integral perspective [35]
4. 06/2017 - Govert Soeters: Operational excellence by continuous improvement of the integral engine MRO chain [37]

The previous research scopes were all Turnaround Time (TAT) focused and are visualized in Figure 1.4. Willemijn Mogendorff created a model to measure, define and improve the TAT with a focus on the combustors [28]. Pien Meijs used theory of constraints methodology and created a framework for TAT improvement of the fanblades [26]. After which Amber Rozenberg analysed the control of the Integral MRO chain resulting in a new measurement method from a stage approach to a value stream approach. Most recent, Govert Soeters analysed the management decision that needs to be taken in order to improve the integral engine MRO chain.

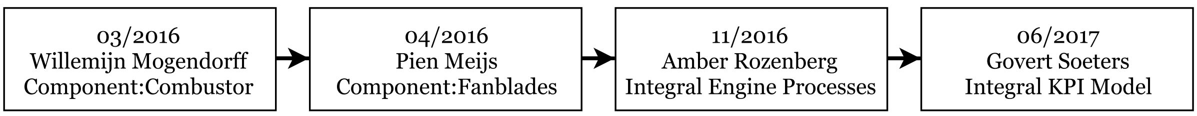


Figure 1.4: TU Delft - Thesis Case Studies at KLM Engineering & Maintenance Engine Services

KLM Engineering & Maintenance Engine Services has four fully analysed, turnaround time optimizing cases ready for implementation and is currently busy implementing these control models in order to improve the Engine MRO process.

1.3. Research problem definition

This research focuses on the Engine Services process chain from a quality point of view. To understand the Engine Services process chain, an analysis has to be made to determine the critical aspects of the control on quality. Furthermore, research needs to be done on how value is added and measured within the MRO chain. One of the goals of this research is to understand how the quality is measured and controlled within the process. In order to do so, the Key Performance Indicators need to be understood, since they are the indicators that are used by management to steer the process. As stated before, the result KPI's for Engine Services are defined as the following:

- On Time Performance
- Product Quality EGT
- Test Cell Yield
- Productivity
- Serviceable Spare Engines

There are many improvement projects in place at KLM E&M ES that are focused on improving the On Time Performance. The 2017 On Time Performance (OTP) is displayed in Figure 1.5 . The next logical step is to improve the next unstable KPI, the engine Quality Performance which is shown in Figure 1.6. This also matches with the strategy determined by the VP Engine Services, Paul Chün.

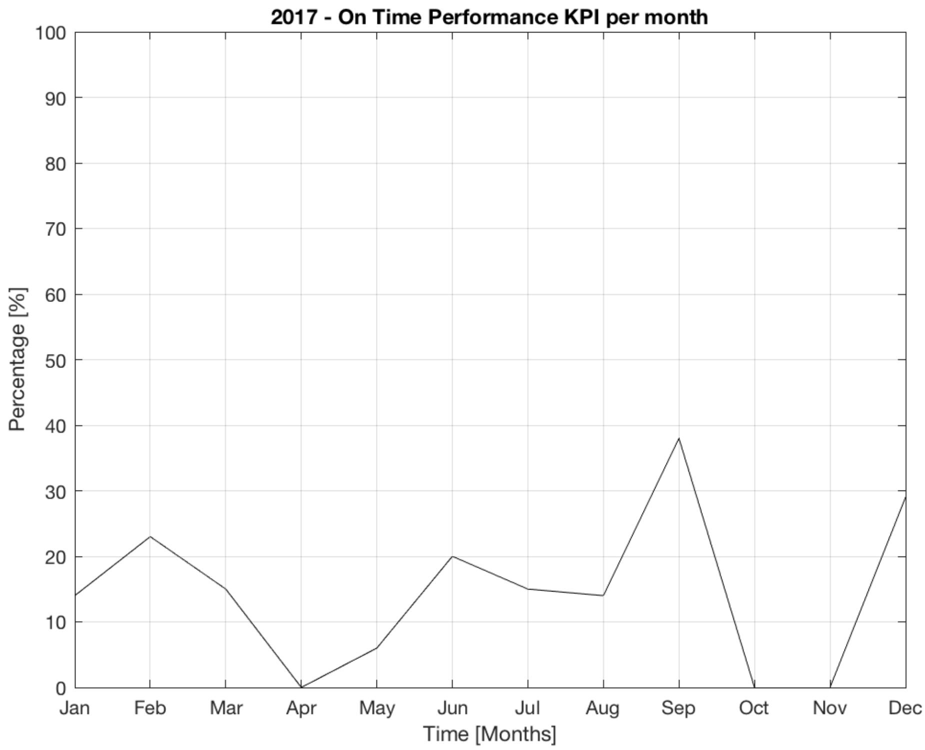


Figure 1.5: 2017 OTP Performance

As stated before, every division of KLM can set its own goals in order to meet the Perform 2020 objectives. Every year the goals of the different shops are registered in the Objectives, Goals, Strategy Measurers (OGSM) action plans. The 2017 KLM E&M ES action plan is based on the 2020 ES objectives as defined by the VP of KLM E&M ES, Paul Chün. It can be observed that most of the objectives are turnaround time focused, but some of the objectives in the 2017 action plan of Engine Services are also product quality focused:

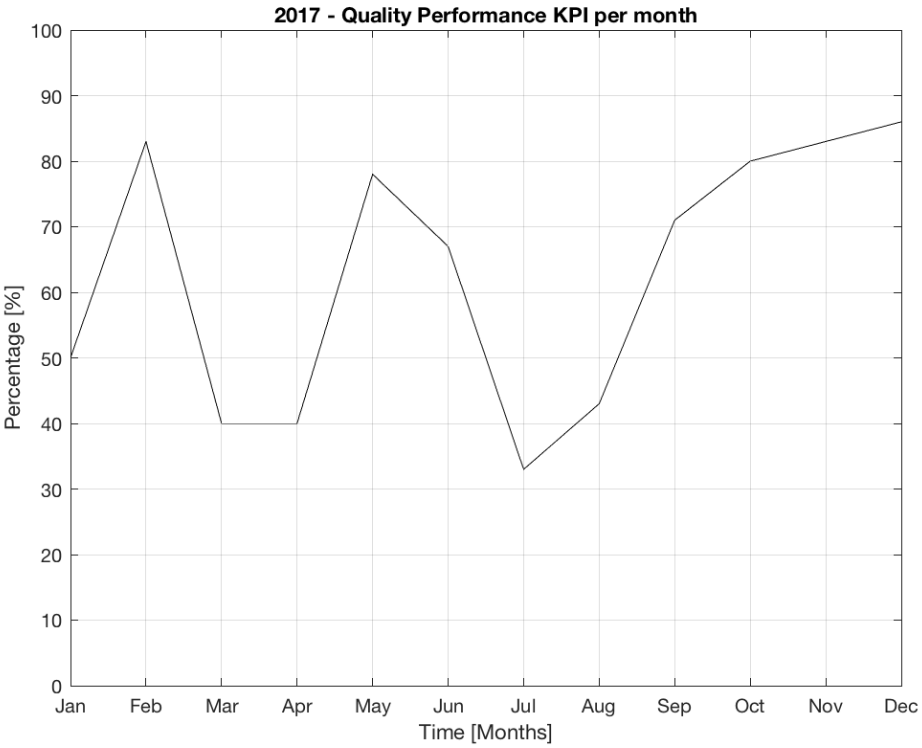


Figure 1.6: 2017 EGT Performance

- Improve Mean Time Between Unscheduled Removal(MTBUR)/Time on Wing (ToW) by preparing and executing engineering improvement programs.
- Increase predictability of maintenance and engine availability against lower cost.

The engine quality is currently only measured in terms of the Exhaust Gas Temperature (EGT) Margin. When an engine is operating, it will result in wear of the engine. There will be more friction within the engine and friction will result in a higher operating temperature. When the temperature of the engine is lower, the efficiency of the engine is higher. The goal is to have an engine with an as low as possible EGT temperature, in order to have a long life expectancy. In Chapter 3 the EGT Margin and engine overhaul process is described in depth.

The KPI currently is measured as a *yes* if the contractual EGT Margin is met or a *no* if it is not. The current product quality performance in 2017 was 67%. This means 33% was under performing and could be delivered with a financial penalty depending on the type of contractual agreement with the customer. This 33% was not only a problem because of the financial penalty, but because the engine is not delivered as agreed upon and the customer will not be satisfied with the quality of the final product. When looking into the 67% that was delivered above the contractual quality limits it can be noted that the performance is too high. The trigger to this research is a statement made by United Airlines to KLM E&M ES:

When engines are overhauled by KLM E&M ES as a part of the GE Offload Pool, the EGT Margin is way higher than contractually agreed on and higher than an overhaul with other GE Offload MRO Providers.

In terms of customer satisfaction, the customer satisfaction of United Airlines as part of the GE Offload is increased, hence, this is not a problem. However, for KLM E&M this is a problem, the engines are delivered with a too high quality and no monetary value to KLM is added for this increase in EGT Margin for the customer. The customer gets direct monetary value in terms of an increased Time on Wing (ToW). Furthermore, an increased EGT Margin might be the cause of KLM E&M ES spending too much resources on an engine overhaul. The performance of the quality is not stable and needs to be analysed from an over-performance perspective.

The research problem for this thesis is defined as follows:

There is currently not enough quality control within the MRO process to match the actual EGT Margin output with the contractual

1.4. Research scope

This research focuses on identifying the quality contributions within the aircraft MRO Engine chain, in order to obtain a stable process in terms of quality. The performance in quality is defined as the match between customer based contractual EGT Margin and actual EGT Margin at the end of the Engine MRO process, this is the monetized value with a direct relation to the quality control. Customers want an as high as possible EGT Margin, while the MRO supplier wants to spend as little resources in order to meet the contractual EGT Margin as close as possible. Furthermore, the customer wants the Engine MRO Process to be finished within a certain time span that cannot be exceeded.

KLM E&M ES handles 4 main engine types: The GE CFM56-7B, the GE CF6-8C, the GE CF6-8E and the newest GE GEnx. As mentioned before, this research aims to continue on the research conducted by previous students. Although the other students had a focus on the Turn Around Time, their analyses can be used to determine the influence of the quality control improvements on the Turn Around Time. Therefore, this research will focus only on one engine type,i.e. the CFM56-7B. This engine is the main engine type that receives MRO by KLM E&M and over 50% of their total engine pool consists of this type of engine. Furthermore, this engine is the reference engine for KLM E&M ES improvement projects.

In a gas turbine engine, the compressors and turbines are the most critical to the quality performance of the engine since they are contributing directly to the combustion process. In this research, the compressors and turbines are within the scope, the other components that do not have direct influence on the combustion are not taken into account for the engine performance.

1.5. Research objectives

The objective of this research is to develop a model that can create insights to help control the quality of an Engine MRO process chain and to influence the critical to quality points within the process chain. The case study at KLM E&M ES will be used to create the model based on empirical data. Based on the research problem as described in Section 1.3 and research scope as described in Section 1.4, the research objective is formulated as the following:

Create a model for the quality performance in terms of the Exhaust Gas Temperature Margin of an Engine MRO process chain and implement this model on the most critical to quality assy of the engine in order to stabilize the quality performance.

1.6. Research questions

The main research question of this thesis follows from the research objective as described in Section 1.5:

How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?

The following sub questions are based on the literature analysis and are formulated in order to answer the main research question:

1. What characteristics from literature can be used to define product and process quality?
2. What tools are available from quality improvement theories that can support this research?
3. What agreements are made on quality performance with the customers?
4. From a technical point of view, what factors influence the quality of the engine?
5. What is the main qualitative value driver in order to be airworthy?

6. What levels of maintenance are available in the engine MRO process?
7. How is the workscope determined for engine MRO?
8. What is the relation between quality and Time On Wing?
9. Which assy's & modules can be identified that contribute the most to the quality of an Engine?
10. How is the current quality performance controlled during the MRO process at KLM E&M ES?
11. How do you measure the quality output of the HPC and LPC assy's?
12. What strategies can be proposed in order to decrease the variance in the process?
13. How do you model the quality output of an individual assy?
14. What is the potential in increasing the quality performance?

1.7. Research approach

This research focuses on process and product quality in an MRO environment. There are several possible approaches to conduct this research. Since a case study is conducted, the case study methodology in business research [13] is used. This case study methodology is combined with a process improvement approach to form the research approach.

1.7.1. Case Study Research

As the main structure for this research, the Case Study Research methodology [13] will be used as a backbone. According to a literature review, the case study has two main distinctions:

- Practice-oriented
- Theory-oriented

The literature review in the Case Study Research methodology description [13] states that research is more often practice oriented (65%) than theory-building oriented (31%) or theory-testing oriented (4%). The practice-oriented research describes the design, implementation and evaluation of a theory in a company or situation. The theory-oriented research is more exploratory and the aim is to contribute to theory development by exploring instances of the studied object.

This research will use the theory-oriented research approach since the objective of this research is theory oriented [13]. The theory-oriented framework for the Case Study Research is shown in Figure 1.7.

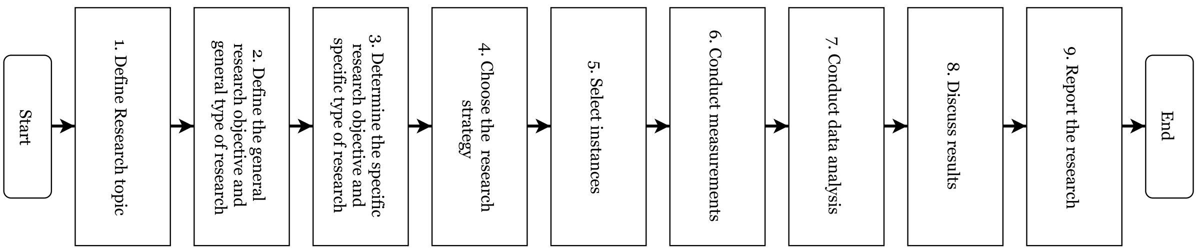


Figure 1.7: Case Study Research stepwise approach [13]

The theory-building oriented case study methodology [13] states that the aim of data analysis is to draw conclusions about:

- Where there is a relationship between concepts A and B
- If there is a relationship, what type of relationship this relationship is

The process of discovering relations according to the case study methodology focuses on finding relationships with a strong deterministic relationship and to look for weaker relationships if the strong ones are not found. The order to discover relationships is as follows:

1. Looking for a sufficient condition
2. Looking for a necessary condition
3. Looking for a deterministic relation
4. Looking for a probabilistic relation

This approach will be used as the basis to find relationships in the data collected from this research.

1.7.2. Deming

W. Edwards Deming was an American engineer who had the nickname *the godfather of quality*. Deming was responsible for making the Plan-Do-Check-Act (PDCA) cycle popular [7]. He also is accredited for getting process improvement tools and quality improvement tools adopted from industry in other markets. The PDCA cycle is meant to structure continual improvement of a process or product [27]. The PDCA cycle is shown in Figure 1.8.

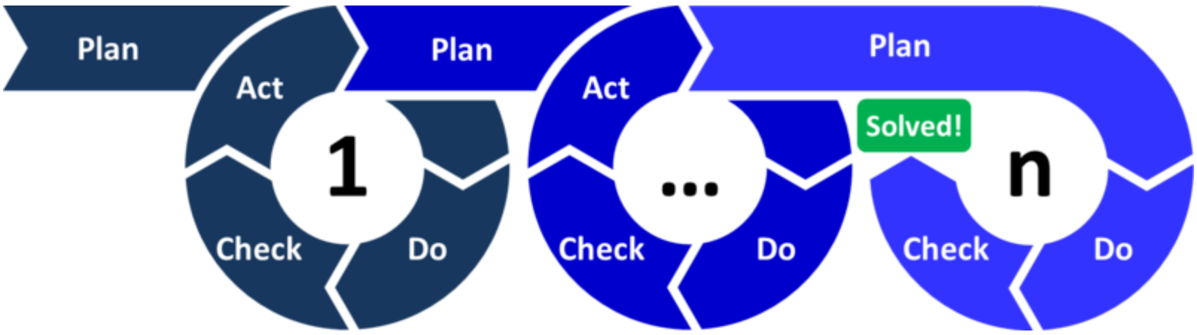


Figure 1.8: Plan-Do-Check-Act cycle of continuous improvement

There are different frameworks created to structure the PDCA cycle. Two of them that are well known are the Model For Improvement (MFI) and Find-Organize-Clarify-Understand-Select (FOCUS) frameworks.

The first framework, MFI, asks three questions before the cycle:

1. What are we trying to accomplish?
2. How will we know that a change is an improvement?
3. What change can we make that will result in improvement?

This framework is very practice oriented and is used to improve the speed of the PDCA cycle

The second framework FOCUS refers to a more detailed Plan stage of the PDCA cycle. *Find* stand for finding a process to improve. *Organize* is organizing the effort to work on improvement. *Clarify* focuses on getting the current knowledge of the process. *Understand* has a focus on understanding the causes for variation in the process. Finally, in the *Select* phase the improvement can be chosen and done in the PDCA cycle.

1.7.3. Lean Six Sigma

Lean Six Sigma methodology has a focus on improving performance of a process by systematically removing waste and reducing variation. The goal is to create an optimized stable process that is lean. The cycle consists of a five step approach:

- Define the problem and requirements
- Measure defects and process operations
- Analyse data and discover the root causes
- Improve the process to remove the causes of defects
- Control the process

Lean Six Sigma provides many tools that can be used for Process Improvement and Quality Improvement cycles. The literature study in Chapter 2 will provide a selection of tools that Lean Six Sigma offers in quality improvement like SIPOC and the Fishbone diagram.

1.7.4. Conclusion research approach

This research will combine the Case Study Research Methodology, the Deming FOCUS framework and the Lean Six Sigma tools as the approach to this research. The research approach with its corresponding chapters is visualized in Figure 1.9

1.8. Data collection

The data will be consisting of different sources. First of all, the understanding of the quality performance of the Engine MRO environment will be gathered from literature. Previous research will be used to get a fast understanding of the engine MRO process in general and the engine MRO Process at KLM E&M ES with the corresponding current bottlenecks and possible recommended solutions.

In the case study phase of this research, data will be collected from the by KLM provided databases. Furthermore, scanned documents with quality measurements will be digitized and analysed. All the data from the data systems will be combined with observations, measurements and interviews.

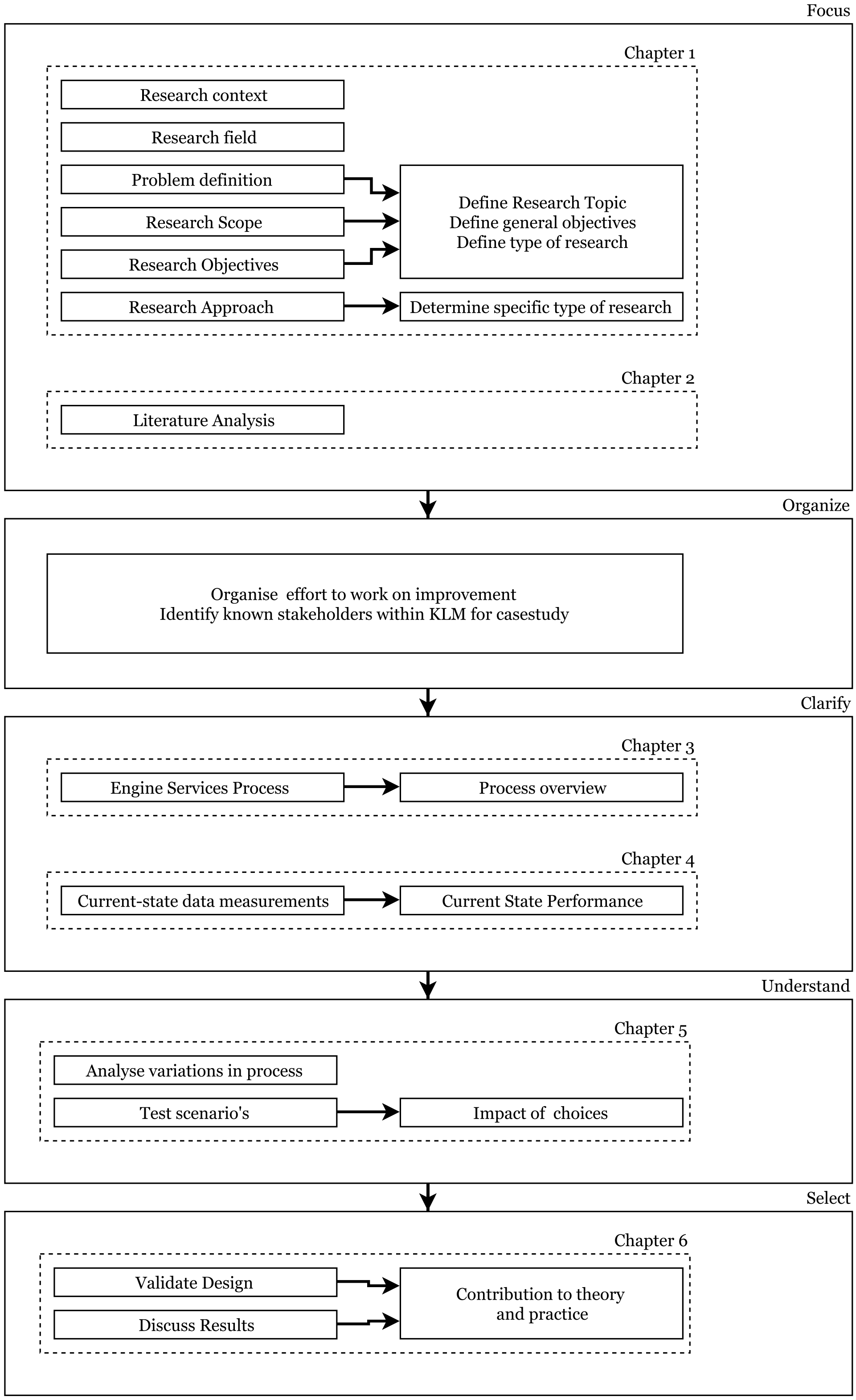


Figure 1.9: Research Approach

2
Literature Analysis

In the previous chapter the research was introduced and a general understanding was given of the integral engine MRO chain at KLM E&M ES. The main problem, a lack of quality control within the MRO process in order to accurately match the actual EGT margin to the contractual was introduced.

This chapter focuses on the theory needed in order to create a model that can be used to control the quality of the integral engine MRO chain. In order to create this framework, quality should be defined in general and within the KLM E&M ES environment. Furthermore, process improvement theories are studied and serve as a basis for the quality control framework. A choice is made to implement the available tools that follow from this literature research in a control framework. Finally, this chapter presents a control framework for the quality of an integral engine MRO chain.

The following sub research questions will be answered in this chapter:

1. What characteristics from literature can be used to define product and process quality?
2. What tools are available from quality improvement theories that can support this research?

2.1. Previous Research

As stated in the previous chapter, research has been conducted at KLM E&M ES previously. Chronically, Willemijn Mogendorf, Pien Meijs, Amber Rozenberg and Govert Soeters conducted case study research at KLM E&M ES. As stated in Section 1.2, Willemijn Mogendorff analysed a module, the Combustor[28]. Pien Meijs analyzed the Fanblades [26]. Amber Rozenberg started to create a model of KPI performance for turnaround time related measurements [35]. Govert Soeters continued on Amber Rozenberg's model an finalized the integral KPI model and redefined the stages of the MRO process [37] taking into account the case studies on module level.

Govert Soeters defined the performance measures for the MRO process as:

- Waiting time (days)
- Process Time (days)
- Average Turnaround time (days)
- Turnaround Time (days)
- Standard Deviation (days)
- On-Time Performance (percentage)

Then Govert identified the constraints in the system and used Theory of Constraints (TOC) methodology to elevate these constraints. He made the following iterations in his research:

- Least Slack Policy at outbound transport and cleaning

- Exploit Contract outsourced repairs
- Exploit Transport
- Elevate In-House repairs
- Elevate Assembly
- Elevate Outsource repairs

The conclusion of the research was that the deviation of the average TAT can be decreased, and the average value of the TAT can be decreased as well.

Now that the most previous research is known, it can be noted that all the previous research is Turnaround Time related. All the control in previous model is based on elevating and exploiting waiting time and picking order within the MRO process. In the final phase of this research, the previous research can be used to give a good estimation if there is room for quality improvement in terms of Turnaround Time. Furthermore, the previous research identifies bottlenecks in the systems. These can be used as first steps to analyse if these are bottlenecks within the quality performance of the system.

2.2. Aircraft Engine MRO Quality Characteristics

Within the aircraft Engine MRO industry, there is no room for defects. The standards per part are set so high in order to guarantee serviceability of a component. Therefore, this literature study does not focus on getting a process to a state of zero defects, but to get stability within the process in order to have a predictable quality output performance.

Before the quality definitions for an engine MRO environment can be set and the type of control can be identified, the observations regarding quality at the KLM E&M ES case study are highlighted.

At KLM the product quality of the engine is mostly determined by the workscope, which is determined by the engineering department. The customer agrees with the engineering department on the workscope before the engine enters the process. During the process quality performance actions are taken by KLM E&M ES according to this workscope. The parts are visually inspected and refurbished/replaced as prescribed by regulations. The parts are monitored and measured on an individual level, and no in-situ measurements are analysed to predict the outcome of the product quality after the MRO process.

Process quality within KLM E&M ES is defined as the first time right performance. When rework is needed, the quality of the process shows variance to the normal situation which is shown in product quality defects. Furthermore, the process is steered by regulations from the OEM and all steps need to be performed as prescribed.

2.3. Quality Control

The next step in the literature research is to identify quality control methodologies. Deming, Juran and Crosby have been analysed on their vision of quality control.

2.3.1. Deming

Deming is known for making the PDCA cycle for continuous improvement a popular tool in quality improvement. It is the basis for many quality related frameworks (MFI, FOCUS). The PDCA cycle is sometimes applied to internal quality procedures by asking the following questions [38]:

- What are we trying to accomplish?
- How will we know that a change is an improvement?
- What changes can we make to improve?

These three steps are the basics of every improvement theory that is based on the PDCA cycle.

As mentioned in Section 1.7, the framework FOCUS refers to a more detailed Plan stage of the PDCA cycle. This framework will be used as the approach to this research.

- *Find* stand for finding a process to improve
- *Organize* is organizing the effort to work on improvement
- *Clairfy* focusses on getting the current knowledge of the process
- *Understand* has a focus on understanding the causes for variation in the process
- *Select* phase the improvement can be chosen and done in the PDCA cycle

Total Quality Management (TQM) has been a very popular tool made popular by Deming and is still used for quality improvement. TQM is also based on the PDCA cycle and it consists of the following elements in its basis [36]:

- Leadership
- People management
- Customer Focus
- Strategic planning
- Information and analysis
- Process management
- Performance

TQM drives organizations to be analytical and creative in order to have a high quality performance and be competitive at the same time [8]. TQM tools consist of many known tools used to visualize the performance of a process: Pie charts, histograms, run charts, Pareto charts, force field analysis, tree diagrams, flow charts and scatter diagrams and relations diagrams. The last two play a very important part since they can show relations between steps of a process and can be used to identify cause and effect relationships.

2.3.2. Juran

Juran is another father of quality management. He studied the Pareto principle which states that 80% of the effect follows from 20% of the causes and applied this principle to quality performance. Juran focused on the quality of the end product by identifying ten steps for quality improvement [18]:

1. Build awareness of both the need for improvement and opportunities for improvement
2. Set goals for improvement
3. Organize to meet the goals that have been set
4. Provide training
5. Implement projects aimed at solving problems
6. Report progress
7. Give recognition
8. Communicate results
9. Keep Score
10. Maintain momentum by building improvement into the company's regular systems

Furthermore, Juran developed a trilogy in order to reduce the cost of poor quality[24]. When quality is poor, waste can be identified from this poor quality performance. The Juran trilogy consists of identifying [24]:

- Quality Planning, this creates awareness of the necessity to improve
- Quality Control, this develops the method to test the quality and shows deviation

- Quality Improvement, this involves the continuous improvement cycle

2.3.3. Crosby

Crosby believes in the *Doing it right the first time* principle. He defines quality as a full conformance to the customers requirements. Crosby defined four absolutes of Quality Management [12]:

1. The definition of quality is conformance to requirements
2. The system of quality is prevention
3. The performance standard is zero defects
4. The measurement of quality is the price of non-conformance

Crosby had 5 pilars in order to prevent poor quality [3]:

1. Integrity: Quality must be taken seriously throughout the entire organization, from the highest levels to the lowest. The company's future will be judged by the quality it delivers.
2. Systems: The right measures and systems are necessary for quality costs, performance, education, improvement, review, and customer satisfaction.
3. Communication: Communication is a very important factor in an organization. It is required to communicate the specifications, requirements and improvement opportunities of the organization. Listening to customers and operatives intently and incorporating feedback will give the organization an edge over the competition.
4. Operations: a culture of improvement should be the norm in any organization, and the process should be solid.
5. Policies: policies that are implemented should be consistent and clear throughout the organization.

2.4. Quality Definitions

Before continuing to quality control and process improvement theories, the quality definitions need to be set for product and process quality in an engine MRO environment. Also, the relationship between product and process quality and steps to identify this relation needs to be researched .

2.4.1. Product Quality

Research in Quality Management has not been able to introduce a definition of product quality. Therefore, Garvin [16] [17] identified five major approaches to the definition of quality and the conclusion was that different quality definitions can be justified under different circumstances.

Table 2.1: Alternative approaches to the definition of product quality [16]

Approach	Definition variables	underlying discipline
Transcendent	Innate excellence	Philosophy
Product-Based	Desired quantity of attributes	Economics
User-Based	Satisfaction of individual consumer preferences	Economics, marketing and operations management
Manufacturing- Based	Conformance to requirements	Operations Management
Value Based	Affordable excellence	Operations management

Within the engine MRO environment, the product quality can be identified as a combination of the alternative approaches as shown in Table 2.1:

1. The product quality can be identified by using the manufacturing-based approach, the Operations Management principle is the underlying discipline. The engine needs to conform to requirements set by regulation of CFM to assure airworthiness.

2. The product quality can be identified as the user-based approach, with operations management as its underlying discipline. Every customer has different demands to the Quality Performance output, so there is no standard output preference except airworthiness, which is covered by the manufacturing-based quality definition.

2.4.2. Process Quality

Now the quality definition is gathered from literature, the relationship with process quality is explained. Hackman and Wagemant [21] state that there is a large importance in variance in quality management. Variation is a normal common feature of process characteristics. For production processes some variation is statistically random, while others reflect actions from the production process. Statistically non-random variations reduce the product quality. Process improvement theories like TQM can be used to identify the random variation within a process and to reduce these.

2.5. Process Improvement Theories and Quality

There are many known improvement theories and frameworks that prescribe quality improvement. In this section Lean, Six Sigma, Lean Six Sigma, Theory of Constraints and Statistical Process Control are shortly described with focus on their vision on quality management and improvement.

2.5.1. Lean

Lean is a management system that focuses on delivering value to the end customer by continuously improving the value delivery processes. Lean provides a robust framework that facilitates improving efficiency and effectiveness by focusing on critical customer requirements [43].

Womack, Jones and Roos [44] identified five core prinicples of lean:

- Eliminate waste
- Identify the value stream
- Achieve flow
- Introduce pull
- Pursue perfection

Lean is not product quality focused but has the goal to eliminate waste and create a system with high efficiency [9]. In lean theory, there are seven types of waste identified [30]

- Transport
- Inventory
- Motion
- Waiting time
- Overproduction
- Over-processing
- Defects
- Skill

These forms of waste do not focus on product quality measurement, only on zero defects at the end of the process. In the aircraft engine MRO market, the lean improvement theory can be used to improve the process quality by improving the first time right yield.

2.5.2. Six Sigma

Six-Sigma is an analytical technique that focuses on quality and reduction of defects within the process. Continuous improvement efforts are made to reduce process variations resulting in predictable process results[32]. Achieving quality improvement requires effort from the entire organization [31].

Sig Sigma has the following three focal points that are different from other quality-improvement theories [32]:

- Focus on achieving measurable and quantifiable financial returns from any project
- Increased emphasis on strong and passionate management leadership
- Clear commitment to making decisions on the basis of verifiable data and statistical methods

Six Sigma knows many tools that can be used to measure the process variance and stability:

- 5 Whys analysis (Root Cause Analysis)
- Statistical and fitting tools
  - Analysis of variance
  - General linear model
  - ANOVA Gauge R&R
  - Regression analysis
  - Correlation
  - Scatter diagram
  - Chi-squared test
- Cause & Effects diagram (Fishbone)
- Run Charts
- Control chart (Swimlane)
- Critical to Quality tree (CTQ tree)
- Histogram
- Pareto analysis / Pareto chart
- SIPOC analysis
- Taguchi method

In this research the Six Sigma tools will be used in order to map the current state of the process and identify the improvements.

2.5.3. Lean Six Sigma

Lean Six Sigma combines Lean methodology for process improvement and Sig Sigma methodology for zero defects. Lean Six Sigma aims to maximize the performance of a process by improving quality, customer satisfaction, cost, flexibility and process speed [11].

