Reducing the Turnaround Time of In House Repairs of Aircraft Engine MRO Services

A Case Study at KLM Engineering and Maintenance Engine Services

by

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TIL5060 - Master Thesis Project

Delft University of Technology

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For the degree of Master of Science in Transport, Infrastructure and Logistics
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Preface

Thousands and thousands of flights are carried out every day and even millions of people are transported through the air. For a lot of people this is business as usual; they have been on a plane for multiple times and use it for business or leisure purposes. Despite the fact that so many people are using a plane as a way of transportation, only a few people are aware of the complexity of the associated maintenance of the aircraft. During my graduation project at KLM Engineering and Maintenance I got the unique opportunity to become familiar with the maintenance of aircraft.

The result of this project is presented in the report lying in front of you. With this master thesis project I complete my master studies Transport, Infrastructure and Logistics (TIL) and I conclude my time as a student at the Delft University of Technology. I conducted my master thesis project at the Lean Six Sigma Office of KLM Engineering and Maintenance. The project focuses on improving the performance of the KLM Engine Services at Amsterdam Airport Schiphol. This report presents factors that influence the turnaround time of in house repairs of aircraft engine MRO services. Moreover the report assesses different alternatives that influence these factors in order to reduce the turnaround time. The alternatives are selected based on findings in literature and the case study at the Engine Services. Both the factors and the alternatives are presented and discussed in this report.

I could not have completed this master thesis project without the help of others. Therefore I would like to use this opportunity to thank these people.

First of all, I would like to thank Guus Philips van Buren en Alex Gortenmulder for giving me the opportunity to conduct my master thesis at KLM E&M and for their help and feedback during the project. I also want to thank all my colleagues at Engine Services for their time, information and help. Moreover I want to thank my graduation committee, Gabriël Lodewijks, Wouter Beelaerts van Blokland and John Baggen, for their supervision, input and critical questions during my master thesis project. Besides I would like to thank Roeland, Job en Arjan for their ”gezelligheid” and the endless amount of table football matches. And last, but definitely not least, I would like to thank my family and friends for their support and for the distraction when needed.

Hope you enjoy reading my thesis.

Delft, April 14, 2016

Pien Meijs

Management Summary

The aircraft engine MRO market is changing. The customers are increasingly demanding due to fierce competition as a result of the growing number of airlines. Therefore the customers are looking for faster and cheaper MRO services of high quality. Moreover the competition between the MRO providers is fierce as a result of the high number of companies offering MRO services. In order to maintain or increase their market share, MRO providers have to offer quick and cheap maintenance of high quality. MRO providers therefore need to change the way they work and offer faster and cheaper services of high quality, but currently it is still unknown how.

KLM E&M is the perfect case study for this research topic because of the following reasons. First, KLM E&M states it is too complex, too slow and too expensive to update their processes smoothly. Moreover, in 2015 KLM E&M Engine Services delivered only 43% of the engines on time. Besides, KLM E&M is also not market leading in terms of turnaround time and costs. Therefore KLM E&M needs to change her way of working. However, how KLM E&M needs to change her way of working is still unclear.

This research focuses on reducing the turnaround time of the in house repairs of full shop visits. In order to reduce the turnaround time, this research aims to determine the factors that influence the turnaround time of in house repairs of aircraft engine MRO services, to identify a set of alternatives to reduce the turnaround time of the repairs and to present their impact on the performance of the aircraft engine MRO services, based on a case study at KLM E&M Engine Services. Herewith this research answers the main question of this research: *Which alternatives can be identified in order to reduce the turnaround time of the in house repairs of aircraft engine MRO services and what is the impact of these alternatives on the performance of the system?*

Literature Review
The literature review presents different methods for process improvement in order to find factors that influence the turnaround time of in house repairs. The analyzed methods are Business Process Management, Lean, Six Sigma, Lean Six Sigma and the Theory of Constraints.

The findings from literature can be summarized in a literature framework. This framework consists of four conditions, namely: *process focused*, *end-to-end process*, *continuous improvement* and *insight into the customer value*. Without fulfilling these conditions, solutions will always be sub-optimal. Next, there are multiple factors influencing the turnaround time. These factors can be divided in two categories: waste and assets and resources. The category waste consists of *transport*, *inventory*, *motion*, *waiting*, *overprocessing*, *overproduction* and *defects and*

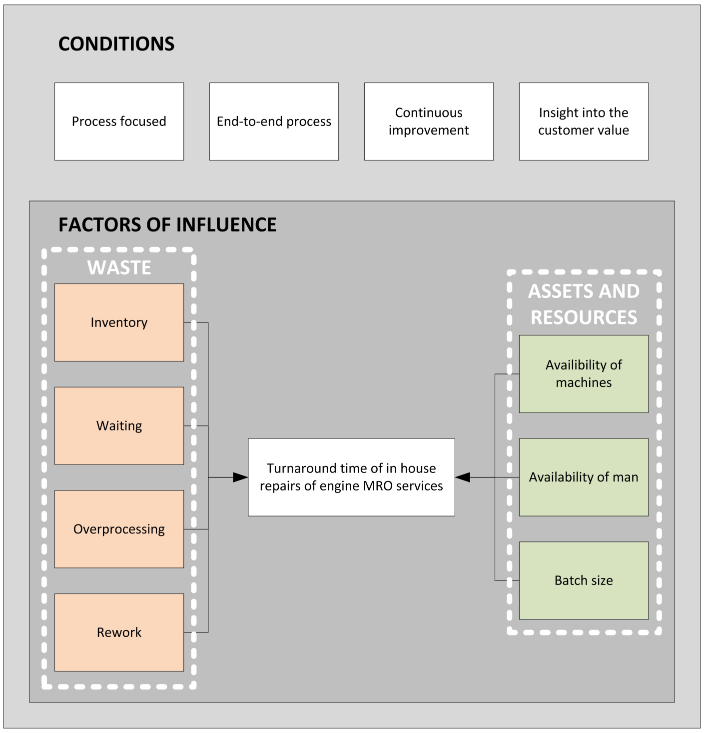
rework. The category assets and resources consists of the *availability of man*, the *availability of material*, the *availability of methods*, the *availability of machines* and the *batch size*.

Case Study at KLM E&M
Next a case study is performed in order to assess the factors found in literature to practice. The case study is performed at KLM E&M and focuses on the in house repairs that are part of the full shop visits at the Engine Services. The in house repairs are performed on several specialized workstations. The fanblades workstation performs worst regarding the turnaround time of the repairs. Currently, only 29% of the complete sets of fanblades are delivered on time. The average turnaround time is 40 days and mainly consists of waiting times. 74% of all waiting times is caused by four techniekcodes, namely:

- Q504: Shotpeening Overall
- Q810: Benchwork Airfoils
- Q811: Seal Replacement
- Q813: Insp/prts/rep Fanblades

These waiting times are mainly caused by *inventory*, *waiting*, *overprocessing*, *rework*, the lack of *availability of machines*, the lack of *availability of man* and the *batch size*.

Factors of Influence
When combining these findings from the case study at KLM E&M with the findings of the literature review, it can be concluded that not all factors that influence the turnaround time according to the literature, actually have a strong impact on the turnaround time of the in house repairs of engine MRO services. As only the factors that have a strong influence on the turnaround time of the in house repairs of engine MRO services are interesting, the literature framework is updated into a current state framework, which is depicted in the figure below.



It can be seen that only seven factors of influence are included in the current state framework. These factors are still a combination of Business Process Management, Lean, Six Sigma, Lean Six Sigma and the Theory of Constraints. Therefore this current state framework can still function as a tool for the combined implementation of the different process improvement methods.

Performance Measurement

The case study shows that the current performance measurement of the in house repairs of engine MRO services at KLM E&M is not sufficient for measuring the performance of the fanblades workstation. First, not the complete process is taken into account. Moreover the current performance indicator does not measure the performance of a complete set of fanblades. A new performance indicator is introduced in order to measure the performance of the complete process for a complete set of fanblades:

$$TAT^{i}_{CompleteSet} = CompleteSet^{i}_{end} - CompleteSet^{i}_{start} \tag{1}$$

$$CompleteSet^{i}_{OnTime} = \begin{cases} 1, & \text{if } TAT^{i}_{CompleteSet} \leq 33 \\ 0, & \text{otherwise} \end{cases} \tag{2}$$

$$TAT_{performance} = \frac{\sum_{i \in I} CompleteSet^{i}_{OnTime}}{n} * 100\% \tag{3}$$

with:

$TAT^{i}_{CompleteSet}$ = Turnaround Time of the complete set i [day]
$CompleteSet^{i}_{end}$ = Finish day of a set i [day]
$CompleteSet^{i}_{start}$ = Start day of a set i [day]
$TATperformance$ = % of complete sets of fanblades delivered on time [%]
I = Set of all sets of fanblades
n = Number of complete sets in set I [#]

Next to the performance indicator on the turnaround time, also performance indicators within the process are needed in order to early notice deviations in the process and to be able to localize the problems in the process. The performance within the process needs to be measured using the set of process performance indicators on *inventory*, *waiting*, *overprocessing*, *rework*, *availability of machines*, *availability of man* and *batch size*.

Set of Alternatives

A set of 12 different alternatives is designed in order to reduce the turnaround time. These alternatives influence the main problem areas on the factors of influence. The alternatives are assessed on five criteria using a Multi-Criteria Analysis (MCA). The assessment criteria are turnaround time, process costs, implementation costs, quality of the product and ease of implementation.

Based on the criteria the MCA selected five alternatives that influence the performance of the system best. These alternatives are:

- A1: Advanced Operator Planning
- A3: Combining Shotpeen Capacity
- A6: Self-Inspections
- A10: Batch Size of 8 Fanblades
- A12: Drum, buffer, rope

At the moment the average turnaround time of the system is 40 days. The implementation of the selected alternatives results in a turnaround time of 16.4 days. Thus, on average all sets of fanblades will be delivered on time. Looking at the data set used for this research, currently only 29% of the sets of fanblades is delivered on time. After implementing the alternatives, 98% of all sets of fanblades is delivered on time.

Recommendations for Science
From a scientific perspective it is recommended to perform multiple case studies in order to validate the framework containing the factors of influence as currently the framework is based on the findings of only one case study. First of all, it is interesting to perform another case study within KLM E&M Engine Services. Next, it is also interesting to perform a case study at another engine MRO service provider or a company in another MRO business. It is expected that the framework will be specifically useful for processes that contain shared resources, work with large batches of parts and have similar workscopes.

Recommendations for KLM E&M
For KLM E&M Engines Services it is recommended to directly implement the new way of performance measurement at all workstations in the engine shop. This way managers can quickly notice and localize irregularities in the process and thus intervene fast and effective. The new way of performance measurement can only be implemented when the way of data collection is more precise. It is required to note the exact starting and finish moment of the task. Moreover the precise set-up times, processing times and waiting times are required.

Next to the new way of performance measurement, it is recommended to first implement alternatives A1, A3, A6 and A10. Alternative A12 should be implemented after the other alternatives are implemented. However, before the alternatives are implemented, it is important do more in-depth research on the costs and the benefits of the alternatives as the current numbers are based on estimates. Moreover it is advised to organize an action-workout session when implementing the alternatives. This way the employees can be involved in the process and the implementation can be kick-started. This workout session can also be used to organize a pilot for the alternatives in order to test the potential of the alternatives again.

Finally, it is interesting to look for opportunities to introduce the different alternatives at other workstations. The alternatives will be specifically interesting for the workstations that contain shared resources, work with large batches of parts and have similar workscopes.

Contents

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List of Abbreviations

Abbreviation	Explanation
Aprep	Assembly Preparation
BoW	Bill of Work
BPM	Business Process Management
BPR	Business Process Reengineering
CBBSC	Connected Business Balance Score Card
CC	Completeness Check
CS	Component Services
DMAIC	Define, Measure, Analyze, Improve and Control
DPMO	Defects Per Million Opportunities
EGT	Exhaust Gas Temperature
E&M	Engineering and Maintenance
EOR	Engine Overhaul Report
ES	Engine Services
IC	Incoming Check
JIT	Just in Time
KLM	Koninklijke Luchtvaartmaatschappij
KPI	Key Performance Indicator
LCC	Low Cost Carrier
LSS	Lean Six Sigma
MCA	Multi-Criteria Analysis
MRO	Maintenance, Repair and Overhaul
NDT	Non-Destructive Testing
ODE	Order, Data and Engine
P&D	Parts & Disposition
PDCA	Plan, Do, Check and Act
PW1	Plasma and Welding 1 workstation
Q504	Shotpeening Overall
Q810	Benchwork Airfoils
Q811	Seal Replacement
Q813	Inspections Parts Repair Fanblades
SIPOC	Supplier, Input, Process, Output and Customer
SV	Shop Visit
TAT	Turnaround Time
TIL	Transport, Infrastructure and Logistics
TOC	Theory of Constraints
TPS	Toyota Production System
TQM	Total Quality Management
VSM	Value Stream Map
WIP	Work In Progress
Z42	Cleaning and Inspection Phase
Z51	In House Repair Phase

Chapter 1

Introduction

1.1 Context of the Research

As can be seen in figure 1.1, in the past air traffic has shown a continuous growth as air traffic has doubled every 15 years (Airbus S.A.S., 2015). It is expected that air traffic will keep growing in the future. Research shows that air traffic will also double in the next 15 years (Airbus S.A.S., 2015). This equals an average annual air traffic growth rate of 4.6% (Airbus S.A.S., 2015), see figure 1.1.

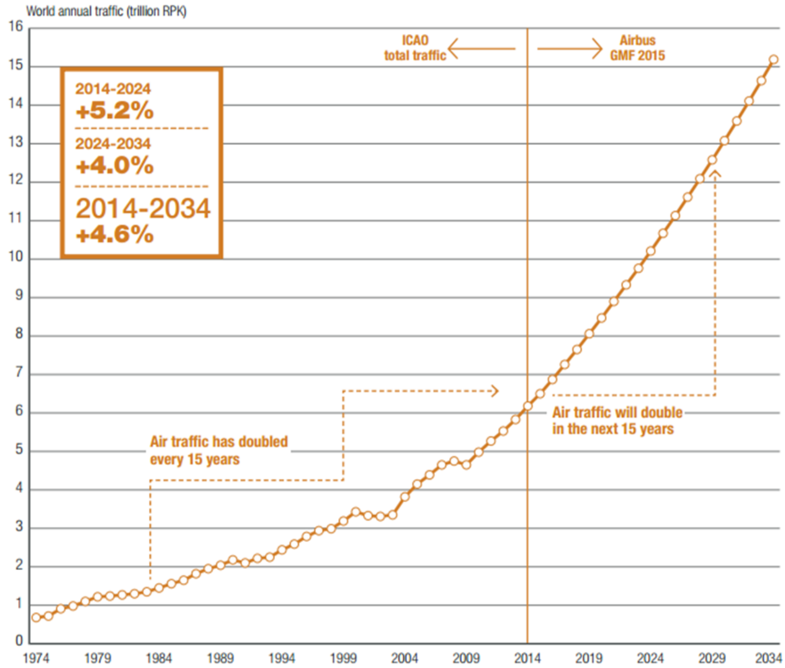


FIGURE 1.1: Trend in world annual air traffic (Airbus S.A.S., 2015)

The expected growth of the air traffic is mainly caused by the growth of the amount of Low Cost Carriers (LCC) and airlines in emerging industries (Airbus S.A.S., 2015) (KLM, 2015e). An increase in the number of airlines, leads to an increase in competition. In the coming years, the competition will become more and more fierce. The airlines are fighting for their market share based on differences in the quality, the service and the price of flight. To maintain and increase their market share airlines have to offer frequent, cheap and comfortable flights. In order to be able to offer this, it is important for airlines to utilize their aircraft to the fullest without experiencing defects. The time the aircraft is in the hangar for maintenance is waste and must be minimized. Moreover the costs of these maintenance activities should be minimized. At the same time the customer expects that the aircraft always are in perfect condition.

The increase of air traffic and the number of airlines indicates that the number of aircraft will grow as well. It is expected that in the coming 20 years the number of passenger aircraft increases with 106% and the number of full freight aircraft with 65% (Airbus S.A.S., 2015). As the number of aircraft increases, it is logical that the aircraft Maintenance, Repair and Overhaul (MRO) demand will grow as well.

Worldwide there are a lot of different parties offering aircraft MRO services. Because of the high amount of parties on the aircraft MRO market, the competition between the MRO providers is fierce. These MRO providers compete on the quality of the product they deliver, but mostly on the turnaround time of the repair and the costs of the repair. In order to maintain or increase their market share, MRO providers have to offer quick and cheap maintenance of high quality.

So, it can be concluded that the aircraft MRO market is changing. The customers are increasingly demanding and besides the competition is fierce as there are more and more competitors on the MRO market. MRO providers therefore need to change the way they work and offer faster, cheaper and better services.

1.2 Koninklijke Luchtvaartmaatschappij

'Koninklijke Luchtvaartmaatschappij' (KLM) is founded on October 7, 1919 (KLM, 2015d) and is the oldest airline still operating under its original name (KLM, 2015b). Nowadays KLM is a large worldwide carrier. In 2014, KLM transported 27,740,000 passengers and 759,732 tons of cargo to 135 destinations (KLM, 2014a). The vision of KLM for the future is 'to become the most customer centric, innovative and efficient European network carrier' (KLM, 2015b). 'KLM wants to be the customers' first choice, to be an attractive employer for its staff and, a company that grows profitably for its shareholders' (KLM, 2015b). In order to realize this vision KLM offers services in three different businesses: the passengers business, the cargo business and the engineering and maintenance business. This research focuses on the engineering and maintenance business. More in depth information on KLM can be found in appendix A.

In order to keep up with the competitors KLM developed a strategic plan. In September 2014, KLM presented the new strategic plan: PERFORM 2020, figure 1.2. PERFORM 2020 is the successor of the TRANSFORM 2015 program. The PERFORM 2020 program focuses on growth and competitiveness combined with financial discipline (KLM, 2014b). This means KLM E&M should be leading in the aircraft maintenance business in 2020, but at the same time KLM E&M should reduce its costs by 1.5 percent each year (KLM, 2014a). In total KLM has to save 700 million euros from now till 2020 and the CEO of KLM announced that KLM cannot maintain its "keeping the family together" principle (NRC, 2014). In order to assure these savings KLM announced to reduce the number of flights to several destinations, both European and intercontinental. Besides KLM is planning on reorganizing its organization to a High Performance Organization (KLM, 2015e). This reorganization will involve the elimination of about a quarter of the management functions (NOS, 2015). Next to these savings, KLM is also optimizing its processes in order to work more efficient and to save money (KLM, 2014a). Hereby KLM uses a bottom-up approach using tools like Lean Six Sigma (KLM, 2015c).

So KLM has developed a strategic plan for the future, but it is still unknown how the goals of this strategic plan can be realized. This research contributes to the realization of PERFORM 2020.