Lean Sig Sigma methodology can be used to understand and improve both the process and product quality aspects within the aircraft engine MRO chain. This research focusses more on the product quality and how the process influences the process quality, so the emphasis will be on the Sig Sigma tools to determine the quality influences.

2.5.4. Theory of Contraints

The Theory of Contraints (TOC) methodology is a management philosophy created by Goldratt [19]. TOC focuses on identifying constraints in a process. When the constraints are found, the bottlenecks are identified and solved. The method describes that there is always a bottleneck present in a system. The method describes five steps [33]:

1. Identify the constraint
2. Exploit the constraint
3. Subordinate other activities to the constraint
4. Elevate the constraint
5. If anything has changed, continue with the next constraint

Theory of Constraints is a systems methodology that has been developed to assist people and organizations to analyse their problems and to create breakthrough solutions. TOC can be used in Total Quality Management frameworks as a mechanism to assist TQM [34]. TOC has a focus on process quality, but TOC can also be applied to bottlenecks within the process that directly influence the product quality. In order to find the bottlenecks that influence the product quality directly, an analysis has to be made of the critical to quality chain.

2.5.5. Statistical Process Control

Statistical Process Control SPC is a method of quality control. SPC uses statistical methods to understand the process and limits [29]. Within SPC quality is defined as *Meeting the requirements of the customer*

The application of SPC involves three main phases of activity [29]:

- Understand the process and the specification limits
- Eliminate assignable sources of variation, so that the process is stable.
- Monitor the ongoing production process, assisted by the use of control charts, to detect significant changes of mean or variation

Statistical Process Control describes two sources for variation [4].

- variation due to chance causes (called common causes by Deming)
- variation due to assignable causes (called special causes by Deming)

These two sources for variation can determine what is changeable within the process and what is not in order to reduce the variation and increase stability.

2.6. Quality Control Framework

This Quality Control framework will combine the principles of the FOCUS framework, SPC and Six Sigma Tools. The FOCUS framework will be the basis for the Quality Control Framework. The Clarify phase of the framework will use tooling derived from SPC and Six Sigma. In the understand phase SPC will be used to verify the causes for variation. The Quality Control Framework is shown in Figure 2.1.

2.7. Conclusion Literature Analysis

This chapter discussed previous research, current aircraft engine MRO quality characteristics at KLM E&M ES, quality control methodologies by Deming, Juran and Crosby, gave quality definitions for product and process quality and discussed process improvement theories and their relationship to both product and process quality.

In this chapter the following research questions are answered:

1. What characteristics from literature can be used to define product and process quality?
2. What tools are available from quality improvement theories that can support this research?

1. What characteristics from literature can be used to define product and process quality?

From literature, the product quality can be identified using two approaches as identified by Garvin. The manufacturer-based approach shows that the engine needs to conform to requirements set by regulation of CFM and the governments in order to assure airworthiness. The user-based approach states that every customer has different demands to the quality performance output with no standard preference, with airworthiness as the minimum threshold.

Literature by Hackman and Wagemant also states that process quality can be defined by the statistically non-random variations. This also shows the relation between product and process quality. High variations on product quality contributing steps within the process will reduce the stability of the quality output, hence they will reduce the product quality performance.

2. What tools are available from quality improvement theories that can support this research?

There are many tools available for quality improvement. Since the quality improvement that will support the main research question is product quality focused, Six Sigma methodology brings many tools that are relevant for product quality improvement. Since the product quality will be determined by the variations of the process quality, statistical and fitting tools like histograms, correlation plots, scatter diagrams and analysis of variance will be useful for this research.

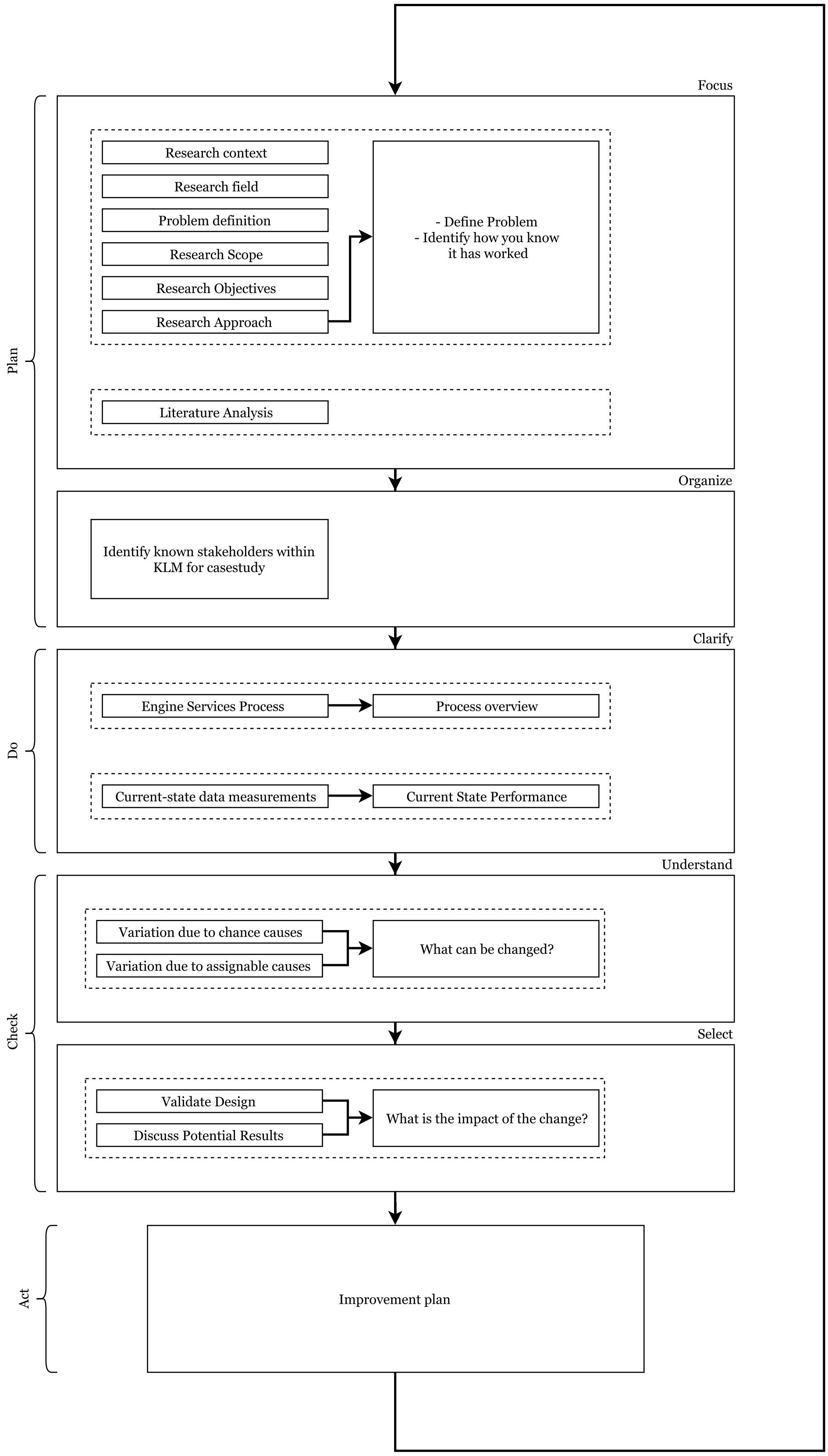


Figure 2.1: Quality Control Framework

3

Engine Services

In the previous chapter, literature was analysed to get characteristics that can be used to define product and process quality. Finally, the chapter concluded with a quality control framework from literature that can be tested to the case study.

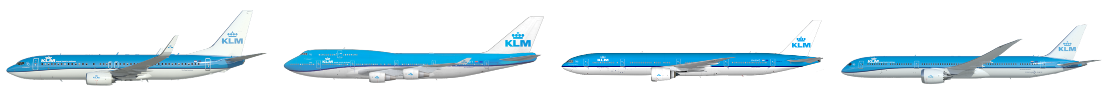
This chapter introduces the main case study environment: Engine Services. The main processes that are performed at KLM E&M ES are explained in depth. The information on the engine operations is obtained during the KLM Engine Familiarization Course for mechanics and interviews during hands on metal experience while working on the assembly and disassembly shifts at KLM E&M ES. This information is backed up by literature from the Workscope Planning Guide and Engine Service Manual. In order to understand quality performance of an aircraft engine and the KPI's described in the scoreboard, this chapter describes the pillars of aircraft engine MRO. This is done for both high bypass turbofan engines and in a more specific way for the CFM56-7B reference engine.

The following sub research questions will be answered in this chapter:

3. What agreements are made on quality performance with the customers?
4. From a technical point of view, what factors influence the quality of the engine?
5. What is the main qualitative value driver in order to be airworthy?

3.1. Reference Engine

The Air France-KLM groups fleet consists of different types of aircraft, each having it's own type of engine. The fleet consists of Boeing 787, 777, 747, Airbus A380, A340 and A330 aircraft for long-haul flights. Boeing 737, Airbus A321, A320, A319 and A318 for medium-haul flights. Fokker 70, Embraer 190, 175, 170, 145 and 135, Canadair 1000, 700 and ATR 72, 42 for regional flights [39].



(a) KLM Boeing 737 (b) KLM Boeing 747 (c) KLM Airbus A330 (d) KLM Boeing 787

Figure 3.1: Aircraft types serviced by KLM E&M ES, not proportional in scale

KLM E&M ES currently handles the following 4 types of engines, all produced by General Electric (GE) or the CFM joint venture in which GE Aviation participates with Safran Aircraft Engines, for 4 types of aircraft which can be seen in Figure 3.1:

- CFM CFM56-7B (7B) (designed for the Boeing 737)
- General Electric CF6-80C (80C) (designed for the Boeing 747)

- General Electric CF6-80E (80E) (designed for the Airbus A330)
- General Electric GEnx (GEnx) (designed for the Boeing 787, Dreamliner)

The other aircraft engines that need MRO are maintained by Air France Industries (AFI). in the future KLM E&M ES will add another type of engine, the CFM LEAP which is designed for the Airbus A320neo and Boeing 737 MAX family [23]. In the long run, the CFM LEAP will replace the CFM56-7B engine type [41].

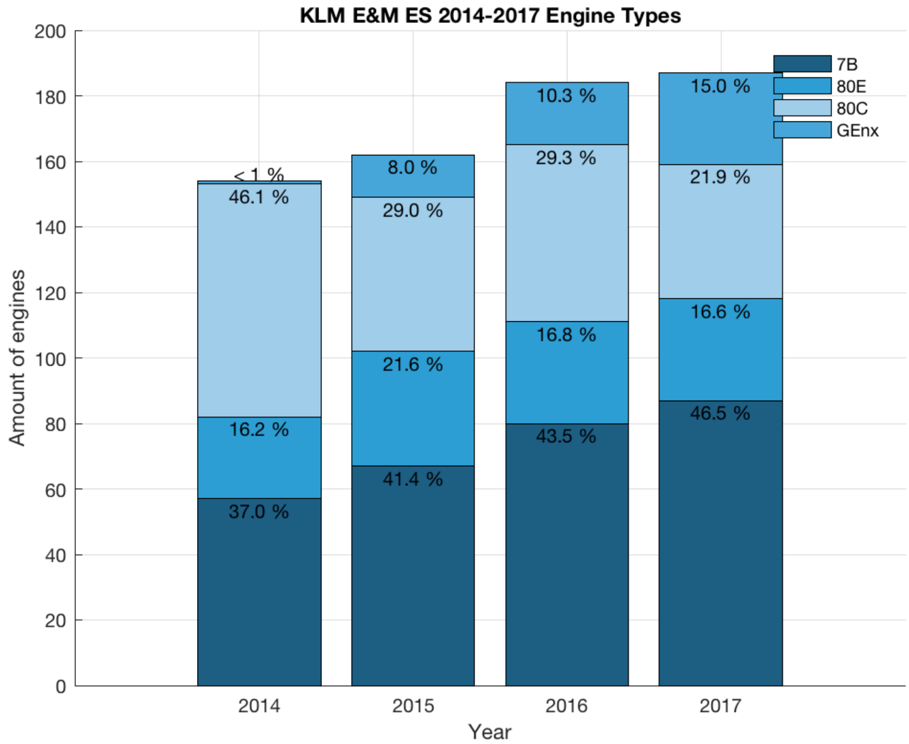


Figure 3.2: KLM E&M ES 2014-2017 engine types MRO mix

When looking into the types of engines that are serviced at KLM, it can be seen in Figure 3.2 that the amount of engines coming in is increasing and also that the percentage of CFM56-7B contribution is increasing within the mixture of overhauled engines. The GE CF6-80C contribution is decreasing since KLM is phasing out the Boeing 747 aircraft [5] [42]. The GE GEnx is increasing in share, but since the engine is a new engine, introduced in 2015, this engine has not yet received a full Shop Visit (SV). A full shop visit is a shop visit where all parts are taken apart in order to restore the performance of the engine, this typically takes place after around 12 years after the aircraft starts flying with the new engine [2] [22].

As mentioned in Section 1.3, there are many action plans in place in order to improve the performance according to the Perform 2020 strategy. One of the improvement plans is to decrease the Turn Around Time (TAT) to a TAT of 45 days, this improvement plan is called the TAT45 and is the most important improvement plan within the Perform 2020 scope. The CFM56-7B engine is chosen as the reference engine for TAT45 because it has the biggest share, the CF6-80C is being phased out and the GEnx engine is not matured as yet.

In this research, the CFM56-7 engine will also be chosen as the reference engine for the same reasons, and for the amount of data that is available about this engine within KLM E&M ES. The GEnx engine is not taken into account in this research since the engine has not been matured yet. The CF6-80E and CF6-80C engines can be taken into account for comparison purposes.

3.2. Customers

KLM E&M ES has many different customers but they can be categorized in three main groups:

1. KLM/AF Pool customers
2. General Electric Offload customers
3. External customers

3.2.1. Customer groups

The first customer group is the KLM/AF Pool. The KLM/AF Pool is considered an internal customer to KLM E&M ES but gets treated like any other external customer. They have contractual agreements with KLM E&M ES about the engine performance in terms of airworthiness and turnaround time for the engines and also pay for the maintenance. The contractual agreements between the KLM/AF Pool customers are standardized in make up.

The second customer group is the General Electric Offload group. General Electric is the Original Equipment Manufacturer (OEM) for many of the engines used by the KLM/AF fleet including the CFM56-7B. GE Aviation is also an MRO provider for the 7B engine and serves many customers worldwide. The customers to GE Aviation are customers like United Airlines, TUI Fly, Copa, TNT. Some of these customers do not have their own engine MRO facilities or enough capacity in their engine MRO facilities and rely on external MRO providers. Sometimes GE Aviation does not have enough capacity and outsources the repairs of their engines to KLM E&M ES with approval of their customers. In these specific cases, GE Aviation is the customer and not the customer who purchased MRO from GE Aviation. However, the customer is involved in the decisions of what repair steps need to be done. The contractual agreements between GE Aviation are standardized but different per customer, GE Aviation is responsible for supplying the documentation received from the owners of the engine which is done in a standardized way.

The last customer group consists of all other external customers who have a lack of capacity within their own engine MRO facilities or don't have engine MRO facilities. These customers have their own individual contractual agreements with KLM E&M ES. The external customers consist of Shandong, Willis, Ehtiopian Air and many more airlines but also customers like Snecma, which is part of the Safran Group. Each customer is responsible for supplying the documentation to KLM, this is not standardized but restricted by regulation.

3.2.2. Statistics

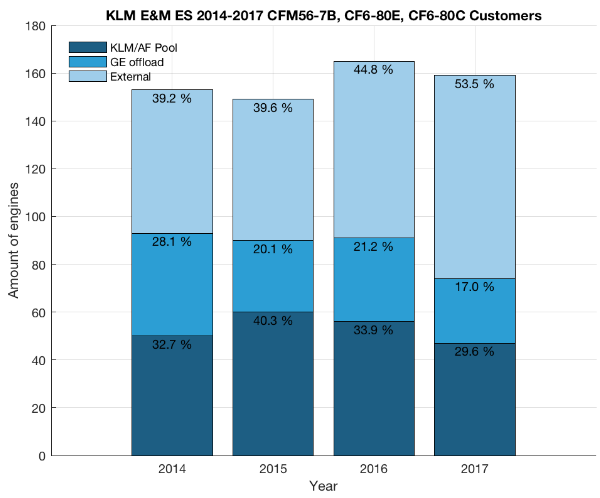
Figure 3.3a shows the contribution of each customer group on the total amount of overhauled engines. In 2017, GE Offload was the smallest customer group, followed by the KLM/AF Pool, in absolute numbers less KLM/AF engines were overhauled by KLM E&M ES. As stated before, this is because of the increase in Boeing 777 aircraft and phasing out of the Boeing 747 aircraft.

Figure 3.3b shows an increase in the total amount of CFM56-7B engines being overhauled by KLM E&M ES. For 2018, the goal is to increase the inflow of 7B's even more. What also can be noted is that from 2015 on, the share of KLM/AF Pool engines receiving MRO decreases slightly, and the share of external customers increases. More is invested in order to attract external customers and long-term contractual agreements are made with these customers to supply engine MRO.

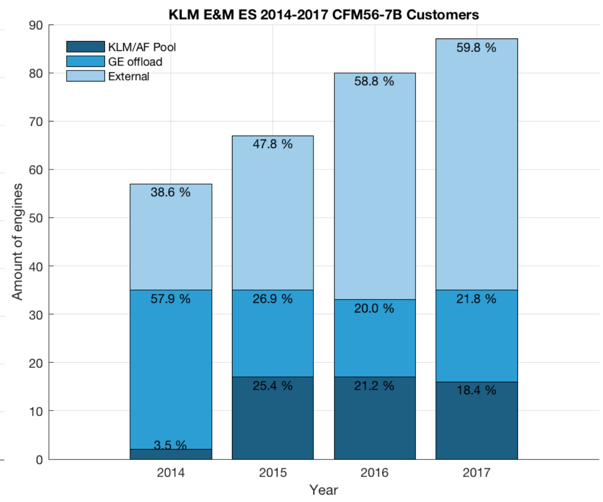
In order to get an overview of who the top customers are to KLM E&M ES, Figure 3.4 shows an overview of the most important individual customers in terms of engine quantity. The GE offloads are split up per customer to them in order to find possible relations in quality performance.

3.2.3. Contract Types

There are different financial contracts made between each customer and KLM E&M ES. The contracts may consist of financial penalties that are imposed when the Quality in terms of EGT Margin, Vibrations or TAT performance are not met within the limits of the agreements.



(a) All engine types without GEnx engine



(b) CFM56-7B type

Figure 3.3: KLM E&M ES 2014-2017 customers

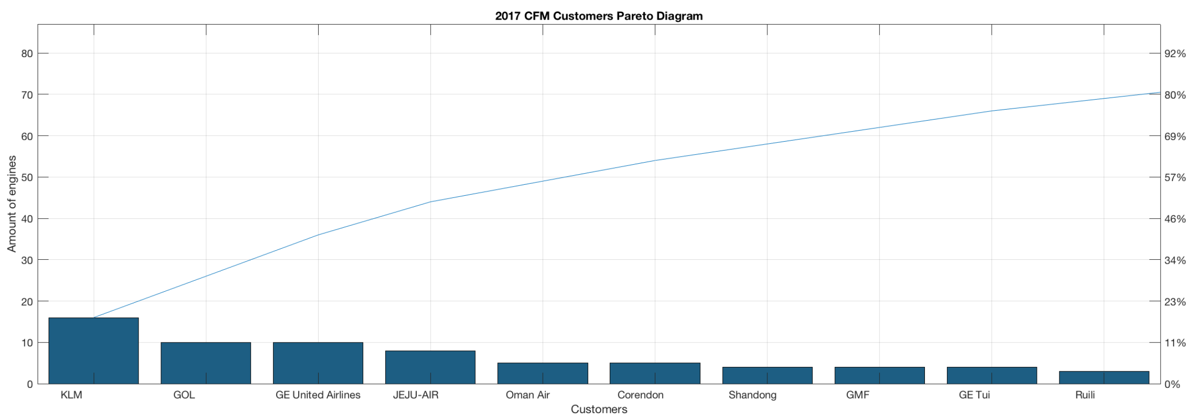


Figure 3.4: KLM E&M ES 2017 Pareto Chart of Customers

Sometimes it is chosen to pay the penalty in the contract and hand out the engine. There are two sets of regulations, the airworthiness regulations by law, and the internal limits as agreed upon with the customer. When the airworthiness of the overhauled engine is at stake, the engine will always be reworked in order to meet the regulated airworthiness requirements.

In Figure 3.5 the percentages of quality contracts per year are shown for 7B, 80E and 80C engines. The percentage of contracts is increasing over the years, one of the causes for this trend is that KLM E&M ES decided to start with quality based contracts for it's own internal KLM/AF Pool customers for the 80E and 80C engine types. A visual overview of the absolute numbers of the quality contracts is shown in Appendix D.

From Figure 3.6 it can be concluded that KLM E&M ES is trying to increase the amount of contractual agreements made with the GE Offload and external customer groups. With the internal KLM AF/Pool customer, no contractual agreement has been made for the 7B engine in terms of product quality. Hence, the KLM AF/Pool customer is not contributing to the quality performance KPI, whilst it has been contributing around 20% to the total volume of maintained 7B engines.

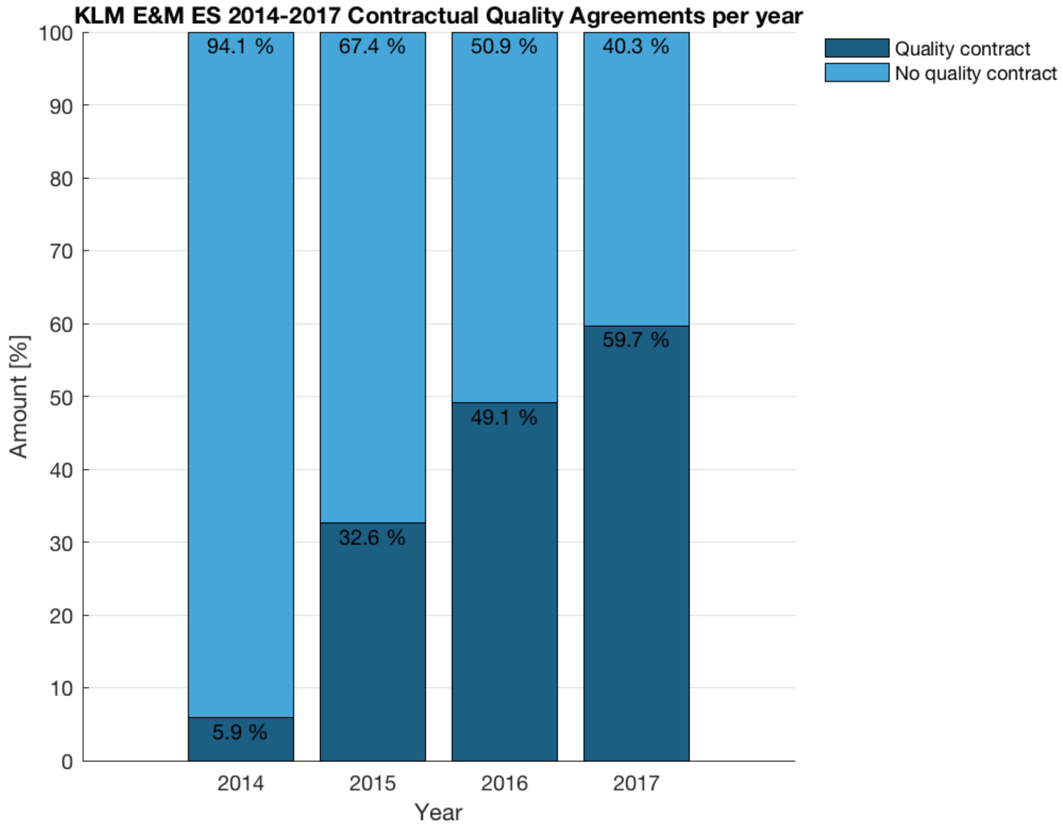


Figure 3.5: KLM E&M ES 2014-2017 engine types MRO mix

3.2.4. Penalties

As stated before, penalties may be applied when a contract is not completely fulfilled. The financial penalties can be subdivided in two main categories: TAT based penalties and EGT Margin based penalties. In general the contractual rules are as follows:

- The TAT based penalty consists for 2017 out of an average penalty of USD 3200 per delta contractual TAT versus actual TAT taken in days.
- The EGT based penalty consists of USD 3000 per degree of delta contractual versus actual EGT margin taken in degrees Celcius.

However, most of the penalties are not paid and the customer is offered a discounts for the next Shop Visit at KLM E&M ES. For non-frequent external customers, the penalties are paid directly to the customer or offered as a discount to the customer for the same Shop Visit.

For the TAT based penalty, the TAT exceedance takes delays caused by the customer into account. A delay caused by the customer may occur through a lack of documentation, not directly agreeing to the workscope and transportation times. The TAT exceedance for the financial penalty is always calculated by the following formula:

$$\begin{aligned} TATexceedance &= (BrutoTAT - CustomerDelay) - ContractTAT \\ &= NettoTAT - ContractTAT \end{aligned} \tag{3.1}$$

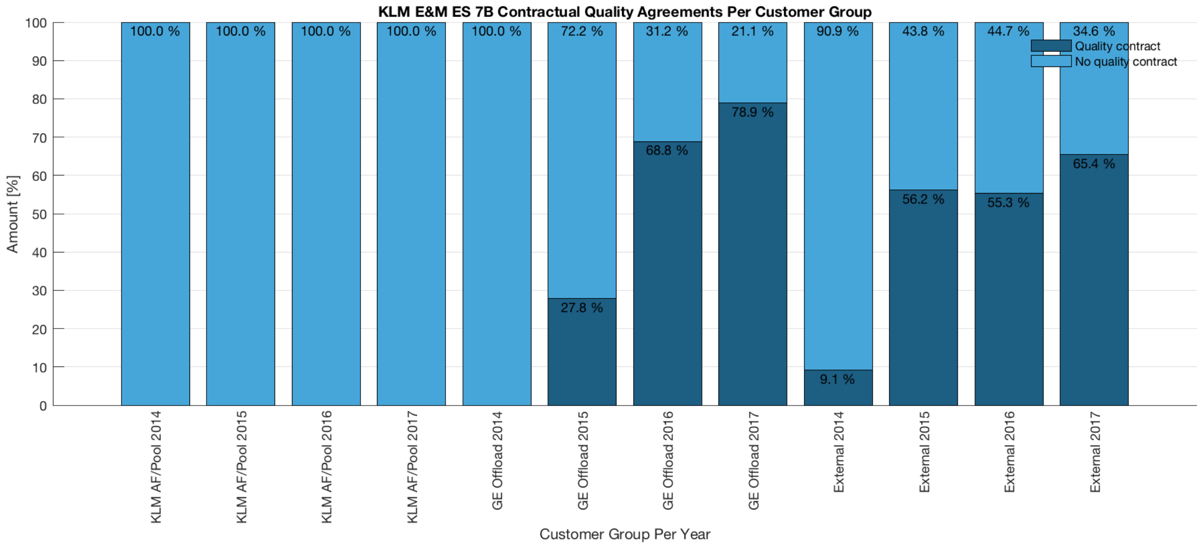


Figure 3.6: KLM E&M ES contractual quality agreements per customer group for CFM56-7B engine type

3.3. Engine Overhaul Process

Before going further into detail of the process chain, the engine build-up needs to be explained. In this section first the engine build-up is described in order to show the basic process chain. Furthermore, the different types of workscopes are introduced and a SIPOC diagram is created. Finally, the governance and accountability is described.

3.3.1. Engine Build-up

An engine is a complex piece of technology, an aircraft engine is built up out of over 10.000 parts, Each individual part has a unique position within the engine. The engine can be broken down to four main levels:

1. Engine level, the entire engine as a whole part
2. Module level, the engine taken apart into 7 modules
3. Assy level, the modules taken apart into 19 assy's, which are basically smaller size modules
4. Part level, the assy's taken apart into a huge amount of parts

An overview of the engine with the different modules and assy numbers can be seen in Figure 3.7.

The modules are from front to back the Fan Module (FAN), the Low Pressure Compressor(LPC), the High Pressure Compressor(HPC), the Combustor (Combustor), the High Pressure Turbine (HPT)and the Low Pressure Turbine (LPT). The Gearbox module is is attached to the front of the engine.

3.3.2. To Provide Engine MRO Process

As described in Section 1.2 the engine overhaul process has three main processes on strategic level:

- To organize Engine Availability
- To provide Engine MRO
- To provide Parts Repair & Engine Accessories MRO

This thesis focuses on the processes related to *To provide Engine MRO*. As seen in the KLM E&M ES overall process chain, as shown in Figure 1.3, this process consists of four main steps. These steps can be seen in Figure 3.8.

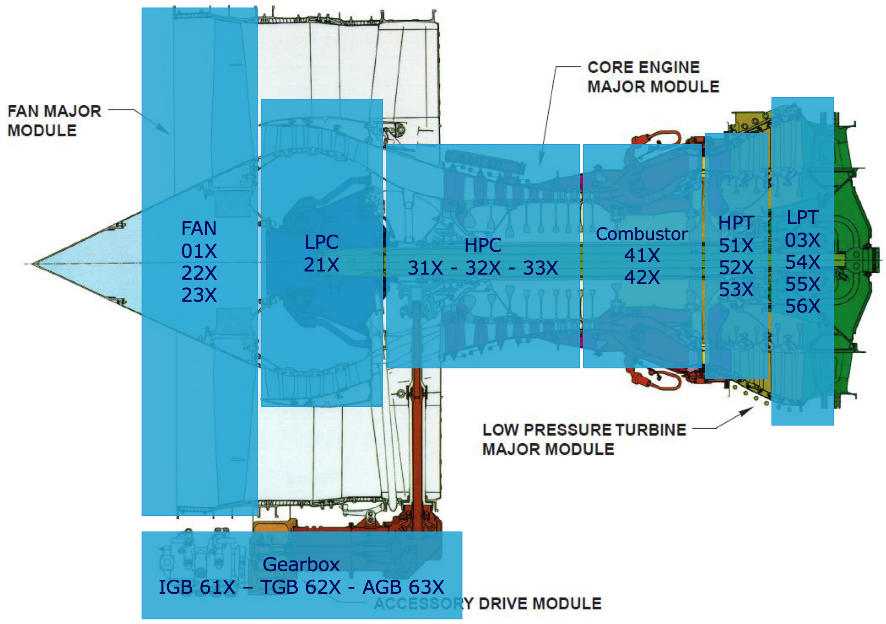


Figure 3.7: CFM56-7B Engine Build-up - Assy and Module map

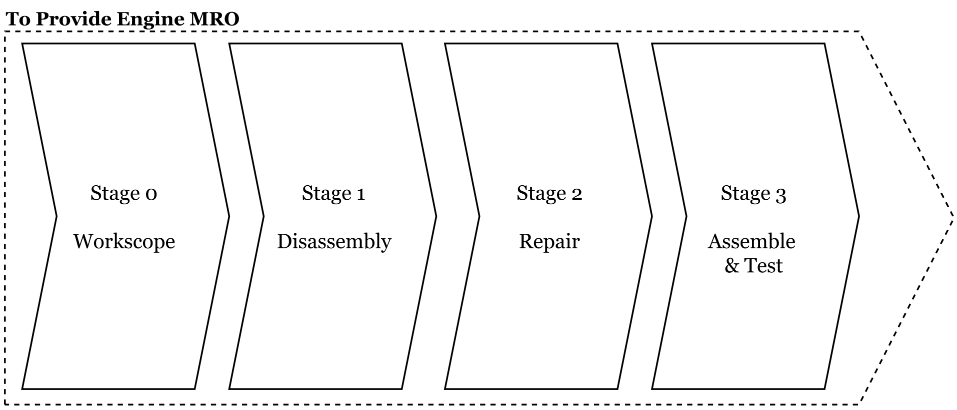


Figure 3.8: KLM E&M ES "To Provide Engine MRO" process chain

The first stage of the engine MRO process, Stage 0, is the stage to determine the workscope of the engine. In this step the engine in examined and visually inspected, a Bill of Work (BoW) is created, the life limits of the parts are checked, the BoW is agreed upon with the customer and the administration is completed. After this step the workscope is set to one of the following four:

1. Full Workscope, where all modules, assy's are disassembled to piece part level.
2. Performance Workscope, where all modules are disassembled, but only some assy's to piece part level.
3. Minimal Workscope, where only the necessary modules, assy's parts are disassembled and repaired.
4. Serviceable Removed, where the part is still serviceable, removed and put away until assembly.