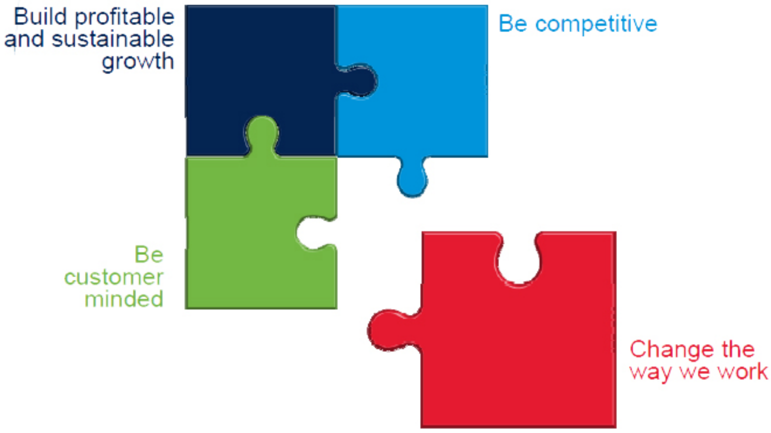


FIGURE 1.2: PERFORM 2020

1.3 KLM Engineering and Maintenance

KLM Engineering and Maintenance (E&M) is part of KLM and is the largest aircraft MRO provider in the Netherlands. Together with Air France Industries, the maintenance business of Air France, KLM E&M is the second largest global multi product MRO unit as they serve 150 airlines and handle 1,500 aircraft each year (Air France KLM, 2015). The turnover in 2014 was 1.25 billion euros and this is approximately five percent of the total revenues of the Air France KLM Group (Air France KLM, 2015).

KLM E&M can be seen as a company within a company. Over 5,000 employees provide aircraft MRO at the more than 20 aircraft positions, the warehouses, the shops and the test facilities (NAG, 2016). KLM E&M offers MRO services in four different categories, namely line maintenance, base maintenance, components services and engine services (KLM, 2015h). This research focuses on the engine services.

At the moment KLM E&M is experiencing force competition. In order to maintain and increase her market share KLM E&M must satisfy the changing requirements of the customers. However, KLM E&M states that the company is too complex, too slow and too expensive to smoothly update her processes (KLM, 2015e). Therefore in the current situation KLM E&M is not able to join the battle for market share. Moreover, the Air France KLM Group has been making losses since 2010 (NOS, 2016). Next, in a lot of cases KLM E&M is not meeting their customer agreements. Engine services delivered only 43% of the engine on time (KLM, 2015h). Besides not meeting the customer agreements, KLM E&M is also not market leading in the field of turnaround time and costs (Bezuijen, 2015). So, it can be concluded that KLM E&M is in dire straits.

1.4 Research Problem

1.4.1 Problem Exploration

As said before, the aircraft MRO market is changing. Customers are increasingly demanding as they want faster, cheaper and better MRO services. Besides there are more and more competitors on the MRO market. In order to keep up with the market developments, MRO providers need to change the way they work. However, at the moment it is not known how these changes need to be realized.

KLM E&M is the perfect case study for this research as KLM E&M states it is too complex, too slow and too expensive to smoothly update their processes (KLM, 2015e). Moreover, in 2015 KLM E&M Engine Services delivered only 43% of the engines on time (KLM, 2015h). Besides not meeting the customer agreements, KLM E&M is also not market leading in the field of turnaround time and costs (Bezuijen, 2015). Therefore KLM E&M must change her way of working, but at the moment it is still unknown how.

So here it is important to find a way to, first, meet the customer agreements and, next, to offer faster and cheaper MRO services of high quality.

1.4.2 Problem Statement

Together with the context description and the information on KLM E&M, the problem exploration leads to the following problem statement:

There is not enough knowledge on MRO providers not meeting their customer agreements in order to design alternatives for the improvement of the performance of the system so MRO providers can offer cheaper and faster services while maintaining the quality of the services.

The missing knowledge mentioned in the problem statement consists of multiple knowledge gaps. First, it is unknown what factors influence the turnaround time of MRO services. Next, there is no general approach for detecting and dealing with these factors. Last, as the factors are unknown, it is also unknown which alternatives can be implemented in order to meet the customer agreements.

This research aims to gather this knowledge based on a literature review and a case study at KLM E&M Engine Services. This way an advice can be given on the alternatives in order to meet the customer agreements.

1.5 Scope of the Research

The research focuses on improving the performance of aircraft MRO services. The performance of the services is defined by the needs of the customers. As said before, customers want faster and cheaper services of high quality. These wishes are depicted in figure 1.3. This research only focuses on faster services and thus on reducing the turnaround time of the services. This focus is chosen because the quality of the service is largely ensured by the extensive regulations on aircraft MRO. Moreover, when reducing the turnaround time, more work can be done within the same amount of time with the same amount of resources. This means that the same services can be offered cheaper. So reducing the turnaround time of the services can lead to cheaper services.

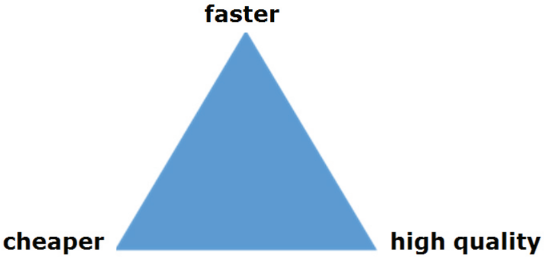


FIGURE 1.3: Objectives Triangle

Next, this research focuses only on a specific part of aircraft MRO services, namely aircraft engine MRO services. Therefore the case study is performed at KLM E&M Engine Services. The processes of other business units within KLM are thus not taken into account. Besides, this research only considers repairs that are part of a full shop visit. Furthermore, only the in house repairs are part of the research as improving the performance of outsourced repairs needs a different approach. Within the in house repairs, only the worst performing workstation is taken into account as this is considered to be the bottleneck. This workstation will function as an example for the other workstations. The scope of the case study is depicted in figure 1.4.

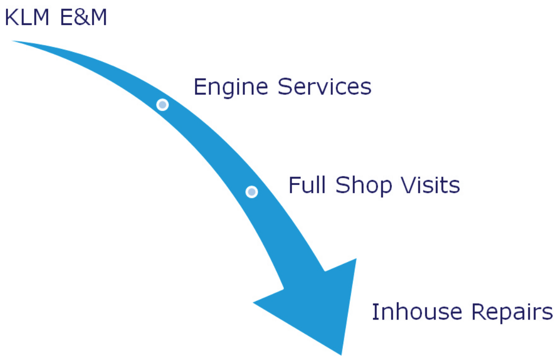


FIGURE 1.4: Scope

1.6 Research Objectives and Deliverables

Based on the problem statement and the scope of the research, the main objective of this research is defined:

Determine the factors that influence the turnaround time of in house repairs of aircraft engine MRO services, identify a set of alternatives to reduce the turnaround time of the repairs and present their impact on the performance of the aircraft engine MRO services, based on a case study at KLM E&M Engine Services.

The results of the research are delivered in this report including both the analysis of the current situation and the assessment of the alternatives. Moreover the results of the research will be presented in a PowerPoint presentation.

1.7 Criteria

The main goal of the alternatives is to reduce the turnaround time of the in house repairs of engine MRO services. However, in order to determine the impact of the alternatives on the complete performance of the engine shop also other criteria need to be taken into account. As stated before, customers are looking for faster and cheaper services of high quality. Next to these customer needs, the ease of the implementation is taken into account as this is important to KLM E&M. Therefore the impact of the alternatives on the performance of the system should be assessed on at least the following four criteria:

- Turnaround time (TAT): this is the time needed for the in house repair. The impact on the TAT is based on the influence of the alternatives on the factors identified in chapter 4.
- Costs: the costs are measured by the costs of a repair, the costs of the implementation of the alternative and the associated investments.
- Quality: the quality determines the quality of the output of the process. This covers both the quality of the product itself and the predictability of the output.
- Ease of Implementation: this criterion indicates the amount of change needed for the implementation. The more change needed, the lower the ease of implementation.

These four criteria will be combined with the factors found in the literature review and the case study. Together they are used to assess the alternatives. Before the alternatives can be assessed, it is important to determine how the criteria should be measured. This will be discussed in chapter 6.

1.8 Research Questions

The main research question of this project follows from the problem statement:

Which alternatives can be identified in order to reduce the turnaround time of the in house repairs of aircraft engine MRO services and what is the impact of these alternatives on the performance of the system?

So the goal of this research is to identify a set of alternatives that all reduce the turnaround time of the in house repairs and to determine the impact of these alternatives on the performance of the system.

In order to answer the main research question, this question is divided into several sub research questions. These sub research questions will be answered during the project and provide the structure of the research.

1. What are currently known methods for process improvement?
2. What factors influence the turnaround time of in house repairs of engine MRO services according to these methods?
3. How is the current process of the in house repairs at Engine Services structured?

4. What factors influence the turnaround time of in house repairs of engine MRO services according to the case study?
5. Do the factors found in literature correspond with the factors found in the case study?
6. How can the performance of the turnaround time of in house repairs of engine MRO services be measured?
7. Which alternatives can influence the factors that influence the turnaround time of in house repairs of engine MRO services?
8. What is the impact of these alternatives on the performance of the system?
9. Which alternatives should be implemented at KLM E&M Engine Services and how?
10. To what extent are these alternatives applicable at other processes within KLM E&M Engine Services?
11. How can the future performance of the system be monitored and controlled?

1.9 Research Approach

For this research the Define, Measure, Analyze, Improve and Control (DMAIC) cycle is used as the DMAIC cycle is a widely used tool in order to structure the research process and to improve and optimize the system. This cycle is part of the Six Sigma methodology. The DMAIC cycle consists of five phases (LeanSixSigma, 2015). Below these phases are linked to the chapters of the report, see figure 1.5. A more detailed description of the DMAIC cycle can be found in section 2.3.2.

- **Define Phase: The definition of the project**
  The definition of the project is described in this first chapter of the report. Here the context, the problem, the scope, the objectives and the main questions of the research are presented.
- **Measure Phase: Collection of data and information**
  The measure phase is focused on the collection of data and information in order to define the current state of the system. This phase consists of the literature review, chapter 2, and the case study, chapter 3. The literature review presents factors influencing the turnaround time of the in house repairs according to different methods for process improvement. The literature review answers research questions 1 and 2. The case study consists of a system analysis, a data analysis and observations. The case study thus answers research questions 3 and 4.
- **Analyze Phase: Analysis of data and information**
  The analyze phase consists of the synthesis of the research, chapter 4. Here the factors influencing the turnaround time found in the literature review are compared to the factors found in the case study. So the synthesis answers research question 5.

- **Improve Phase: Implementation of the alternatives**
  The improve phase is covered by three chapters, chapters 5, 6 and 7. First, new means of performance measurement are introduced in chapter 5. This chapter answers research question 6. Next, chapter 6 designs and assesses the alternatives. This sixth chapter thus answers research questions 7 and 8. Lastly, chapter 7 discusses the implementation of the alternatives at KLM E&M Engine Services and answers research questions 9 and 10.

- **Control Phase: Monitor and control the future state**
  The last phase of the DMAIC cycle is covered in the evaluation and control chapter, chapter 8. Here it is discussed how the new future state of the system can be monitored and controlled. This chapter thus answers the final research question, research question 11.

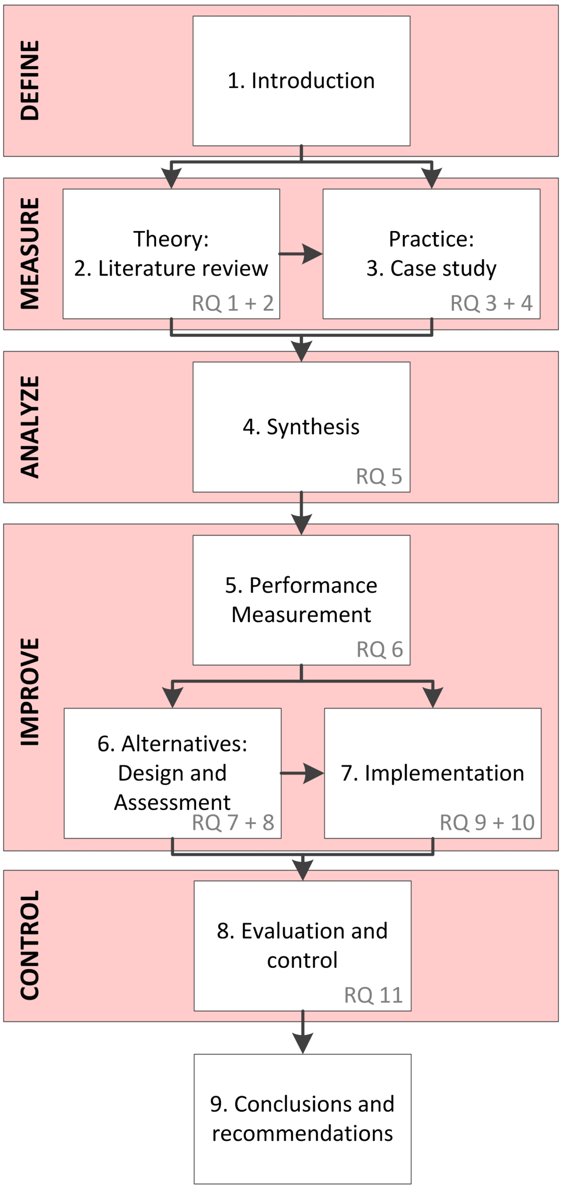


FIGURE 1.5: Report Buildup

1.10 Relevance of the Research

This section discusses the relevance of the research. Here a distinction is made between the scientific relevance, section 1.10.1, and the practical relevance, section 1.10.2. Both are discussed below.

1.10.1 Scientific Relevance

This research aims to explain why aircraft engines are delivered too late and MRO providers do not meet their customer agreements. This is done by identifying the factors that influence the turnaround time of in house repairs of aircraft engine MRO services. These factors provide a framework for improvement projects within aircraft engine MRO. These projects could be within KLM E&M, but also at other MRO providers. Although this research is performed within aircraft engine MRO, it is expected that the research is applicable to a broader scale, i.e. improvement projects within other MRO businesses.

1.10.2 Practical Relevance

The practical relevance is covered by the recommendations for KLM E&M Engine Services. These recommendations are alternatives based on the factors that form the scientific relevance and aim to reduce the turnaround time of the aircraft engine MRO services. Reducing the turnaround time means meeting the customer agreements and thus less fines, but also an improvement of the competitive position of KLM E&M. Moreover it is assumed that these recommendations would also be helpful to other companies within aircraft engine MRO but also within other MRO businesses.

Part I

Measure Phase

Chapter 2

Literature Review: Methods for Process Improvement

This chapter presents the different methods for process improvement, see figure 2.1. The discussed methods are Business Process Management (section 2.1), Lean (section 2.2), Six Sigma (section 2.3), Lean Six Sigma (section 2.4) and the Theory of Constraints (section 2.5). Next, the factors found within these methods influencing the turnaround times of in house repair of engine MRO services are presented in a literature framework (section 2.6). This chapter ends with a conclusion on the literature review (section 2.7).

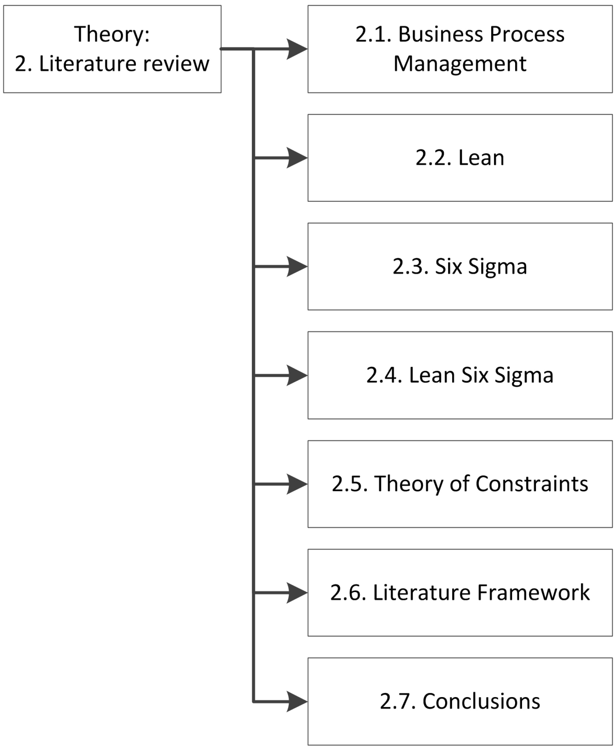


FIGURE 2.1: Chapter Buildup Literature Review

The literature review presents different methods for process improvement in order to find factors that influence the turnaround time of in house repair of engine MRO services. These factors are identified by analyzing the different methods. The factors found in the literature are presented in a literature framework. This framework is a generic framework for the reduction of turnaround times. The framework will become more specific for the in house repairs of engine MRO services by the use of the case study in chapter 3.

Therefore this chapter answers research question 1, *'what are currently known methods for process improvement?'*, and research question 2, *'what factors influence the turnaround time of in house repairs of engine MRO services according to these methods?'*.

2.1 Business Process Management

Business Process Management (BPM) is a management discipline in order to manage and improve the performance of business processes (van Rensburg, 1998). The aim of BPM is to improve these business processes to ensure that the process is performed as efficient and effective as possible (Hung, 2006). Here business processes are defined as "a series of interrelated activities linked together to produce customer value" (van Rensburg, 1998). So a process is "an approach for converting inputs into outputs" (Zairi, 1997). BPM is a management principle to handle with these business processes. Therefore BPM can be defined as "a holistic engineered description to be used as a framework to manage and improve business processes in organizations" (van Rensburg, 1998). BPM is a holistic approach as it focuses on the end-to-end process because the improvements in only small parts of a process often result in sub-optimal solutions (Hung, 2006).

The introduction of BPM affects all levels of the organization in order to make sure the organization is truly process-focused (Hung, 2006). The focus on the process is needed as "the customer cares nothing for the management structure, the strategic plans, or the financial structures, the customer cares about one thing, and one thing alone, results - the value delivered to him" (Hammer, 1996). BPM therefore is a comprehensive problem-solving concept that is process-oriented, customer focused, fact-based, and participative throughout the whole firm while focusing on the end-to-end processes (Benner, 2002).

The main difference between functional-focused organizations and process-focused organizations is that functional-focused organizations are vertical organized while process-focused organizations are horizontal organized (Weilkiens, 2011). This causes that a functional manager focuses on the performance of his own department and a process manager focuses on the performance of all processes in the value chain together (Harmon, 2014, Zairi, 1997). So where the functional-focused organization creates barriers for creating customer value, the process-focused organization focuses on the customer satisfaction (Zairi, 1997).

2.1.1 History of Business Process Management

The history of BPM originates from the 18th century. In 1776 Adam Smith wrote the book 'The Wealth of Nations'. This book states that optimization projects should take the whole end-to-end process into account when optimizing the performance of a process (Harmon, 2014).

More recent, the roots of BPM can be traced back to Total Quality Management (TQM) and Business Process Reengineering (BPR) (Harmon, 2014, Hung, 2006).