The second stage is Stage 1, the disassembly. As the name might reveal, in this step the engine is disassembled. This can be done to different levels depending on the workscope. In this step the disassembled modules, assy's and parts are cleaned and inspected for fractures and damages. Some parts do not need to be cleaned and inspected and are send straight to the next stage. The steps for disassembly are the same for each 7B engine. KLM has the rule that each part that comes off an engine in the disassembly stage, goes back on the same engine in the assembly stage. This rule is almost always valid unless parts are replaced, then the new or refurbished part goes on the engine.

The third stage is Stage 2, the repair. In this stage the parts are repaired, either internally or they are shipped out to OEM's and other aircraft engine part MRO providers to be repaired externally. If parts are not damaged, they will be put apart and can be used in the assembly step. The percentage of parts that are repaired internally is about 60% which means 40% is shipped to external vendors. The vendors will repair the parts, provide a certificate and ship them back. When the parts are coming back into KLM, each part is inspected if the repair has been done in the correct way. KLM E&M ES also provides certificates for the parts that are repaired internally. With these certificates the parts are declared serviceable and can be safely used within the engine. All the serviceable parts are collected at a warehouse called Aprep. When all the parts are back into Aprep, the assembly crew gets a sign that the engine is ready to be built.

The final stage is Stage 3, the assembly. The HPT, HPC, and Combustor form the core, the assembly of the core is the first step in the assembly. The next step is to place the fan in the overhead assembly stand, then the LPC and Gearbox are assembled. The next step is to assemble the core in the overhead stand. The last module that will be assembled is the LPT. When all the modules are assembled together, the QEC needs to be assembled. The QEC consists of all the brackets, wires, tubes and other parts that need to be installed outside of the engine.

Finally, when all the modules are assembled to engine level, the engine needs to be tested in a Test Cell. This procedure is done in order to find leakage and to test the performance of the engine. The Test Cell is checked by GE Aviation on a regular basis in order to assure each engine MRO provider has the same test results for the same engine. In case the engine does not meet the test cell requirements, rework has to be done and the engine is declared unserviceable. When the engine is serviceable, it will be returned to the client.

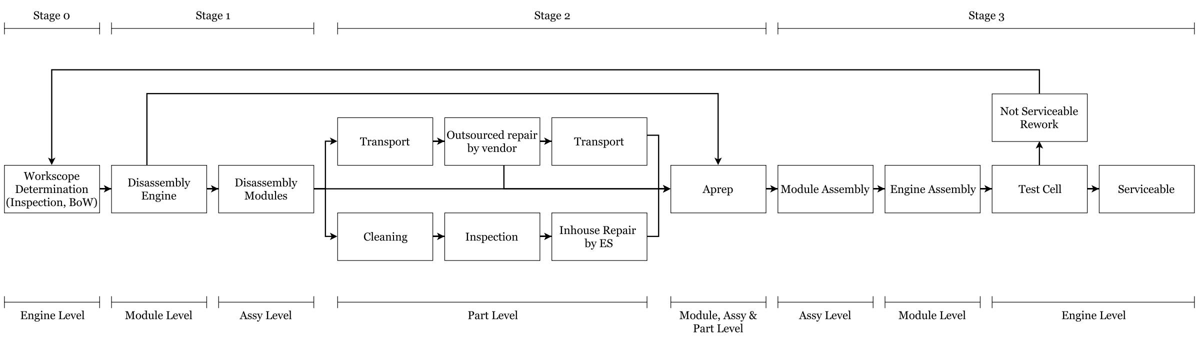


Figure 3.9: KLM E&M ES "To Provide Engine MRO" detailed flow chart

All the stages and flows on Engine, Module and Assy level are visualized in the flow chart that can be seen in Figure 3.9.

3.3.3. SIPOC

The Supplier, Input, Process, Output, Customer (SIPOC) model is a tool that is part of Lean Six Sigma and gives a good overview for the Critical To Quality (CTQ) requirements. The tools is created to help map the process from an overview perspective. The model clarifies the process and gives insights wider than just the process. The model gives input on the suppliers, inputs, outputs and customers per process step and is shown in Table 3.1.

Table 3.1: SIPOC diagram of engine MRO process

S **Suppliers**	**I** **Inputs**	**P** **Process**	**O** **Outputs**	**C** **Customers**
Airline as customer	Order Request	0. MRO Request	Planning, MRO Slot	Planning Department
MRO Team, Engineering	WPG, Technical Input, CFM56-7B Engines	1. Workscope Determination	Inspection Report, BoW	MRO Team
MRO Team	CFM56-7B Engines	2. Disassembly Engine	Modules	MRO Team
MRO Team	Modules	2. Disassembly Modules	Parts	Repair Team, External Vendors
Repair Team, External Vendor	Unserviceable Parts	3. Repair (Part Level)	Serviceable Parts	Aprep Team
Aprep Team	Serviceable Parts	4. Aprep	Categorized Serviceable Parts	MRO Team
MRO Team	Parts	5. Module Assembly	Modules	MRO Team
MRO Team	Modules	6. Engine Assembly	Unserviceable Engine	MRO Team
Testcell Team	Unserviceable Engine	7. Test Cell	Serviceable Engine	KLM E&M ES
KLM E&M ES	Confirmation	8. MRO Request finished	Overhauled Engine	Customer

3.3.4. Governance and accountability

KLM E&M ES has three layers of management corresponding to three levels of operation. The first level op operation is for the entire chain, there is one manager accountable, the VP of Engine Services. The whole chain is then split up into the four stages mentioned in the previous section. Stage 1 and Stage 3, disassembly and assembly have one manager, the MRO manager. The repair step has two managers, one for the internal repairs, and one for the external repairs. One layer below, there are managers for all the process steps within the stages. For example, Stage 2 has separate manager for Clean & Inspect and for the logistics, for the repairs and more .

Between the process steps there are handshakes on the Turn Around Time, 28 days max for each step. There are no handshakes for the quality of the parts. The part/assy/module is considered either serviceable or unserviceable. If the item is passed to the next step after the repair stages, it should meet the quality demands as prescribed by regulations. The only handshakes that are made is that the quality of the parts from external vendors should be inspected before they can go on to assembly and that the lifetime of the parts should be below the life limit.

3.4. Engine Familiarization

Now the process is explained in depth, a technical understanding of the engine needs to be provided in order to understand the quality performance of the engine. This engine familiarization is custom to the CFM56-7B engine, but also applicable to other turbofan engines. This section will give an overview of the Critical To Quality aspects from a technical viewpoint and will explain regulation regarding the performance of engines.

3.4.1. Engine Overview

As stated before in Section 3.3.1 the engine is build up out of Modules, Assy's and Parts. An overview image of the engine, with its corresponding modules and assy's, is provided in Figure 3.10.

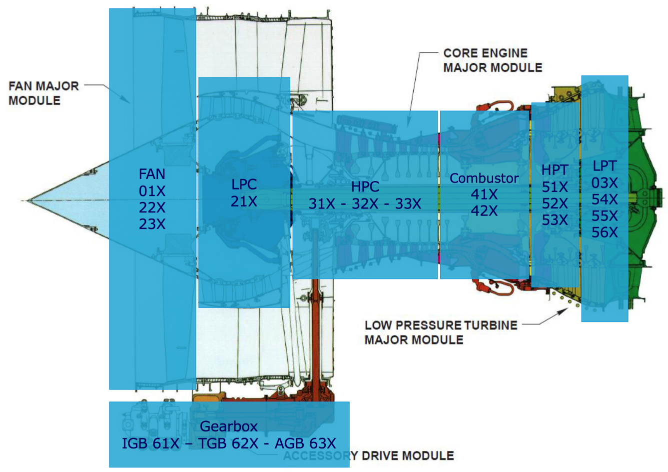


Figure 3.10: CFM56-7B Engine Build-up - Assy and Module map

Table 3.2 shows all assy's with the corresponding KLM Short Names, Names and Modules.

The CFM56-7B turbofan engine is build up out of two main axis, this is called a twin-spool configuration. One axis drives the fan for the thrust, this axis connects the FAN and LPC to the LPT, this axis is called the N1 Axis. The other axis provides the compression of the air before combustion of the fuel. This axis connects the HPC to the HPT. Only about 15% of the inlet air passes through the core of the engine, this is called the core airflow. The other 85% passes through the fan and provides the thrust force. The Bypass Ratio is the ratio between the bypass air that goes around the engine and the air that goes through the core.

Table 3.2: List of CFM56-7 Assy's with KLM abbreviations and matching modules

Code	Short Name	Name	Module
01x	Fan Module	Fan	Fan Module
02x	Core Module	Core	Core Module
03x	LPT Module	Low Pressure Turbine	LPT Module
21x	LPC /Booster	Low Pressure Compressor	LPC Module
22x	Brng Support	Bearing Support	Fan Module
23x	Fan	Fan	Fan Module
31x	HPC Rotor	High Pressure Compressor Rotor	HPC Module
32x	HPC Casing	High Pressure Compressor Forward Casing	HPC Module
33x	HPC Casing	High Pressure Compressor Rear Casing	HPC Module
41x	Combustion Case	Combustion Case	Combustion Module
42x	Combustion Chamber	Combustion Chamber	Combustion Module
51x	HPT Nozzle	High Pressure Turbine Nozzle	HPT Module
52x	HPT Rotor	High Pressure Turbine Rotor	HPT Module
53x	HPT Support	High Pressure Turbine Support	HPT Module
54x	LPT Rotor	Low Pressure Turbine Rotor	LPT Module
55x	LPT Shaft	Low Pressure Turbine Shaft	LPT Module
56x	LPT Rear Frame	Low Pressure Turbine Rear Frame	LPT Module
61x	IGB	Gearbox	Gearbox
62x	TGB	Gearbox	Gearbox
63x	AGB	Gearbox	Gearbox
72x	Engine	Engine	Full Engine

3.4.2. EGT Margin

The temperature within the engine is one of the most important KPI's. When the engine is on wing, the pilots keep monitoring the EGT value to keep track of the performance of the engine during flight. When the engine has had a shop visit, the EGT value is the most important quality parameter of the engine. The engine experiences turbine inlet temperatures of approximately 1200 degrees Celcius. The limitation to the higher temperatures in the turbines is the material temperature limit. The EGT Margin is measured with a probe around the final stages of the High Pressure Turbine. Special composite materials or very expensive materials can be used to increase the maximum allowed temperature in the turbines. Figure 3.11 gives an overview of the gas flow path temperature flow for the 7B engine. The temperature is at its maximum at the inlet of the High Pressure Turbine.

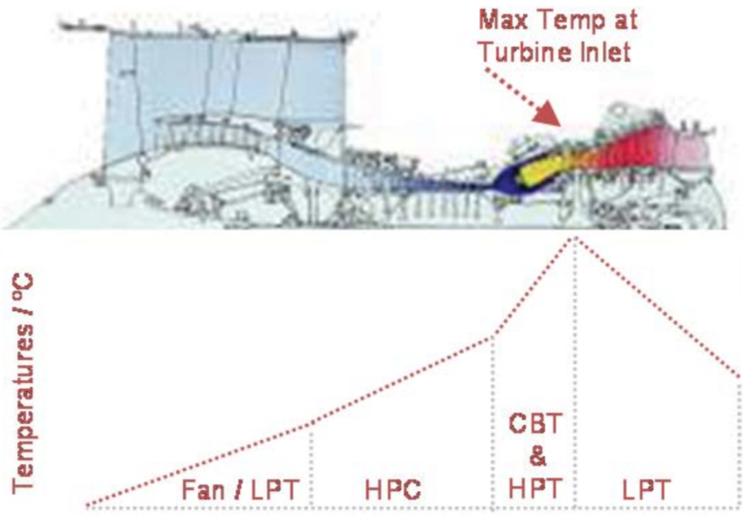


Figure 3.11: CFM56-7B engine gas flow path temperatures

The deterioration of the engine performance is caused by friction and obstruction of the flow path. The EGT will increase with wear of the engine, the higher the EGT is, the more wear and deterioration affect an engine. When the EGT is of high value it indicates that the quality of the engine is decreasing. This influences the fuel consumption of the engine, resulting in a more expensive aircraft to fly. There is a limit to the temperature the engine can reach, this is called the EGT Red Line. Exceeding this EGT limit will result in damage of the engine parts and is not allowed by regulations. The EGT Margin is the difference between the maximum allowable temperature, the EGT Red Line, and the actual EGT. The EGT Margin gives an indication of how many more flights can be made with an engine before the engine is not serviceable.

The EGT needs to be as low as possible for as long as possible

In theory, the EGT margins are the highest when the engine is fresh out of production since the flow path is cleared and the parts have not been deteriorated. The EGT Red Line is a hard limit by regulation, an engine can operate until the EGT Margin is 0. In Figure 3.12 the EGT deterioration is shown until a Shop Visit and the EGT Margin and EGT Red Line are visualized.

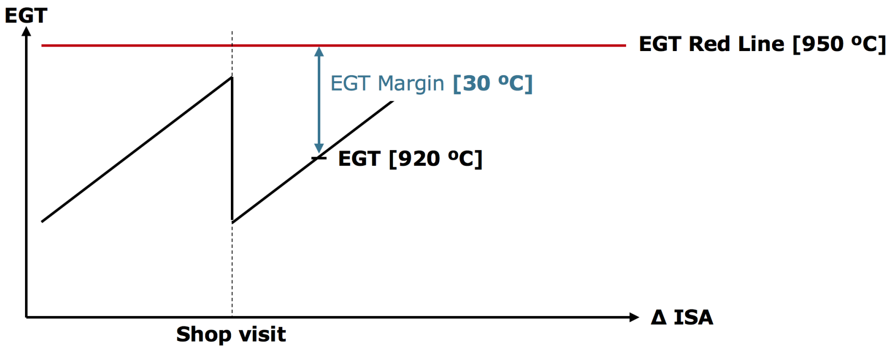


Figure 3.12: CFM56-7 EGT Shop visit relation

When a new engine is on wing, the engine performance deteriorates quite fast up to 2000 cycles. From 2000 cycles onwards the EGT deteriorates quite linear as shown in Figure 3.13. This chart is provided by CFM and used to determine the remaining cycles through the EGT Margin loss.

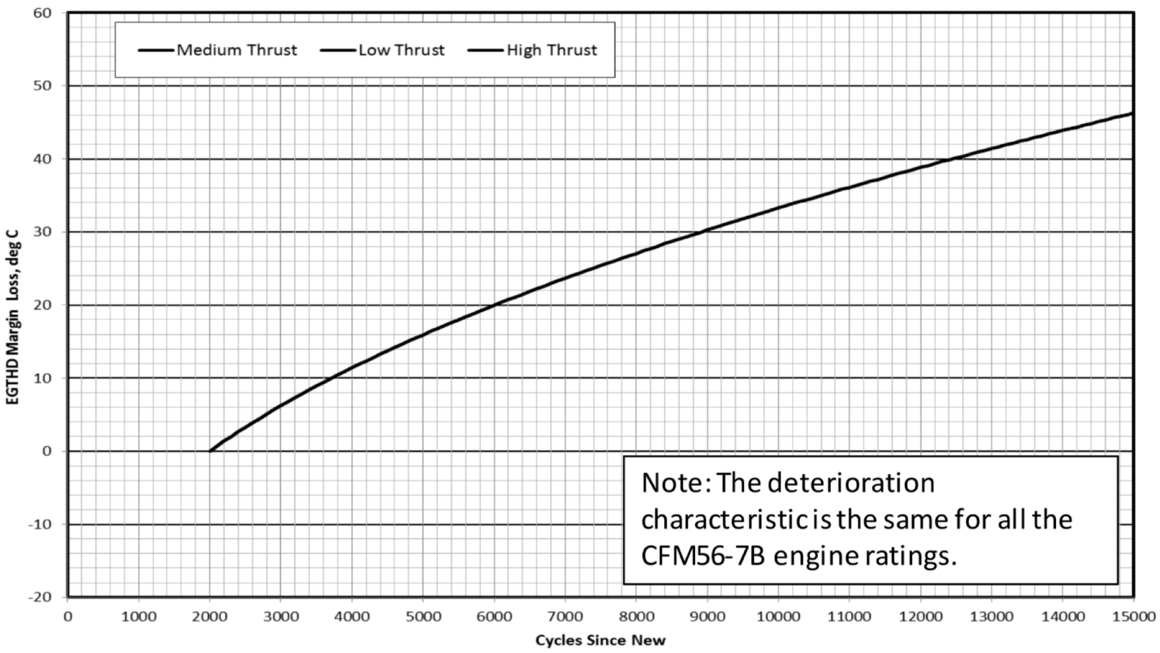


Figure 3.13: CFM56-7 EGT deterioration chart

As you can imagine, there are many factors that influence the linear EGT Margin deterioration, but there are also factors that can influence the EGT Margin in other ways. One of these factors that determine the initial available amount of EGT Margin is the Thrust Setting. The engine can operate under different thrust settings. Thrust is determined by the rotational speed of the N1 axis since this axis drives the Fan. The N1 axis is driven by the low pressure compressor, when the inlet temperature is raised, the rotational speed is increased hence the thrust is increased. The 7B engine can operate under a 20lbf, 22lbf, 24lbf, 26lbf and 27lbf thrust setting. This thrust setting is called the derate of the engine. How the thrust ratings influence the EGT is shown in Figure 3.14. The KLM fleet flies most frequent with the 26lbf thrust setting configuration.

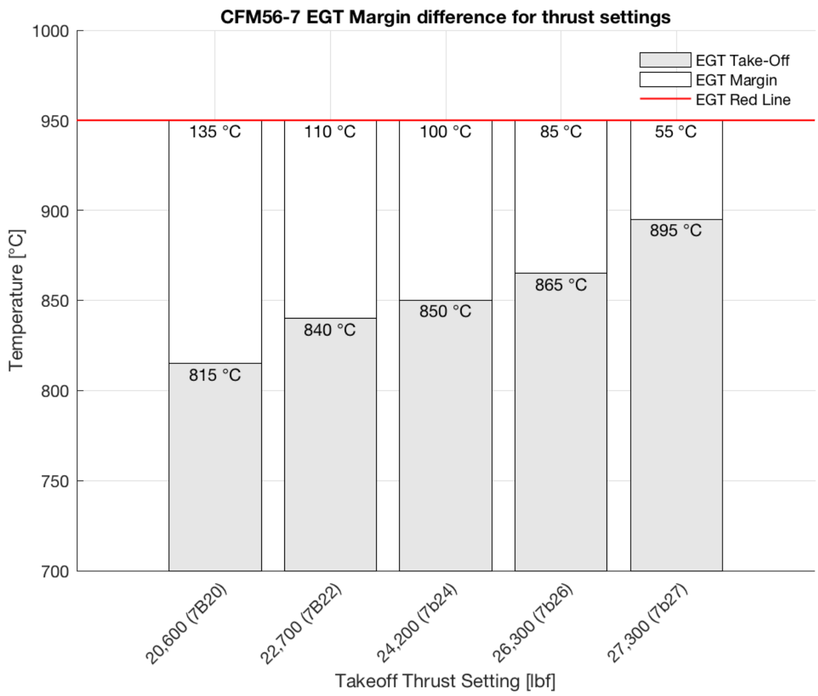


Figure 3.14: CFM56-7 EGT Margin difference for thrust settings

Other than the thrust settings, there are factors that influence the engine performance. The pressure is an important parameter when thinking about the inlet temperature that determines the combustion. The pressure is built up during the compression stages in the LPC and HPC. The LPC and HPC exist of little blades that form chambers where the air is pumped to. Since each stage has a smaller volume, the pressure of the air increases. It is very important for the pressure build-up that the air cannot bleed back to the previous stage. Therefore, the tip clearance of the blades in each stage are the most important factor for the EGT margin within the MRO process and In-Flight process. There is a known direct relationship between the tip clearance of the turbine and compressor blades and the EGT Margin.

3.4.3. Other Engine KPI's

There are many other factors that can influence the engine performance on KPI's other than the EGT or EGT Margin Some factors that can be influenced by control within the MRO chain are as follows:

- *EPR*: The Engine Pressure Ratio, This is the total pressure ratio across the engine. The EPR is calculated by taking the pressure ratio of the LPT and Fan. It is used to measure the engine thrust.
- *N1-speed*: The N1 axis speed, is the rotational speed of the fan and is presented as a percentage of the initial RPM
- *N1-speed*: The N2 axis speed, is the rotational speed of the high pressure compressor and is also designed as a percentage of the initial RPM
- *N2 Vibrations*: The vibrations within the engines N2 axis due to misalignment of the blade weights

- *SFC*: The specific fuel concept is a measure for the amount of fuel that is used per unit of thrust
- *LLP*: The life limited parts, all the non-rotational parts have a life limit since they are prone to fatigue.

The combination of a higher overall EPR and turbine inlet temperature improves thermal efficiency. This, together with a lower specific thrust, leads to a lower specific fuel consumption. All of these factors have the tip clearance for the blades in common. Once the compressors and turbines are working efficiently and the gas path is clear, the engine operates at its best.

3.5. Conclusion Engine Services

This chapter gave an overview of KLM Engineering & Maintenance Engine Services. The customers were analysed in depth and the reference engine for this research was chosen as the CFM56-7B. For the CFM56-7B, the different contractual agreements were discussed and the financial penalties for turnaround time and quality performance were shown.

Furthermore, the engine process was explained in a more detailed manner. The four stages of the process were highlighted and the different types of workscope were explained on assy level. Also, the technical engine description was given which is the pillar of this research. The following sub research questions are answered in this chapter:

3. What agreements are made on quality performance with the customers?
4. From a technical point of view, what factors influence the quality of the engine?
5. What is the main qualitative value driver in order to be airworthy?

3. What agreements are made on quality performance with the customers?

When looking at the trend of the amount of quality contracts created between KLM E&M ES and it's customers, the analysis shows that it is increasing. The KLM AF/Pool customer group does not have contracts for the engine quality with KLM E&M ES. There are currently three types of contractual agreements that can be differentiated on EGT Margin. The first is a contract where a financial penalty is applicable if the quality output is not met according to the contract. The second is a contract where no financial penalty is applicable if the quality output is not met according to the contract, but the engine needs to be delivered airworthy with a certain amount of EGT Margin. The last is a contract where the engine needs to be delivered serviceable with no agreement on EGT Margin, this contract type is for the KLM/AF Pool engine group where availability of the engines is the main driving value.

4. From a technical point of view, what factors influence the quality of the engine?

From a technical point of view, the quality of the engine is mostly influenced by the pressure build up within the engine towards the combustion chamber. The air needs to be highly compressed for an optimal combustion process. The deterioration of the engine is caused by wear, friction, surface dirt accumulation and temperature. Deterioration is most prone to happen in places with a high amount of rotating parts and temperatures. The gas flow path is the factor that influences the quality of the engine throughout the entire engine.

5. What is the main qualitative value driver in order to be airworthy?

The main quality value driver is the tip clearance per stage in the compressors and turbines. The tip clearance needs to be as small as possible to prevent air to bleed back to the inlet of the engine. The closer the fanblades are to the casings, the less air can bleed back, the higher the pressure can build up. The tip clearance has a direct relationship to the EGT Margin.

4

Current State - Measurements

In the previous chapter, the process flow of KLM E&M ES was explained in a more detailed manner and the most important engine quality parameters within the MRO process were identified. The objective of this research is to develop a model for the quality performance in terms of the Exhaust Gas Temperature Margin of an Engine MRO process chain using the KLM E&M ES case study as the main data and model validation source. The literature framework has been created in Chapter 2. The goal of this chapter is to observe and measure the current state, and analyse the critical to quality parameters before it can be analysed in the next chapter.

First, the KPI performance is measured for 2017. Then an analysis is made of the front end BoW input and of the rear end TestCell output. Furthermore, the assy's that are critical to quality are determined, and the quality performance of these assy's are measured in depth.

The following sub research questions will be answered in this chapter:

6. What levels of maintenance are available in the engine MRO process?
7. How is the workscope determined for engine MRO?
8. What is the relation between quality and Time On Wing?
9. Which assy's & modules can be identified that contribute the most to the quality of an Engine?
10. How is the current quality performance controlled during the MRO process at KLM E&M ES?

4.1. Test Cell Measurement

The first step in understanding the current state is understanding how the EGT Margin measurements are determined. Every engine gets a quality performance measurement test at the end of the MRO process. This is done in a test cell on KLM E&M ES ground. The test cell is located away from the Engine Services Shop, so transport is needed when an engine is tested. The engine needs to hang in the Test Cell, and additional parts are assembled to the engine to form an on-wing situation.

The Test Cell consists of two main rooms, the room where the engines are placed in a mount and assembled/disassembled and an actual test room. Once every few years GE Aviation performance measurements on the test cell to assure the same quality performance measurement is taken in all approved test cells. An engine with known performance parameters is physically transported from GE Aviation to the KLM test site and tested. Then the parameters are calibrated according to GE's standards.

The process of measuring the EGT margin is a process assisted by a computer scheme. First the absolute EGT value is measured and then the Hot Day EGT value is calculated. As you can imagine, just like in a vehicle, more fuel is consumed when accelerating. The Hot Day EGT is the highest EGT during take-off and landing (reverse thrust), this is simulated in the test cell by a multiplier.

Figure 4.1: KLM E&M ES Test Cell Location With CF6 Engine, Image courtesy of KLM

After the hot day EGT Margin is calculated, the certified thrust is measured. If the thrust is not sufficient or too high, the N1 axis rotational speed will get modified. This is done by programming this in the ID plug of the engine. This will result in a different EGT margin, therefore a new measurement is done and the EGT N1 Modified Hot Day EGT is calculated.

In the next step, the workscope is taken into account. For the KLM test cell these values are determined by the GE Aviation calibration process. When nothing is done to the engine, just a small repair, 10 degrees are added to the EGT. This will result in a lower EGT Margin, hence in a shorter flight life length. When a minimal workscope is performed on engine level, 8 degrees are added to the EGT. When a performance workscope is performed, 5 degrees are added and when a full workscope is performed, 0 degrees are added. This addition will result in the EGT Modified including workscope addition EGT value.

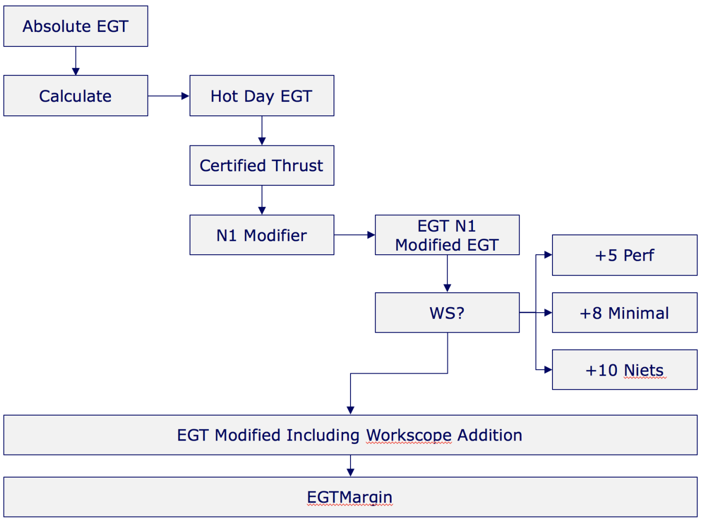


Figure 4.2: KLM E&M ES Test Cell Scheme

From this EGT Modified including workscope addition EGT value the final EGT Margin can be calculated. This process is visualized in Figure 4.2.

4.2. EGT KPI Performance

In order to understand the EGT KPI Performance better, the actual and contractual EGT margins for the CFM56-7B engine are measured and analysed. As you can see in Figure 4.3, the actual values of the EGT Margin as output of the MRO process are normally distributed. The average value is about 60 degrees of EGT Margin.

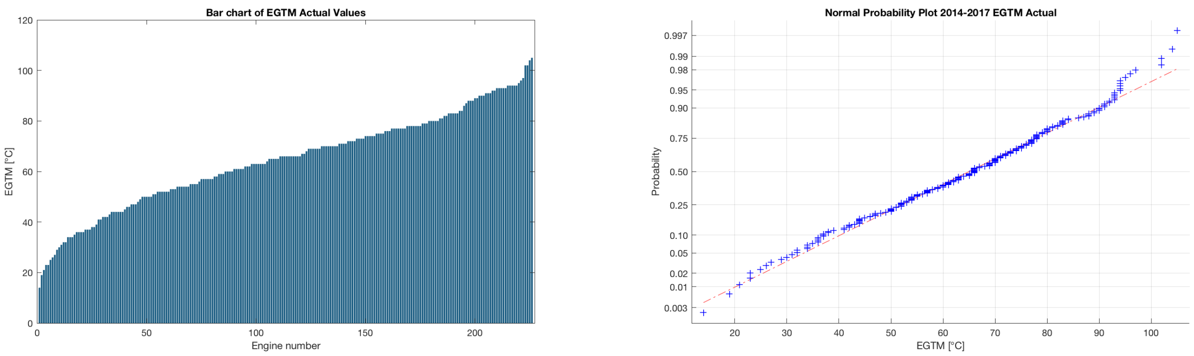


Figure 4.3: KLM E&M ES 2014-2017 actual EGT analysis

The contractual value is not normally distributed as expected. On the kernel density plot, as shown in Figure 4.4, several frequently recurring values for the contractual EGTM value can be identified, 40°C, 50°C,60°C and 65°C are the most recurring values for the contractual EGTM.

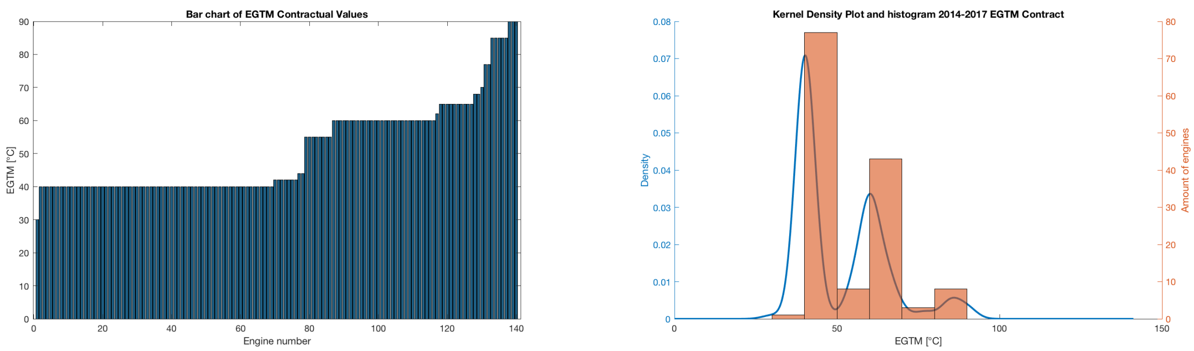


Figure 4.4: KLM E&M ES 2014-2017 contractual EGT analysis

4.2.1. Contractual EGTM performance all customers

In order to scope the quality measurements to the customer groups, an overview is made of the delta contractual EGT vs actual EGT margin for 2014-2017. This overview can be seen in Figure 4.5. This group does not take the KLM customer group into account, since the KLM customer group does not have a contractual quality agreement with KLM E&M ES.

As stated in Section 3.2.3, the quality performance is contractually bound with some of the engines and a financial penalty is applied if the contract is not met. The Financial penalty is worth 3000 USD on average per degree of EGTM below the contract. KLM E&M ES always makes the trade-off to let an engine re-enter the process or to pay the financial penalty. Also, as stated before, the penalty is not always paid in a direct manner, it can also be given to the customer as a discount for next Shop Visits .