TQM originates from 1940 when it was developed by William Deming and Kaoru Ishikawa Harmon (2014). During the 1980s TQM became a well-known management concept as it was successfully used by multiple Japanese organizations (Hung, 2006). TQM can be summarized in four concepts, namely (Harmon, 2014):

- Process-focused management.
- Analysis of process deviations.
- Quality improvement projects.
- Continuous quality improvement.

In the 1990s, Business Process Reengineering (BPR) became more popular (Harmon, 2014). BPR is focused on goals for the complete process and not on fixing local bottlenecks (Davenport, 1990). Therefore instead of improving the existing processes, BPR develops new processes (Hammer, 1990). BPR aims for huge steps forward in the performance of the process (Harmon, 2014).

At the end of the 1990s, the term BPM was used for the first time (Harmon, 2014). BPM integrates TQM and BPR and is a widely used improvement model for organizations nowadays (Hung, 2006). The BPM concept creates an environment that is ready for the implementation of other improvement methodologies like Lean and Six Sigma (Harmon, 2014).

2.1.2 Business Process Management Rules

BPM can be summarized in seven rules. These rules can also be used as a guideline when implementing the BPM concept. The seven BPM rules are (Hung, 2006):

1. Major activities have to be properly mapped and documented.
2. BPM creates a focus on customers through horizontal linkages between key activities.
3. BPM relies on systems and documented procedures.
4. BPM relies on measurement activity to assess the performance.
5. BPM has to be based on a continuous approach.
6. BPM has to be inspired by best practice.
7. BPM is an approach for culture change.

2.2 Lean

Lean Manufacturing or Lean Production, abbreviated 'Lean', is a way of thinking focusing on maximizing the customer value of the process. The customer value equals the process steps that the customer is willing to pay, in other words the process steps that add value for the customers. Process steps that do not add value for the customer are called waste and must be eliminated. So the goal of Lean is reducing waste from the process in order to improve the customer value. This way the same customer value is created with less effort. This way the Lean way of thinking reduces the complexity of the system and stabilizes the system.

The Lean way of thinking can be depicted using the House of Lean, figure 2.2. The House of Lean presents the most important aspects of Lean (Höök, 2008). The foundation of the Lean House consists of stability. Stability of the process means that the process constantly gives the same output and thus is reliable and predictable. In order to reach stability standardization of the process and constant availability of the 4 M's are key. The 4 M's consist of Man, Material, Machines and Methods. The next level of the Lean House consists of the reduction of waste, *muda*, and continuous improvement, *Kaizen*. The foundation of the left pillar focuses on balancing the system, *Heijunka*. The balanced system is needed for Just In Time (JIT) production of the products. In order to produce Just In Time (JIT) it is important to work with a *takt time* and with pulled flows. The foundation of the right pillar is standard working. A standardized way of working is required in order to produce all products the first time right, *Jidoka*. In order to reach *Jidoka*, it is important to separate the man and the machines. When the work is standardized, the machines can be operated by different employees. (Höök, 2008)

The last part of the Lean House is the roof. The roof presents the most important things a company wants to achieve: low costs, high level of quality and short delivery times. These three factors lead to high customer value and profitability of the company. It is important to find a balance of the three factors in the roof as all three factors are important for the customer. A customer would for example not buy a product that is very cheap, but at the same time the quality of the product is low and it takes very long to deliver the product. The customer probably wants to pay a bit more in order to make sure that the quality is higher and the delivery time is shorter. (Höök, 2008)

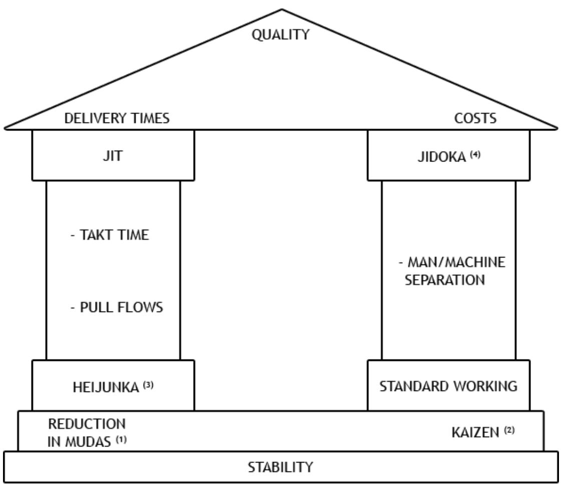


FIGURE 2.2: House of Lean

2.2.1 History of Lean

The history of Lean goes way back. Lean is not introduced all of a sudden, but it is a process of more than 200 years (Taylor, 1911). All these years people were optimizing production processes, for example the standardization of the production of cannons and weapons in the 18th and 19th century. An important man in the development of Lean is Frederick Taylor who wrote the book 'Scientific Management'. Taylor showed in his book that eliminating waste in the production process has more influence on the performance than maximizing the sales (Taylor, 1911). With the introduction of Scientific Management, Lean becomes more and more similar to the version of Lean as we know it nowadays.

Next to Taylor, two other men are also very important in the history of Lean, namely Henry Ford and Kiichiro Toyoda (Womack, 1991). Henry Ford introduced an integrated production system by introducing a belt conveyor. Ford called this new production system Flow Production. Ford used his new production line for the first car for the ordinary man, the T-model. The line enabled Ford to offer vehicles for relatively low prices, but the line was only able to produce one specific type of car. This caused all T-model vehicles being identical. Another problem of the new production line was the amount of inventory and work in progress. This problem is caused as the system functions as a push-system. Despite the drawbacks, the new production line enabled Ford to produce vehicles in a very short period of time in order to offer vehicles for relatively low prices. (Womack, 1991)

After World War II, Kiichiro Toyoda wanted to increase the number of vehicles produced at Toyota. At that moment in time Toyota had produced 2,500 vehicles during the last 13 years whilst Ford produced 8,000 vehicles per year. This made Toyoda very interested in the way of producing at Ford. However, Toyoda did not have the financial resources to produce the same way as Ford has a lot value locked in inventory and work in progress. So Toyoda took a closer look at the Ford production system and adjusted the system with only minor changes in order to create both continuity of the process and differentiation of the products (Womack, 1991). The new system developed by Toyoda is called the Toyota Production System (TPS). TPS is based on the principles of Ford, but also includes the 'Just in Time' principe (JIT) and the pull concept in order to fix the problem of the high costs as a result of the large inventories (Womack, 1991). The Toyota Production System (TPS) can be summarized in the 4P model (Liker, 2006), figure 2.3.

1. **Philosophy:** is the backbone of a Lean organization. Philosophy stands for long-term thinking and for the future of the company (Liker, 2006). It is important to not only take care of the needs of the customers, but also of the future of the company.
2. **Process:** includes the elimination of waste. The waste is eliminated by restructuring the processes in order to make sure that all steps add value (Liker, 2006).
3. **People and Partners:** represents all employees and partners of the company. When implementing Lean as a new company culture, it is important to make sure the employees on all levels of the company are aware of the Lean philosophy (Liker, 2006). They should be motivated to join the improvement process. Also partners need to be involved in this process as co-operation with suppliers and purchasers is essential.

4. **Problem Solving:** is a very important part of Lean. By constantly identifying and solving problems the company ensures the continuous improvement of the process, *Kaizen* (Liker, 2006).

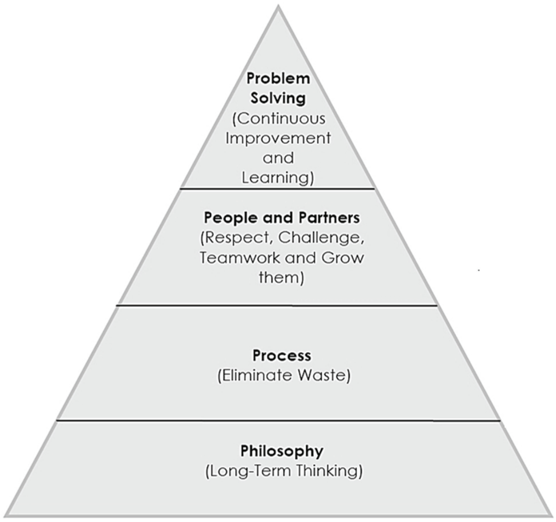


FIGURE 2.3: 4P Model

Due to the implementation of the TPS, Toyota in 2008 grew to the worlds largest car manufacturer based on turnover. In the meanwhile different version of TPS are used within the vehicle industry, for example the Scania Production System and the Nissan Production Way. These production types are all derived from the TPS and are based on Lean.

The success of Toyota caused that Lean became very popular all over the world. During the last years are lot of books, papers, et cetera, are written on Lean Management as the number of interested companies keeps growing. Lean is nowadays practiced in multiple industries, like production, logistics, health care, distribution and construction. Even though these industries are very different, the applications of Lean have the same goal: eliminating waste and improving the customer value.

2.2.2 Lean Principles

Restructuring processes in order to make them more Lean can be summarized in the five principles of Lean. These principles can also be used as a guideline when implementing the Lean philosophy. The principles focus om maximizing the customer value. The five Lean principles, figure 2.4, are (Cardiff University, 2016):

1. Identify customers and specify value
2. Identify and map the value stream
3. Create flow by eliminating waste
4. Respond to customer pull
5. Pursue perfection

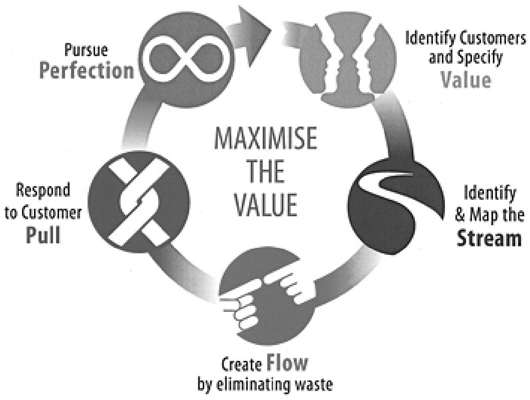


FIGURE 2.4: Lean Principles

These principles of Lean are discussed below (Cardiff University, 2016).

1. **Identify Customers and Specify Value**
   Customers are only willing to pay for processes that add value to the product. Therefore it is very important to specify what is valuable in the eyes of the customer. Here it is interesting to check to what degree the product meets the needs and wishes of the customers.

2. **Identify and Map the Value Stream**
   A value stream gives an overview of all value adding and non value adding activities of the process. First the current state of the system needs to be mapped from beginning of the production until delivery of the product at the customer. A value stream map is an often used tool to generate this process overview. Besides the process steps, a value stream map also includes the lead times of the (sub)processes and the information flow. After mapping the current state, the value stream map can also be used to design the future state of the system.

3. **Create Flow by Eliminating Waste**
   When the process steps and their lead times are known, a flow needs to be created. In order to create a flow it is important to eliminate the waste in the process.

   Waste can be divided in two categories. The first category of waste does not add value to the process and can easily be eliminated from the process. This category of waste should directly be eliminated from the process. The second category of waste also does not add value to the process, but this step in the process can not be eliminated as it is unavoidable in order to complete the production. This category of waste can not be eliminated from the process. Therefore it is not possible to eliminate all waste from the process, but it is possible to minimize the amount of waste.

   There are multiple theories on the different types of waste. This report presents the eight types of waste as described in the Toyota Way Fieldbook (Liker, 2006):

   (a) **Transport:** is sometimes necessary in the process, but it does not add value for the customer. Therefore the amount of transport in the process should be minimized. Besides that transport does not add value, it also takes time which increases the lead time. Moreover transport increases the chance of damage and damage to the product costs money and takes time to repair.

(b) **Inventory:** are the products stored in the process that are not yet needed. Inventory ties up capital as more products, and thus capital, than needed are in the system. Moreover inventory causes extra transport of the products as the products need to be stored and taken out of the storage. Inventory is also a waste of space as the storage of the products takes space. When a lot of products are placed in storage, it becomes hard to find the needed material. This causes extra lead time. Lastly, inventory is also a waste of capital as the products in storage are aging and become obsolete.

(c) **Motion:** is the movement of employees. This movement does not add value for the customer but it takes time which increases the lead times. Because movement takes time, the employee has less time left for the value adding steps. Therefore motion has a negative effect on the efficiency of the employees. Moreover high amounts of motion can lead to ergonomic concerns for the employees.

(d) **Waiting:** stands for employees waiting before they can continue their work. Waiting is a waste of time, because waiting times increases the lead times without adding any value for the customer. Moreover the employees are not able to work during the time they are waiting and this decreases their productivity. The more waiting time during the process, the more products are in the system and this is a waste of capital.

(e) **Overprocessing:** means that too many process steps are performed in order to produce a product. These unnecessary process steps cost time and thus increase the lead times without adding value for the customer. The unnecessary steps need to be executed by an employee. This means that the efficiency of the employee is influenced in a negative way by overprocessing as the employee is working on steps that do not add value for the customer.

(f) **Overproduction:** means that the company produces more products than they can sell. This builds an inventory that is not needed in order to meet the current demand. Moreover overproduction consumes time of valuable resources for the production of products that are not immediately needed.

(g) **Defects and rework:** are products that do meet the customers needs. These products need to be repaired and this repair takes time and causes higher lead times. Moreover repairs and rework consumes extra time of the employees which causes employees to be less effective.

(h) **Staff's unused knowledge and experience:** means that the company does not make use of the knowledge of the employee. The employees are the specialists of the process; they work there every day and know all details of the processes. Their experience on the system helps finding the problems and designing alternatives that solve the problems.

4. **Respond to Customer Pull**
The traditional way of production uses a push concept. This means that companies produce products regardless the size of the market demand and then pushes it into the market to the customers. The push concept causes problems within companies as it leads

to overproduction and thus high inventories. It would be wise for companies to only produce products when there is demand for the products, the pull concept. This means that the production is driven by the demand of the customers and that the inventories will be minimized.

5. **Pursue Perfection**
The last Lean principle focuses on pursuing perfection. This means that the system needs to improve over and over again. There are two different ways of implementing improvements: *Kaikaku*, for the radical improvements, and *Kaizen*, for the less radical improvements.

Kaikaku
Kaikaku is the Japanese word for a fast change in a system within a short time span (Yamamoto, 2013). These changes are mostly a result of decisions of the management and include the introduction of new knowledge, new strategies, new approaches, new production techniques or new equipment (Yamamoto, 2013).

Kaizen
The Japanese word Kaizen stands for continuous improvement of the system and focuses on small changes. It is important that employees of all levels of the company are involved in the improvement process. The process of continuous improvement consists of four steps that should be taken over and over again as an iterative process. The Plan, Do, Check, Act (PDCA) cycle, figure 2.5, is developed by Deming (1952) and is widely used as a tool in improvement processes. Below the PDCA cycle is discussed in more detail.

- *Plan:* is the first phase of the PDCA cycle. Here the current state of the system is analyzed and the improvement goals are set (Deming, 1952). This leads to an action plan for the improvement process.
- *Do:* covers the actual execution of the improvements (Deming, 1952).
- *Check:* is the third phase of the cycle. During this phase the results of the improvements are analyzed (Deming, 1952). Here the new performance is compared with the old performance of the system and it is checked whether the goals of the improvements are achieved.
- *Act:* covers the adjustments to the improvements. These adjustments are based on the findings of the check phase. The aim of the adjustments is to meet the goals of the improvements and to eliminate the waste from the process (Deming, 1952). When the waste is eliminated from the process, it is important to standardize the improvements so the knowledge gained can be used again later.

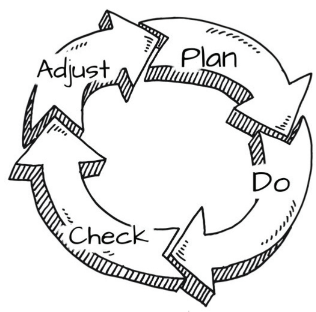


FIGURE 2.5: PDCA cycle

2.2.3 Employee Involvement

When implementing improvements using the Lean philosophy, it is very important to involve the employees in the process. The main reason for this is that the management only knows about 5% of the process (KLM E&M, 2016). The employees on the other hand know up to 95% of the process (KLM E&M, 2016). So involving the employees in the process leads to more and new opportunities for solutions and improvements. Moreover the support of the employees is needed when implementing a solution. The effectiveness of a solution is namely determined by the quality of the solution times the acceptance of the solution by the employees. So regardless to the quality of the solution, when the employees do no accept the change, the effect of the solution will be negligible. Therefore it is extremely important to make the employees part of the improvement team, to use their knowledge and experience and to make sure that they accept the change (KLM E&M, 2016).

2.3 Six Sigma

Six Sigma is a methodology in order to improve the quality of the output of the system (Procesverbeteren, 2015). The aim of Six Sigma is to maximize the probability that products or services comply with the customer expectations (Tang, 2006). In order to do so, the defects of the system are identified and removed causing less variations in the process. The less variability in the process, the smaller the chance of defects in the products and thus the smaller the chance of dissatisfied customers. So Six Sigma is a real customer focused concept in which the voice of the customer is key (Tang, 2006). Therefore not the company, but the customer decides whether a product meets the requirements.

Six Sigma forces companies to make their decision based on objective statistics instead of subjective emotions or experiences (Tang, 2006). In order to make the right decision, it is important to collect the right data within all levels of the company. The structured collection of data throughout the company creates a uniform measurement of the level of quality throughout the company. This makes Six Sigma an ideal tool for solving complex quality issues. Here it is important that the quality of the product is measurable or can be made measurable.

The term Six Sigma stands for six times sigma, the standard deviation. This can be depicted by the belly curve shown in figure 2.6. As can be seen in the figure, six times sigma corresponds with a quality level of 99.99966%. This means that the chance on defects is equal to 0.00034%, 3.4 defects per million opportunities (DPMO). The amount of defects per million opportunities is so small that it is negligible. When using a lower sigma the quality level will be lower as the chance on defects and thus DPMO will be higher.

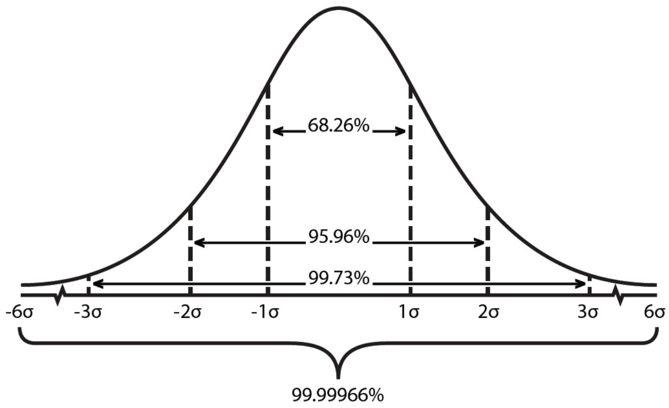


FIGURE 2.6: Six Sigma Normal Distribution

2.3.1 History of Six Sigma

The first rudiments of Six Sigma originate from the early 19th century. In 1809 Carl Gauss introduced the concept of the belly curve in his book 'Theoria Motus Corporum Arithmeticae'. The belly curve was a new graph that presented the variation of data next to the mean of the data. This graph will later be the basis of Six Sigma.

The first version of Six Sigma is developed by Motorola during the mid 80s (Folaron, 2016). Motorola developed Six Sigma as a tool for solving quality issues and problems on customer satisfaction. Traditionally Motorola measured its performance based on defects per thousands of opportunities, but the introduction of Six Sigma changed this to measuring defects per million opportunities. This change had a huge impact on the organization culture of Motorola and resulted in a total saving of $16 billion.

Motorola was the first company implementing Six Sigma, but Six Sigma became popular after General Electrics implemented it on a large scale within the company in the early 90s (Folaron, 2016). The saving of multiple billions at General Electrics demonstrated the potency of Six Sigma and inspired other companies to implement Six Sigma at their companies as well.

Nowadays Six Sigma is implemented within hundreds of companies worldwide and a lot of books are written on Six Sigma. At first Six Sigma was only introduced within companies in the process industry and the high-tech industry, but currently Six Sigma is also used for optimization studies in other industries.

2.3.2 DMAIC Cycle

A widely used tool for the implementation of Six Sigma is the DMAIC cycle. DMAIC stands for the five phases of the cycle: Define, Measure, Analyze, Improve and Control (George, 2002). The DMAIC cycle is used for improving the performance of a system. The cycle is repeated until the goal of 3.4 DPMO is achieved. When using the DMAIC cycle it is important to complete one phase before starting the next one and to not jump to solutions until the problem is clearly defined.

Each phase of the DMAIC cycle has its own function in the improvement process. These functions are described below (George, 2002):

- **Define**
  During the define phase the project is defined. This project definition consists of a definition of:
  - The goal of the project,
  - The customers requirements and wishes,
  - The problem and its boundaries,
  - The process,
  - The stakeholders, and
  - The project planning.
- **Measure**
  The measure phase focuses on quantifying the current state of the system. This helps in getting an objective overview of the system, but also in monitoring the changes in the performance later on after implementing one of more improvements. Moreover this is useful in order to fully understand the process and the problem.

  During the measure phase the data needed for the project is collected and the current performance of the system is determined. The performance of the system is based on the customers needs. Next goals are set for the KPI values after improving the system.
- **Analyze**
  During the analyze phase the data collected in the previous phase is analyzed. The goal of this phase is to find the best improvement opportunities in order to reach the goal of the project set in the first phase. In order to find these opportunities, first gaps between the current state and goal of the project are defined. Then the possible root causes for the different types of waste are identified. Next, the impact of the root causes is analyzed. This way the different root causes can be ranked and the best improvement opportunities can be defined and quantified.
- **Improve**
  In the improve phase the real improvement of the system takes place. First a lot of possible solutions are developed. Here it is important to be creative and to come up with new and innovative ideas. Next the impact of the solutions needs to be evaluated and the most promising solutions are selected. These solutions are implemented in order to improve the performance of the process. After the implementation it is important to validate the improvement and to quantify the effect on the performance of the process.
- **Control**
  The last phase of the DMAIC cycle focuses on controlling the new system. The goal of this phase is to maintain the new state of the system to ensure that the improvements are sustained. This requires a lot of discipline of the employees as they have the tendency to fall back into old habits. In order to control the new system, adjustments of the process management and control system are needed and the new state needs to be standardized and documented.

2.4 Lean Six Sigma

Lean Six Sigma (LSS) is a combination of both Lean and Six Sigma that is used in order to improve processes. The term Lean Six Sigma indicates the integration of both methods (Pepper, 2010). Both Lean and Six Sigma aim for the same goal: increasing customer satisfaction and shorten the lead time in order to make money (Pepper, 2010). Therefore by combining the two methods, the methodologies complement each other and the best of both worlds is implemented (Tenera, 2014). Six Sigma complements Lean as Six Sigma focuses on the quality of the output and it provides the statistical tools needed to realize improvements in the process (Pepper, 2010). Lean complements Six Sigma as Lean focuses on the speed of the process and it provides tools for the process of identifying waste in the process (Pepper, 2010).

The integration of Lean and Six Sigma is useful as some aspects of the methods correspond to each other and other aspects are complementary to each other. Both types of aspects contribute to the usefulness of LSS. The most characteristic aspects of Lean, Six Sigma and LSS are discussed below.

- **Waste and Variation**
  Lean focuses on the elimination of waste from the process (Tenera, 2014). However, Lean does not recognizes the impact of variation on the performance of the process (George, 2003). Six Sigma does recognize this importance, but has a lack of tools for data collection in order to identify waste (George, 2003). Integrating Lean and Six Sigma leads to a combination of tools that are useful for both the identification of waste and the reduction of variation.

- **Speed and Quality**
  The main focus of Lean is the turnaround time and thus the speed of the process. Six Sigma focuses on the variation of the output and thus on the quality of the process. By integrating both methods a new methodology arises that both takes speed and quality into account as both are important factors for the customers (George, 2003).

- **Customer Focus**
  Both methods take the needs of the customer into account. Lean uses the needs of the customers in order to identify the waste in the process. Six Sigma uses the voice of the customers in order to find the requirements for the output of the process. So the methods strengthen each other in focusing on the customers needs (George, 2003).

- **Cultural Change**
  The implementation of both Lean and Six Sigma is accompanied by cultural changes in the organization. Implementing Lean asks for maximizing the customer satisfaction and changing the process bottom-up (George, 2003). Six Sigma needs cultural changes for decision making as Six Sigma prescribes that decisions need to be based on facts (George, 2003). Combining Lean and Six Sigma leads to an organization that is focused on the improvement of the process based on facts while improving the customer satisfaction (Pepper, 2010).

2.4.1 Integration of Lean and Six Sigma

When integrating Lean and Six Sigma into LSS a new balance between costs and customer value arises, see figure 2.7 (Pepper, 2010). This new balance lies in the middle of Lean on the one hand and Six Sigma on the other hand. Lean focuses on eliminating waste, reducing turnaround time and thus maximizing the customer value. The risk of Lean is becoming too lean to easily adapt to changing markets (Pepper, 2010). Six Sigma focuses on reducing the variation of the output. The risk of Six Sigma is reducing the variation even more than valuable for the customer and thus investing without increasing the customer value (Pepper, 2010). LSS combines Lean and Six Sigma and finds a balance in the advantages and the risks of both methods. LSS focuses on both creating customer value and reducing the variation, but at the same time not over-engineering the processes (Pepper, 2010).

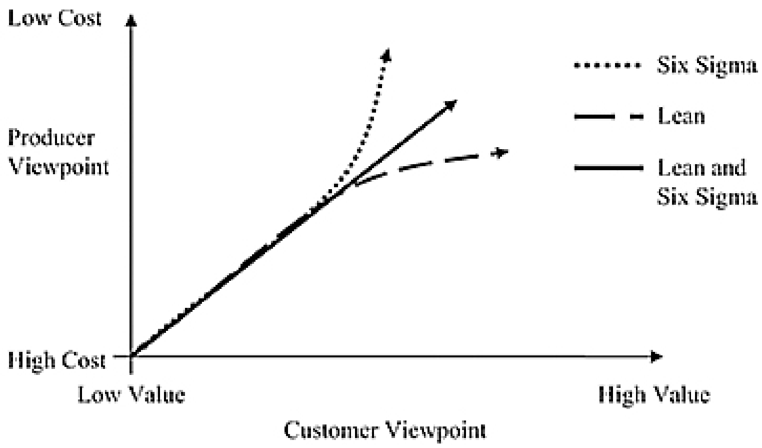


FIGURE 2.7: Comparison of Lean, Six Sigma and Lean Six Sigma

2.4.2 Implementation of Lean Six Sigma

For the implementation of Lean Six Sigma multiple tools can be used. This section discusses three of these tools, namely the DMAIC cycle, the root-cause analysis and visual management.

The DMAIC cycle is part of Six Sigma and is the most used tool for the implementation of LSS. The cycle is discussed in section 2.3.2. The cycle is the same for the implementation of Six Sigma and LSS.

Another helpful tool for the implementation of LSS are the four M's. The four M's stand for Man, Material, Methods and Machines. LSS states that all four M's should be available in order to ensure the system performs optimal. The absence of one of the four M's can be a cause of waste or variation in the process (Six Sigma Study Guide, 2016a). The four M's are discussed below (Charpentier, 2016):

1. **Man:** stands for the right employee for the right job. The employee must be qualified for the job and must be alert for the continuous improvement of the system.
2. **Material:** indicates the right supply of the right materials needed for the execution of the process.

3. **Methods:** focuses on the right way of working. Here it is important that the work is standardized in order to guarantee the quality of the output and the maximize the flow through the process.

4. **Machines:** stands for all equipment needed for the execution of the process. It is essential that the right equipment and right amount of equipment is available.

In order to identify the 4 M's, the root-cause analysis, also called the fish bone diagram, can be used. In some cases a fifth and sixth M are added: measurement and mother nature (Six Sigma Study Guide, 2016a).

A third LSS tool is visual management of the process. The goal of visual management is to visualize the performance of the system (George, 2003). The performance of the system can be measured by for example the amount of work in progress, the waste and the turnaround times (George, 2003). By visualizing the performance it is easier to prioritize the work and visual management stimulates the communications between employees and managers (George, 2003).

2.5 Theory of Constraints (TOC)

The Theory of Constraints (TOC) is a management philosophy that states that every system is limited by one or more bottlenecks, the so-called constraints (Goldratt, 2013). The TOC sees a process as a chain containing multiple links that are connected to each other (Şimşit, 2014). The weakest link in this chain is the bottleneck of the process as the chain is as strong as the weakest link (Carl Pegels, 2005). This constraint prevents the company from achieving its main objective: making profit (Ehie, 2013). There are different types of constraints, namely physical resources, like equipment, materials, machines, employees and suppliers, or policies (Carl Pegels, 2005). The TOC aims to identify and eliminate the constraints of the process.

By restructuring the system in order to eliminate the constraints, the system will become more efficient. Here not the local performance, but the overall performance of the system is important. The TOC states that the performance of the system, the profit, should be measured by the throughput, the inventory and the operating expenses of the system (Goldratt, 2013). Here the throughput of the system indicates the speed the system makes money as this equals the revenue of the system minus the costs of materials (Izmailov, 2014). The inventory equals the value of all materials that are in the system as work in progress (WIP) or as finished products (Izmailov, 2014). The inventory does not add value to the product and costs money while it does not create revenue yet. Therefore the inventory should be minimized. The third performance indicator is the operational expenses. These are the expenses that are needed to transform inventory into throughput (Izmailov, 2014). The profit of the system, the overall performance, can be found by the throughput minus the operational expenses (van Ede, 2013).

2.5.1 History of the Theory of Constraints

Dr Eliyahu Goldratt introduced the Theory of Constraints in 1984 in his novel 'The Goal' (Goldratt, 2013). Goldratt originally was a physicist and philosopher from Israel. In the 1970s he developed a new method for scheduling based on mathematics (van Ede, 2013). This scheduling method was new as this was the first method that focused on the complete process instead of only parts of it. Goldratt states that the conventional scheduling methods led to sub-optimal solutions causing large inventories' in the process (van Ede, 2013). He called this new scheduling method the Theory of Constraints and introduced this in his novel The Goal' (Goldratt, 2013).

Nowadays the TOC is a widely known method for process improvement and is practiced in all kind of industries, like production, logistics, and supply chain, but also in accounting, sales and health care (Şimşit, 2014). The TOC is applicable is all situations with a chain with interdependencies (van Ede, 2013).

2.5.2 Five Steps of the Theory of Constraints

The TOC provides a process of five steps to identify and eliminate the constraints (Goldratt, 2013). These steps of the TOC are discussed below.

1. **Identify the constraint in the system**
   The first step of the TOC contains the identification of the constraint in the system. As stated before this is the weakest link in the chain (Şimşit, 2014); the link that constrains the main objective of the organization the most (van Ede, 2013, Rand, 2000). In a lot of cases the constraint can be identified by inventory piling up in front of the constraint and a lack of products downstream the constraint (Carl Pegels, 2005).

2. **Exploit the constraint at its maximum**
   After identifying the constraint of the system, the constraint must be exploited at its maximum. This means that the constraint should produce the maximum output by removing the limitations on the constraint (Şimşit, 2014). This way the capacity of the bottleneck is fully used (van Ede, 2013). In order to reach maximum utilization of the constraint, no time on the bottleneck can be wasted, for example operators of a machine cannot have lunch at the same time because the machine must be running nonstop (Rand, 2000).

3. **Subordinate all other process steps**
   The third step of the TOC is to subordinate all other process steps to the constraint of the system (Şimşit, 2014). The other process steps needs to be subordinated as producing at a higher speed than the constraint is useless as the constraint is decisive for the output of the process (Rand, 2000). This means that all process steps should be operating in order to make sure that the constraint is used at full capacity.

   A useful tool for synchronizing the process steps is the drum, buffer, rope technique (Golmohammadi, 2015). Here the constraint functions like a drum; it sets the pace for all steps in the process (van Ede, 2013). The function of the rope is to control the release of material into the process (van Ede, 2013). The rope ensures that the materials are just in time delivered the drum via the upstream process steps. The buffer functions as an input buffer for the constraint (van Ede, 2013). This buffer is necessary to ensure the constraint is constantly operating even when there are delays in the upstream process steps. The size of this buffer is decisive for the amount of work in progress.

   Moreover the throughput of the process is influenced by the batch size (Golmohammadi, 2015). Especially in job-shop system the size of the batches has a significant impact as smaller batches do not only increase the throughput of the system, but also decrease the amount of work in progress (Golmohammadi, 2015).

4. **Elevate the constraint in the system**
   The next step of the TOC is to increase the capacity of the constraint (Şimşit, 2014). In order to elevate the constraint, investments will be required (Rand, 2000). These investments can be in terms of time, effort, money, and so on (Rand, 2000).

5. **Repeat the steps**
   If the constraint is eliminated from the process, the steps need to be repeated as there will always be a weakest link in the chain and thus also a constraint to eliminate (Şimşit, 2014). This makes the TOC a process of continuous improvement (Carl Pegels, 2005, Rand, 2000).

2.5.3 Theory of Constraints and Lean

The new theory that Goldratt introduced, the TOC, is strongly rooted in the Lean philosophy. Both theories are based on improving the throughput or flow by eliminating the limiting factors, the constraint or the waste (Goldratt, 2013). Besides both theories aim to minimize the amount of inventory in the process (Goldratt, 2013). Moreover both theories focus on balancing the throughput or flow through the system in order to minimize the time lost due to the constraint or the waste (van Ede, 2013). In the article 'Standing on the Shoulders of Giants' Goldratt thanks the founders of Lean because this is the foundation of the TOC (Goldratt, 2013). Goldratt states that Lean and the TOC should be used as complementary methods (van Ede, 2013).

2.5.4 Theory of Constraints and Six Sigma

Also Six Sigma and the TOC can be used as complementary methods for the improvement of processes (Ehie, 2013). Here the TOC provides the identification of the constraints and the changes needed in order to eliminate these constraints. Six Sigma then provides the statistical tools for the measurement of the performance and meeting the customer needs. So the both theories complement to each other and together create a great synergy for improving processes (Ehie, 2013).

2.6 Literature Framework for Reducing Turnaround Times

In the previous sections different methods for process improvement are presented. This section combines the findings from these methods into a literature framework. The findings can be combined as the previous analysis showed that the methods and their goals are complementary.

The first method discussed is Business Process Management (BPM). As stated before, BPM creates an environment that is ready for the implementation of methods like Lean, Six Sigma, Lean Six Sigma (LSS) and the Theory of Constraints (TOC). The BPM environment is ideal for implementing these methods as BPM makes sure that the organization is process-focused and thus focuses on the customer satisfaction. Moreover BPM ensures a holistic approach meaning that the complete end-to-end process is taken into account. Both a process-focus and the holistic approach are needed in order to successfully implement Lean, Six Sigma, LSS and the TOC. So, it can be concluded that BPM provides the conditions for the system in order to reduce the turnaround time. Therefore *process focused* and *end-to-end process* are included in the literature framework as conditions for reducing the turnaround time of in house repairs of engine MRO services.

Within the Lean methodology the most important part is to eliminate waste from the process as the waste has a negative influence on the turnaround time. As the literature framework presents the factors that influence the turnaround time of the in house repairs of engine MRO services, the different types of waste must be included. Therefore the factors *Transport*, *Inventory*, *Motion*, *Waiting*, *Overprocessing*, *Overproduction* and *Defects and Rework* are included in the literature framework.

Staff's Unused Knowledge and Experience is not included in the literature framework as Lean also emphasizes the importance of Kaizen, the continuous improvement the system. Continuous improvement is important when pursuing perfection of the system and thus also when reducing turnaround times. When the system is continuously improvement by eliminating more and more waste, the turnaround time of the process keeps reducing. Therefore *continuous improvement* is included into the literature framework as a condition for the reduction of the turnaround time of in house repair of engine MRO services. The eighth type of waste, *Staff's Unused Knowledge and Experience*, is covered within continuous improvement and is therefore not included in the literature framework as a factor of influence.

The third method presented in the literature review is Six Sigma. As stated before, Six Sigma aims for maximizing the quality of the output by reducing the variation in the system. In order to do so, Six Sigma emphasizes the importance of statistical tools for the measurement of the performance. Six Sigma states that all decisions should be based on facts and not on subjective emotions or experiences. This lesson from Six Sigma is taken into account measuring the influence of the factors in the literature framework.

Six Sigma also underlines the importance of fulfilling the needs and requirements of the customer. Insight into the customer value of the product is essential as a reduction of turnaround time is only interesting as it adds value for the customer. Therefore *insight into the customer value* is included in the literature framework as a condition.

As LSS is an integration of Lean and Six Sigma, LSS confirms the importance of the factors and conditions found in Lean and Six Sigma. In addition, LSS highlights that all four M's should be available om order ensure the system performs optimal. The four M's consist of Man, Material, Methods and Machines. The absence of one of the four M's can cause waste or variation in the process and thus influences the turnaround time. Therefore the *availability of man*, the *availability of material*, the *availability of methods* and the *availability of machines* are added to the literature framework.

The last method discussed in the literature review is the Theory of Constraints (TOC). The TOC emphasizes that constraints must be exploited at maximum capacity. A constraint can be found in different types of resources like machines, materials, man and methods. Therefore this lesson from the TOC is already covered in the factors the *availability of man*, the *availability of material*, the *availability of methods* and the *availability of machines*.

Moreover the TOC underlines the influence of the batch size to the turnaround time of the process. A smaller batch size increases the throughput of the system and thus reduces the turnaround time. Therefore the *batch size* is included as a factor in the literature framework.

All conditions and factors of influence found in literature can be summarized into a literature framework, see figure 2.8. The top of the framework consists of the conditions for reducing the turnaround time of in house repairs of engine MRO services. Without fulfilling these conditions, solutions will always be sub-optimal. If these conditions are fulfilled, there are multiple factors influencing the turnaround time. These factors can be found in the lower part of the framework. On the left the factors on the different types of waste are presented. The right side of the framework contains the factors on assets and resources. The factors in this framework are a combination of the Lean, Six Sigma, LSS and TOC methodologies.