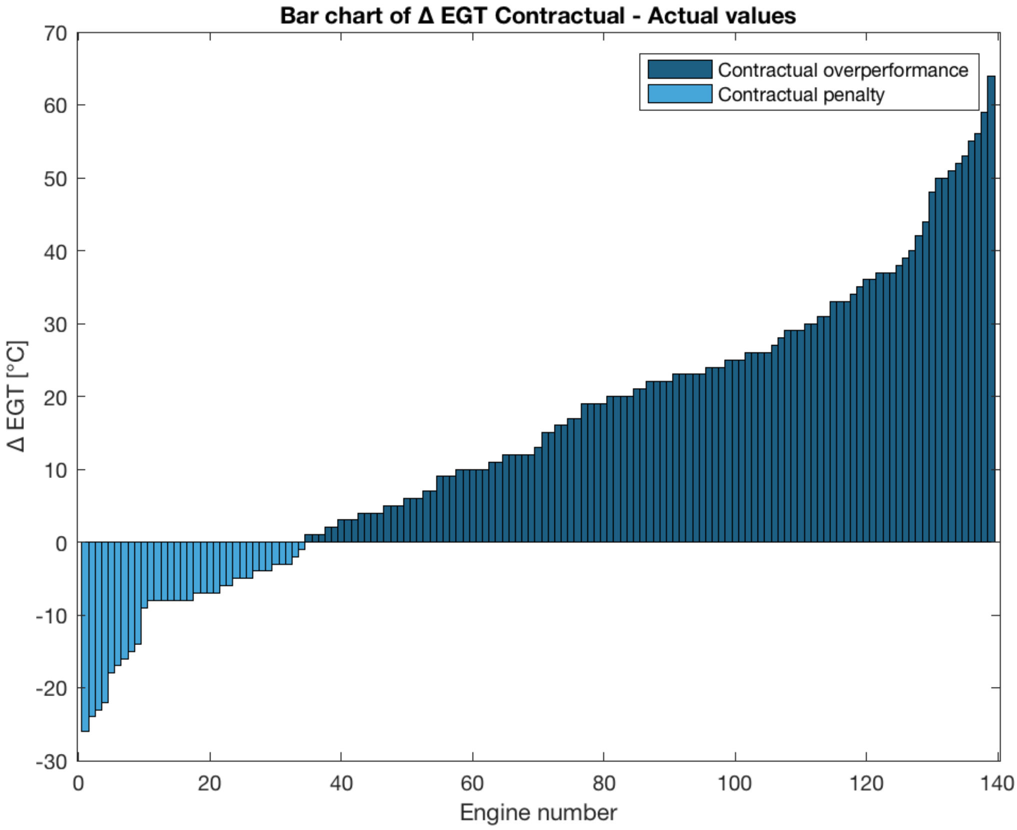


Figure 4.5: KLM E&M ES 2014-2017 contractual EGT performance all customers

If we look at the figure, we can see the area where a contractual penalty is applied, this is done to 34 engine contract. If we take the same estimate for each engine contract, the maximum potential in monetary value of gains through quality improvement can be calculated per year:

- The financial penalty is calculated at USD 957.000 over 2.5 years (2017 to 2014 Jul) equals USD 382.800 per year
- The financial potential is calculated at USD 7.065.000 over 2.5 years (2017 to 2014 Jul) equals USD 2.826.000 per year

4.2.2. Contractual EGTM performance GE/Offload customer

Figure 4.6 shows the same analysis, but then scoped only to the GE Offload customers. The GE Offload customer performs really well in terms of EGT Margin, the average contractual EGT value of this customer group is 50 degrees Celsius. As shown in the figure, only 8 out of the 72 engines perform under the contractual value.

- The financial penalty is calculated at USD 165.000 over 2.5 years (2017 to 2014 Jul) equals USD 66.800 per year
- The financial potential is calculated at USD 5.454.000 over 2.5 years (2017 to 2014 Jul) equals USD 2.181.600 per year

The peaks in EGT margin to the right side of the graph are caused by engines with very high EGT Margin. They were mature engines and had full overhaul workscopes. Almost all engines are tested on the same thrust setting.

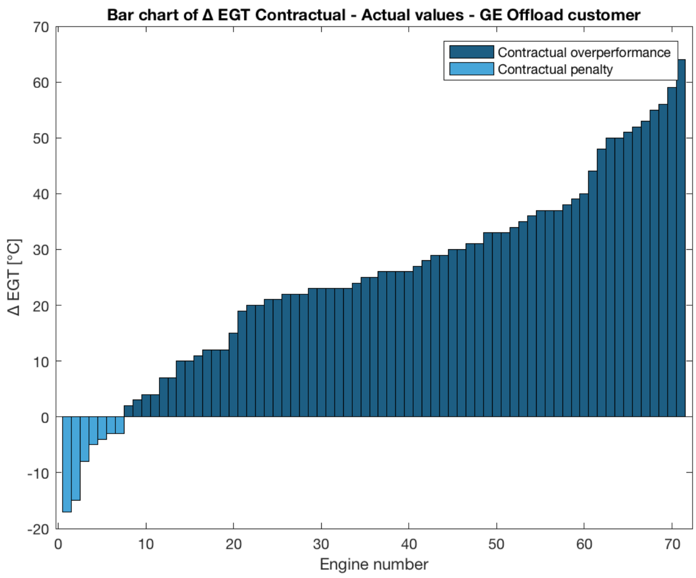


Figure 4.6: KLM E&M ES 2014-2017 contractual EGT performance GE Offload customer

4.2.3. Contractual EGTM performance External customers

Figure 4.7 shows the EGTM performance analysis for the external customers combined. The EGTM performance of the external customer group is the least out of all customer groups. The average contractual value for the external customer group is 60 degrees Celsius.

- The financial penalty is calculated at USD 792.000 over 2.5 years (2017 to 2014 Jul) equals USD 316.800 per year
- The financial potential is calculated at USD 1.611.000 over 2.5 years (2017 to 2014 Jul) equals USD 644.400 per year

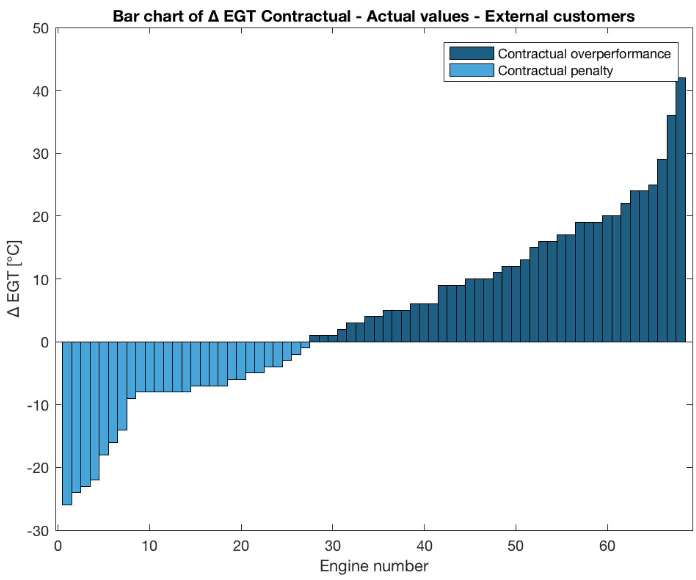


Figure 4.7: KLM E&M ES 2014-2017 contractual EGT performance External customer

4.2.4. Contractual EGTM performance KLM AF/Pool customer

Figure 4.8 shows the delta contractual and actual EGTM. As stated in Section 3.2.3 there is no customer agreement on EGT margin for the AF/KLM pool customer type. Therefore, there is no contractual penalty shown.

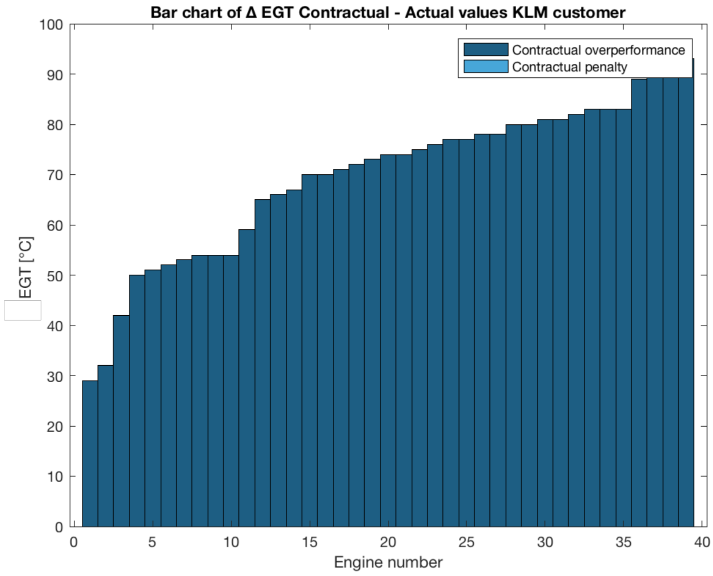


Figure 4.8: KLM E&M ES 2014-2017 contractual EGT performance KLM customer

4.3. TAT KPI Performance

The same way as the TAT performance is analysed, the OTP is analysed per customer group in order to find the maximum penalty potential. Figure 4.9 shows the delta between contractual and actual tat.

- The financial penalty for the TAT performance is calculated at USD 9.913.600 over 2.5 years (2017 to 2014 Jul) equals USD 3.965.440 per year
- The financial potential for the over-performance is calculated at USD 2.451.200 over 2.5 years (2017 to 2014 Jul) equals USD 980.480 per year

This process is repeated for the different customer groups and displayed in Figure 4.10.

- For the GE Offload customer group, the financial penalty for the TAT performance is calculated at USD 2.246.400 over 2.5 years (2017 to 2014 Jul) equals USD 898.560 per year
- For the GE Offload customer group, the financial potential for the over-performance is calculated at USD 723.200 over 2.5 years (2017 to 2014 Jul) equals USD 289.280 per year
- For the External customer group, the financial penalty for the TAT performance is calculated at USD 5.369.600 over 2.5 years (2017 to 2014 Jul) equals USD 2.147.840 per year
- For the External customer group, the financial potential for the over-performance is calculated at USD 924.800 over 2.5 years (2017 to 2014 Jul) equals USD 369.920 per year
- For the KLM customer group, the financial penalty for the TAT performance is calculated at USD 2.297.600 over 2.5 years (2017 to 2014 Jul) equals USD 919.040 per year
- For the KLM customer group, the financial potential for the over-performance is calculated at USD 803.200 over 2.5 years (2017 to 2014 Jul) equals USD 321.280 per year

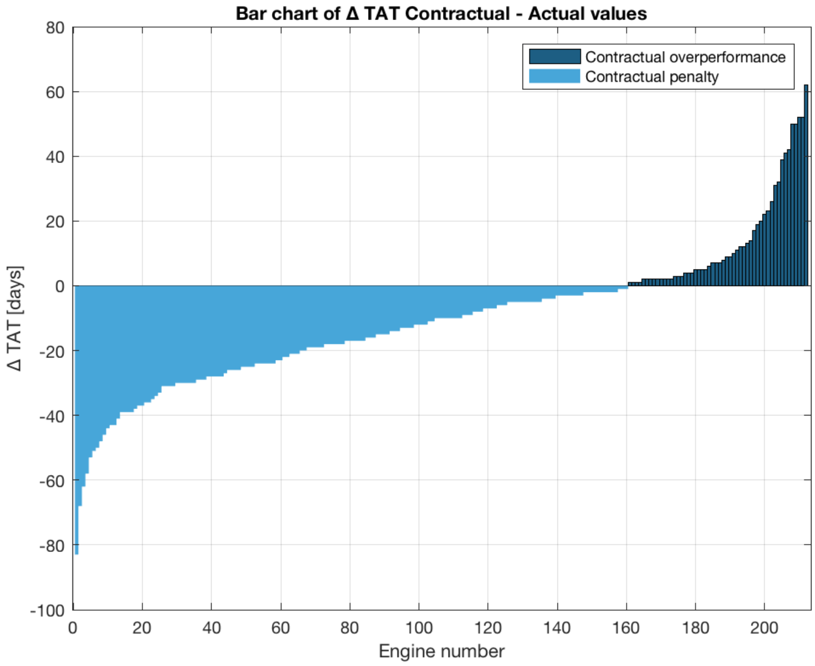
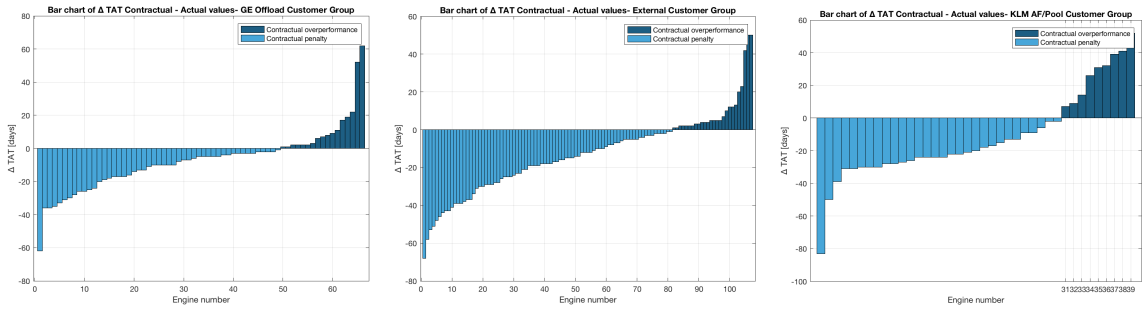


Figure 4.9: KLM E&M ES 2014-2017 delta contractual TAT vs actual TAT



(a) GE Offload customer group (b) External customer group (c) KLM AF/Pool customer group

Figure 4.10: KLM E&M ES 2014-2017 delta contractual TAT vs actual TAT

4.4. Time on Wing expectation

In order to know the Time on Wing (ToW) expectation, the relation between the Time on Wing and the thrust settings needs to be known. Table 4.1 shows the relation between thrust setting and Time on Wing expectancy for the CFM56-7B engine.

To calculate the average ToW for the KLM AF/Pool customer, the amount of cycles per year needs to be known and the engine configuration. Since most of the engines are matured, they are considered to be in their 2nd run. As stated before, KLM flies most with the 26K lbf thrust rating. Most KLM engines have had a Tech Insertion, which is an upgrade made in order to expand the life limit and decrease the fuel consumption of the engines [20]. KLM B737s fly 6 cycles per day on average and they are in flight 300 days per year. This results in 1800 cycles per year as the average cycle usage per year. The Tech Insertion Engine has an Time on Wing expectancy of about 11.000 to 15.000 cycles [22]. This will result in a theoretical expected Time on Wing expectancy of about 6.1 to 8.3 years. Results have shown that the ToW expectancy is closer to 8.3 years since the B737s fly in good conditions, therefore an ToW expectancy of 8 will be used in further calculations.

Table 4.1: Time On Wing Expectancy for different thrust settings

	Cycles	20-24K	26K	27k
Pre-tech Insertion Engines	1st Run	15.000-18.000	12.000-16.000	10.000-13.000
	2ndRun	12.000-17.000	9.000-14.000	7.000-12.000
Tech Insertion Engines	1st Run	16.000-20.000	14.000-17.000	11.000-14.000
	2ndRun	13.000-18.000	11.000-15.000	8.000-12.000

4.5. Bill of work

As stated in the process overview, the Bill Of Work is created in Stage 0 of the engine MRO process. Stage 0 consists of a few necessary steps in order to create the bill of work. The process steps of Stage 0 are shown in Figure 4.11. First the Compliance Check (CC) is done, in this check all the paperwork is verified and the documents for the parts, the life limits of these parts and previous shop visits are analysed. The next step is the Incoming Check (IC), in this step the engine is placed in the overhead stand in the shop. this is where the Shop Visit starts, in this step, the Bill Of Work is created by the engineering department. After the Incoming Check takes place, a meeting is organised with the customer in order to agree on the Bill Of Work. The BoW visual inspection scheme as provided by CFM can be found in Appendix E.

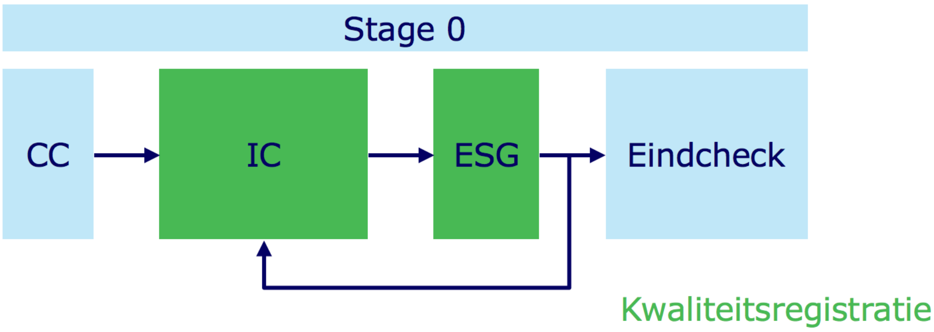


Figure 4.11: Stage 0 process steps

KLM E&M ES might do recommendations based on the engineering report and the customer could accept these if they are voluntary recommendations. If the recommendations are to assure serviceability of the engine, KLM E&M ES will state so at the ESG meeting. If the choice is made not to comply with the recommendations of KLM E&M ES, the engine might be overhauled but not be serviceable at the end of the process. When all these steps are finished, a final check is conducted on all the documentation before the disassembly starts in Stage 1.

Inspections and alterations of the BoW don't only take place in Stage 0, when the engine is disassembled in Stage 1, each module is still inspected. Sometimes findings in Stage 1 can also influence the BoW.

The Engine Service Manual (ESM) describes a list of factors that influence the forecast or planning of the workscopes. Factors that are taken into account in the workscope determination are:

- LLP Remaining – Determines which modules need to be exposed for LLP replacement
- LLP Stub Life Criteria – Be sure to "match" LLP lives across the engine
- HPT Blade recommended removal cycles – be sure to meet or exceed the cycles remaining of the LLP in the the HPT Rotor module or to the next expected shop visit (such as Fan or LPT LLP life expiration shop visit).
- Engine Configuration – Review S/B Status versus Maintenance Specification
- Airworthiness Directives – Comply with at Shop Visit
- Lease Return Requirements – EGT and LLP Requirements are significant driver to workscope
- Equipment Operation Horizon – Consider the age of the Aircraft and future operational requirements

- Engine Distribution (TSV/CSV) – May need to build on wing entitlement into engines to stagger fleet shop visit schedule in the future
- Shop Loading/Manpower – How quickly do we need the engine back? May drive heavy vs. light workscope
- Engine Reliability – What S/B's are to be incorporated at shop visit?
- Environmental Factors : erosion, pollution, ambient temperature Performance Deterioration- Any upgrades available to reduce deterioration?
- Derate Usage – This can impact deterioration rates
- Engine Thrust – Any opportunity to re-rate engine – Impact on LLP life?
- Water Wash Program – This can impact the engine TOW significantly. CFM recommends operators evaluate their engines using CESM 014 - Gaspath Cleaning Recommendations for Installed engines

There are three types of workscopes on an engine level: Minimal, Performance and Full workscopes.

1. Minimal Workscope: Only necessary work is done, this workscope is used for small repairs
2. Performance Workscope: Only necessary work is done in order to optimally perform a quality performance restoration. Some modules are disassembled and repaired on piece part level.
3. Full Workscope: Every module is disassembled to piece part level and overhauled.

Table 4.2: Optimal Workscope as determined by CFM

Assy	Workscope level	Disassembly Level
01X Fan	Level1	"on condition" module assembled
31X HPC Rotor	Level 2	HPC Kept Stacked, with HPC Blades removed
32X HPC Front Case	Level 3	Piece Part
33X HPC Rear Case	Level 3	Piece Part
41X Combustion Case	Level 3	Piece Part
42X Combustion Chamber	Level 3	Piece Part
51X HPT Nozzle	Level 3	Piece part
52X HPT Rotor	Level 2	Rotor Stacked, Blades removed
53X LPTN 1	Level 2	Shroud refurbisment
03X LPT module	Level 1	"on condition" assembled

Every module also receives a workscope. The workscope options for the modules are prescribed by the Engine Service Manual and more described on a practical level in the Workscope Planning Guide (WPG). The module workscopes are similar to the engine workscopes, only with the addition that a module can be removed serviceable. Then it is put away and re-assembled in the assembly stage. In order to optimize the engine performance, CFM created a workscope with the goal to optimize the EGT Margin, this can be seen in Table 4.2.

For KLM E&M ES the workscope distribution per assy for 2017 is shown in Figure 4.12.

4.6. Value Driving Assy's

The Workscope Planning Guide as provided by CFM states that the core is the most value contributing assy in terms of quality. As explained in Chapter 3, the flow path clearance is the most important factor. The pressure build-up in the compressor is the most critical in the engine chain.

The HPC is a 9 stage high pressure compressor and the LPC is a 3 stage low pressure compressor. Since the pressure is high in the high pressure compressor, the bleed air that wants to blow back is more critical to the EGT Margin than the bleed air from the pressure build-up in the low pressure compressor. Since the HPC and LPC are both responsible for the pressure build-up towards the combustion chamber and there is a known direct relation with the EGT Margin, they are chosen as the main focus modules for this research.

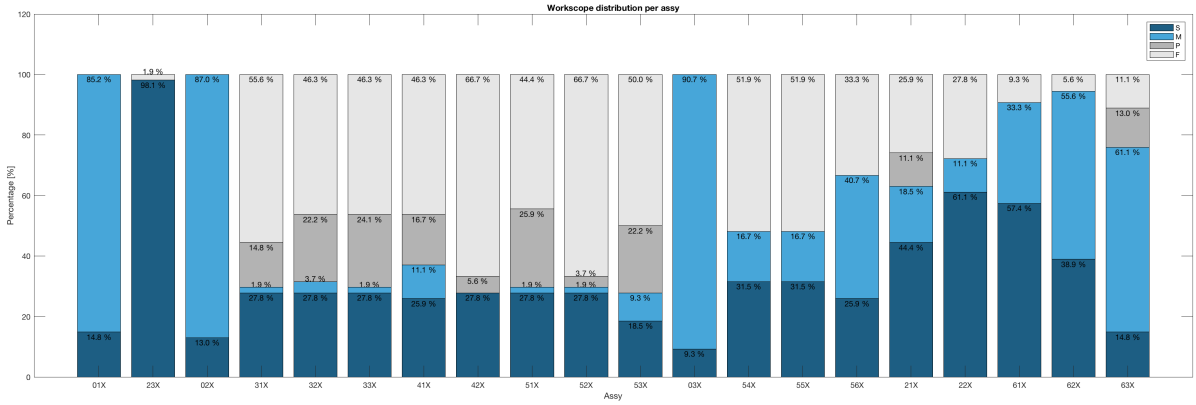
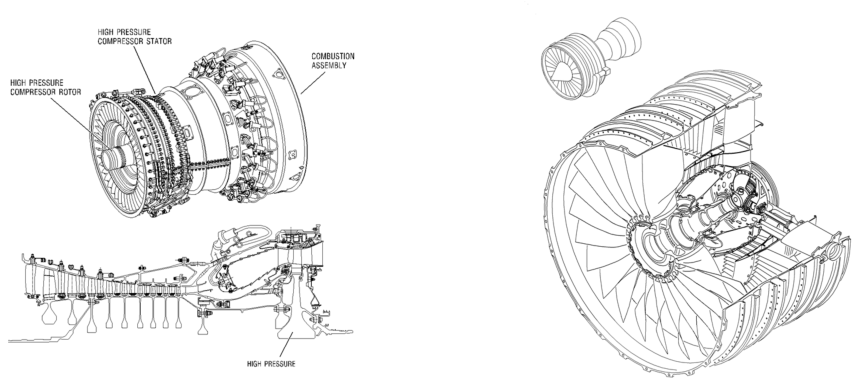


Figure 4.12: 2017 KLM E&M ES BoW measurement



(a) The HPC Module (31X, 32X, 33X0) (b) The LPC Module (21X)

Figure 4.13: The compression modules

The HPC consists of 3 assy's. It has a rotor, the 31X and a stator/casing unit. The frontward casing is the 32X, the rear casing unit is the 33X assy. The LPC is one assy, the 21X. These assys are shown in Figure 4.13.

4.7. Measuring points

When looking into the repair process of the HPC and LPC modules, there are certain points in the disassembly and assembly step where quality related measurements take place. These measurements are described by the WPG [22]. Figure 4.14 describes the chain for the HPC, Figure 4.15 describes the chain for the LPC. The chains are built up out of blocks that represent one shift in order to get an understanding of the nominal timeline for the quality measurements.

4.7.1. HPC: 31X, 32X, 33X

The most critical to quality step in the 7B engine is the HPC Compressor, which consists out of a rotor and a stator which is divided in two parts. In the WPG the key maintenance tasks can be summarized as follows:

31X Minimal Workscope:

- Removal necessary, no disassembly.
- Inspect module
- Water wash module

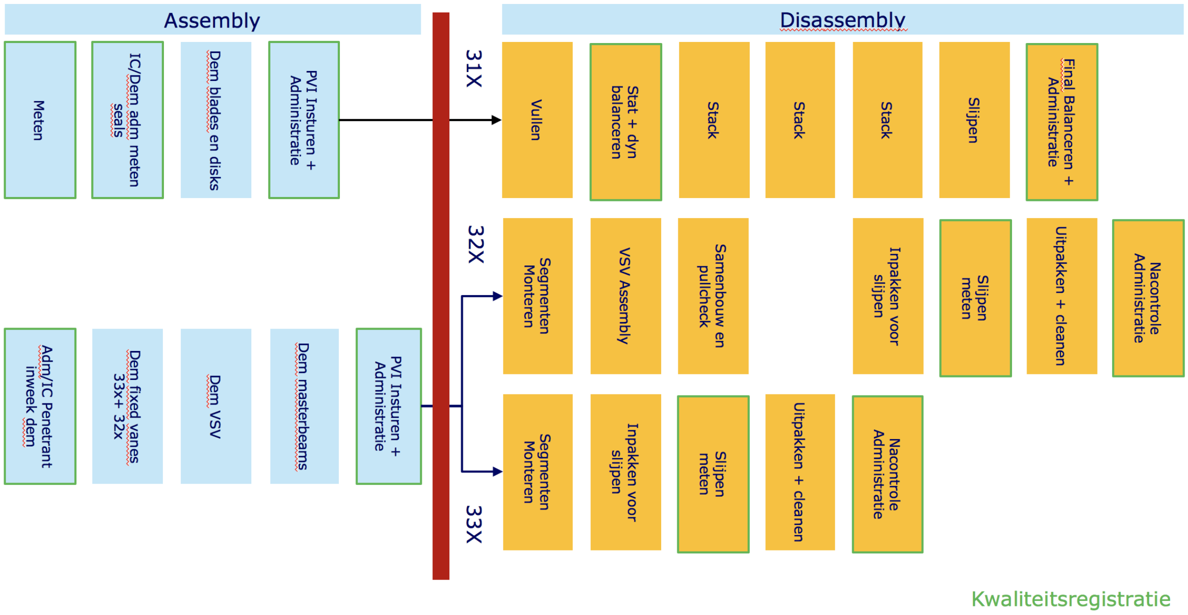


Figure 4.14: HPC (31X, 32X, 33X) chain per shift with measurements

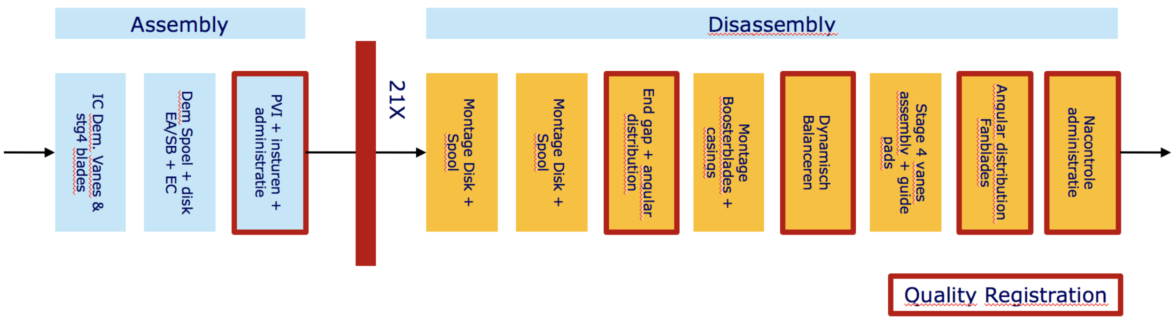


Figure 4.15: LPC (21X) chain per shift with measurements

- If evidence of bird strip in the HPC, a check needs to be done on cooling blockage in the nozzles.

31X Performance Workscope:

- Partial disassembly needed.
- Clean and inspect HPC Blades, dimension check and edge thickness, replace unrepairable blades
- Apply dry film lubricant
- Measure seal diameters for serviceability, if under minimum replace and repair
- Install blades and clean after grind

31X Full Workscope:

- Inspect blades for dimensional and visual limits
- Unstack HPC rotor and measure seal diameters
- Replace Blade seals stage 4 to 9
- At assembly, determine stage by stage HPC clearance by measuring Blade radius and Stator cases
- Perform HPC linipot inspection in the vertical position

- Balance the HPC Rotor

The optimal workscope for the 31X is prescribed to a performance level workscope since the main critical to quality components are the blade sets. For all 9 stages the blades are measured, and the variance in each stage is measured. An overview of the blade sets is shown in Figure 4.16. For each step the radius of the casing and the diameters of the blades are matched in a similar manner. Note, there are two groups visible, the group to the left is for the engines without a tech insertion, the group to the right is for the engines with a tech insertion. For clarification, the images used in the analysis and future state will only show tech insertion engines, but non tech insertion engines are also used in the next phases of this research since they have the same bandwidth and the quality contribution factors are known.

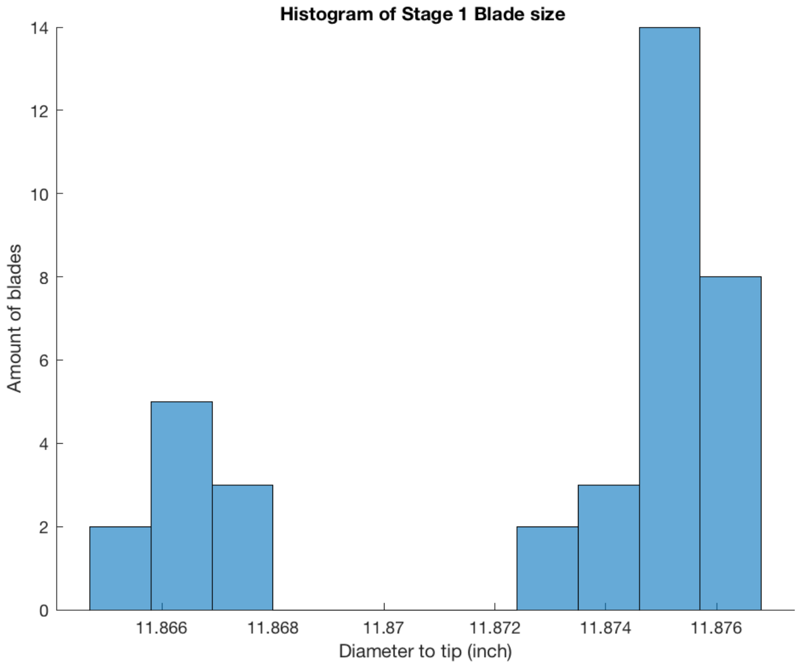


Figure 4.16: Histogram of HPC stage 1 blade lengths

Table 4.3 shows the prescribed performance of the HPC Module as prescribed in the Workscope Planning Guide. The WPG has prescribed EGT performance effects. These performance effects are empirically determined by CFM. CFM gathered data from all CFM clients and test cell setups to see what type of influence certain process steps have. For example, when a repair takes place. Stage 8 has the highest EGT coefficient for both the tip clearance and seal rub depth. If the rub depth is 0.019", the additional rub is the Depth - Post break-in value. This will result in an EGT Impact of 0.019-0.016=0.003" = 3mils. The impact on the EGT is 3 * 0.0999=0.297 degrees of EGT Margin. Using this method, the maximum possible performance improvement for each stage can result in the maximum improvement of the engine. For each stage, this can be calculated in the same way.

4.7.2. LPC: 21x

The compression in the 7B engine starts with the LPC compressor, within CFM the 21X LPC is called the booster. In the WPG the key maintenance tasks are created by analysing and summarizing the work descriptions from the Engine Service Manual. Per workscope the key maintenance tasks are described as follows:

Minimal Workscope:

- Perform a water cleaning of the module assembly removed.
- If stage 2& 4 Booster Outer Shroud abradable seal shows rubs or erosion, restore the inner shroud

Table 4.3: High Pressure Compressor Module Performance Effects [22]

Feature	Post break-in value (mills/microinch)		SFC Effect % (mils/microinch)	EGT Effect deg C (mils/microinch)
	Non-TI	TI/7BE		
HPC Stage 1 tip clearance	51	59	0.0081	0,1323
HPC Stage 2 tip clearance	63	57	0.0045	0,0738
HPC Stage 3 tip clearance	32	28	0.0051	0,0828
HPC Stage 4 tip clearance	47	45	0.0065	0,1062
HPC Stage 5 tip clearance	32	36	0.0062	0,1008
HPC Stage 6 tip clearance	38	43	0.0062	0,1008
HPC Stage 7 tip clearance	32	37	0.0066	0,1080
HPC Stage 8 tip clearance	33	38	0.0072	0,1179
HPC Stage 9 tip clearance	35	39	0.0063	0,1026
HPC Stage 4-9 average blade tip clearance throttling impact	36.2	39.7	0.0266	0.4320
HPC Stage 1 I/S seal rub depth	18		0.0017	0.0270
HPC Stage 2 I/S seal rub depth	8		0.0023	0.0369
HPC Stage 3 I/S seal rub depth	15		0.0026	0.0432
HPC Stage 4 I/S seal rub depth	13		0.0035	0.0567
HPC Stage 5 I/S seal rub depth	22		0.0043	0.0702
HPC Stage 6 I/S seal rub depth	18		0.0047	0.0774
HPC Stage 7 I/S seal rub depth	17		0.0054	0.0891
HPC Stage 8 I/S seal rub depth	16		0.0061	0.0999
General HPC airfoil erosion	None		0	0
	Medium		0.4	4
	Heavy		0.7	7
Stage 1-3 blade RTV liberation (per percent missing)			0.00165	0.027

abradable seal of the Booster by partially disassembling the module.

Performance Workscope:

- Restore Booster Shroud abradable seals stages 2, 3, 4

Full Workscope:

- Restore booster blades dovetail coating for all stages
- Restore booster vanes for all stages
- Repair the seals of the booster for all stages

Experience shows that Performance restoration on Fan module has limited impact on overhaul engine performance restoration results. All the workscopes have a similar effect on the EGT limit since they are minimizing the tip clearance and clearing the gas flow path in a similar way. The maximum EGT restoration potential of the full workscope of the 21X is estimated around 4 degrees EGT Margin.

In STREAM there is quality data available about the blades:

- Balance Report (Dynamic Balancing measurement)
- Coating Report
- Fan Blades Report (Angular Distribution measurement)

- Weight before and after repair (End Gap measurement, before repair measurement)

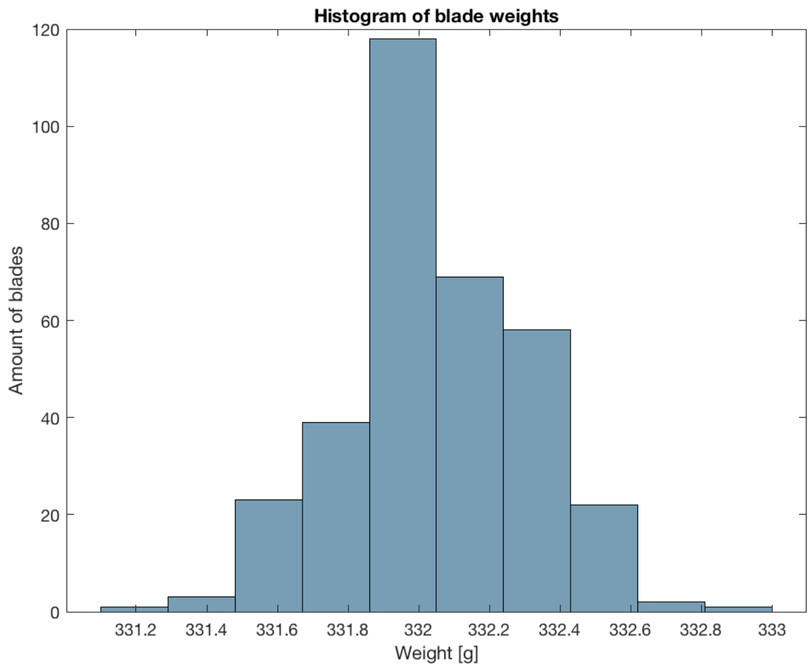


Figure 4.17: Histogram of blade weights for 21X assy

The repair step self is done externally by GE Aviation and consists of combinations of the following repair steps:

- Rejuvination Heat Treatments
- Surface Modifications
- Re-Coating
- Welding

4.8. Observations

This section describes the observations made during the measurement of the current state of KLM E&M ES. Although they are not quantitative, they are important to describe the current state of quality control.

4.8.1. Quality of data

The data that is used for this research consists of documents that are written by hand and scanned into a central document system called STREAM. The scans are of bad quality, therefore sometimes numbers cannot be read properly. Also, almost every measurement is written by another person so there is a lot of variation in the hand writings which makes it hard to decode.

Because the measurements are written by hand the values are not 100% reliable. Since there is a limit by regulation of some of the measurement values, this can be used to aid the deciphering of the STREAM data. Furthermore, the STREAM system sometimes lacks files, so the data is not complete per engine. Almost every engine misses 1 or 2 documents in this system, the files for the documents are made but empty with a note that the document is not scanned as yet.

4.8.2. Engineering

The engineering department focusses on the quality of the engine and makes the life time prediction calculations. They are responsible for the Test Cell operations and for the BoW creation. The engineers do not use the in situ data available in STREAM but only use data from:

- The Workscope Planning Guide
- The Aircraft Maintenance Manual
- The Engine Service Manual
- The ESG meeting
- The Test Cell

The data from the internal repair steps in relation with the EGT output has not been researched for the CFM56-7B engine. The vision is that the workscope determines the gross EGT contribution to an assy, and the workscope determination controls the output quality of the process.

4.8.3. Interviews Awareness

When looking into the awareness of the management and the workforce, it is noticeable that there is not a lot of focus on quality. Quality is seen as a boolean value that always needs to be a yes in order to be airworthy. The engineering department looks into the quality using the Workscope Planning Guide. Engineering looks at direct shop costs and is only able to control the process by tweaking the workscopes per assy. Within the serviceable limits, there is no focus on quality improvement.

Although there is no real focus on quality, the management always states that the quality should be as high as possible. High quality is one of the pillars of KLM Engineering & Maintenance. There is also no real identification where the bottlenecks in the process are for quality performance. Furthermore, most mechanics do not know how the quality within the process is registered except for the serviceable certification per part.

4.9. Conclusion Current State - Measurements

This chapter describes the current state of the Engine MRO Process. First, the test cell measurement procedure is explained in order to understand the EGT Margin determination process. Then, the EGT performance per customer group (KLM AF/Pool, GE, External customers) is measured with the financial impact. Next, the TAT Performance is measured with the financial impact.

Then, the procedure of creating the Bill of Work is walked through in detail, explaining the current sate of quality control in the process. Next, the BoW is shown per Assy, and the value driving assy's are picked. For the High Pressure Compressor and Low Pressure Compressor the data available within the process is mapped and explained and the coefficients per process/measurement step are gathered from literature. The values from literature are empirically determined from CFM56-7B engines from all OEM customers.

This chapter answers the following research questions:

6. What levels of maintenance are available in the engine MRO process?
7. How is the workscope determined for engine MRO?
8. What is the relation between quality and Time On Wing?
9. Which assy's & modules can be identified that contribute the most to the quality of an Engine?
10. How is the current quality performance controlled during the MRO process at KLM E&M ES?

6. What levels of maintenance are available in the engine MRO process?

There are four levels of workscopes available within the process. From high to low they are respectively: Full Overhaul Workscope, Performance Workscope, Minimal Overhaul Workscope and Serviceable Removed Workscope. The first workscope is one where all parts are stripped to piece-part level and then repaired or refurbished. At the performance workscope the assy is stripped where necessary, but not completely overhauled. The minimal overhaul consists of repairs where needed. When the assy is serviceable removed the assy is placed back at the assembly stage, and no repairs are done to the assy.

7. How is the workscope determined for engine MRO?

The workscope for the engine is determined per assy. A visual inspection takes place after which the engineering department creates a Bill of Work. In this Bill of Work many factors are taken into account, including previous shop visits and the life limit of parts. When something is found where the airworthiness can be in danger, KLM E&M ES has to discuss this with the customer. The customer is obliged to confirm with the KLM recommendation if airworthiness is at stake.

8. What is the relation between quality and Time On Wing?

When the EGT Margin is increased, there is a direct increase in the Time on Wing. The Time on Wing depends on the EGT Margin and the thrust settings of the aircraft. Also, the Time on Wing depends on the Tech Insertion upgrade from CFM. The Time on Wing expectancy of CFM56-7 engines for the KLM fleet is about 8 years. The relation between quality and Time on Wing is 7 degrees EGT deterioration per year. When the engin is matured, the relationship between the EGT Margin and ToW can be considered linear.

9. Which assy's & modules can be identified that contribute the most to the quality of an Engine?

According to literature, the High Pressure Compressor module contributes the most to the quality of the engine since it is responsible for the pressure build up towards the compression chamber. As stated in the previous chapter, the flow path clearance is the major driver for quality.

10. How is the current quality performance controlled during the MRO process at KLM E&M ES?

The current quality performance is controlled by determining the workscope planning through the Bill of Work. There currently is no quality control on the process steps since the parts need to be serviceable, which is sufficient by regulation.

5

Current State - Analysis

This Chapter focusses on the current state data analysis. The measurements from Chapter 4 will be analysed combining the separate measurements from the previous chapter, using Sig Sigma tools to do so. The variations within the process are divided into two sources for variation according tot the Statistical Process Control methodology. Finally, the current state of quality control can be described.

The following sub research questions will be answered in this chapter:

11. How do you measure the quality output of the HPC and LPC assy's?
12. What strategies can be proposed in order to decrease the variance in the process?

5.1. Match workscope to prescribed optimum

As stated in Section 4.5, the bill of work has a prescribed optimal performance restoring workscope per engine and per module. The optimal workscope gives the most critical assy's an overhaul and leaves the other assy's serviceable removed. Figure 5.1 shows the matching of the actual BoW to the prescribed BoW while Figure 5.2a shows the amount of assy's which have the optimal workscope chosen or higher. As shown, the optimal workscope is not always chosen, most of the times a workscope higher than optimal is performed. However, for the critical parts, the compressors and turbines, a lower workscope is chosen quite frequently as well. This can be seen in Figure 5.2b.

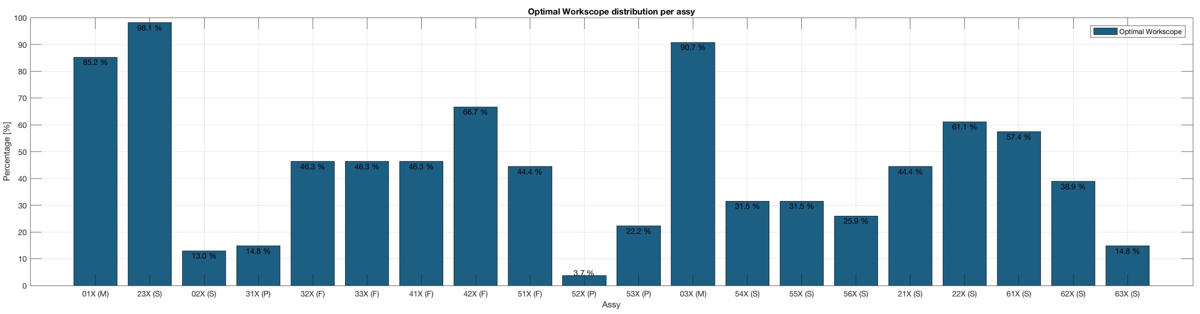
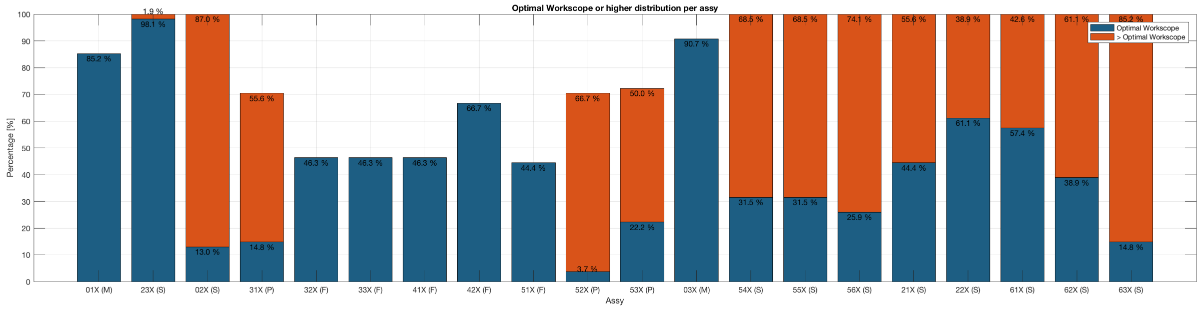
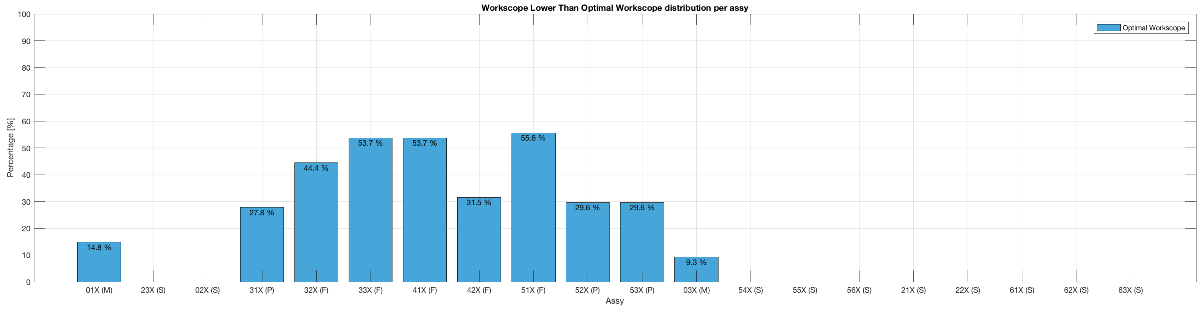


Figure 5.1: Matching of the actual BoW to the prescribed actual BoW per assy



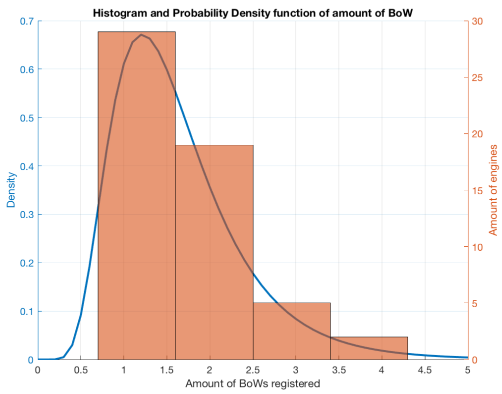
(a) Matching of the actual workscope or higher to the prescribed workscope per assy



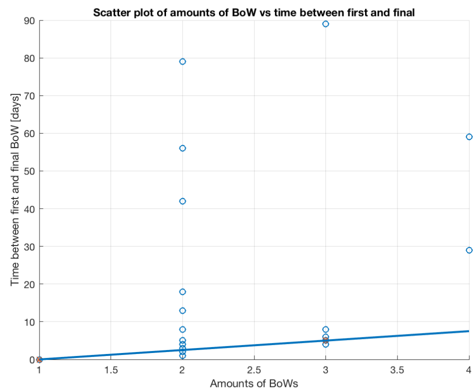
(b) Distribution of the lower workscope than the prescribed workscope per assy

Figure 5.2: Matching of the actual BoW to the prescribed BoW

Apart from the BoW matching to the workscope, the BoW can also have an effect on the Turnaround Time performance. For the 2017 engines with a quality contract, the number of BoW's is visualized in figure 5.3a. When looking at the scatter plot of Figure 5.3b it can be seen that a trend line is drawn through the 2017 data from the amount of BoW changes and the delays caused by it. From the 2014 to 2017 data it can be concluded that there is a positive association relation present which can be categorized as medium strength (0.5 <r <0.7) since r=0.62.



(a) Histogram and Probability Density Plot



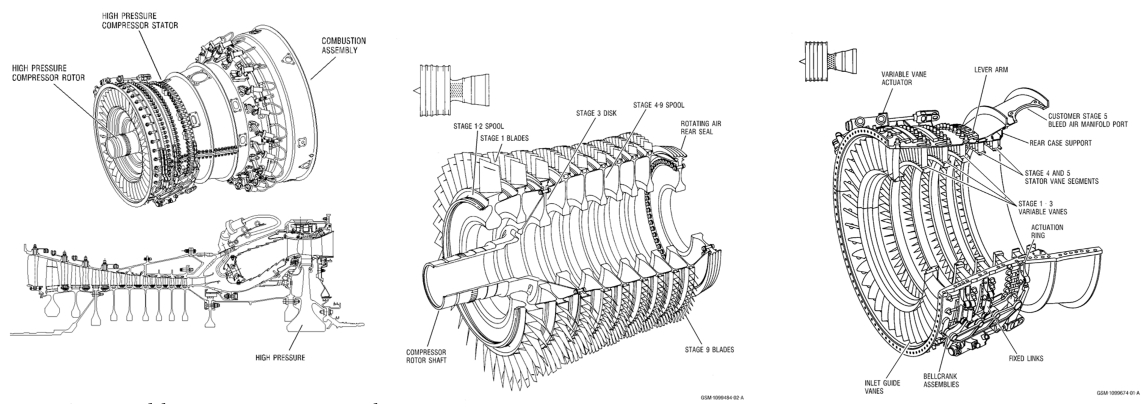
(b) Scatter plot of Bow Changes vs Delay Time

Figure 5.3: The amount of BoW changes and the delay effect

5.2. Variation in quality

This section describes the variation in the process steps in order to understand the process. In Section 4.7 the measurements were described, a quick overview of the results was given and the norms for repair according to the Engine Service Manual translated into the Workscope Planning Guide were shown. This section analyses the results from the measurements and combines it with the Workscope Planning Guide in order to get an overview of the variation in the process.

5.2.1. HPC: 31X, 32X, 33X



(a) HPC Assembly (31X, 32X, 33X) and combustor

(b) HPC Rotor (31X)

(c) HPC Forward Casing (32X)

Figure 5.4: Stage 1 dimensional value histograms

For the 31X, 32X and 33X as shown in Figure 5.4, there are more measurements available within the STREAM database:

- Balance Report (Dynamic Balancing measurement)
- Coating Report
- Blades Report (Angular Distribution measurement)
- Size of the Rotor blades after repair
- Diameter of the casing

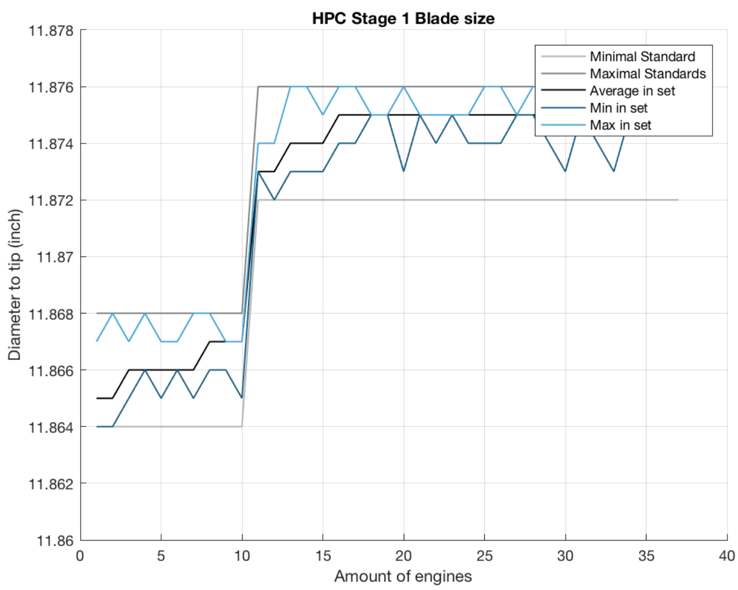
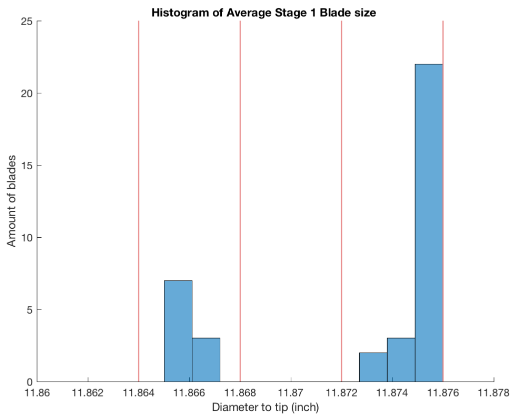


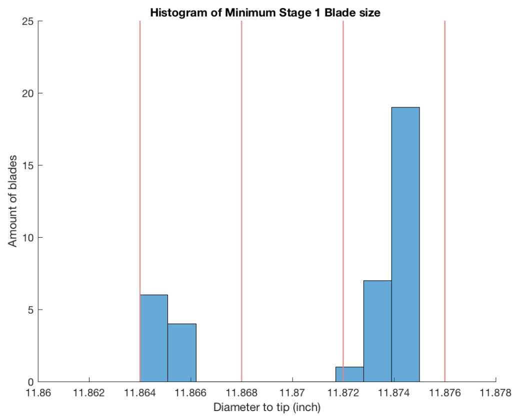
Figure 5.5: Stage 1 blade size distribution per set

To start, Figure 5.5 is a run chart of the 31x stage1 blade size. There are two different sizes of blades, the ones with the lower and upper limit of 11,864 and 11,868 respectively have the older serial numbers. The ones with the lower and upper limit of 11,872 and 11,876 are newer. This is the case in each stage with different sizes and values.

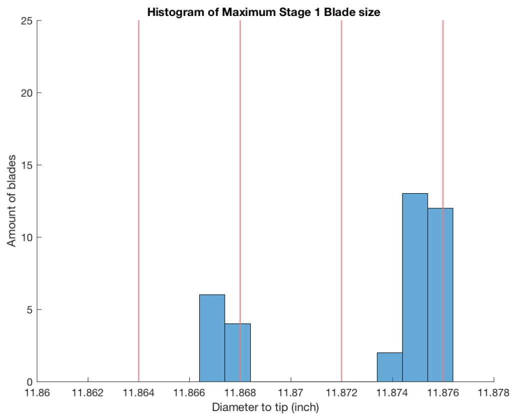
The amount of variation within the blade set is clearly visible, also the bandwidth in which the values fall is never exceeded. Figure 5.6 shows histograms for the average, minimum and maximum dimensional values within the set. The red lines are the WPG limits, the left group corresponds to the older engines without tech insertion, the right group to the newer engines. This process is repeated for every stage for the rotor and the casings and can be seen for the tech insertion engines in the Appendix F. What can be seen from this analysis is that the variance in stage 8 and 9 are the highest, each engine has a variance within the set of fanblades resulting in a loss of potential EGT Margin.



(a) Average dimensional values



(b) Minimum dimensional values



(c) Maximum dimensional values

Figure 5.6: Stage 1 dimensional value histograms

5.2.2. LPC: 21X

For the 21X there are a few measurements present within the STREAM data:

- Balance Report (Dynamic Balancing measurement)
- Coating Report
- Fan Blades Report (Angular Distribution measurement)
- Weight before and after repair (End Gap measurement, before repair measurement)

The first analysis is done on the balance reports. The outcomes from the balance report are very diverse in magnitude and outcome. When studying the Workscope Planning Guide, the balance is an adjustment to the outcome of the weight distribution process and is not calculated at the front end of the process. Also, the balance does not contribute to the EGT Margin performance. The balance report can only contribute to the amount of vibrations of resonance. The starting imbalance weight is always lower than 20 grams, the final imbalance weight is always lower than 5 grams and is therefore considered neglect-able.

The second analysis is done on the coating report. The coating has a norm to be 5 μm thick. There is a 100% performance on the coatings. All 22 engines from 2017 who had a 21X Full Overhaul workscope have had a registered coating of 5 μm thickness.

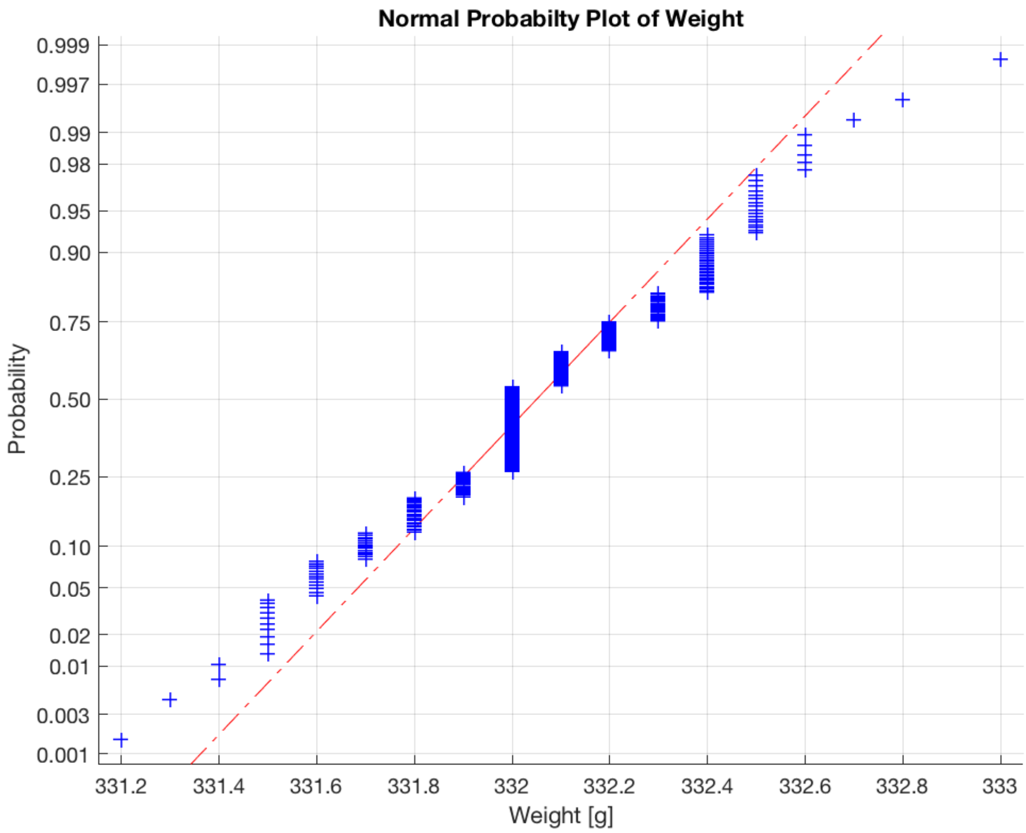


Figure 5.7: Normal probability plot of stage4 blade weights

The third analysis is done on the weights of the fan blades. This is divided in two section. First, the weight of the blades after repair is analysed. Second, the increase of the weight of the blades is analysed. Figure 5.7 shows the normal probability plot of the weight. As shown by the plot, the weight can be assumed normally distributed.

Figure 5.8 shows the Stable probability density plot of the weights of the blades and a histogram. A random variable is said to be stable if its distribution is stable. and this distribution seems stable. but there is a small peak around 332,4 grams of weight.

The second section of the analysis analyses the removed weight distribution of each separate fanblade from Stage4. As shown in Figure 5.10, it can be concluded that the removed weight is not normally distributed.

Figure 5.10 shows there are two major peaks for the removed weight of the stage 4 blades: One peak at around 3 grams and one peak at around 4 grams.

From the measurements of the 21X it can be concluded that the outcome of the process is stable, but there is still room for improvement in the stability of the final weights. The goal is to have all equal blades that

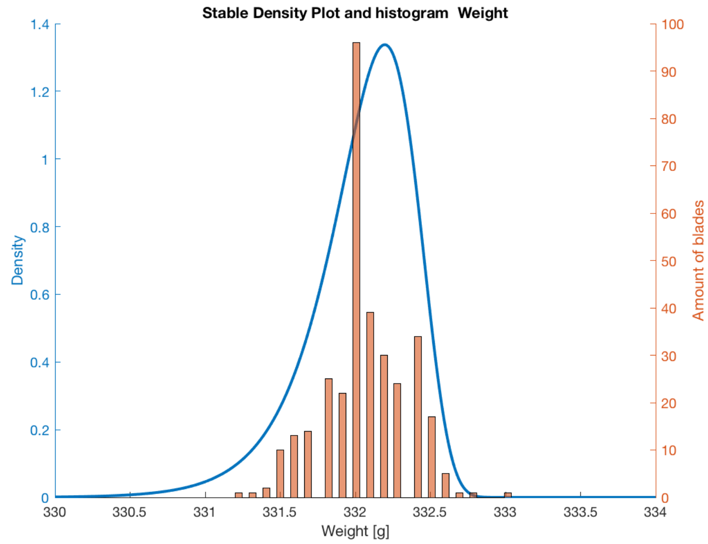


Figure 5.8: Histogram and stable density probability plot of stage 4 blade weight

weighs 332grams. In the diameter of one stage, all blades must have the same proportions in order to have no leakage. Only in this way, the outer seal diameter can match the diameter of the blades.

5.3. Strategies

In order to decrease the variance of the sets of blades, different strategies can be chosen. First, it needs to be assured that all engines have similar quality contracts, also for the internal KLM AF/Pool customer group. Without a quality contract, active control on quality is not possible since there is no demand to be met. When looking into the repair steps that can be altered in the process, the strategies need to be within the assembly and disassembly stages of the repair. The fanblades that are critical to quality are outsourced to General Electric, and other than new vendor agreements, there is no control possible on the process. The bandwidth of 5 microinch variation is standard for each stage and cannot be tweaked.

A way to decrease the variance is by replacing the blades with the lowest and highest diameter to blades with the average quality measurement.This way, when the seals are broken in, the blade tip clearance is equal and there is less bleed air going through since all blades match the seal diameter.

Furthermore, since the most variance is presented in the stages that have the largest quality contribution, stage 8 and 9, these stages can serve as a test case for variance removal within the blade set. The impact of stage 8 and 9 blade replacements would be the largest on the engine.

Another way of decreasing the variance is swapping the blades with a high varying diameter between engines so they have less variance on set level. This currently is not allowed since all parts stay at the same engine at KLM E&M ES, but it would have high economical benefits compared to total part replacement.

5.4. Conclusion current state analysis

This chapter describes the current state analysis of the CFM56-7B. First, the match between the workscope and the prescribed optimum is discussed, showing that there frequently is a lower workscope than prescribed for the critical to quality assy's and a higher workscope for the non quality critical qualities.

This chapter also identifies the measurement points for the HPC and LPC assys. For the HPC the size of the rotor blades after repairs and the diameters of the casings have a direct relationship to the EGT Margin. For the LPC the weights before and after repair give an indication for the wear of the blade, which has a relationship to the EGT Margin.

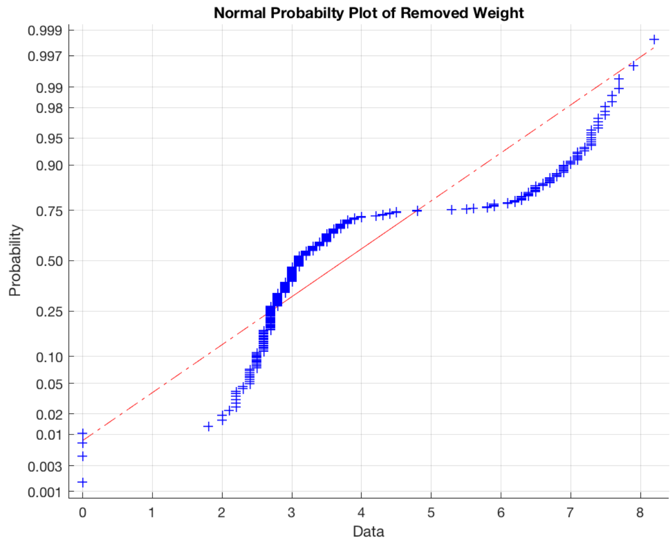


Figure 5.9: Normal probability plot of removed stage 4 blade weight

This chapter answers the following sub research questions:

11. How do you measure the quality output of the HPC and LPC assy's?
12. What strategies can be proposed in order to decrease the variance in the process?

11. How do you measure the quality output of the HPC and LPC assy's?

The measurements for the quality from the HPC and LPC components are taken in the assembly phase. For the HPC, the diameters of the rotor blades and the diameters of the casings are known and have a direct relationship to the EGT Margin. For the LPC, the weights from before and after repair give an indication of the tip clearance and have a direct relationship to the EGT Margin.

12. What strategies can be proposed in order to decrease the variance in the process?

As described in Chapter 4, the repair steps for the parts within the HPC and LPC are mostly outsourced. Therefore, the strategies for improvement need to be able to be implemented within the assembly and disassembly stages of the MRO process. The variance needs to be decreased by swapping the low quality parts by high quality parts. The proposed strategies consist of replacing the low quality fanblades by fanblades that match the average within a set, this way there is less bleed air leakage. Another strategy is swapping fanblades between engines in order to create an optimum for the different sets.

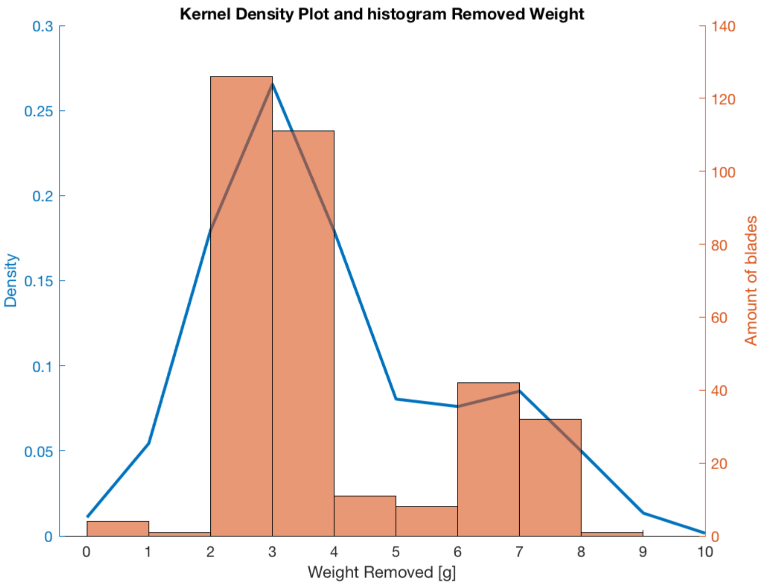


Figure 5.10: Histogram and kernal density probability plot of stage 4 removed weight

6 Future state

From the current state measurements in Chapter 4, the potential of the quality based contracts is explained. From the current state analysis in the previous chapter, the most quality contributing assys are analysed and the variances in the process that have a known link to the EGT margin are identified. To improve the control of the quality, first the impact of a quality based contract is estimated on the KLM customer for the CFM engines. Then, two future quality improvement steps are modelled, discussed and their financial potential is analysed.