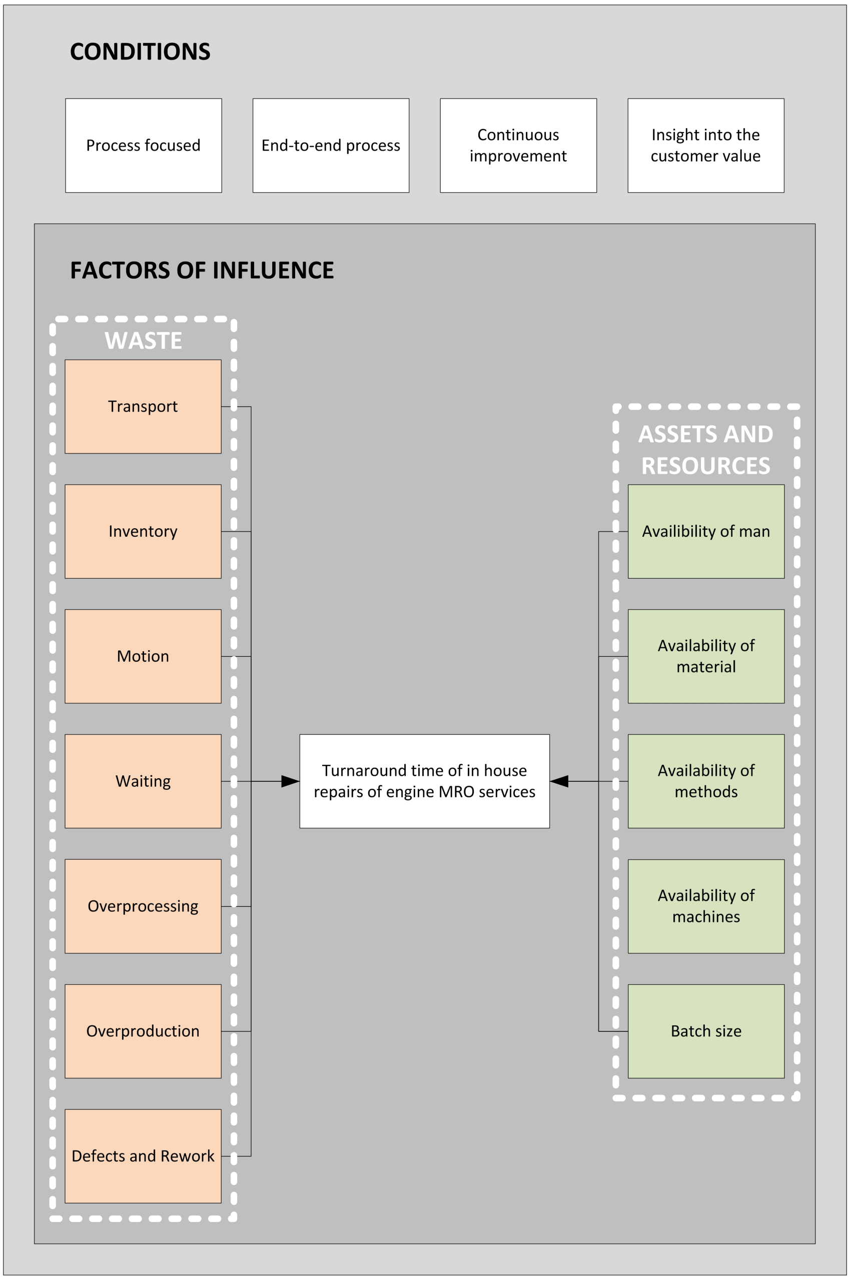


FIGURE 2.8: Literature Framework: Conditions and Factors of Influence

2.7 Conclusions on Methods for Process Improvement

Research question 1: What are currently known methods for process improvement?

Business Process Management, Lean, Six Sigma, Lean Six Sigma and the Theory of Constraints are widely known methods for process improvement. These methods can be combined as the methods and their goals are complementary.

Research question 2: What factors influence the turnaround time of in house repairs of engine MRO services according to these methods?

The methods all highlight multiple factors influencing the turnaround time. All factors and the associated conditions can be summarized in a literature framework. This literature framework can be found in figure 2.8.

The literature framework functions as a starting point for the case study at KLM E&M Engine Services. The framework will be tested and validated by the findings of the case study. The case study will show which of the factors in the literature framework influence the turnaround time of the in house repairs of engine MRO services the most.

Chapter 3

Case Study at KLM E&M

This chapter presents the current state of the system, see figure 3.1. First the methods used for the case study are discussed in section 3.1. Next the system analysis is presented in section 3.2. The system analysis zooms in from a company level to a specific workstation level. Next, the results of the data analysis are presented in section 3.3. Moreover, this chapter presents the observations in the engine shop in section 3.4. Lastly, this chapter ends with the conclusions of the case study at KLM E&M.

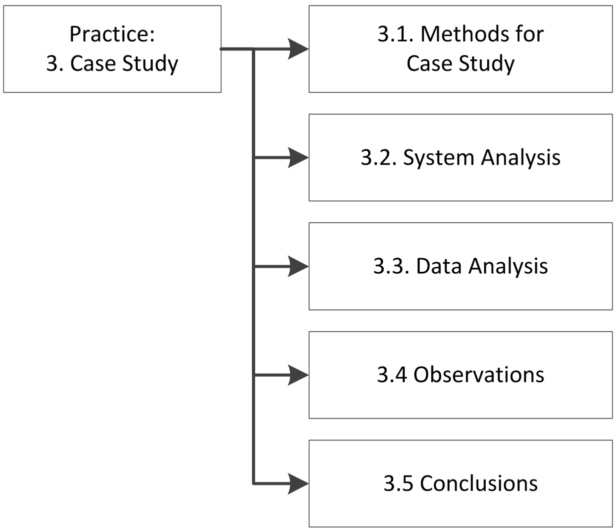


FIGURE 3.1: Chapter Buildup Case Study

The goal of the case study is to determine the current state of the system and to identify factors influencing the turnaround time of the in house repairs. These factors are identified by analyzing the different waiting times in the system. The factors found will be combined with the factors from the literature framework in chapter 4.

This chapter thus answers research question 3, *'how is the current process of the in house repairs at Engine Services structured?'*, and research question 4, *'what factors influence the turnaround time of in house repairs of engine MRO services according to the case study?'*.

3.1 Methods Used for Case Study Analysis

This section discusses the methods and tools used during the system analysis and the data analysis. The functioning of all tools is elaborated below.

3.1.1 Methods System Analysis

- **Connected Business Balance Score Card**
  First, the Connected Business Balance Score Card (CBBSC) is used. The CBBSC is a quantitative tool used by KLM E&M in order to monitor the performance of the processes. The score card contains of different levels. The first level presents all processes of KLM E&M and is the top level of the CBBSC. Next, there is a level that presents the performance of the Engine Services. Here the performance of the different activities in the shop is presented. The next level in the CBBSC zooms in on the performance of the in house repairs at the Engine Services. At all levels the performance is quantified and compared with the customer agreements.

- **Flowchart**
  A flowchart is a diagram that depicts the flow of the process. The flowchart presents the different events and decisions in the process (NLDIT, 2016). The events or actions are presented by a rectangle. The decisions are represented with a diamond (NLDIT, 2016). The flowchart is an useful tool to understand the process and to make the process transparent for all parties. The simplicity of the concept of a flowchart ensures that all parties can use and understand the diagram (LeanInfo, 2016b).

- **SIPOC Model**
  The Supplier, Input, Process, Output, Customer (SIPOC) model is a tool that is part of the Lean Six Sigma methodology (Lean Six Sigma Tools, 2016). This tool helps to map the process on a high abstraction level. Next to the process the model also gives insight in the suppliers, the input, the output ans the customers. The supplier delivers the needed resources to the process. These resources are the inputs of the process. This can be materials, information or capabilities. The process is the chain of steps that all contribute to the completion of the process. The outputs of the process are the results of the inputs after being adjusted by the process. Finally, the customer receives the output of the process. This way the SIPOC model gives a complete overview of the system. (Lean Six Sigma Tools, 2016)

- **Value Stream Map (VSM)**
  The Value Stream Map (VSM) is a Lean Six Sigma tool. The VSM gives a schematic overview of a process (LeanENT, 2016). The VSM does not only present the flow of materials through the process, but also takes information flows into account (LeanENT, 2016). A VSM is an useful tool when reducing turnaround times as the VSM presents both the turnaround times and the process times (LeanInfo, 2016c). Therefore this tool is ideal for tracing the waste in the process and designing the future state of the process.

- **Kano Model**
  The Kano model is also part of the Lean Six Sigma methodology. This tool is helpful for prioritizing the customers needs (Six Sigma Material, 2016). The Kano model combines

the extent the customers needs are delivered with the satisfaction of the customer. It is important to note that the customer needs and their priorities change over time (I Six Sigma, 2016). Here the Kano model distinguishes three categories of customer needs, see figure 3.2 (I Six Sigma, 2016).

– The first category are the dis-satisfiers. The dis-satisfiers are the must-be needs of the customer and are the basic requirements of the product. If the dis-satisfiers are delivered, this will not lead to customer satisfaction. Although not delivering these dis-satisfiers will lead customer dissatisfaction.
– The satisfiers are the second category within the Kano model. These are customer needs that directly affect the customer satisfaction. The more these needs are delivered, the more the customer will be satisfied with the product. At the same time, when these customer needs are not delivered, the customer will be dissatisfied.
– The third category consists of the delighters. These are customer needs that are not needed for the customer to be satisfied, but these needs can make the customer extra satisfied. These are customer needs that are surprising the customer; the customer gets delighted. These delighters differentiate the product from the products of competitors. The more delighters are delivered, the more the customer is satisfied, but the absence of delighters does not have a negative impact on the customer satisfaction.

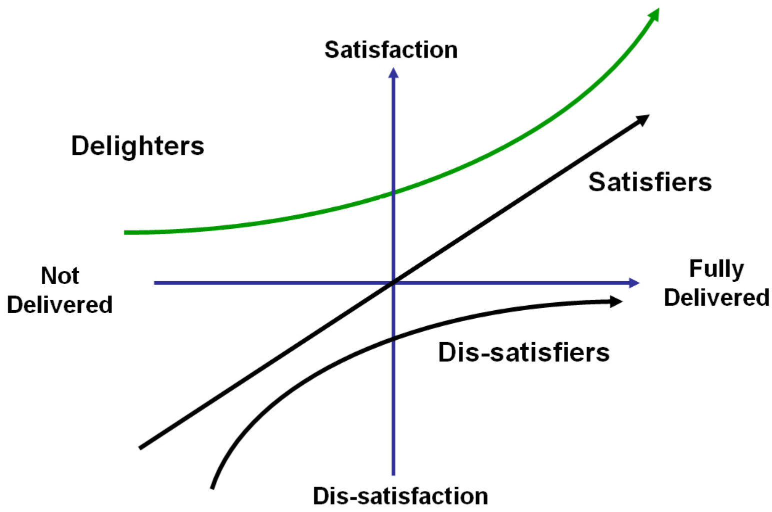


FIGURE 3.2: Kano Model

3.1.2 Methods Data Analysis

- **Pivot table**
  A pivot table is a widely used tool when analyzing spreadsheets in software like Microsoft Excel. The pivot table helps to summarize, order, group and analyze data from a spreadsheet into a table. This way, large amounts of data are translated into a clearly ordered overview (MacDonald, 2004). It is not necessary to use pivot tables for the analysis of data, because it is possible to create the same tables by writing the formulas by hand. However, using pivot tables saves a lot of time (MacDonald, 2004).

- **Normal Probability Plot**
  A Normal Probability Plot (NPP) is a graph for assessing normality assumptions (The Analysis Factor, 2016). The NPP plots the data of the data set on the x-axis against a normal distribution on the y-axis (Six Sigma Study Guide, 2016b). A straight line indicates that the data is normal distributed (Six Sigma Study Guide, 2016b). Deviations from this straight line indicate that the data is not normal distributed. Moreover the NPP presents the variation of the data points. A large variation of the data points indicates an unpredictable process. Therefore, the steepness of the line indicates the predictability of the process. Next, the NPP also shows the mean of the data set.

- **Pareto Distribution**
  The Pareto distribution is a helpful tool for the identification of the main causes of the problem. The Pareto distribution is based on the 80-20 rule. This rule states that 80% of the problems is caused by 20% of the causes (Koch, 2008). This 20% of the causes are the main causes that needs to be eliminated. These main causes can be found using the Pareto distribution. The Pareto distribution is a bar chart that shows the frequency of all causes in descending order (LeanInfo, 2016a). Moreover the Pareto distribution shows the cumulative amount of causes in percentage of the total amount of the causes (LeanInfo, 2016a). Together these graphs form the Pareto distribution and show what causes are the main causes of the problem.

3.2 System Analysis

This section presents the analysis of the current state of the system. The analysis zooms in from a company level to a specific workstation level in order to provide a complete overview of the system and its context. This is useful for the understanding of the system on a workstation level, but also later on when designing alternatives for improving the system.

3.2.1 KLM Engineering and Maintenance

KLM E&M offers maintenance, repair and overhaul (MRO) services in four categories, namely (KLM E&M, 2015):

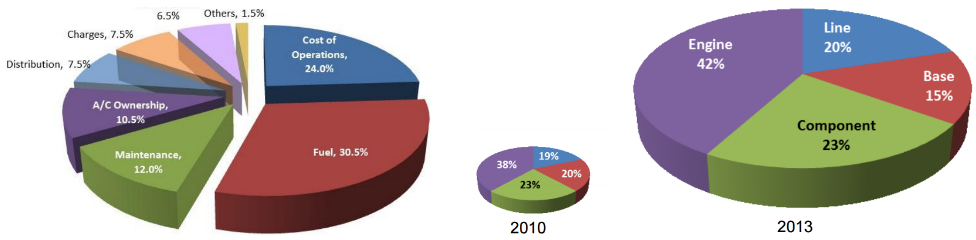
- **Line maintenance**
  The part 145 regulation defines line maintenance as 'any maintenance that is carried out before flight to ensure that the aircraft is fit for the intended flight' (EASA, 2012). In practice, this means that line maintenance covers all maintenance tasks that can be performed under open skies (Airline Basics, 2014) . These are the maintenance tasks that are needed on a frequent basis, for example the daily and weekly checks. Besides, also ad-hoc line maintenance can be provided.

- **Base maintenance**
  Base maintenance is defined by the part 145 regulation as maintenance tasks falling outside the criteria for line maintenance (EASA, 2012). In practice, this covers all maintenance tasks that are performed in the hangars (Airline Basics, 2014). Base maintenance mainly consists of the heavy checks like the C check and the D check.

- **Components services**
  At the components services (CS) aircraft components are repaired. When customers deliver a component for repair, there are two options. Firstly, customers get their own component back after repair. Secondly, customers receive a spare component from the component pool. This way the customer does not have to wait for the repair. The broken component is included in the component pool after repair. (AFI KLM E&M, 2016a)

- **Engine services**
  Engine Services (ES) is responsible for the repair of the engines. There are two options when a customer delivers an engine. First, customers want their own engine back after the repair. Second, customers receive a spare engine from the engine pool. This way the customer does not have to wait for the repair. The broken engine is included in the engine pool after repair. (AFI KLM E&M, 2016b)

Figure 3.3a shows the breakdown of the operational costs of airlines. It can be seen that the maintenance costs of airlines add up to 12% of the total operational costs (IATA, 2013). These maintenance costs can be divided into the four maintenance categories, see figure 3.3b. It can be seen that the largest share of the maintenance costs of airlines is spent on engine costs, namely 42% (IATA, 2014). Moreover is can be seen that the share of the engine costs has been growing over the last three years (IATA, 2014). This means that the costs for the engines services are around 5% of the total operational costs.



(A) Operational Costs Breakdown 2011 (B) Direct Maintenance Costs 2010 - 2013

FIGURE 3.3: Costs Breakdown of (A) Operational Costs 2011 (IATA, 2013) and (B) Direct Maintenance Costs 2010 - 2013 (IATA, 2014)

The performance of the maintenance activities of KLM E&M is depicted in the Connected Business Balance Score Card (CBBSC). The top level of this score card gives an overview of all activities of KLM E&M, figure 3.4. The middle part of the score card shows the main processes. The first process is named aircraft and this consists of line and base maintenance. The second and third process correspond respectively to engine services and component services. The fourth process is named engineering and focuses on maintaining configuration management and providing designs. On the left side of the processes the customers of KLM E&M are presented. The customers can be divided into three groups: KLM, members of the KLM Air France group and other customers. The right side of the score card shows the deliverables of the processes: continuing of the airworthiness and satisfaction of the customers and other stakeholders. At the upper side and the bottom side of the score card the issues that need to be managed and provided are presented.

This research focuses on the second process of the score card: engine maintenance.

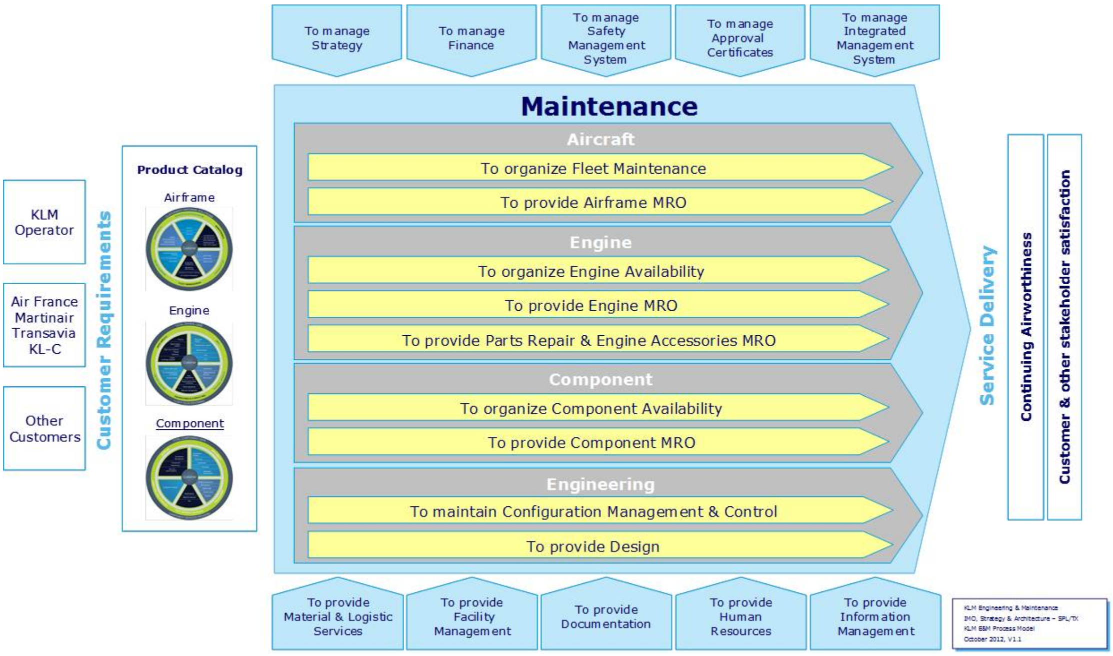


FIGURE 3.4: Connected Business Balance Score Card (CBBSC)

3.2.2 Engine MRO Market

At the moment the size of the global aircraft engine MRO market is around 27.9 billion U.S. dollars (Statista, 2016). The aircraft engine MRO market is expected to be a growing market with an annual growth rate of 5 to 6 percent (Bezuijen, 2015). This will lead to a market size of 37.1 billion U.S. dollars in 2020 and of 46.3 billion U.S. dollars in 2025 (Statista, 2016). The fastest growing market is the Asian market, especially the Chinese market (Bezuijen, 2015).