The following sub research questions will be answered in this chapter:

13. How do you model the quality output of an individual assy?
14. What is the potential in increasing the quality performance?

6.1. Contract Potential KLM based on EGT Performance

To identify a potential quality based contract for the KLM customer group, a few limits need to be chosen as discussed in Chapter 4. The contractual average of the EGTM performance of the GE/Offload group was 50 degrees. The contractual average for the External customer group was 60 degrees EGTM.

This section simulates the quality performance for a 40, 50 and 60 degree EGTM contract for the KLM AF/Pool customer group.

6.1.1. 40 degree EGTM contract

The first simulation consists of a contractual performance of 40 degrees. Figure 6.1 shows the first simulation with the 40 degree ETGT contract. The figure shows the area where a contractual penalty is applied, this is done to 39 engine contract. If the same estimate for each engine contract year is taken, the maximum potential in monetary value of gains through quality improvement can be calculated per year:

- The financial penalty is calculated at USD 57.000 over 2.5 years (2017 to 2014 Jul) equals USD 2.280 per year
- The financial potential is calculated at USD 3.519.000 over 2.5 years (2017 to 2014 Jul) equals USD 1.407.600 per year

6.1.2. 50 degree EGTM contract

The second simulation consists of a contractual performance of 50 degree.

- The financial penalty is calculated at USD 141.000 over 2.5 years (2017 to 2014 Jul) equals USD 56.400 per year

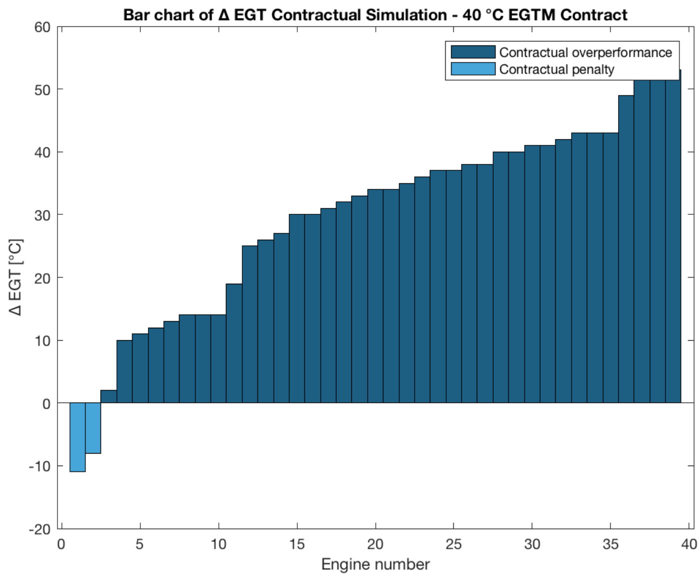


Figure 6.1: Contractual performance of KLM customer with 40 degree EGTM contract

- The financial potential is calculated at USD 2.433.000 over 2.5 years (2017 to 2014 Jul) equals USD 973.200 per year

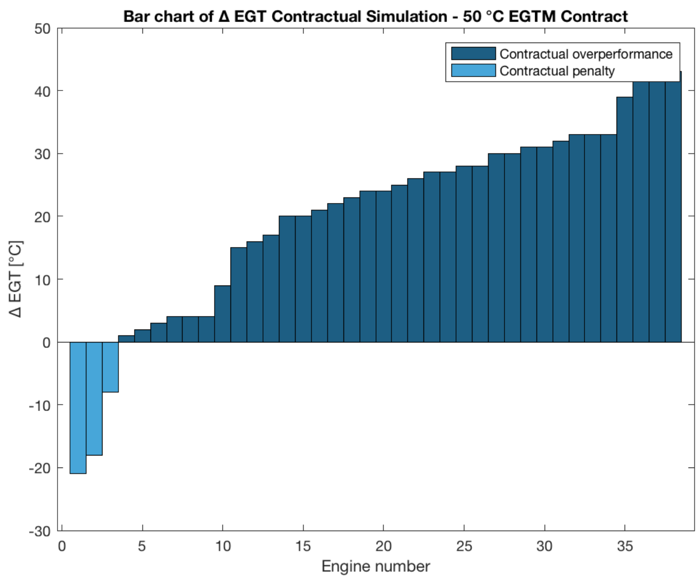


Figure 6.2: Contractual performance of KLM customer with 50 degree EGTM contract

6.1.3. 60 degree EGTM contract

- The financial penalty is calculated at USD 390.000 over 2.5 years (2017 to 2014 Jul) equals USD 156.000 per year
- The financial potential is calculated at USD 1.512.000 over 2.5 years (2017 to 2014 Jul) equals USD 604.800 per year

From this analysis it can be concluded that the difference between the 40 and 50 EGTM contract would

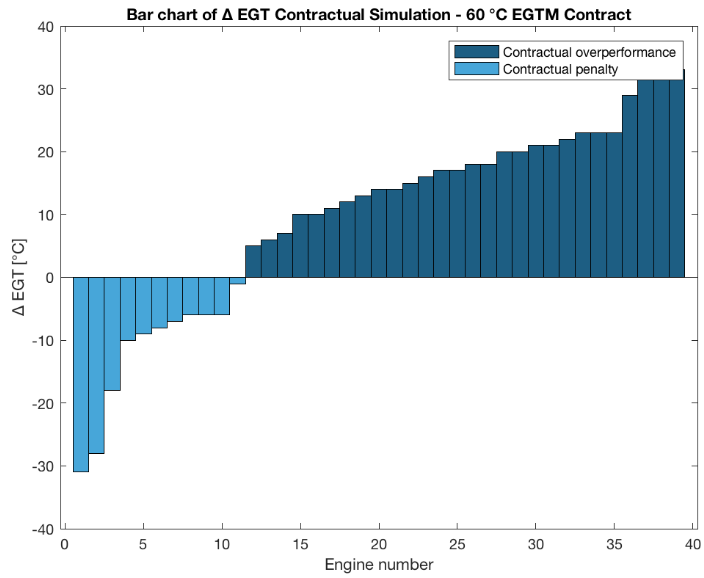


Figure 6.3: Contractual performance of KLM customer with 60 degree EGTM contract

financially be large, but in terms of OTP over 2014-2017 would be small. The OTP for the 40 and 50 EGTM contract are 94,9% and 92,3% respectively.The 60 degree EGTM contract would have an On Time Performance of 71,8%. It is recommended to introduce a 60 degree EGTM handshake with the KLM customer group to make quality a focus point and to create awareness at the management.

6.2. Simulation

In order to see what the potential is of the EGT Margin, a discrete simulation will be created using Matlab programming software. The simulation will calculate what the EGT impact is per control step taken. The simulation will consist of the following steps:

1. Load quality measurement data per engine for each stage for the HPC and LPC.
2. Check the variance of the Full overhaul or Performance HPC assys.
3. Calculate the potential in EGT Margin based on the WPG coefficients and HPC diameters, taking into account if the engine is a tech insert or non tech insert engine.
4. Calculate the potential in EGT Margin based on the WPG coefficients and HPC seals
5. Calculate the potential in EGT Margin based on the WPG coefficient and LPC blade weight values
6. Calculate the total potential of the specific engine

The WPG states that each coefficients per assy can be added up to each other to see the total impact on the EGT value of the engine. The WPG states that non linearities of the assy's have some impact but can be considered neglectable. For the HPC and LPC the impact of improving the EGT Margin of each stage is a linear combination.

6.3. Potential in EGT Margin

This section describes the amounts of EGT that can be introduced when the variance of the sets of measurements is reduced to the average within each individual set.

6.3.1. HPC: 31X, 32X, 33X

The first module that is being simulated for its potential in EGT Margin Performance is the HPC 31X, 32X, 33X module.

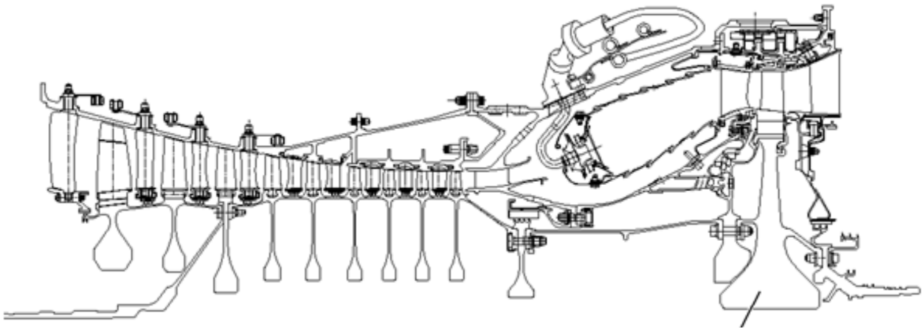


Figure 6.4: Vanes and Blades matching from Rotor and Casing

As described by the Workscope Planning Guide, each set has characteristics as described in Table 4.3. One of the variations is due to assignable causes, the blades are not treated as a set when they are repaired by the external vendor. There is too much variation within a set, which causes the casing not to match the rotor blades. Figure 6.4 shows a section cut of the different stages. When looking at the blades distributions per set, the lowest blade 11,872mm does not come by frequent.

The blade distance that is acceptable has to fall in a 4 microinch limit as can be seen in Figure 6.5. The aim is to have a diameter that is as high as possible, the size of the upper limit. Also, the variance in one set needs to be as low as possible to prevent bleed air leakage. When the diameters are all uniform the seal coating can compensate for leakage. There are two proposed strategies that need to be simulated to calculate the potential EGT Margin in order to remove the variance:

1. Replace blades with the lowest blade size with new blades, update lowest seal performance
2. Replace blades that are on the top 3 most important stages with new blades, update lowest seal performance

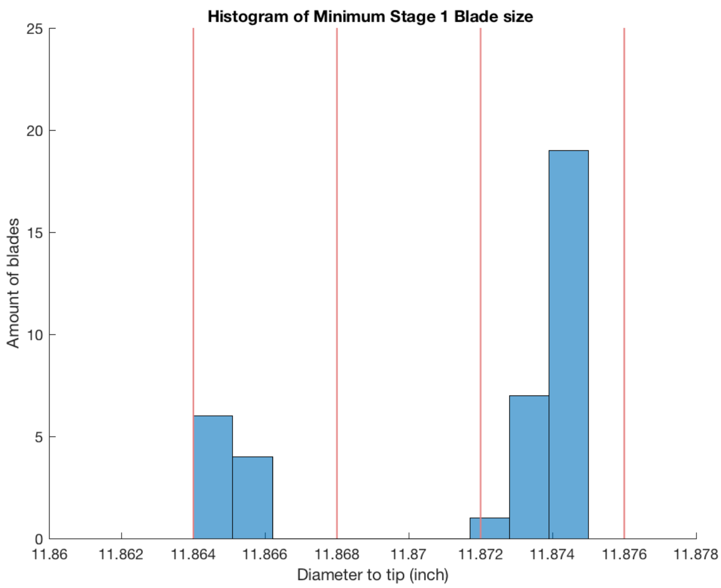


Figure 6.5: Minimum dimensional values

The first step before the two proposed control strategies is to determine the maximal potential for the EGT profitability per stage. This can be seen in Table 6.1.

Table 6.1: High Pressure Compressor Module Potential EGT Values

Feature	Max Bandwith for improvement [microinch]	Coefficient [(mils/microinch)]	Total EGT Potential [Degrees Celcius]
HPC Stage 1	4	0,1323	0,5292
HPC Stage 2	4	0,0738	0,2952
HPC Stage 3	4	0,0828	0,3312
HPC Stage 4	4	0,1062	0,4248
HPC Stage 5	4	0,1008	0,4032
HPC Stage 6	4	0,1008	0,4032
HPC Stage 7	4	0,1080	0,4320
HPC Stage 8	4	0,1179	0,4716
HPC Stage 9	4	0,1026	0,4104
Total			3,7008

The maximum potential of the fanblades is determined at 3,7 degrees EGTM. The maximum potential EGTM can be matched with the Life Expectation calculation for KLM as described in Section 4.4. The maximum potential is a life expectancy of 24,5 weeks flying.

The next step is to simulate the control strategies for all the different stages, and to match the distributions of the minimal stage improvements with each individual stage. This process can be seen in the Appendix.

- The outcome of replacement with the lowest blade size with new blades can benefit 0,6 degrees EGTM.
- The outcome of replacement for the most influential stages will result in a benefit of 0,9 degrees EGTM

For the seal dept the same procedure is followed.

- The outcome of stretegy one including the blades results in a benefit of 1.3 degrees EGTM
- The outcome of stategy two including the blades results in a benefit 0f 1,6 degrees EGTM

6.3.2. LPC 21X

A similar calculation is done for the 21X. The histogram for stage 4 is shown in Figure 6.6.

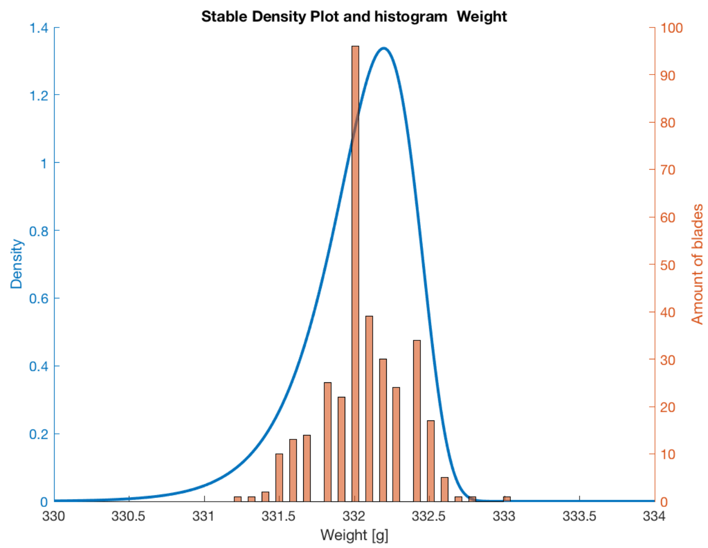


Figure 6.6: Histogram and stable density probability plot of stage 4 blade weight

For the LPC only one strategy is proposed since there is one controllable aspect:

- Decrease the top level weight

This control step is easily implemented since at the end of the repair process, the material of the blades can be taken away when they are being weighed, in order to match the sets optimum.

When the peak is optimized the maximum EGT contribution of the 21X is 0.7 degree EGT Margin. Figure 6.7 shows the stable density plot and histogram of the blade weights after optimization.

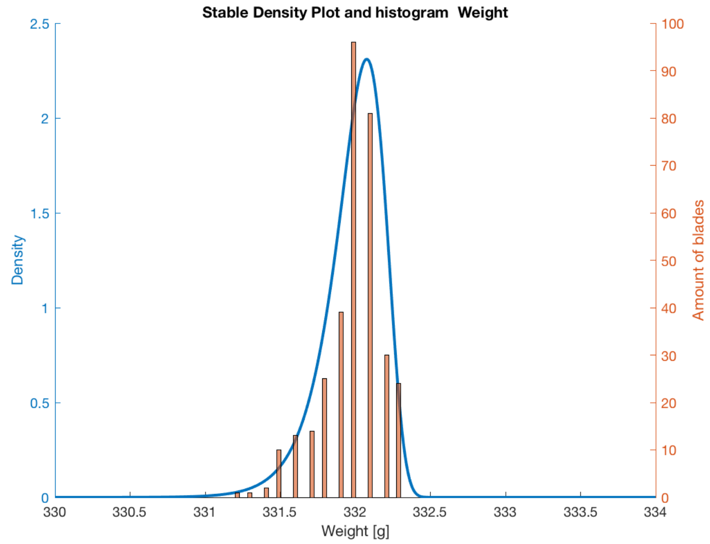


Figure 6.7: Histogram and stable density probability plot of stage 4 blade weight after simulation

6.4. Impact on quality contracts

The impact of the proposed simulation can be scaled to every single individual engine and compared to the quality contract. Currently, the quality performance for 2017 was 67% Each of the engines used in the simulation has a quality contract, some did not meet the demands of this contract and therefore the amount of engines with a quality contract is 139 from 2014-2017. The quality performance could reach 70% in 2017 by reducing the variance in the process.

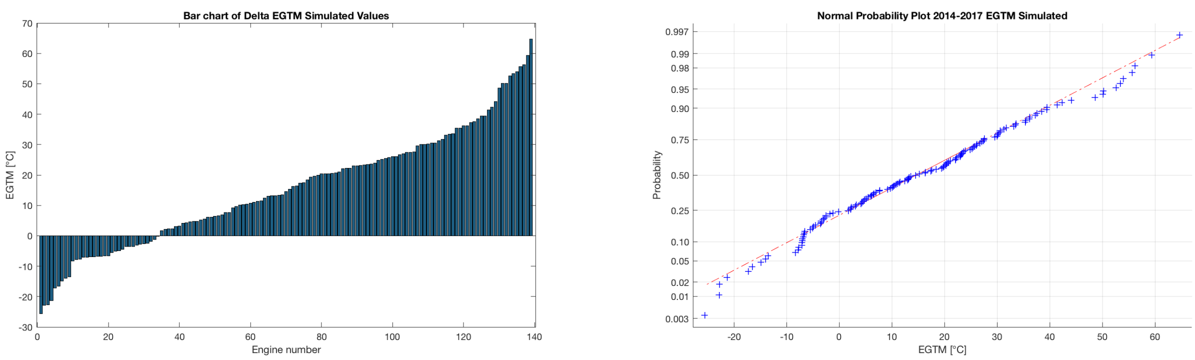


Figure 6.8: Impact on the quality contracts

6.5. Conclusion Future State

This chapter describes the future state of the quality performance by decreasing the variance within the repair steps. First, the quality contract for the KLM customer was simulated, and a recommendation was made to set a quality contract for 60 degrees EGT Margin in order to create awareness of quality control within the process. Then the simulation model was described and the potential in EGT margin was simulated per engine per assy. Finally, the impact of the total quality additions on the quality performance was measured.

This chapter answers the following sub research questions:

13. How do you model the quality output of an individual assy?
14. What is the potential in increasing the quality performance?

13. How do you model the quality output of an individual assy?

The quality output of an individual assy can be modelled by combining the stages in a linear matter. The coefficients are empirically determined by CFM and give the relationship between the EGT and the repair step quality potential. Furthermore, the bandwidth of improvement after the repair step needs to be implemented in the model, since that is the maximum potential.

14. What is the potential in increasing the quality performance?

For the HPC the maximum potential for the engines within the KLM E&M ES case study is 1.6 degrees EGT Margin addition. For the LPC the maximum potential for the engines in the case study is 0.7 degrees EGT Margin.

7 Conclusion

This chapter presents the conclusions, recommendations and the discussion. In section 7.1, the conclusion, the main research question is answered, this is done by highlighting the conclusions of the different sub research questions. In section 7.2, the recommendations for scientific research and the recommendations for implementation of this research at KLM E&M ES are presented. Finally, section 7.3 discusses the limitations and the scientific contribution of this research.

7.1. Conclusion

This section will answer the main research question:

How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?

This main-research question can be answered by describing the following sub-aspects to the question:

- First, the definitions of quality need to be made clear within the aircraft engine MRO environment.
- Second, the main quality contributing assy's need to be defined in order to show the critical to quality path.
- Third, the current state needs to be described. The variance and contributions of these quality contributing assy's to the general performance are discussed.
- Next, the Matlab simulation model needs to be discussed. This model is used in order to estimate the influence of improvement in each stage on the total engine quality performance.
- Finally, the model is evaluated.

7.1.1. Quality within the aircraft engine MRO Environment

In order to indicate which assy's are critical to quality, product and process quality have to be defined within this research. The product quality can be identified using a literature study using two aspects of theory by Garvin. Garvin identifies several approaches to product quality and two are applicable to KLM E&M ES. The manufacturer-based approach shows that the engine needs to conform to requirements set by regulation of CFM and the governments in order to assure airworthiness. The user-based approach states that every customer has different demands to the quality performance output with no standard preference, with airworthiness as the minimum threshold. The product quality therefore consists of a manufacturer regulated part, and a customized user-based part that is still bound by regulation.

Regarding the process quality definition, literature by Hackman and Wagemant states that process quality can be defined by the statistically non-random variations within the process. This directly shows the link between product and process quality. High variations on product quality contributing steps, a lower process quality, will reduce the stability of the quality output, hence they will reduce the product quality performance.

When looking at the trend of the amount of quality contracts created between KLM E&M ES and it's customers, the analysis shows that the amount of contracts set is increasing. The KLM AF/Pool customer group does not have contracts for the engine quality with KLM E&M ES and is therefore the only customer group that is not partaking in this trend. This is visualized in Figure 7.1.

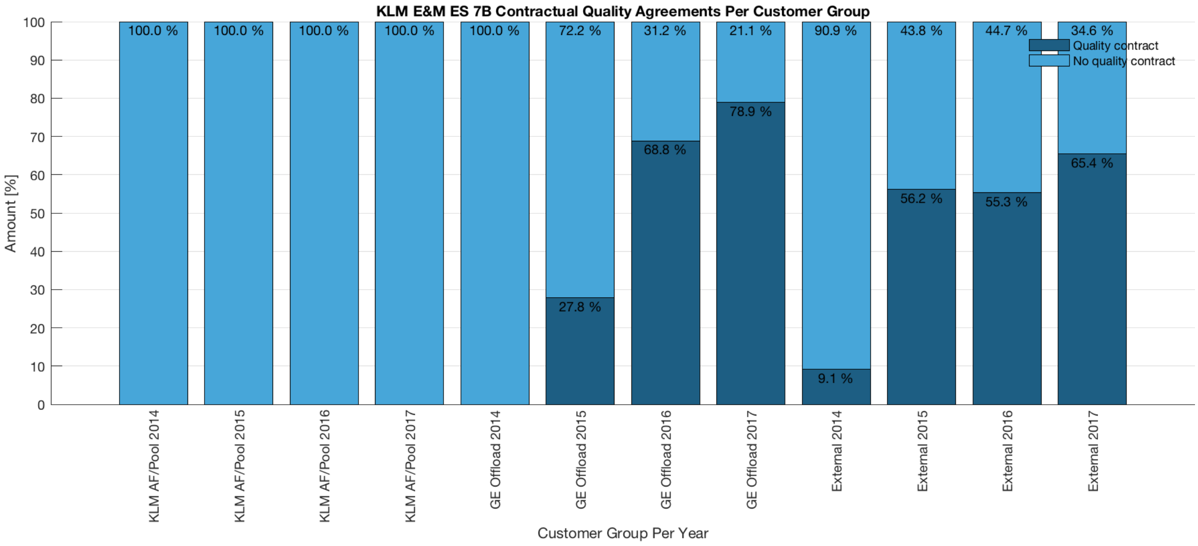


Figure 7.1: KLM E&M ES contractual quality agreements per customer group for CFM56-7B engine type

There are currently three types of contractual agreements that can be differentiated on EGT Margin. The first is a contract where a financial penalty is applied if the quality output is lower than contractually agreed upon. The second is a contract where no financial penalty is applied if the quality output is contractually met. The engine still needs to be delivered airworthy with a certain amount of EGT Margin to meet the manufacturer-based quality definition. The last is a contract where the engine needs to be delivered serviceable with no agreement on the EGT Margin, this contract type is for the KLM/AF Pool engine group where availability of the engines is the main driving value.

7.1.2. Quality contribution

From a technical point of view, the quality of the engine is mostly influenced by the pressure build up within the engine towards the combustion chamber. The air needs to be highly compressed for an optimal combustion process and therefore the compressing stages are most critical to quality.

The deterioration of the engine is caused by wear, friction, surface dirt accumulation and temperature. Deterioration is most prone to happen in places with a high amount of rotating parts and temperatures. The gas flow path is the factor that influences the quality of the engine throughout the entire engine. Gas flows through the core, first enters the compressors, then goes through the combustion chamber after which the gas goes through the turbines to create thrust and leave the engine.

The main quality value driver is the tip clearance per stage in the compressors and turbines. The tip clearance needs to be as small as possible to prevent air to bleed back to the inlet of the engine. The closer the fanblades are to the casings, the less air can bleed back, the higher the pressure can build up. CFM states that the tip clearance is known to have a direct relationship to the EGT Margin.

7.1.3. Current State

There are four levels of workscopes available within the process. From high to low they are respectively:

- Full Overhaul Workscope

- Performance Workscope
- Minimal Overhaul Workscope
- Serviceable Removed Workscope

The first workscope is one where all parts are stripped to piece-part level and then repaired or refurbished. When the performance workscope is chosen, the assy is stripped where necessary but not completely overhauled. The minimal overhaul consists of repairs where needed. When the assy is serviceable removed the assy is placed back at the assembly stage, and no repairs are done to the assy. Workscopes can be chosen on engine level, module level or assy level.

The workscope for the engine is normally determined per assy. A visual inspection takes place after which the engineering department creates a Bill of Work. In this Bill of Work many factors are taken into account, including previous shop visits and the life limit of parts. When something is found where the airworthiness can be in danger, KLM E&M ES has to discuss this with the customer. The customer is obliged to confirm with the KLM recommendation if airworthiness is at stake. By determining the workscope, the process the engine will go through during a shop visit is determined. This is how the engineering department determines on the forehand of the process what the expected quality of the engine at the end will be.

When the EGT Margin is increased, there is a direct increase in the Time on Wing. The Time on Wing depends on the EGT Margin and the thrust settings of the aircraft. Also, the Time on Wing depends on the Tech Insertion upgrade from CFM. The Time on Wing expectancy of CFM56-7 engines for the KLM fleet is about 8 years. The relation between quality and Time on Wing is 7 degrees EGT deterioration per year. When the engine is matured, the relationship between the EGT Margin and ToW can be considered to be linear after 2000 cycles of flying after a shop visit.

According to literature, the High Pressure Compressor module contributes the most to the quality of the engine since it is responsible for the pressure build up towards the compression chamber. As stated in the previous chapter, the flow path clearance is the major driver for quality. The flow path clearance is determined by the diameters of the blades, the diameter of the casings and the depth of the seals.

The current quality performance is controlled by determining the workscope planning through the Bill of Work. There currently is no quality control within the process steps since the parts only need to be serviceable, which is sufficient by regulation. No research has been done before on the bandwidth and variation of the parts within the serviceable limits.

7.1.4. Variations in process

The measurements for the quality from the HPC and LPC components are taken in the assembly phase. For the HPC, the diameters of the rotor blades and the diameters of the casings are known and have a direct relationship to the EGT Margin. For the LPC, the weights from before and after repair give an indication of the tip clearance and have a direct relationship to the EGT Margin. In the process variations can be identified.

Table 7.1: High Pressure Compressor Module Potential EGT Values

Feature	Max Bandwith for improvement [microinch]	Coefficient [(mils/microinch)]	Total EGT Potential [Degrees Celcius]
HPC Stage 1	4	0,1323	0,5292
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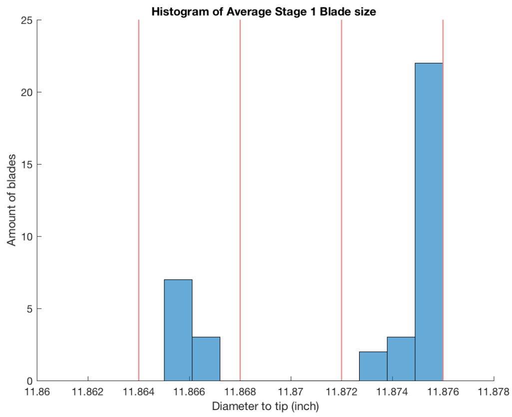
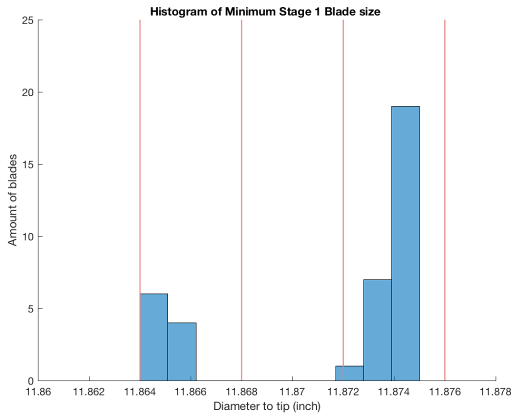
HPC Stage 4	4	0,1062	0,4248
HPC Stage 5	4	0,1008	0,4032
HPC Stage 6	4	0,1008	0,4032
HPC Stage 7	4	0,1080	0,4320
HPC Stage 8	4	0,1179	0,4716
HPC Stage 9	4	0,1026	0,4104
Total			3,7008

The measurements used to determine the variations within the stages are taken from the STREAM database of hand scanned records. The diameters of the stages are always within the boundaries by regulation. This gives a bandwidth of 5 microinch to tweak the quality of the fanblades set. The maximum potential in EGT Margin for the HPC blades is shown in Table 7.1.

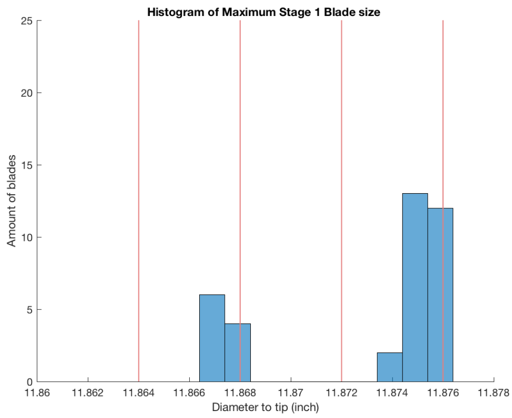
For stage 1, histograms are created of the dimensional values. Each set has a minimum diameter blade, a maximum diameter blade and average diameter blades. The distributions are shown in Figure 7.2. In order to have a high product quality, the variations of the diameters within one set need to be reduced. In an optimal situation all blades in the set have the same diameter to have an optimal pressure built up. Figure 7.2 shows two groups of quality registrations. The one to the left is for pre Tech Insertion engines, the group to the right is for Tech Insertion engines, although it is the same engine type, the diameters and quality coefficients are different.



(a) Average dimensional values



(b) Minimum dimensional values



(c) Maximum dimensional values

Figure 7.2: Stage 1 dimensional value histograms

7.1.5. Matlab Model

For the model, the compression stage of the engine is the only part considered. The compression stage consists of the High Pressure Compressor and the Low Pressure Compressor. The repair steps for the parts within the HPC and LPC are mostly outsourced. Therefore, the strategies for improvement need to be able to be implemented within the assembly and disassembly stages of the MRO process. The variance needs to be decreased by swapping the low quality parts by high quality parts. The proposed strategies consist of replacing the low quality fanblades by fanblades that match the average within a set, this way there is less bleed air leakage. Another strategy is swapping fanblades between engines in order to create an optimum for the different sets.

The quality output of an individual assy can be modelled by combining the stages in a linear matter. The coefficients are empirically determined by CFM and give the relationship between the EGT and the repair step quality potential. Furthermore, the bandwidth of improvement after the repair step needs to be implemented in the model, since that is the maximum potential.

In the matlab model, the following steps are done on an per engine level:

1. Load quality measurement data per engine for each stage for the HPC and LPC.
2. Check the variance of the Full overhaul or Performance HPC assys.
3. Calculate the potential in EGT Margin based on the WPG coefficients and HPC diameters, taking into account if the engine is a tech insert or non tech insert engine.
4. Calculate the potential in EGT Margin based on the WPG coefficients and HPC seals
5. Calculate the potential in EGT Margin based on the WPG coefficient and LPC blade weight values
6. Calculate the total potential of the specific engine

7.1.6. Results

For the HPC the maximum potential for the engine within the KLM E&M ES case study is 1.6 degrees EGT Margin addition. For the LPC the maximum potential for the engine in the case study is 0.7 degrees EGT Margin.

7.1.7. Evaluation of model and main research question

The main research question to this research was formulated as:

How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?

The answer to this research question is given by answering the different sub research questions above. The model shows that if the variance within the process is decreased, the quality will increase. Even within the serviceable limits of the parts value can be added in terms of quality. The model created brings a new aspect to quality prediction based on measurements taken from within the process. The model can be expanded further to create a real prediction model based on all assy's. Since the turbines work in a similar nature, the next logical step is to expand this research to the turbine modules. Further research is needed in order to create an overall framework for CFM56-7B quality prediction.

7.2. Recommendations

This section described the recommendations for continuing the scientific research and the recommendations for further research and recommendations to leverage the value of this research at KLM E&M ES.

7.2.1. Recommendations for scientific research

With the outcome of this research a path is opened for further research into aircraft engine MRO quality control. There are multiple research questions that arise from the conclusions of this research.

Firstly, the quality measurements of the compressor assy's, the HPC and LPC are taken into account in this research. It is recommended that the research needs to be expanded to the other assy's within the CFM56-7B engine. This framework is used to determine the quality output of the engine based on repair steps for the CFM56-7B compressor. The next recommendation is to verify this framework for the other engine types like the 80E and GEnx. A literature study needs to be conducted to see the relations between the flow path clearance of this engine type and the EGT Margin at the end of the process.

The following step is to combine research on all modules, and create a framework for quality prediction of the total engine performance of all repair steps. This way, the repair steps can be taken into account in situ and prediction of the final EGT Margin can be done accurately based on all assy's and modules. This prediction then needs to be verified in practice with a few test engines to see the impact of the variance reductions within the total engine.

The hypothesis for the research to estimate the EGT Margin could be formulated as follows:

The quality of the CFM56-7B engine in terms of EGT Margin can accurately be predicted using the repair step measurements of the Combustor, Compressors and Turbines.

Finally, the concrete recommendation to achieve this framework and to secure the research in this thesis is continued is to conduct three other case studies at KLM E&M. The first on the other assy's, with emphasis on the Combustor since the repair step is different to the High and Low Pressure Compressors, also using this research to investigate the High and Low pressure Turbines. The Second to research the proposed hypothesis in order to create and estimation model for the EGT Margin. The third to verify this research over a timespan of a few years and to scale the models to other engines.

7.2.2. Recommendations for KLM E&M ES

As stated in this research, the control of the engine MRO chain is currently turnaround time focussed. Within the pillars of the 2020 performance model for KLM E&M ES, a focus is placed on the quality performance.This research opens the path to an alternative control approach taking both the turnaround time and quality performance into account. Good quality control will result in higher quality performance and a higher first time right yield, hence in a shorter turnaround time.

In order to achieve an increased quality performance and to leverage this research the most, recommendations are made to KLM E&M ES. Firstly, awareness should be created using this research in order to assure the focus is placed on both KPI's.

The second step in creating a framework for total quality prediction is digitization of the measurement steps during the repair process. The quality measurement steps can be integrated into the current business operations system SAP and added to the repair step codes that are already present. Currently, the engineering department stated that they do not use the quality measurements within the process, but only the outcomes of the test-cell and the serviceable/non serviceable approach for the assy's. Most of the repair measurements are conducted using embedded computer systems, research needs to be done if these measurement outputs can be directly integrated within SAP.

Next, decreasing the variance of the fanblades needs extra investments. An analysis needs to be made if the variance decrease is financially beneficial to the addition in monetary value added by increasing the Time On Wing. Since the fanblades are high value components, there is a trade-off to be made between using the specific fanblades and decreasing the variance of the set of fanblades by replacing them. Another solution with less financial impact could be swapping fanblades from different sets in order to have them matching within this set. This way fanblades are swapped based on condition, the replacements can be stored within their serviceable limits and used on a next set of fanblades with the same quality performance to keep the variance low within the set. More research needs to be done on the monetary impact of the proposed strategy.

Also, the impact on the turnaround time of decreasing the variance needs to be researched. How much impact does it have on the total chain. The current process is believed to contain a lot of waiting time, this is based on the research conducted on the Combustor and Fanblades by W. Mogendorff [28] and P. Meijs [26] respectively. If the waiting time is about 80% of the process time, the extra time needed for fanblades replacement within the fanblades set assembly can be neglected. However, this impact still needs to be researched.

Furthermore, the repair steps of the fanblades tips are now outsourced to General Electric. General Electric has a weird relationship with KLM E&M ES: It is the customer, the repair vendor and manufacturer of the engine (as the CFM subsidiary). In order to be independent of the vendor, it is recommended for KLM E&M ES to gain knowledge of the fanblades tips repair step and to make investment into fully in-sourcing this specific repair. The fanblades are the most value added components within the engine, in order to control the process, this repair step needs to be controlled.

7.3. Discussion

In the discussion section of this research, the limitations to the research and the scientific contributions are discussed.

7.3.1. Limitations

There are a few limitations to this research. First of all, the data that is used for this research is not fully reliable. The main data source used for this research consists of hand scanned documents taken from the STREAM computer system, see Appendix **??** for the overview of the data systems.

The data in stream consists of hand measured values, they have three factors of uncertainty. Uncertainty because of the measurement devices, uncertainty because of the hand written values and uncertainty about the registration protocol.

Even though there is a lot of uncertainty, the measurements give a realistic reflection of the reality. The measurement devices used are used on every part from the same engine, therefore if there is an error in measurement, they are the same for every device. Every few years, the devices get calibrated and the error is reduced. The uncertainty caused by the hand written values is a harder uncertainty. Every measurement on the measurement sheet is written down by a mechanic, and stamped off by this same mechanic. This results in almost all values having a different hand writing, some being non decipherable. Also, sometimes the repairs are all conducted and in the final stage, the stamps are placed for the repair steps with the corresponding measurements. Sometimes with all values being the same measurement value, all signed off by the same mechanic. These measurements are not taken into account, 14 out of 139 engines showed abnormalities in the registration process.

The Matlab model used to calculate the performance impact on the total only uses the flow path clearance criteria as explained in the Workscope Planning Guide and Engine Service Manual. The model does not take previous repairs caused by disturbances like bird strikes into account in the prediction model. It only looks at the extra increase in performance that can be obtained by decreasing the variance of a full overhaul workscope. Future research is required to investigate the influence of abnormal engine repair procedures within the engine lifetime on the next workscope planning.

7.3.2. Scientific contribution

The aim of this research is to contribute to science in multiple ways. The first is to show from practice that the control of the quality within an engine MRO environment is mainly turnaround time focussed. The quality is regulated, and always needs to be up to an airworthy standard. However, there is lots of potential to control the quality even further within these airworthy boundaries.

The second contribution is an expansion on the first contribution. The model shows that the quality can be improved by tweaking the repair steps within the serviceable boundaries and can have real noticeable value impact on the total engine performance.

The new aspect of this research was introducing control on the quality performance within the aircraft engine MRO process. This research is the first step into quality output prediction of the engine MRO process and has an impact on the Time On Wing of the CFM56-7B aircraft engine. This method of predicting the EGT contribution of the measurements steps can be used for other engine types as well.

Furthermore, this method can be used to determine an approach for in situ quality output prediction on both module and engine level. The quality measurements during the maintenance process can be determined for the other high quality contributing modules that are not scoped within this research (HPT, LPT and Combustor). For further studies, these modules first need to be researched in order to understand the measurements and quality determination within the process. For the HPT and LPT this research can be used as the basis since it is highly depending on the flow path clearance model. For the combustor, subsequently more research has to be done. The in situ prediction framework can be created using this research and the research on the other modules.

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A

Research Paper

Quality of the integral aircraft engine MRO chain

A case study on the Low and High Pressure Compressors at KLM Engineering & Maintenance Engine Services

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The paper addresses the main research question: *"How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?* The relationship between the quality measurements of the aircraft engine MRO process and the EGT margin was studied. The study scoped two critical to quality engine modules and used the CFM56-7B engine as the reference engine for this research. The objective of this research was to create a model for the quality performance in terms of the Exhaust Gas Temperature Margin of an Engine MRO process chain. This model can be scoped on the most critical to quality modules of the engine in order to stabilize the quality performance. For the analysis of this research the data of 139 by KLM E&M ES overhauled engines were used. These 139 engines belonged to three customer groups, KLM services engines for: KLM/Air france, General Electric and other external customers. The current state of product and process quality control is investigated. The quality from a technical perspective is investigated resulting in identification of the most critical aspect: The flow path clearance. Furthermore, the quality measurements in process are analysed for the compressor modules which have great impact on the flow path clearance. The compressor modules consist of the High Pressure Compressor and Low Pressure Compressor.

The impact of reducing the variance of the High Pressure Compressor and Low Pressure Compressor were simulated. A strategy was chosen to replace the fanblades with the lowest or highest value diameter within the set with the average value diameter fanblades. This way, the set of fanblades reduces the bleed air escaping and increases the pressure build up. It was simulated that the maximum value of EGT addition per engine for the KLM test data set is 1.6 degrees EGT Margin for the HPC and 0.7 degrees EGT Margin for the LPC. The main recommendations following from this research are: Implementing the same methodology on the High Pressure Turbine, Low Pressure Turbine and Combustor. After this, a framework can be created for prediction of the total engine quality based on the in situ measurement steps. When the framework is validated and tested, self learning algorithms can be added to the model to increase the predictability. A hypothesis for the continuation of this research was formulated as: *The quality of the CFM56-7B engine in terms of EGT Margin can accurately be predicted using the repair step measurements of the Combustor, Compressors and Turbines.*

I. Introduction

This research is concentrated on developing a model for quality performance estimation based on in situ measurements. The aim of this research is to be the stepping stone to a complete model for smart engine quality prediction based on measurements while the process is still ongoing. In this way, the quality output of the process can be controlled . A single case study was conducted through the Lean Six Sigma office at KLM Engineering & Maintenance Engine Services and a simulation on the High Pressure Compressor and Low Pressure Compressor are presented. First, some background information will be introduced and an outline of the research will be given.

II. Methodology

Qualitative data of 139 CFM56-7B engines from all customer groups that KLM Engineering & Maintenance (KLM E&M ES) serve are used for this research. Furthermore, the maintenance of the CFM56-7B is regulated by law by the manufacturers airworthy procedures. These procedures are registered within the Engine Service Manual (ESM) and Workscope Planning Guide (WPG). KLM Engineering & Maintenance serves three different customer groups. The first one being KLM Air France Pool customers, this group is KLM as a client of KLM E&M ES. For this group there are no quality agreements made for the EGT Margin. The only agreement set is that the engine needs to be delivered serviceable at the end of the process. The second group being GE Offload customers. This group consists of customers that buy MRO from GE Aviation. GE Aviation outsources some of the engine repairs to KLM E&M ES. The last group being the external customer group. This group consists of individual customers who do not own engine maintenance facilities and outsource this to KLM E&M ES. The CFM56-7B is a high bypass turbofan engine built up out of modules, which consists of assy's. The data used in this research consists of:

- Workscope Planning Guide provided by CFM
- Workscope Planning Guide provided by KLM
- Engine Service Manual provided by CFM
- Workscope determination on engine level by customer
- Bill of Work (BoW) determination on assy level by the engineering department
- Technical Engine Data
- HPC Handwritten Quality Measurements (STREAM)
- LPC Handwritten Quality Measurements (STREAM)
- WPG empirical correlation coefficients

The EGT margin varies with different settings. The lower the thrust setting, the higher the EGT Margin. The older the engine, the more wear, the lower the EGT Margin is. The quality measurements of the 139 engines are researched. Only the fully overhauled assys have data registration available regarding the measurement steps within the process. For all assy's, the workscopes are registered. For each engine, currently only the output EGT Margin of the process is registered. The input quality of the engine is not registered. The Workscope Planning Guide and Engine Service Manual are used to determine the critical to quality path components of the engine. The quality depends on the flow path clearance within the engine. Every compression stage creates a build up of pressure in order to have a high pressure at the combustion chamber. The pressure in each next chamber is higher since the volume per stage is decreasing, therefore the gas wants to flow back. In order to prevent this from happening, the gaps between the casing and the fanblades needs to be as small as possible in order to have an efficient pressure build up. Because of this, the compression modules are the most critical to quality for the engine.

This research makes a distinction in product and process quality. Product quality is defined using two approaches according to Garvin [16]. The product quality can be identified by using the manufacturing-based approach, the Operations Management principle is the underlying discipline. The engine needs to conform to requirements set by regulation of CFM to assure airworthiness. The product quality can also be identified as the user-based approach, with operations management as its underlying discipline. Every customer has different demands to the Quality Performance output, so there is no standard output preference except airworthiness, which is covered by the manufacturing-based quality definition.

The relationship with process quality can also be explained by Hackman and Wagemant [21]. They state that there is a large importance in variance in quality management. Variation is a normal common feature of process characteristics. For production processes some variation is statistically random, while others reflect actions from the production process. Statistically non-random variations reduce the product quality. Process improvement theories like TQM can be used to identify the random variation within a process and to reduce these.

For the High and Low Pressure Compressor, this research analysed the process based on the STREAM handwritten quality measurement system. Since the variance in the process can be used to influence the product quality, the variance of the process steps is analysed.

III. Model Development

In order to develop a model for the quality influence of the HPC and LPC the following sub research questions were defined:

- What is the main qualitative value driver in order to be airworthy?
- What levels of maintenance are available in the engine MRO process?
- How is the workscope determined for engine MRO?
- What is the relation between quality and Time On Wing?
- Which assy's & modules can be identified that contribute the most to the quality of an Engine?
- How is the current quality performance controlled during the MRO process at KLM E&M ES?
- How do you measure the quality output of the HPC and LPC assy's?

Using the answers to these research questions the model van be formed and used to analyse the EGT Margin impact of decreasing the variance of the process. The main quality value driver is the flow path clearance. The tip clearance and the seals determine the flow path clearance and are the main value drivers. Therefore, the blade diameters, the case diameters and the seal depth rub are the critical measurements used in the model.

The relationship between quality and Time On Wing can be considered a linear one according to CFM. The deterioration of the EGT Margin can be considered linear after 2000 cycles after the next shop visit. For KLM, the relationship between the EGT Margin and the ToW is about 7 degrees EGT Margin deterioration per year.

The HPC consists of the HPC Rotor assy, and two casing assy's named the HPC Forward Casing and the HPC Rear Casing. The LPC consists of one assy, and is sometimes called the booster. The compression step is taken as the part which contributes the most to quality since it is responsible for building up the pressure towards the combustion chamber.

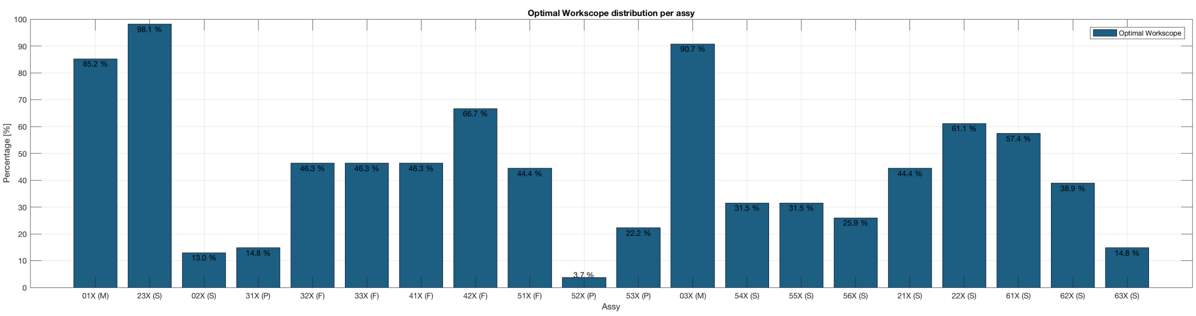


Figure A.1: Matching of the actual BoW to the prescribed actual BoW per assy

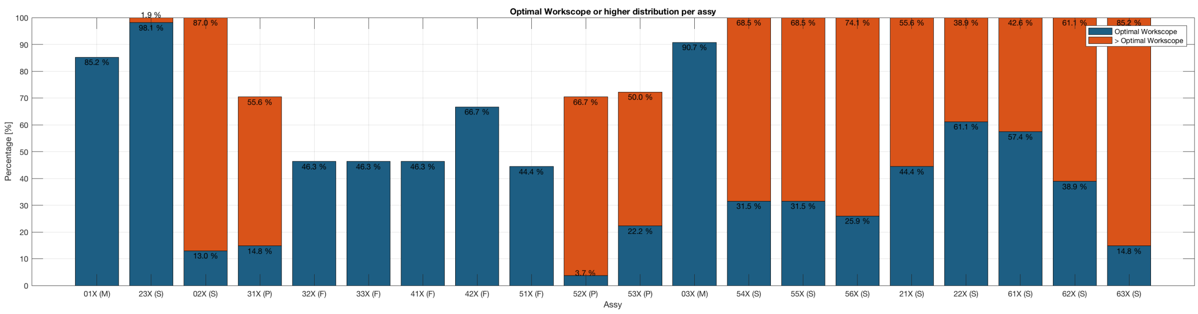
The current quality is controlled solely through the engineering department when creating the Bill of Work. The Bill of Work depends on the visual inspections conducted by the mechanics, and an analysis of the life limits of the static parts. The choice can be made per assy to do a full workscope where all the parts are removed and repaired. A performance workscope, where only the necessary assy's are removed and repaired. A minimum Workscope, where only on inspections parts are replaced. Or the choice can be made to remove the item and place it back serviceable. From the beginning of the process to the final test cell, there is no control on the quality since parts are only accepted with a certificate and most cases of rework are not registered. If the quality of the engine fails at the test cell, rework has to be done in accordance with the customer. If the engine is considered not serviceable due to a too low EGT Margin, extra repairs are demanded. General electric also prescribed an optimal workscope package per assy in order to have an optimal quality output by getting the maximum of the resources. Figure A.1 shows the matching of the BoW from klm to the actual BoW per assy as prescribed by General Electric.

The quality output of the HPC and LPC assy's can be measured through the factors mentioned before: fanblades diameters, the coatings, the seal depth rub, casing diameters and the weight of the blades.

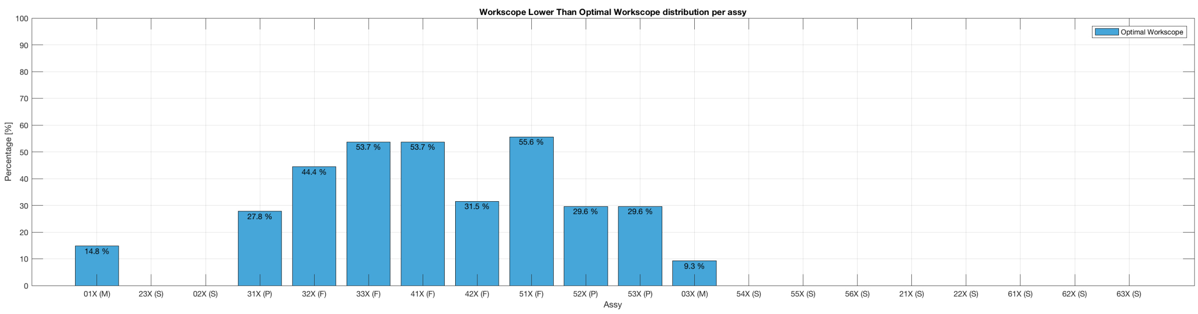
The simulation method consists of the following steps:

1. Load quality measurement data per engine for each stage for the HPC and LPC.
2. Check the variance of the Full overhaul or Performance HPC assys.
3. Calculate the potential in EGT Margin based on the WPG coefficients and HPC diameters, taking into account if the engine is a tech inserted upgraded or non tech upgrade inserted engine.
4. Calculate the potential in EGT Margin based on the WPG coefficients and HPC seals
5. Calculate the potential in EGT Margin based on the WPG coefficient and LPC blade weight values
6. Calculate the total potential of the specific engine

IV. Results



(a) Matching of the actual workscope or higher to the prescribed workscope per assy



(b) Distribution of the lower workscope than the prescribed workscope per assy

Figure A.2: Matching of the actual BoW to the prescribed BoW

Figure A.2b shows the workscopes that are lower than the prescribed optimal workscope. What can be seen is that the workscopes for the critical to quality parts, which have influence on the flow path clearance

(31X,32X,33X: HPC, 21X: LPC, 51,52,53: HPT) are having lower workscopes than optimal. Hence, the BoW determination is not fully quality focused but more financially focused. Figure A.2a shows the matching of the higher than actual and actual workscope to the BoW.

The simulation identifies per engine, per stage what the fanblades are that need to be replaced in order to have a reduced variance bandwidth. Figure A.3 shows how the minimum and average are located per engine. It is clearly visible that per engine, the average diameter is not the maximum or minimum diameter. The relationship is that more outliers per set will generate less of an EGT Margin increase. Within the serviceable repair limit, for each stage there is a variation allowance of 5 microinches of tip clearance in which the fanblade is considered serviceable. The section to the left with lower upper and lower limits is for engines without a tech insertion. The section to the right with higher upper and lower limits is for engines with a tech insertion.

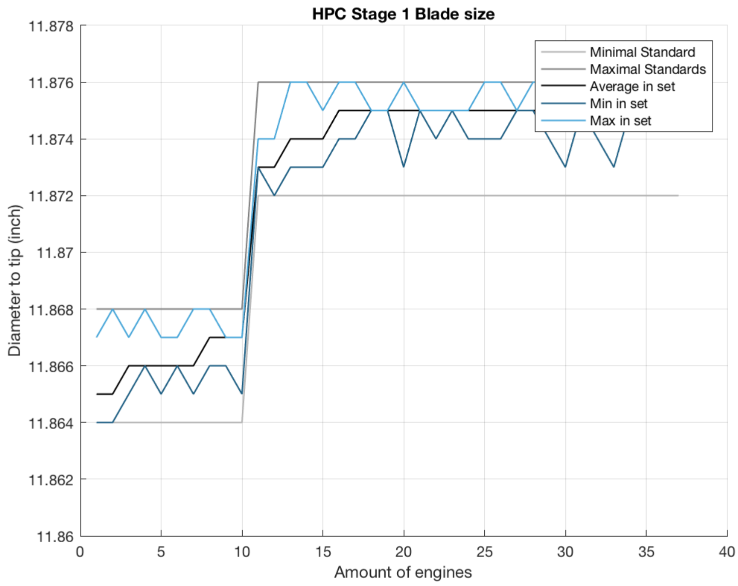


Figure A.3: Stage 1 blade size distribution per set

Figure A.4 shows the histograms of the average minimum and maximum repair values for the Full Overhaul Workscope 31X repaired assy's. This process is repeated for every engine, for every stage within the compressor. When the engine has the lowest quality with high variance, the maximum potential in removing the variance is calculated at 3.7 Degrees EGT Margin for the HPC. The peeks to the left of the image with the corresponding red boundaries are for the engines with no tech insertion, the peeks to the right for the engines with a tech insertion upgrade.

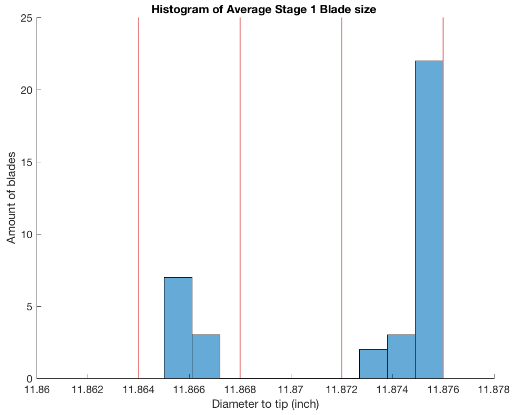
The proposed strategy is replacing fanblades with a low quality performance according to the set. The simulation stated that the maximum potential EGT recovery for an engine was 1.6 degrees for the HPC, and 0.7 degrees for the LPC. The EGT Margin increases can be considered as linear functions if they are increased on the same engine. Hence, the EGT Margin increases can be summed.

V. Conclusion

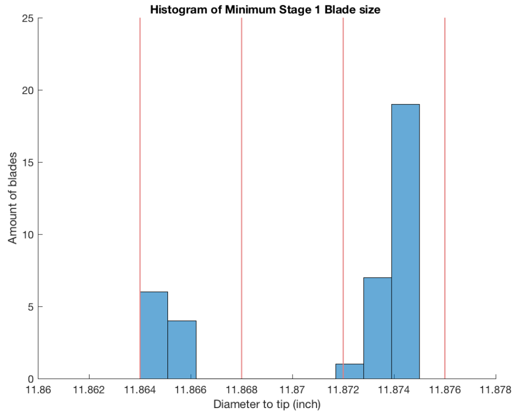
The main research question to this research was formulated as:

How can the quality performance of the engine MRO process steps be used in order to improve the stability of the engine quality output measured in Exhaust Gas Temperature Margin?

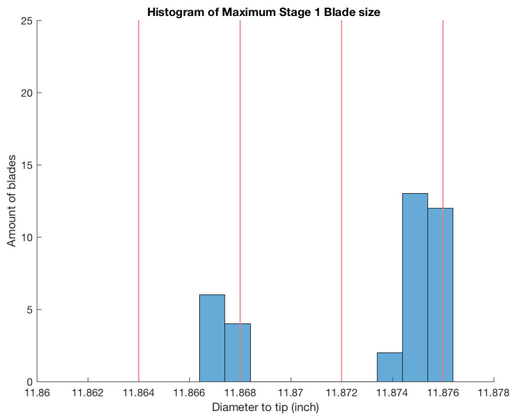
The answer to this research question is given by answering the different sub research questions mentioned in this paper. The model shows that if the variance within the process is decreased, the quality will increase. The impact of reducing the variance of the High Pressure Compressor and Low Pressure Compressor is



(a) Average dimensional values



(b) Minimum dimensional values



(c) Maximum dimensional values

Figure A.4: Stage 1 dimensional value histograms

noticeable. An increase of 1.6 degrees EGT Margin means 12 extra weeks on wing. The strategy to replace the fanblades with the lowest or highest value diameter within the set with the average value diameter fanblades is simulated to help. The main recommendations following from this research are: Implementing the same methodology on the High Pressure Turbine, Low Pressure Turbine and Combustor. The turbines have a similar EGT correlation as the compressor since the turbines also use the pressure to rotate. After this research is scaled to the other modules, a framework can be created for prediction of the total engine quality based on the in situ measurement steps. When the framework is validated and tested, the final step is to add self learning algorithms to the model to increase the predictability. A hypothesis for the continuation of this research is formulated as:

B

KLM Fleet

Table B.1: 2016 KLM Fleet Overview

		Total
Boeing 787-9	Wide Body	8
Boeing 747-400 PAX	Wide Body	6
Boeing 747-400 Combi	Wide Body	11
Boeing 747-400 ER Freighter	Wide Body	3
Boeing 747-400 BC Freighter	Wide Body	1
Boeing 777-300 ER	Wide Body	12
Boeing 777-200 ER	Wide Body	15
Airbus A330-300	Wide Body	5
Airbus A330-200	Wide Body	8
Boeing 737-900	Narrow Body	5
Boeing 737-800	Narrow Body	54
Boeing 737-700	Narrow Body	26
Embraer 190	Regional	30
Embraer 175	Regional	4
Fokker 70	Regional	11
Training Aircraft	-	4
Total	-	203