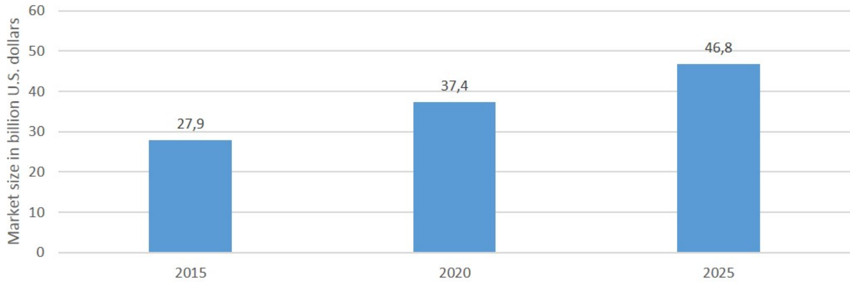


FIGURE 3.5: Global aircraft engine MRO market size from 2015 to 2025 (in billion U.S. dollars)

There are three types of companies offering engine MRO services:

- Airline related shops, like KLM E&M en Lufthansa Technik.
- Original Equipment Manufacturers (OEM), like General Electrics (GE).
- Independent shops, like MTU Aero Engines and SR Technics.

The main competitors of KLM are two independent shops, namely MTU Aero Engines (MTU) and SR Technics (SRT) (Bezuijen, 2015). MTU Aero Engines has competing engine shops in Hannover, Germany (MTU Aero Engines, 2016a), and Zhuhai, China (MTU Aero Engines, 2016b). SR Technics is located at the airport of Zurich, Switzerland (SR Technics, 2016). These competitors are offering MRO services for one or more of the engine types that KLM E&M is serving as well (MTU Aero Engines, 2016a,b, SR Technics, 2016). They are offering the same quality while using the same materials from General Electrics (GE) and paying the same price per hour for their employees (Bezuijen, 2015). Yet they can offer this faster and cheaper to their customers than KLM E&M. This difference is mainly caused by the fact that KLM E&M outsources more of the work than MTU and SRT and this costs extra time and money (Bezuijen, 2015).

Despite the fact that KLM E&M is not the cheapest and the fastest, there are multiple Unique Selling Points (USPs) that make KLM E&M an interesting MRO provider for her customers (Bezuijen, 2015). First, KLM E&M is an airline related shop which means that KLM herself makes use of the engines. This makes that KLM has a better understanding of the behavior of the engines on wing than shops that are not airline related. Due to this knowledge KLM E&M is able to predict the needed maintenance activities. Besides, KLM E&M offers air frame facilities which may be interesting in the case of an engine swap. Moreover KLM E&M offers quick on wing support because KLM E&M is part of an airline and this causes easy access to tickets for the engineers and to cargo space for a spare engine or engine parts. Lastly, KLM E&M is an interesting MRO provider because KLM has her own training center. It is not unusual that KLM E&M offers her customers a package deal: KLM E&M is allowed to repair the engine and the customers get a training for their employees for free. During this training the employees learn more about their engines and the associated maintenance.

3.2.3 Engine Services

As stated before, Engine Services (ES) is responsible for the repair of the engines. This responsibility falls apart in three sub-tasks. The processes that are part of these tasks are depicted in figure 3.6 and described below.

- **Organize engine availability**
  This first task focuses on the inventory of serviceable spare engines. After receiving a customer request for a spare engine, a serviceable engine is picked from the warehouse. This serviceable engine is shipped to the customer and exchanged for the unserviceable engine. The unserviceable engine is shipped to the warehouse where the engine is issued. Next the unserviceable engine is transported to the engine shop where the engine is repaired. After the repair the engine is stored in the warehouse and can again be used as a spare engine in the engine pool.
- **Provide engine MRO**
  The engine MRO task includes the repair of a complete engine. This is called a full shop visit (SV). Here the unserviceable engine is shipped to the warehouse where it is issued. Next the engine is transported to the engine shop. Here the workscope is determined and the engine is disassembled, repaired, assembled and tested. After the repair the engine is serviceable and can be delivered to the customer.
- **Provide parts repair and engine accessories MRO**
  The third task is very similar to the engine MRO task, but here not whole engines but

only engine parts and engine accessories are repaired. The process is the same, the unserviceable part is delivered to the warehouse where it is issued. Then the part is transported to the engine shop. At the engine shop the workscope is determined. The parts are, when necessary, disassembled after which the repair takes place and the parts are assembled and tested. The serviceable part is then delivered to the customer.

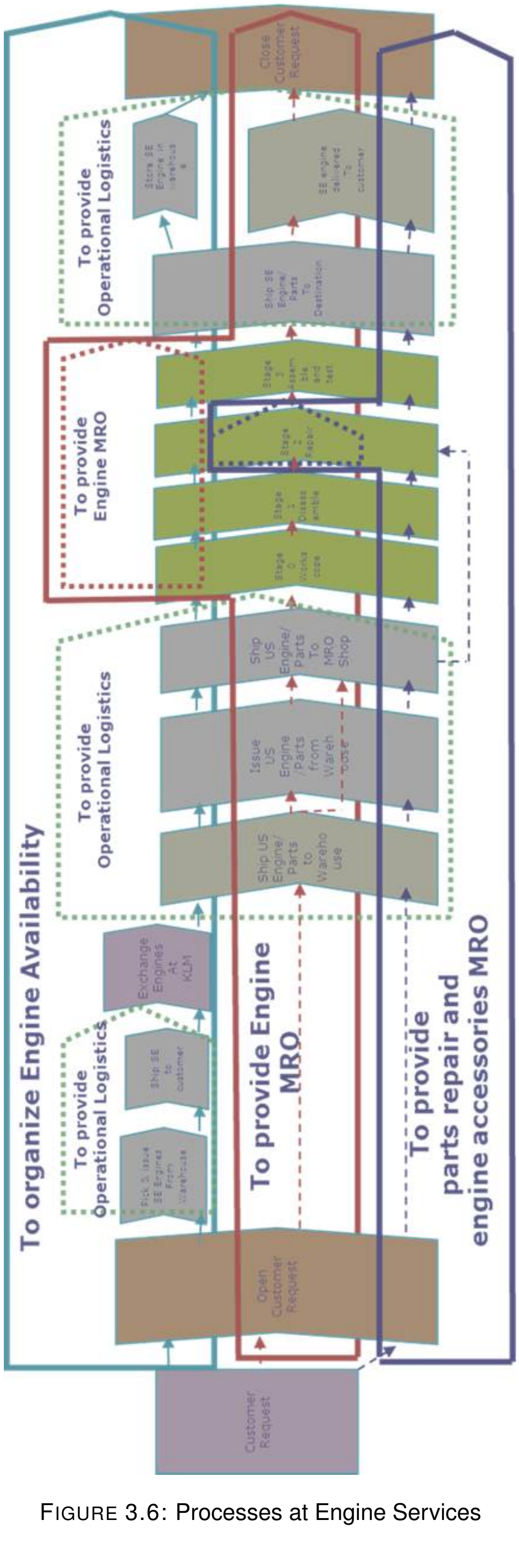


FIGURE 3.6: Processes at Engine Services

The performance of the Engine Services is measured using a score card, see figure 3.7. In the score card all three tasks of ES are presented including the key performance indicators (KPI).

As can be seen in the score card, in 2015 until August, the availability of the engines is performing well. The number of serviceable spare engines is high enough. Next it can be seen that there is no information available on the parts repair task. There is also no information available on the costs efficiency for all three tasks. The performance of the engine MRO task is not high enough. In 2015, until August, only 43% of the engines were delivered on time by the Engine Services of KLM E&M. In the other cases the engine maintenance took more time than agreed with the customer. Moreover the EGT margin, a measure for the quality of the engine, see section 3.2.4.2, as agreed with the customers is achieved in only 50% of the engines. These violations with the customer agreements lead to considerable fines for KLM E&M, because KLM E&M does not comply with the agreed TAT and EGT margin. Next, due to dissatisfied customers, this causes that customers choose another service provider for the maintenance of their engines and KLM E&M thus loses her customers. Besides the score card shows that the productivity of the employees is only 54%. Only the testcell results are doing good as 100% of the engines are approved by the testcell.

As ES at the moment does not meet the customer agreements for engine MRO, this research focuses on improving the processes of engine MRO. The biggest problems are on the TAT and the EGT margin as these are performance indicators KLM E&M agreed on with her customers.

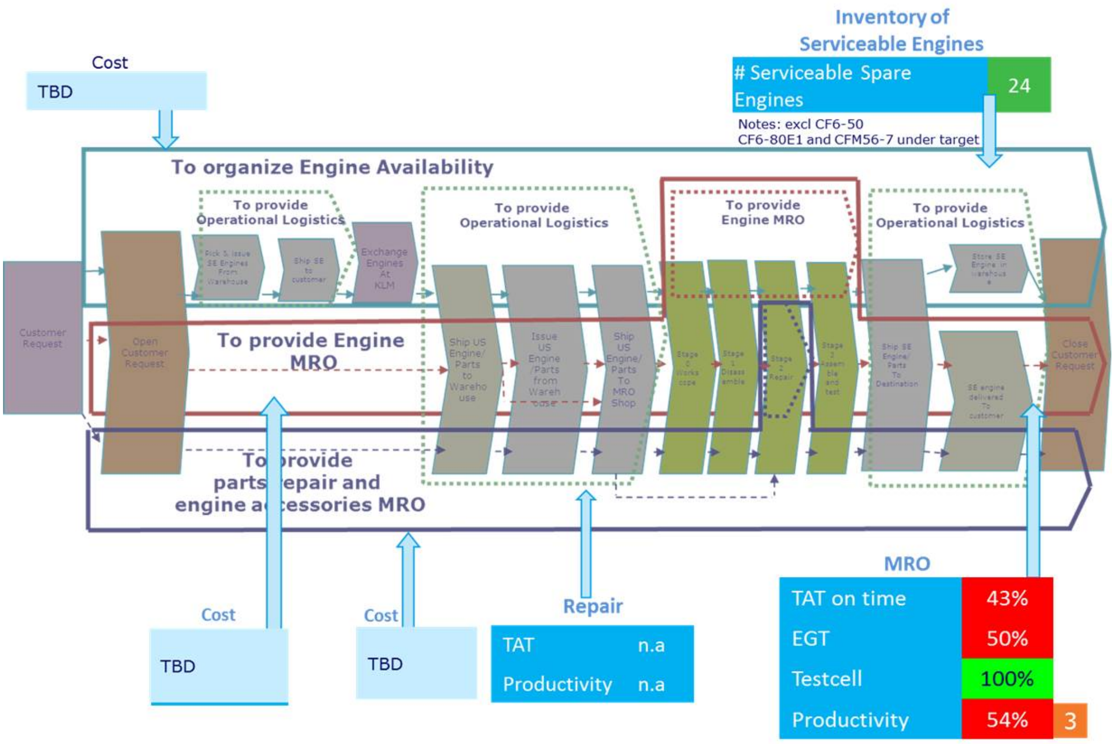


FIGURE 3.7: Score Card Engine Services

3.2.4 Engine MRO Process

As stated before, the engine MRO task covers the repair of a complete engine. This is called a full shop visit (SV). First the unserviceable engine is shipped to the warehouse where it is issued. Next the engine is transported to the engine shop. Here the workscope is determined and the engine is disassembled, repaired, assembled and tested. After the repair the engine is serviceable and can be delivered to the customer.

During the process the customer value is only added when the engine is in the engine shop. Moreover KLM E&M only sets customer agreements on performance indicators based on the processes within the shop. Therefore this research zooms in on the processes within the shop. These processes are called stage 0, stage 1, stage 2 and stage 3.

Each stage covers another part of the repair process. As can be seen in figure 3.8, the repair process starts with determining the workscope, stage 0. Next, the engine is disassembled during stage 1 and this takes around 12 days. Then the actual repair takes place in stage 2. There are 35 days available for this stage. During stage 3 the engine is assembled and tested. This takes around 13 days. (Rippen, 2008)

FIGURE 3.8: Engine MRO Process

The processes within the stages 0 to 3 are discussed in more depth below (Rippen, 2008).

- **Stage 0 - Workscope:** in this stage the workscope is determined. This stage starts with a completeness check (CC) to make sure the engine is complete at the start of the maintenance activities. In order to determine the workscope the incoming check (IC) is performed. This check consists of multiple inspections on both the outside and the inside of the engine. Based on all inspections the Bill of Work (BoW) is compiled.
- **Stage 1 - Disassemble:** during this stage the engine is disassembled, the different parts are inspected and based on this inspection the route of each part through the process is determined. First the engine is disassembled into several modules. After an inspection of the modules, the modules are disassembled into multiple assemblies. These assemblies are also inspected. Based on the findings of the inspections, it is possible to make some changes in the BoW. Then all parts are cleaned and send to the Parts & Disposition (P&D) department. P&D checks the parts following the Engine Manuals of the engine manufacturer. Based on these findings P&D decides whether the parts are serviceable or not. When a part is serviceable, the part goes to the Assembly Preparation (aprep) department. When a part is unserviceable, there are two options. If a part can be fixed, the part is sent to the repair department. If a part cannot be fixed, it is sent to salvation.
- **Stage 2 - Repair:** this stage consists of the actual repair of the engine parts. Within this repair stage, there are two options: the part is repaired by ES, so in house, or the part is

repaired by an external repair shop. Besides, this stage consists of the order process of new parts. These new parts will replace the parts that were sent to salvation in stage 1. The new parts and the repaired parts are sent to aprep.

- **Stage 3 - Assemble and Test:** this stage starts with the delivery of all engine parts from aprep. First, it is checked if all parts are delivered, the completeness check (CC). When the delivery is complete, the assemblies are assembled. Afterwards the modules are compiled and finally the engine is assembled. Next, the quality of the engine is tested in the test cell. After the test, the engine returns to the engine shop for a final inspection. Finally, if the test results and the final inspection are OK, the engine is released and transported to the engine storage.

As stated before, the repair stage takes more than half of the TAT available. When reducing the TAT of the complete MRO process, the largest reduction of TAT should thus be realized at the repair stage. This research therefore focuses on the repair stage, stage 2. Within in stage 2, most of the parts are being repaired in house. Moreover KLM E&M has more influence on the in house repairs than on the outsourced repairs. Therefore this research considers the in house repairs within the engine shop.

3.2.4.1 Engine Types

At the KLM E&M Engine Services different types of engines are repaired. Only three types of engines are repaired as a full shop visit, namely the CFM56-7B, CF6-80C2 and CF6-80E1 engines.

The CFM56-7B engine is used for the Boeing Next-Generation single-aisle airliner (737-600/-700/-800/-900/-900ER/ BBJ). The combination of the CFM56-7B engine and the 737 aircraft is the most popular combination in commercial aviation as there are 8,400 of these combinations in service. The CFM56-7B engine is very popular because the high reliability, the environmental friendliness, the low cost of ownership and the excellent customer support. (CFM, 2016)

The CF6-80C2 engine is used for widebody aircraft. At the moment the engine is certified for 14 different models (A300-600/-600R/-600F/-600ST, A310-200/-300, 747-200/-300/-400, 767-200ER/-300/-300ER/-400ER, MD-11). This engine type is popular because it has the lowest fuel consumption of the commercial engines in its class. Moreover this engine offer the highest reliability and longest lifetime in its class. (General Electrics, 2016a)

The CF6-80E1 engine is specifically designed for the A330 aircraft. The engine has the lowest weight, the lowest fuel burn and proven maintenance-free operation. This way, the utilization of the A330 is maximized: more people can be transported over longer distances, for less money and without compromising on the reliability of the product. (General Electrics, 2016b)

All three engines are high-bypass turbofan engines. This means that a large share of the air that flows through the engine, at least 80%, flows through the bypass duct. The functioning of a turbofan engine is illustrated in figure 3.9.

As can be seen in figure 3.9, the engine consists of multiple parts. Each part has its own task within the engine. In order to make an aircraft move forward, we need a pushing force, *thrust*. This is based on Newton's law: 'for every action there is an equal and opposite reaction'. The thrust is generated by the acceleration of the air flowing through the engine. Most of the thrust is provided by the secondary airflow. This airflow only passes through the fan at the front of the engine where it is accelerated. The secondary airflow bypasses the core of the engine to be ejected directly into exhaust stream at the back of the engine. This secondary flow covers at least 80% of the total airflow through the engine and provides at least 80% of the engines thrust. (Safran, 2015)

Next to the secondary airflow there is the primary airflow which passes through the core of the engine. The primary airflow covers around 20% of the total airflow and is needed in order to drive the engine. The primary airflow also enters the engine through the fan. The fan functions like a propeller as it accelerates the air into the engine. After the fan, the airflow enters the low- and high-pressure compressors. Here the air is compressed and can reach temperatures of 450 degrees centigrade. The compressor generates the optimal conditions of the airflow for combustion. When the air is compressed, the airflow enters the combustion chamber, the combustor. In the combustor the airflow is mixed with fuel and burnt. By burning the mixture of air and fuel, the temperature rises and can reach 1700 degrees centigrade. Next the airflow enters the high- and low-pressure turbines. Here the pressure of the hot gas is reduced as it passes through the turbines and makes the turbines spin. The spinning of the turbines drives the fan and the two compressors at the front of the engine as their shafts in the core of the engine are linked. The airflow is then ejected through the primary duct and the nozzle. Here the primary airflow joins the secondary airflow. Together the primary flow and the secondary flow make sure that the aircraft moves forward. The primary flow drives the engine and the secondary flow provides most of the thrust. (Safran, 2015)

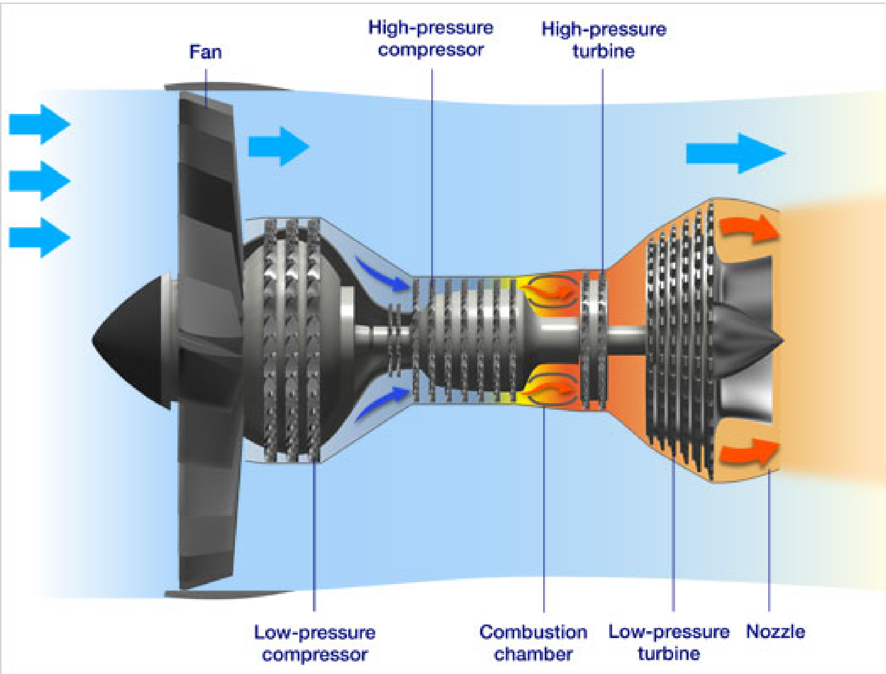


FIGURE 3.9: Turbofan Engine

3.2.4.2 Customers and Customer Agreements

KLM E&M does not only provide maintenance for aircraft of the KLM Air France Group, but also for external customers. Besides these external customers, KLM E&M also provides maintenance for the so-called GE offload. These are engines are maintained by General Electrics (GE), but when they do not have enough capacity, they outsource engines to KLM E&M. These engines are called the GE offload. As can be seen in figure 3.10, only 34% of the maintained engines are part of the Air France KLM engines pool. The GE offload engines cover 30% of the maintained engines. The engines of external customers add up to 37%, the largest share, of the work. The category external customers consists of 32 different airlines, like Finn-Air, Kenya Airways and Shandong Airlines.

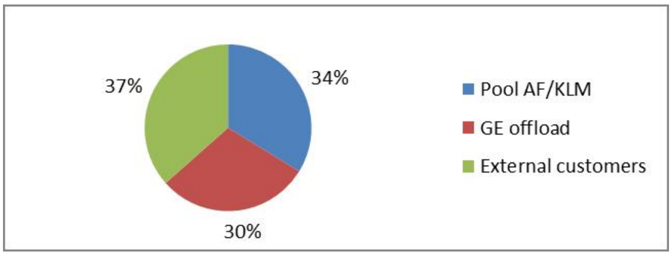


FIGURE 3.10: Distribution of the Customers per Customer Type

All customers set agreements with KLM E&M for the turnaround time (TAT) of the repair and for the quality of the engine after repair.

The TAT of a repair is measured in days and equals the difference between the moment that an unserviceable engine including all associated paperwork enters the engine shop and the moment that the engine is serviceable again and is ready for delivery to the customer. Most of the customers agree on a TAT of 60 days.

The quality of the engine is measured using the exhaust gas temperature (EGT) margin. The exhaust gas temperature is the temperature of the gases that are being exhausted from the back of the engine (CFM, 2006). The EGT margin is a measure of the health of the engine (General Electrics, 2016c). As can be seen in figure 3.11, the EGT margin equals the difference between the maximum allowable EGT in the ISA conditions, the EGT redline, and the maximum EGT during takeoff, the corner point temperature (Ackert, S, 2011). The EGT margin is highest when the engine is new. Due to the aging of the engines, wear and deterioration affect the performance of the engine and the EGT during takeoff increases (Ackert, S, 2011). This causes the EGT margin to decrease. By cleaning and maintaining the engine, the maximum EGT during takeoff can be decreased and thus the EGT margin will increase. Most of the customers agree on an EGT margin of 40 degrees centigrade.

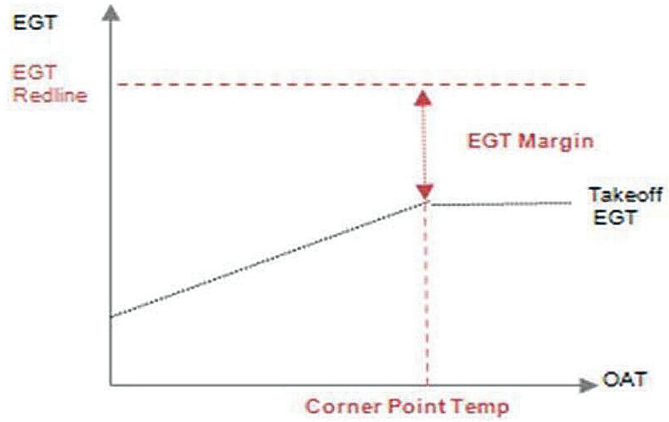


FIGURE 3.11: EGT Margin

3.2.4.3 Plans for the Future

This research aims to improve the performance of the engine MRO processes. Here it is important to know about other improvement projects and plans for the future within the engine shop. At the moment black belts are working on several projects within the engine shop. The primarily goal of these projects is to make sure KLM E&M complies with the customer agreements in terms of TAT and quality. Besides meeting the customer agreements, ES has more ambitious plans for the future. ES wants to become a center of excellence and wants to deliver engines in less than the current TAT of 60 days. Two projects focus on these ambitions for the future:

- **From a Vision to a Plan:** this project focuses on the repair part of ES. The goal is becoming a center of excellence, this means being better, faster and cheaper than the competitors. The goal is to be 10 percent cheaper in January 2017 and to perform the second stage of engine maintenance, the actual repair, for all parts in 21 days, now 28 days. In order to reach this goal, the operational plan consists of two tracks:
  - Operational Plan: this plan aims for 'getting the basics right', i.e. comply with the customer agreements. Therefore it is important to reduce the TAT and to improve the quality of the engines. The goal was to comply with the customer agreements at the end of October 2015, but this has not been successful.
  - Transformation Plan: this part of the project focuses on becoming a center of excellence. This means that the TAT of the repair stage has to be reduced to 21 days and that the productivity has to increase with 10 percent. The goal is to be a center of excellence at the end of May 2016.
- **TAT45:** this second project focuses on reducing the TAT of the whole MRO process, so including phase 0, 1 and 3. First, the project will only focus on reducing the TAT for the CFM engines, but later on it is possible to widen the scope and to include other types of engines. At the moment, the process is identified and a Value Stream Map (VSM) chart is created. This VSM will be used to identify the bottlenecks in the process that needs to be fixed. There is no deadline defined for reaching TAT45.

3.2.5 In House Repairs

The in house repairs at the KLM E&M Engine Services are performed at twelve different workstations, namely accessories electric, seal, accessories mechanic, engineering HW & ECQ, combustor, fanblades, plasma & welding 1, plasma & welding 2, airfoils repairs 1, airfoils repairs 2, airfoils nozzles and plating. Each workstation has its own function within the repair of the engine. At only ten of these workstation in house repairs are performed. The repairs at the other two workstations, namely airfoils 1 and airfoils 2, are outsourced to other MRO providers or the parts are replaced because the part cannot be repaired.

As the names of the workstation suggest, there are two types of workstations. First there are workstations that are technology-driven. These workstations perform repair within a specific technology, for example the plasma and welding workstations. Next there are product-driven workstation. These workstations focus on the repairs of a specific part of the engine, like the combustor and fanblades workstations.

Figure 3.12 provides an overview of the performance of parts repair of the workstations. This figure shows that most of the workstations have an average performance over 90%, on average 94%. However, two workstations are obviously underperforming. The combustor and the fanblades workstations deliver their parts most often after TAT in percentage terms. Moreover these workstations deliver assemblies that consists of multiple parts. The information in figure 3.12 is based on parts repair. So when looking at a complete combustor or a complete set of fanblades, consisting of multiple parts, the performance of the workstation would even be lower. Therefore these two workstations seem to be the bottlenecks of the process.

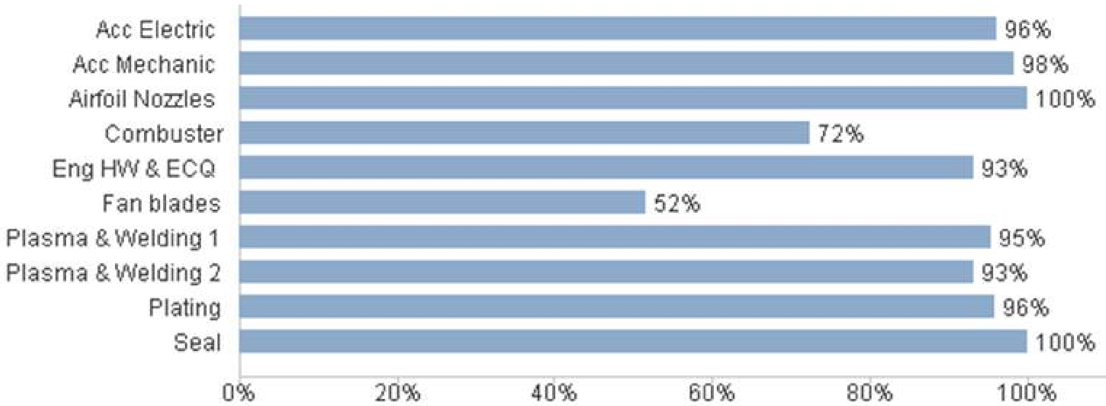


FIGURE 3.12: % of parts delivered on time in 2015 for the different workstations

At the moment there is ongoing research into combustor workstation. This research focuses on the analysis and the improvement of the repair process of the combustor. The research states that 72% of the combustor parts is delivered on time and therefore only 14% of the complete combustors leaves the workstation in time. The project shows that the largest share, around 88%, of the TAT is waiting time. As there is ongoing research into the combustor workstation, this research considers the fanblades workstation.

3.2.6 Fanblades Workstation

At the fanblades workstation the fanblades of the engines are repaired. The fanblades are the curved blades in the fan at the front of the engine, see figure 3.13. Due to their shape, see figure 3.14, these blades are able to accelerate the air into the engine like a propeller.

FIGURE 3.13: Disassembly of the Fanblades

FIGURE 3.14: Fanblades

Figure 3.15 gives a complete overview of all activities at the workstation. As can be seen in the figure, there are two main routes through the workstation. Firstly, the route of the CFM56-7B engines on the upper side of the figure. Secondly, the route of the CF6-80C2 and CF6-80E1 engines on the bottom side of the figure.

The route of the CFM56-7B engines is a short route as the fanblades are directly outsourced to Propulsion Technologies International (PTI) in Florida, USA. PTI is a joint venture of GE Aviation and Snecma. The fanblades are outsourced because of technical reasons. KLM E&M is not certified to repair of the fanblades of CFM56-7B engines. Moreover KLM E&M does not have the needed tools and skills to perform these repairs. After the external repair, the fanblades return to the fanblades workstation. Here the fanblades are being inspected. If the results of the inspection are positive, the fanblades are transported to aprep. At aprep the fanblades are stored until the engine is assembled. If the results of the inspection are negative the fanblades are returned to PTI, but this has not happened in the past year.

The route of the CF6-80C2 and CF6-80E1 engines is a more complex route. Within this route, there are two options:

1. Firstly, the engine is not completely disassembled and the blades are inspected while they are on the engine. If the results of the inspection are positive, the fanblades remain on the engine. If the results of the inspection are negative, the unserviceable fanblades are removed from the engine and a heavy maintenance route is started. The heavy maintenance route is performed at the fanblades workstation and is able to fix minor damages. This route ends with a final check. If the results of the check are positive the fanblades are installed to the engine. If the results of the check are negative, a new route is started for a full repair of the fanblades. Here the fanblades join the fanblades that follow the second route.

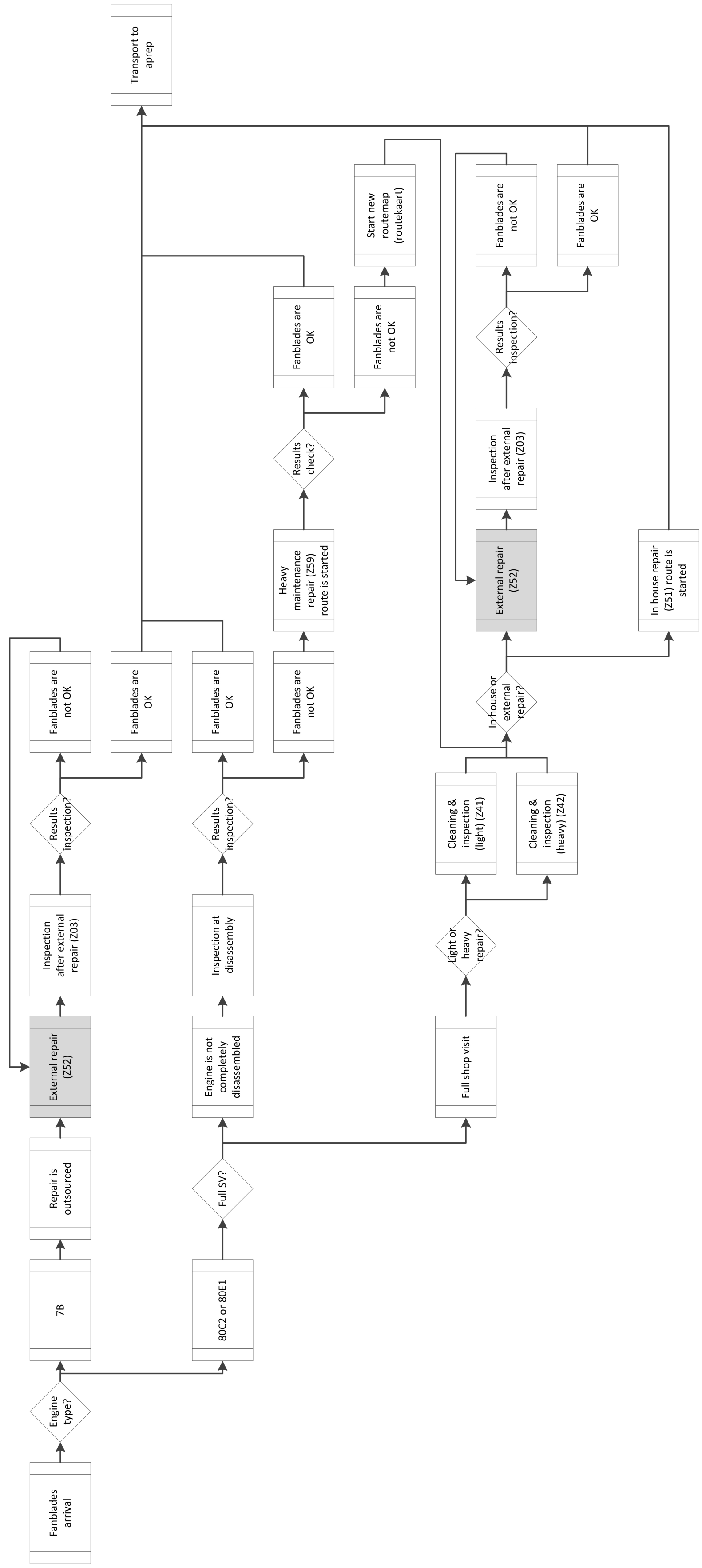


FIGURE 3.15: Flowchart Fanblades Workstation

2. Secondly, the engine gets a full shop visit and is thus completely disassembled. First the fanblades are cleaned and inspected. Most of the time the heavy version is needed, but in some cases the light version is sufficient. During the inspection a shop traveler is compiled. This shop traveler contains all information on the needed repairs for the fanblades.

   Most of the repairs can be performed in house. These in house repairs include multiple tasks that need to be performed. After finishing all tasks, the fanblades are delivered at aprep. Here the fanblades are stored intil the engine is assembled.

   Only the repair of the midspan of the CF6-80C2 fanblades is outsourced as KLM E&M does not have the needed skills and tools for this repair. If the repair is outsourced, the fanblades are inspected when they return at the engine shop. If the results are positive, the fanblades are sent to aprep where they will be stored until the engine is assembled. If the results are negative, the fanblades are sent back to the external vendor, but this has not happened in the past year.

As this research considers the in house repairs and the full shop visits, this research zooms in at the route for the full shop visits of the CF6-80C2 and CF6-80E1 engines. This process is presented in more detail using the SIPOC model, see figure 3.16. The function of the SIPOC model is already discussed in section 3.1.1.

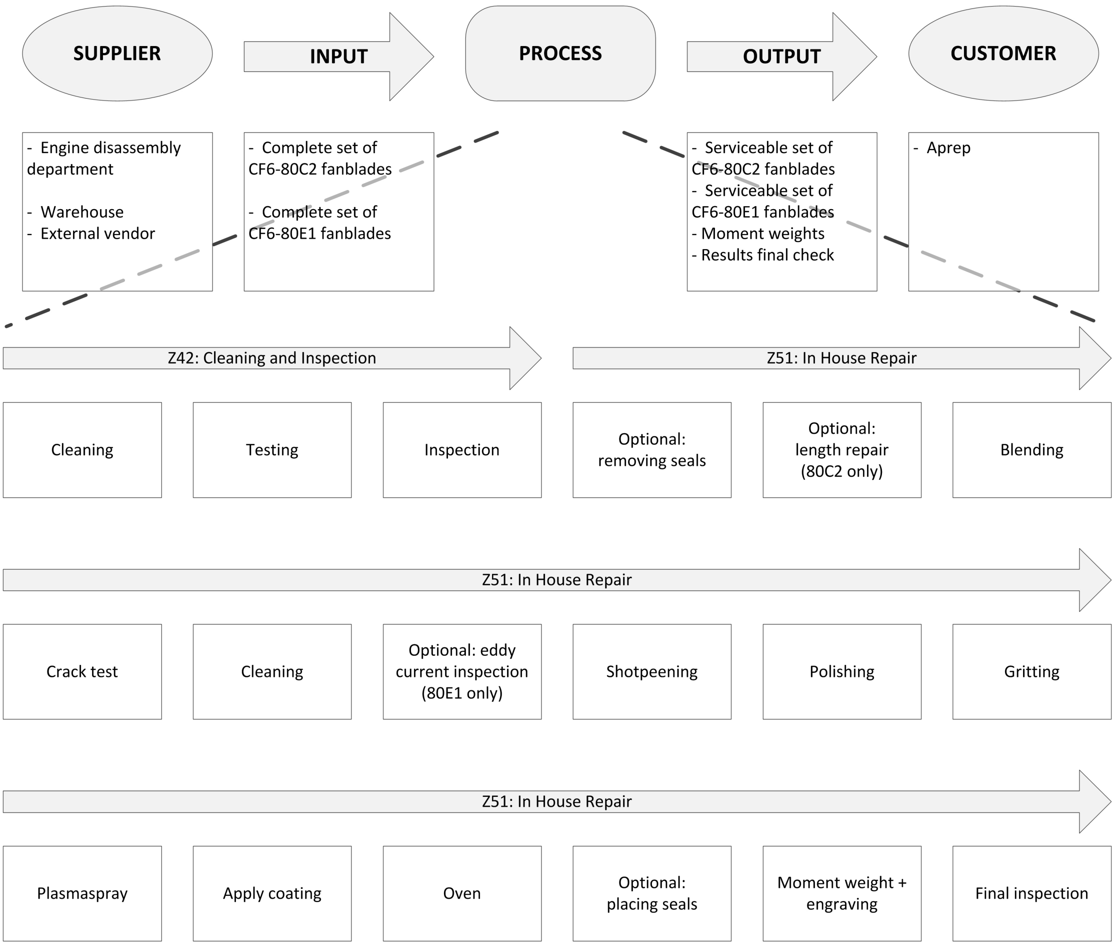


FIGURE 3.16: SIPOC Model of the In House Repairs at the Fanblades Workstation

The SIPOC model consists of five parts, namely the supplier, the input, the process, the output and the customer. All parts are discussed below.