C

KLM Engine MRO Process Chart

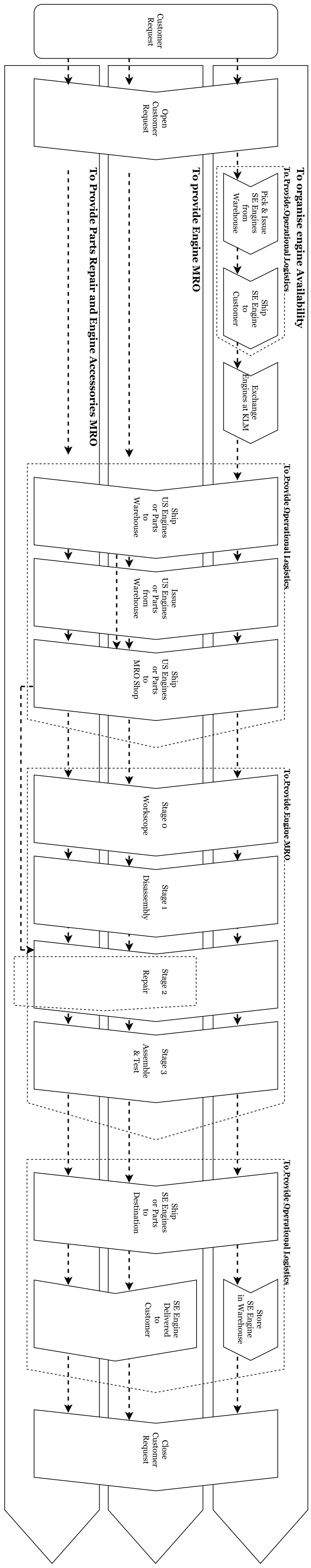


Figure C.1: KLM E&M ES overall process chain

D

KLM Overview Quality Contracts

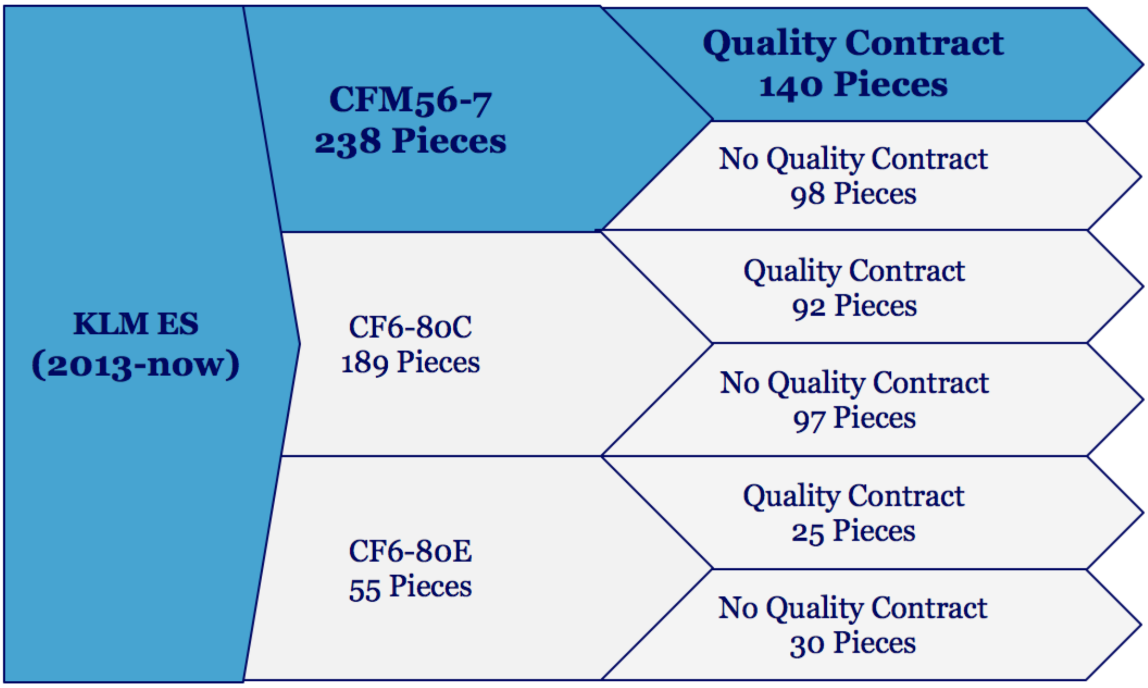


Figure D.1: KLM quality contracts per engine type

E

BoW Determination Scheme

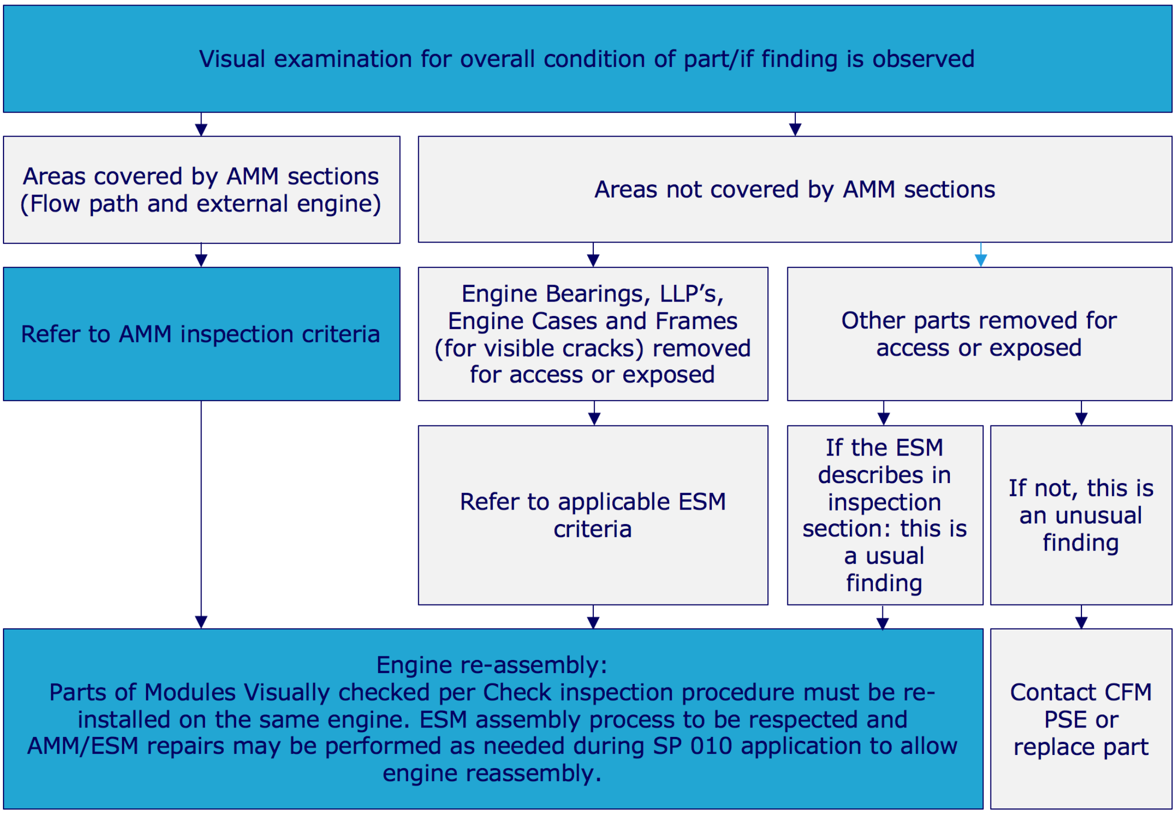


Figure E.1: Workscope determination visual inspection scheme

F

High Pressure Compressor Stages

F.1. Stage 1

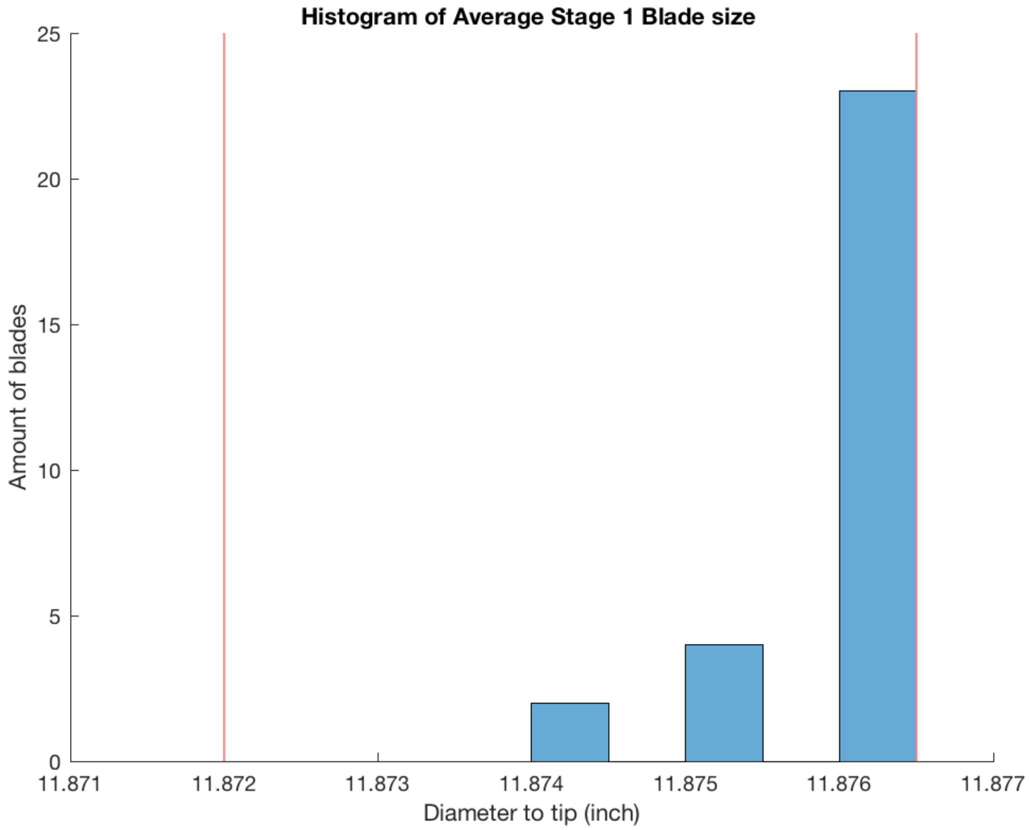


Figure F.1: A histogram of the average set values of stage1

F.2. Stage 2

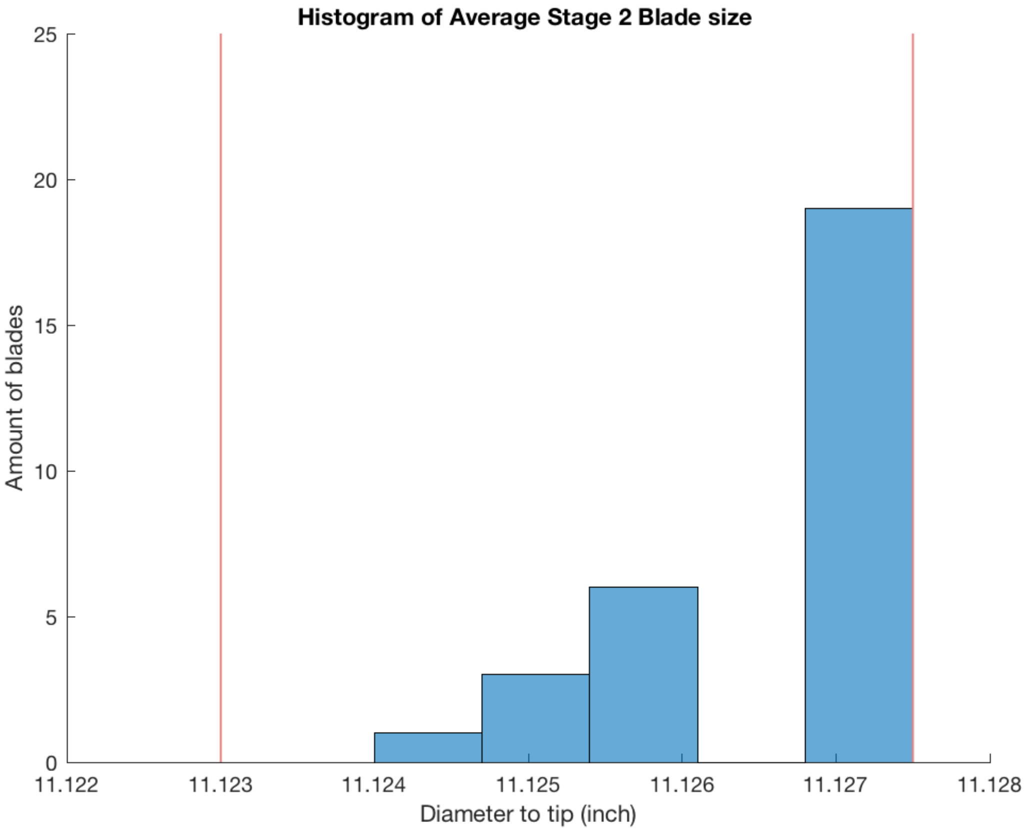


Figure F.2: A histogram of the average set values of stage2

F.3. Stage 3

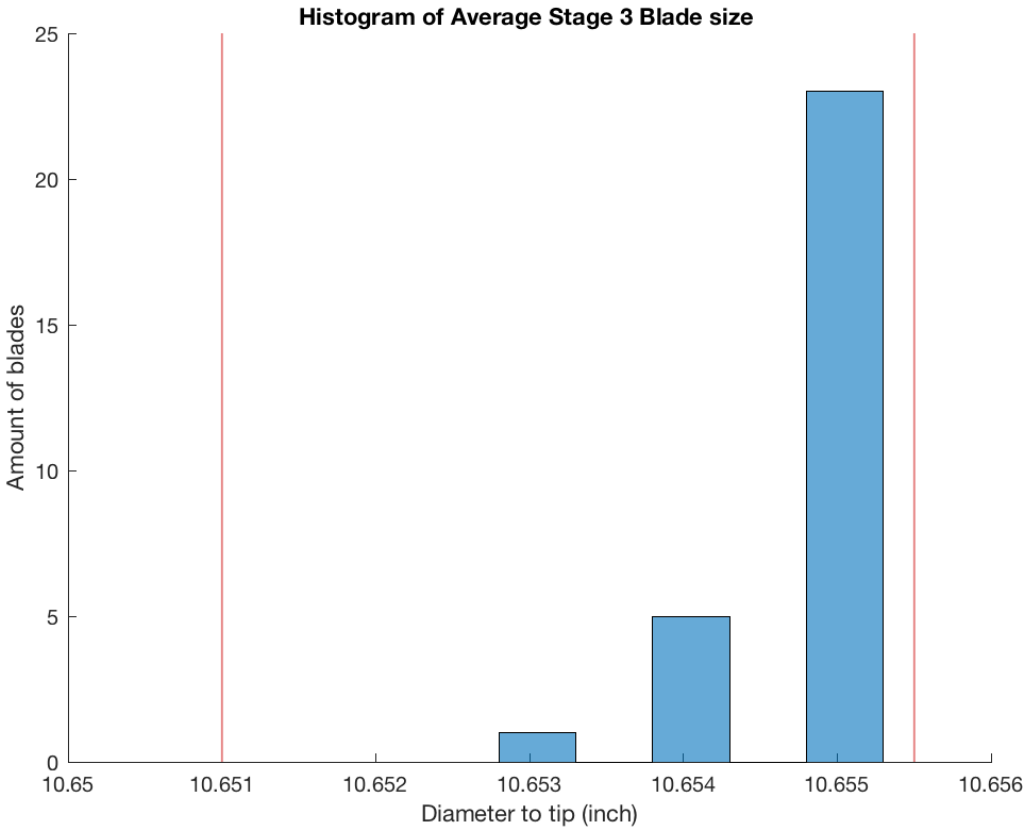


Figure F.3: A histogram of the average set values of stage3

F.4. Stage 4

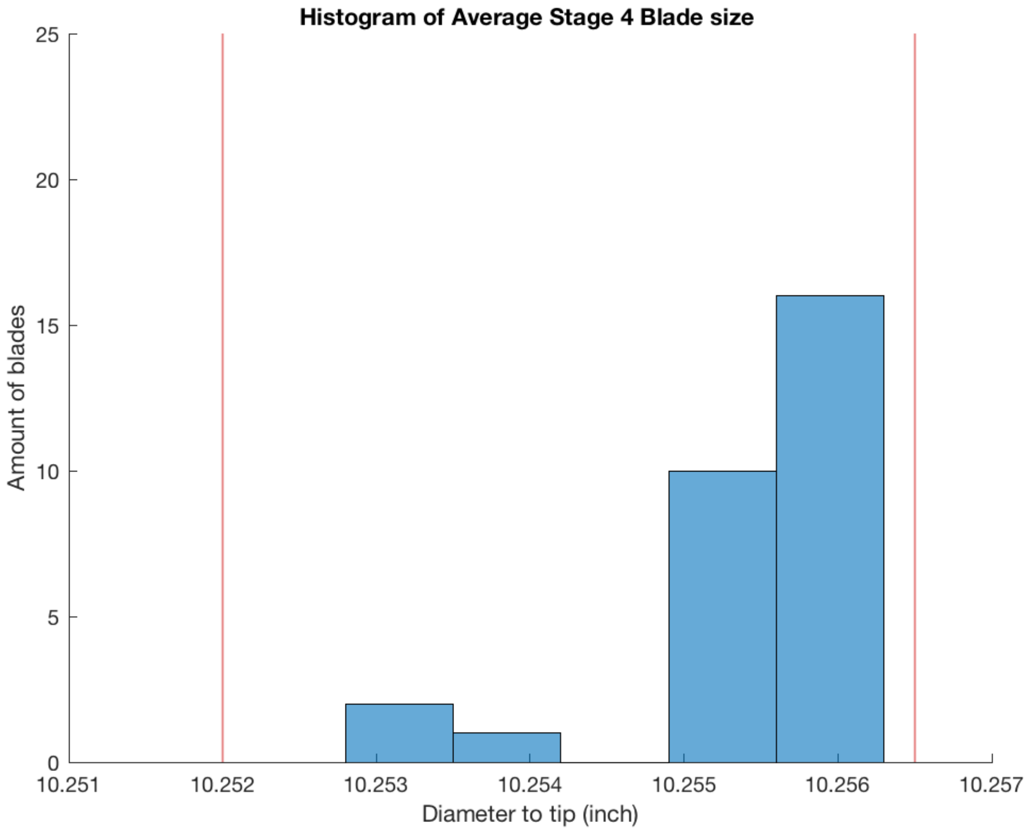


Figure F.4: A histogram of the average set values of stage4

F.5. Stage 5

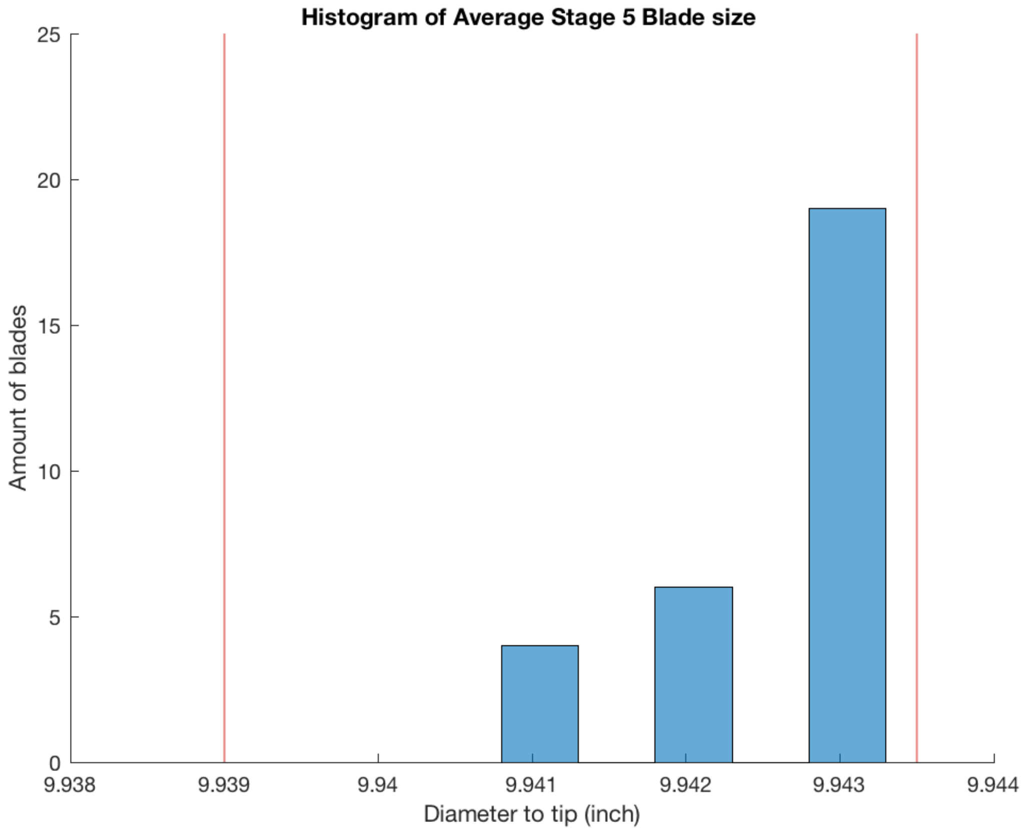


Figure F.5: A histogram of the average set values of stage5

F.6. Stage 6

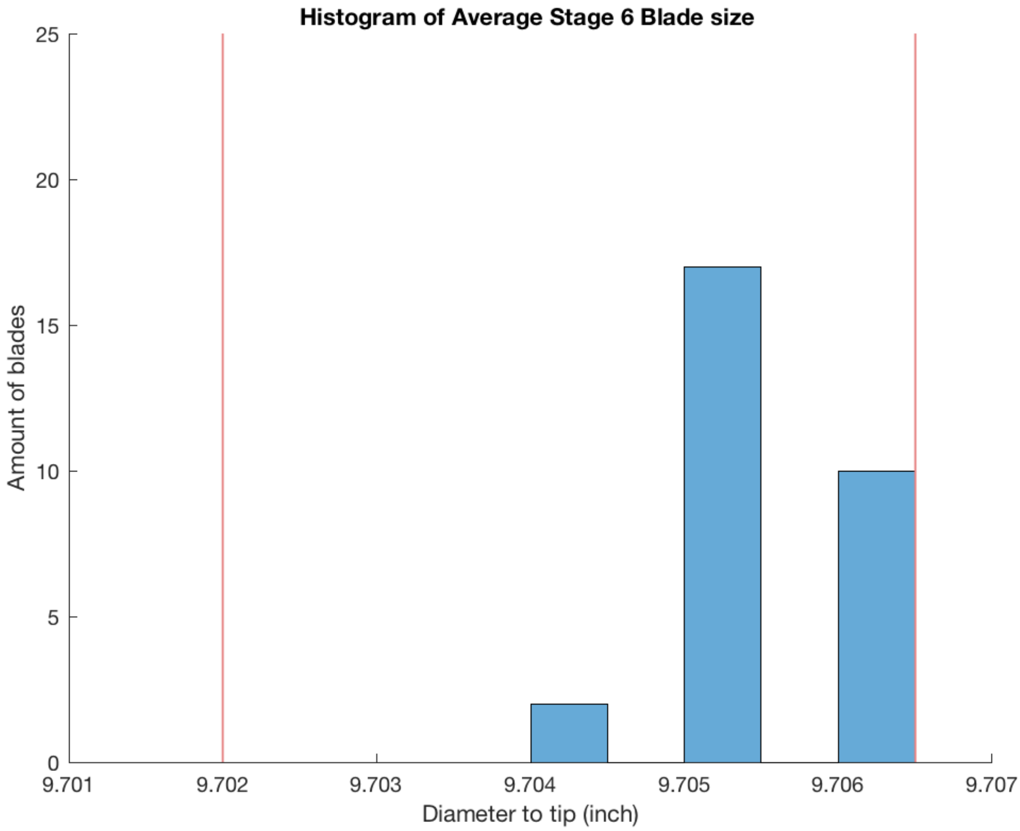


Figure F.6: A histogram of the average set values of stage6

F.7. Stage 7

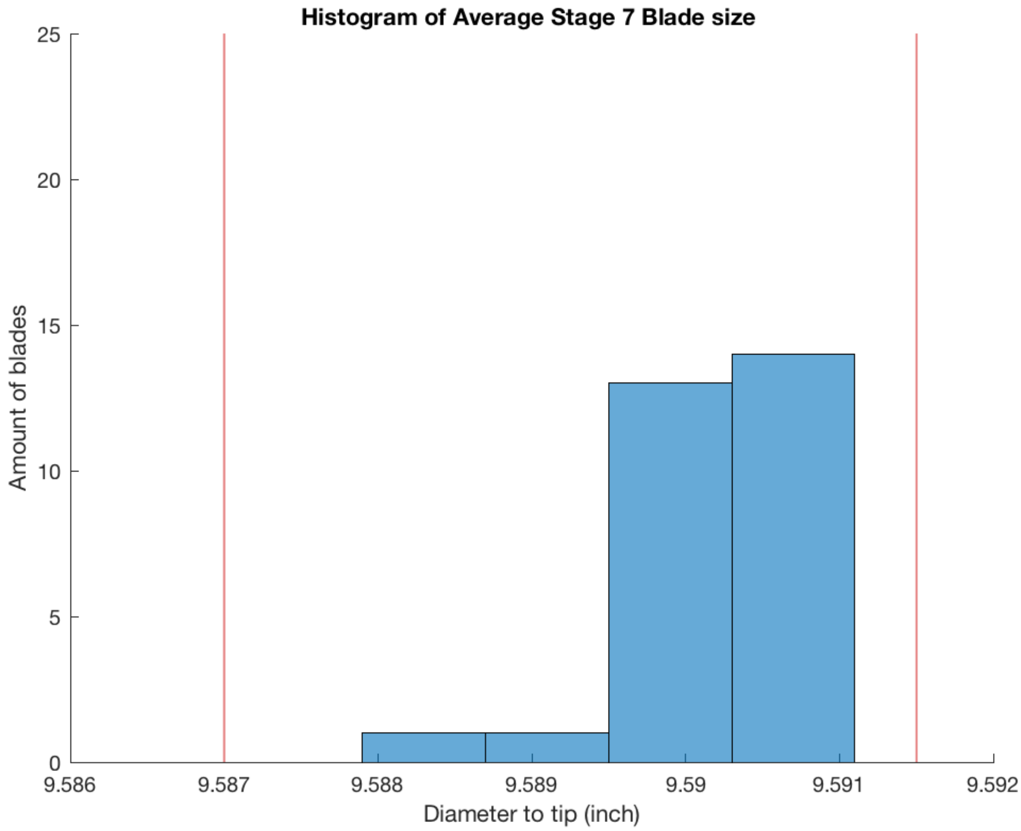


Figure F.7: A histogram of the average set values of stage7

F.8. Stage 8

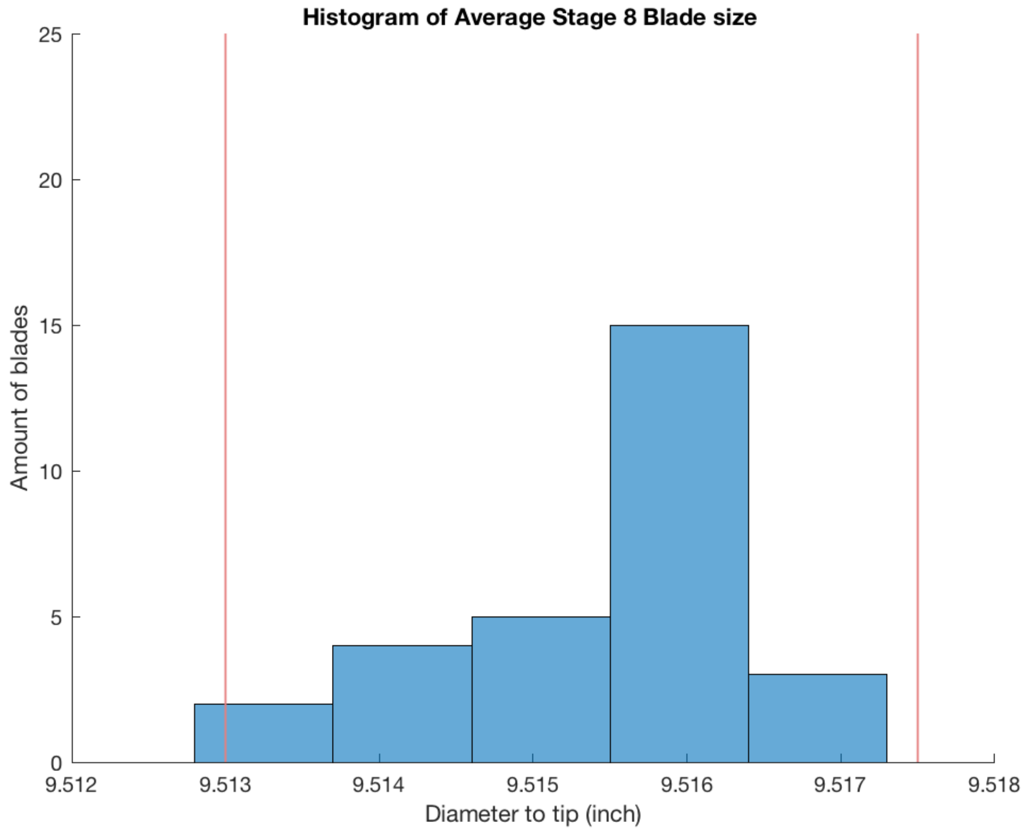


Figure F.8: A histogram of the average set values of stage8

F.9. Stage 9

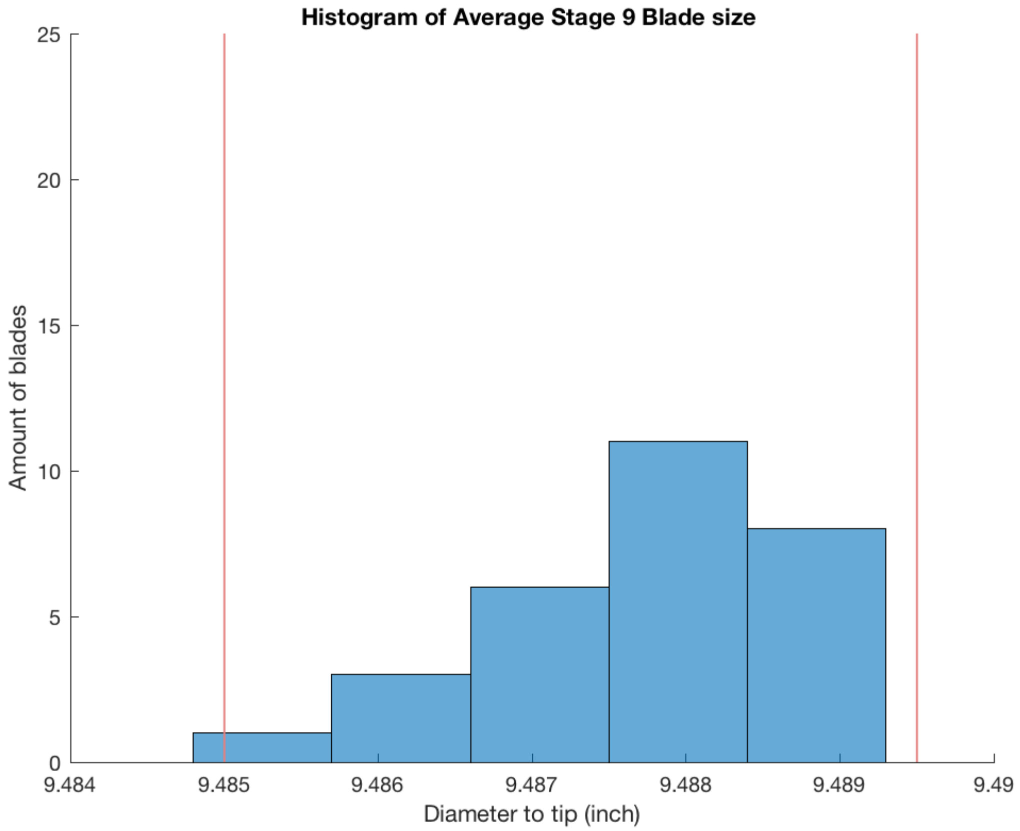


Figure F.9: A histogram of the average set values of stage9

G

STREAM

HIGH PRESSURE COMPRESSOR ROTOR MODULE -
ASSEMBLY POST AEROSPECT

Subtask 72-31-00-440-065, -440-074, -220-054, -440-075, -220-056. 72-31-00 assembly 001 par 3 D.			
Install the narrow and wide blades as necessary.			
(14) / (15) Record dimension "MX" and "MY". See figure 1005.			
	(14) Set Screw Limits "MX"	(15) Blade Gap Limits "MY"	
Stage 4	-0,02 mm./ -0,03 mm.	0,40 mm.	stamp mechanic Beverwijk, R 06185 D-EM
Stage 5	0,08 mm./ 0,07 mm.	0,25 mm.	stamp mechanic Beverwijk, R 06185 D-EM
Stage 6	0,11 mm./ 0,13 mm.	0,25 mm.	stamp mechanic Beverwijk, R 06185 D-EM
Stage 7	0,20 mm./ 0,22 mm.	1,00 mm.	stamp mechanic R. Burgmeijer 1 26484 - D-EM
Stage 8	0,015 mm./ 0,015 mm.	1,55 mm.	stamp mechanic R. Burgmeijer 1 26484 - D-EM
Stage 9	0 mm./ 0,05 mm.	2,30 mm.	stamp mechanic R. Burgmeijer 1 26484 - D-EM
Completed by:			stamp mechanic R. Burgmeijer 1 26484 - D-EM

Subtask 72-31-00-440-155* 72-31-00 assembly 004 Par.4.F.	
Check for present of the Calculated Stack Optimizer from the HPC Rotor shaft, stage 3 disk, stage 4-9 spool and the CDP seal with Aerospect.	stamp mechanic R. Burgmeijer 1 26484 - D-EM

Subtask 72-31-00-440-160. 72-31-00 assembly 004 Par.4.H.(13).(c).4.	
Measure the concentricity of the forward journal relative to the stage 4 thru 9 spool face and rabbet diameter.	CONCENTRICITY = 0,0137 mm
Completed by:	stamp mechanic Beverwijk, R 06185 D-EM

Subtask 72-31-00-440-160. 72-31-00 assembly 004 Par.4. H.(13).(c).5. and Par.4. H.(13).(d).	
Measure the perpendicular of the aft face from the stage 4 thru 9 spool face and rabbet diameter.	PERPENDIC. = 0,0290 mm
Completed by:	stamp mechanic Beverwijk, R 06185 D-EM

Figure G.1: A visual overview of STREAM measurement data

H

Flow chart of steps in disassembbly and assembbly stages per assy

Shift	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A
TAT	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
71X Engine	Adm Dem QEC	Dem Gearbox + TGB LPT	Dem LPT + core	Dem HA + Brg1/2 + IGB	Dem LRU's insturen adm	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D							
QEC LH / RH			QEC PVI+ Insturen	Clean	Clean	Clean	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.	QEC disp.			
63X Gearbox			IC adm lru's dem	Dem Pads + inwendig	Inwendig/IC afronden Se. Removen LRU's	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D						
61X IGB							IC/Dem	PVI+ insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D				
62X/63X RDS/TGB							IC/Dem	PVI+ insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D				
03X LPT				IC Dem 55X+56X	Dem 54X	PVI + Insturen + adm																
55X LPT shaft						IC Dem	Dem	PVI+ insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D				
56X TRF					IC Dem	spoelen	spoelen	PVI+ insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D				
54X LPT st/ro						IC Dem	Dem rotor	Dem/softgrit steamcleaning	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D			
53X HPT STATOR					IC Dem	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D						
52X HPT ROTOR					IC Dem	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D						
51X 1st. Nozzle						IC Dem	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D					
42X Combuster						Wasserij																
02X HPC				IC Dem 53X/52X adm	Dem 51X Dem Fuel Dem 42X	Dem 32X/33X/31X /adm	PVI / Insturen adm 02X / 41X	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D					
CFM HPT					Synchronisatie																	
31X HPC rotor								Meten	IC / Dem adm meten seals	Dem blades en disken	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D	
32X + 33X HPC Stator							Adm/IC Penetrant inweek Dem fixed vanes	Dem Fixed vanes 33X + 32X	Dem VSV	Dem masterbeams	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D	
41X CRF								Synchronisatie	Synchronisatie	Synchronisatie	Synchronisatie											
21X LPC					IC Dem. Vanes & stg4 blades	Dem. Spoel + disk EA/SB + EC	PVI + insturen + administratie	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D					
01X Fan						fan uit storing halen Dem IGB Check adm /clening module scheurcontrole check	IC module adm findings vastleggen module status geven Dem orders starten	Dem OGV-LINERS +VBV	Dem QEC FFC	Dem QEC FFC	Dem QEC FFC Pvi insturen adm	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D	
22X no.1 &2 Brg Supp.					IC adm/ dem	Dem / pvi / insturen	Clean	Clean	Clean	NDO	NDO	P&D	P&D	P&D	P&D	P&D						

Figure H.1: Disassembly process steps chart

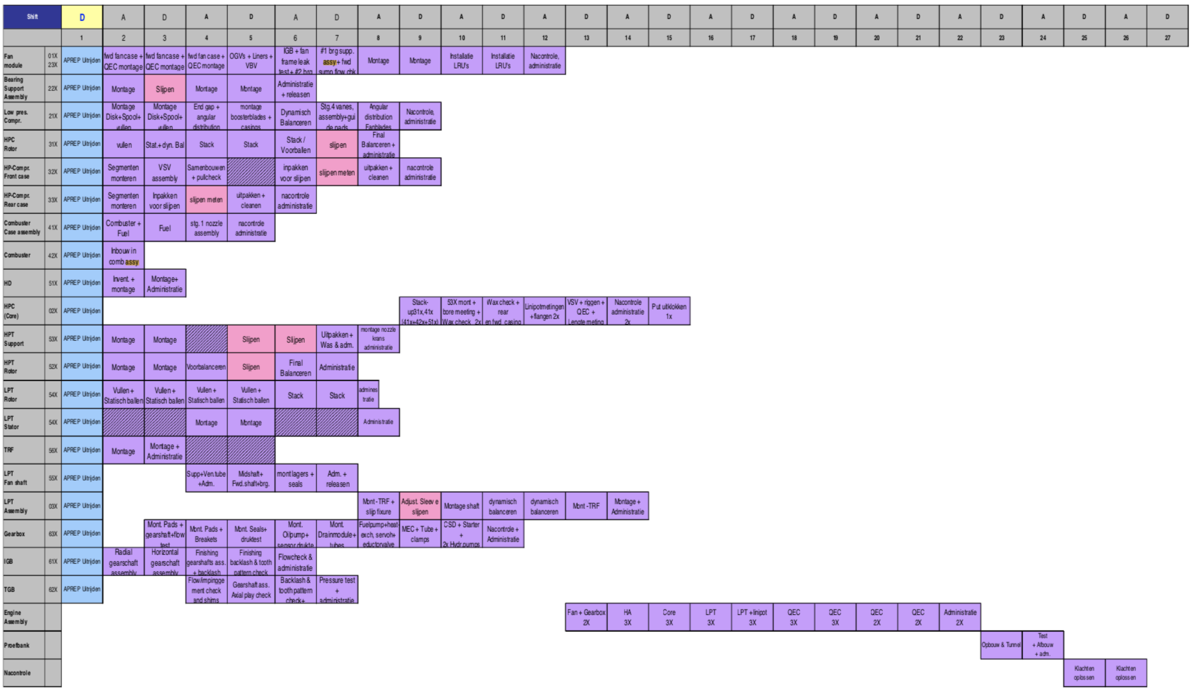


Figure H.2: Assembbly process steps chart