- **Supplier**
  The main supplier of this process is engine disassembly, part of the MRO department of the engine shop. After the fanblades are disassembled from the engine, the repair process of the fanblades starts. The warehouse and the external vendor can also be suppliers of the process. The warehouse is the supplier when new or spare parts are needed for the repair. The external vendor is a supplier if the repair of fanblades is outsourced and the fanblades are delivered to the fanblades workstation afterwards. However, in almost all cases the engine disassembly department is the supplier of the process.

- **Input**
  The inputs of the process are complete sets of CF6-80C2 and CF6-80E1 fanblades. A set of CF6-80C2 fanblades consists of 38 fanblades and a set of CF6-80E1 fanblades consists of 34 fanblades. The blades are placed on specially designed carts in order to minimize the chance on damage during transportation and repair. The carts are designed for one complete set of fanblades and are suitable for both the CF6-80C2 and CF6-80E1 fanblades. The input is unpredictable as it is not known when and how many engines arrive at the engine shop. It is hard to plan the work on the long term as the input strongly varies.

- **Process**
  The different process steps within the process are depicted in a VSM diagram in appendix B. The process in figure 3.16 is a simplified version of this VSM diagram. As can be seen in figure 3.16, the process consists of two main phases: the cleaning and inspection phase (Z42) and the in house repair phase (Z51).

  The cleaning and inspection phase (Z42) consists of three parts. First the fanblades are cleaned using different types of chemical baths. Then the fanblades are tested via non-destructive testing methods. These two parts are performed by the employees of the MRO department. Lastly, the fanblades are inspected. The inspection is performed by the inspector of the fanblades workstation. After the inspection the shop traveler is compiled and the in house repair phase (Z51) is started.

  The in house repair phase (Z51) consists of 15 parts. All parts consist of multiple tasks. The different parts of the in house repair phase are described below.

  - The first part of the in house repair phase is optional. Most fanblades need replacement of the seals as these seals are damaged during flights. The seals of these fanblades are removed one by one. However, not all seals need to be replaced. Which seals need to be replaced is determined during the cleaning and inspection phase. The seals removal is performed by an employee of the fanblades workstation.
  - The second part is optional as well. This part of the Z51 phase is the length repair. This repair is performed if the length of the fanblades is too short according to the manual. The length of the fanblades is affected because the fanblades rub against the inside of the motor casing during landing. If the fanblades are not long enough the fanblades need an additional repair: the length repair. Here an extra ridge is welded

on the end of the fanblades so that the blades are again as long as required by the manual. The length repair is performed by an employee of the fanblades workstation.

- Next, the fanblades are blended in order to optimize the curvature of the front edge and the tip of the fanblades and to remove minor cracks. This part of the process is required for all fanblades and contains of heavy and physical work. The employees of the fanblades workstation blend all fanblades by hand one at a time.
- Then the fanblades are subjected to a crack test. Here it is checked whether all cracks are removed from the fanblades. First the fanblades are checked with a substance that lights up in blacklight. This substance gets into the cracks and lights up when in blacklight. This way the employee can check whether there are cracks in the fanblades even if the cracks are not visible to the naked eye. This crack test is performed by an employee of the fanblades workstation.
- After the crack test, the fanblades are cleaned in order to remove all dirt and the substance used for the crack test. This cleaning tasks are performed by an employee of the fanblades workstation.
- In some cases an extra inspection is needed, the so-called eddy current inspection. This check is needed for a specific range of part and serie numbers. This optional check is performed by an inspector of the fanblades workstation.
- Then the fanblades enter the shotpeen machine. Here the blades are pelted with minuscule beads. This way the molecules in the blade are rearranged in order to make sure tension in the fanblades is optimal. The shotpeen machine is located at the Plasma and Welding 1 (PW1) workstation. Here not only fanblades, but also other engine parts are handled, so the shotpeen machine is a shared resource. As the fanblades machine is at the PW1 workstation, the shotpeening is performed by an employee of the PW1 workstation. All fanblades enter the shotpeen machine twice. First the lower part of the fanblades is shotpeened. Here eight fanblades are handled at the same time. Next, the upper part of the fanblades is pelted. Here only one fanblade can be handled at the same time.
- The next step of the in house repair process is the polishing of the fanblades. Here eight fanblades are placed in the polishing machine in order to ensure that the surface of the blades is smooth. The polishing is done by rotating the fanblades in a vibrating tray with pebble stones. The polishing is performed on the fanblades workstation by an employee of the fanblades workstation.
- Next, the fanblades are gritted as a preparation for the plasma spray they get afterwards. Only the surface that needs to be sprayed is operated by the gritting machine. The gritting machine sprays sand on the surface so this surface becomes rough and the plasma spray will adhere better. The gritting machine is a shared resource as the machine is part of the PW1 workstation and is used for multiple types of parts. As the machine is part of the PW1 workstation, the machine is operated by a PW1 employee. The fanblades are gritted one at a time.
- Then the plasma spray is applied to the fanblades. The plasma machine is also a shared resource as the machine is part of the PW1 workstation and is used for different types of parts. The plasma is applied to 7 or 14 fanblades at the same time

depending on the size of the fanblades. This is done by an employee of the PW1 department.

- Afterwards, a coating is applied to the blades. The coating is applied by an employee of the fanblades workstation and this is done for one blade at a time.
- Next, the coating hardens in the oven. The fanblades enter the oven on a special oven cart that fits 8 or 12 fanblades at the same time depending on the size of the fanblades. An employee of the fanblades workstation places the fanblades on the oven cart and enters them into the oven.
- When the fanblades have cooled down, the seals are placed on the fanblades without seals. In order to apply the new seals, the fanblades are placed in special clamps. Here the seals are glued to the fanblades. Then the fanblades enter the oven another time in order to make sure the seals are securely attached to the fanblades. The placing of the new seals is done for one blade at a time by an employee of the fanblades workstation.
- After, the moment weight of the fanblades is determined. The moment weight is needed in order to determine the position of the fanblades in the fan of the engine. The findings of the moment weight are engraved in the fanblades. Both tasks are performed by an employee of the fanblades workstation and this is done for one blade at a time.
- Lastly, the final inspection is performed by the inspector of the fanblades workstation.

• **Output**
The output of the process is a serviceable set of fanblades. The fanblades are accompanied by paperwork on the moment weights of the fanblades and the results of the final inspection.

• **Customer**
The customer of the process is aprep, part of the MRO department of the engine shop. When the fanblades are repaired, they are delivered to aprep. Here the fanblades are stored until the engine is assembled. The customer requirements for the output can easily be structured using a Kano analysis. This analysis is already discussed in section 3.1.1. The Kano analysis distinguishes three types of customer needs, namely the dis-satisfiers, the satisfiers and the delighters:

- Dis-satisfiers: the customer wants to receive the exact same set of fanblades as the set he delivered, unless agreed otherwise. Moreover the customer expects the quality of the fanblades fulfills at least the requirements of the manual.
- Satisfiers: the turnaround time of the repair is a satisfier, because the quicker the repair, the more satisfied the customer. The same counts for the costs: the lower the costs , the more satisfied the customer.
- Delighters: possible delighters for the customers are free training at KLM training center, a free engine swap and quick on wing support.

3.2.7 Conclusions System Analysis

KLM E&M offers MRO services in four categories, namely line maintenance, base maintenance, components services and engine services. This research focuses on the engine services. Within engine services, KLM E&M fulfills three tasks, namely organize engine availability, provide engine MRO and provide parts repair and engine accessories MRO. As the score card shows providing engine MRO services is under-performing, this research focuses on engine MRO. The engine MRO process consists of four stage. Stage 0 covers the determination of the workscope. During stage 1 the engine is disassembled. Stage 2 consists of the actual repairs. The last stage, stage 3, covers the assembly of the engine. Most of the repairs are performed in house. These in house repairs are performed on several specialized workstations. The fanblades workstation performs worst looking at the turnaround time of the repairs. Therefore this workstation is the focus of this research. The repair of the fanblades consists of two main phases: the cleaning and inspection phase (Z42) and the in house repair phase (Z51). Both phases consist of multiple tasks which are performed by the employees of the fanblades workstation or, in cause of shared resources, by the employees of the PW1 workstation. This process is further analyzed by the data analysis presented in section 3.3.

3.3 Data Analysis

This section presents the results of the data analysis. The data analysis zooms in on the performance of the fanblades workstation. The goal is to identify reasons for the sets of fanblades being delivered late.

3.3.1 Data set

The data analysis is based on raw data from SAP. This data is generated by the employees when they scan the barcode of a task on the shop traveler in order to confirm they finished this task. This is the only data available on the progress of the repair process. The data set is obtained via the Repair Control Group of Engine Services. The data is filtered from SAP based on the words 'fan' and 'blade' in the part description. Besides, the data is filtered for the period November 2014 to October 2015.

The data set consists a lot of data categories. The most important categories are explained below.

- **WBS Element** represents the sales order. The WBS element consists of three parts, for example 8C/185875-21X:
  - 8C stands for the type of the engine, here CF6-80C2,
  - 185875 is the sales order number, and
  - 21X is the module number. 21X represents the fanblades.
- **Service order** gives the repair order number. A sales order consists of the whole set of fanblades. These fanblades do not all need the exact same repairs. Therefore the sales order is divided into multiple service orders. Within a service order all fanblades need the exact same repair. All service orders together equal the sales order.

- **Service product quantity** states the number of fanblades of a service order.
- **Maintenance Activity Type** indicates the phase to which the task belongs. These phases are indicated using different Z-codes, for example Z42 stands for cleaning and inspection and Z51 for the in house repairs.
- **Operation** gives the number of the specific task. These task numbers correspond with a specific task in the manual.
- **Techniekcode** presents the type of task, for example inspection or benchwork tasks.
- **Operation description** gives a description of the task.
- **Duration** is the normative time for a task.
- **Operation start date** is the start date of the task, but this data is in most of the cases not accurate.
- **Operation finish date** is the finish date of the task. In contrast to the data on start date, this data is correct.

A first analysis of the dataset shows that during the past year 105 sets of fanblades are repaired in the engine shop as part of a full shop visit. These 105 sets of fanblades can be divided into:

- 51 sets of CFM56-7B engines,
- 28 sets of CF6-80C2 engines, and
- 26 sets of CF6-80E1 engines.

As this research is focused on the in house repairs of the fanblades and the repairs of the CFM56-7B engines are outsourced, this data analysis only considers the sets of the CF6-80C2 engines and the CF6-80E1 engines.

Besides these complete sets of fanblades the data set also includes:

- Specials: these are not taken into account as this includes only one fanblade during the past year.
- Parts repair: these are not taken into account as these are not part of the full shop visits and thus not in the scope of the research.

3.3.2 Assumptions

The data analysis is based on multiple assumptions, namely:

- First it is assumed that the employee scans the shop traveler on the same day that he finishes the corresponding task.

- Next, it is assumed that the normative times of the tasks correspond to reality. The normative times are based on experiences of repairs from the past. Employees have the possibility to update the normative times by submitting a request to their supervisor. Then it is examined whether the normative time should be updated. If this is the case, the normative time is adjusted. This ensures that the normative times are up to date.
- Furthermore it is assumed that there is no difference in the time it takes for the different employees to finish a task.
- Besides it is assumed that the employees work five days per week. During these days two shifts are performed. The shifts last eight hours, but only 5.4 hours are productive. This means that a workday consists of 10.8 productive hours based on one employee per shift. A workweek then consists of 54 productive hours.
- Lastly it is assumed that a task starts when the preceding task is finished. This assumption is needed as the start dates in the data set are not accurate.

3.3.3 Handshakes

For each phase of the process there is a handshake between the workstations and the customer, the MRO department. Handshakes are agreements on the maximum turnaround time, in days, that may be used in order to complete the phase. The cleaning and inspection phase (Z42) has a handshake of 5 days. The handshake of the in house repair phase is 28 days. So the handshake for the complete Z42,Z51-process is 33 days. The handshakes are depicted in figure 3.17.

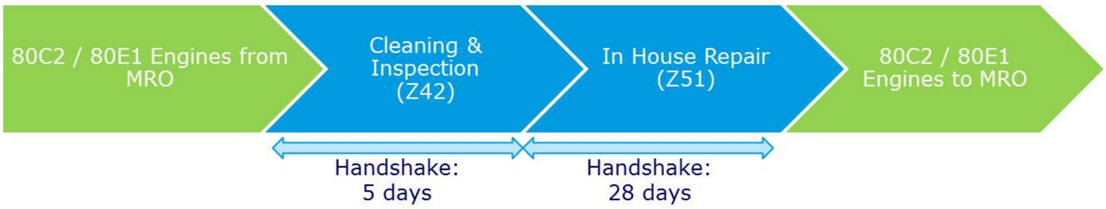


FIGURE 3.17: Handshakes for the in house repairs of the CF6-80E1 and CF6-80C2 Engines

3.3.4 All Engines

As stated in the system analysis 52% of the repair orders of the fanblades workstation is delivered on time. This performance indicator is based on the turnaround times for the different repair orders and only on data of the repair phase (Z51). However, the system analysis showed that the process at the fanblades workstation also consists of the cleaning and inspection phase (Z42). Therefore the turnaround of the Z42 phase should also be taken into account. Moreover a complete set of fanblades consists of multiple repair orders. So the on time delivery of only one repair order does not add value to the customer. The customer wants the complete set of fanblades to be delivered on time. Therefore the turnaround time of the complete set for the complete process should be measured. These turnaround times of the different sets of fanblades are presented in figure 3.18. It can be seen that only 29% of all complete sets of fanblades is delivered on time from the fanblades workstation. So, where 52% of the repair orders leaves the Z51 phase on time, only 29% of the complete sets of fanblades leaves the complete process on time. The average turnaround time of a complete set of fanblades is 41 days.

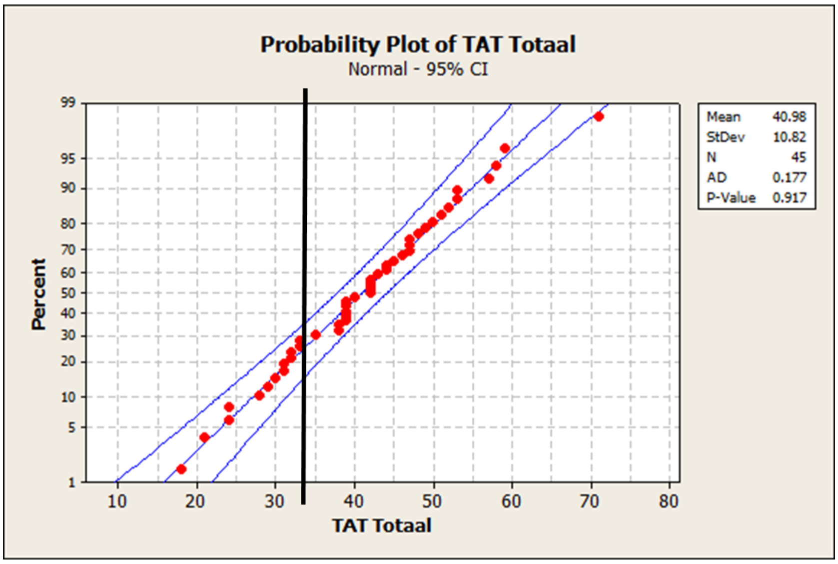


FIGURE 3.18: Normal Probability Plot Total TAT for All Engines

Figure 3.19 also shows the turnaround times of the complete sets of fanblades for the complete process, but this figure makes a distinction between the different engine types. It can be seen that the fanblades of the CF6-80E1 engines on average are delivered slightly earlier than the fanblades of the CF6-80C2 engines. The average turnaround time of the fanblades of the CF6-80E1 engines is 40 days where the turnaround time of the fanblades of the CF6-80C2 engines is 42 days. The complete sets of fanblades of the CF6-80E1 engines are delivered on time in 30% of all cases. The fanblades of the CF6-80C2 engines are delivered on time in 28% of the cases.

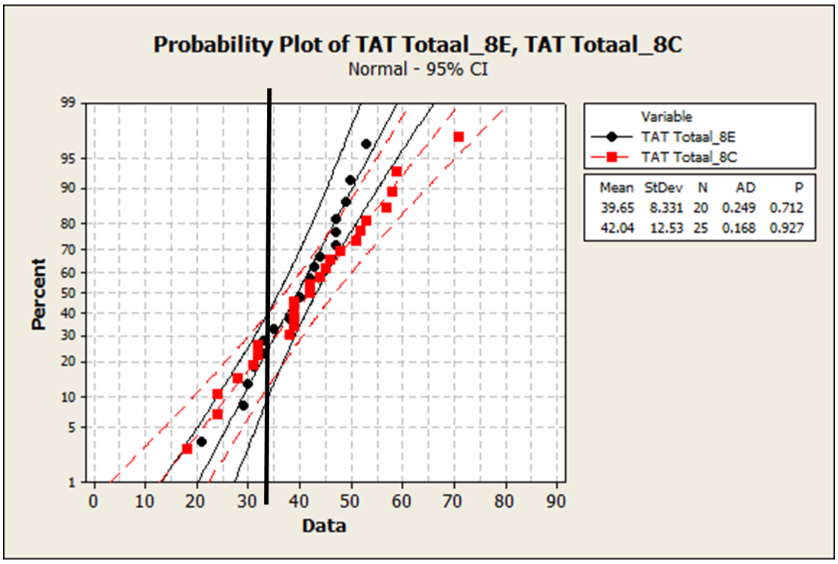


FIGURE 3.19: Normal Probability Plot Total TAT for CF6-80C2 Engines and CF6-80E1 Engines

Figure 3.19 shows that the TAT is approximately normally distributed as the data points approach a straight line. However the range of the data points is large. This large variety in the TAT indicates that there is a lot of waste in the system. Moreover this causes that the system is very unpredictable. Next, the figure shows that the average TAT is too high. The goal is to reduce the variety in the TAT and to lower the average TAT. Reducing the variety leads to a more straight line and lowering the TAT leads to a shift of the line towards the left (Beelaerts van Blokland, 2016). Therefore the process is analyzed more into depth for both of the engine types. Here waste is located in the process.

3.3.5 CF6-80C2 Engines

Figure 3.20 shows the routes of the analyzed engines through the fanblades workstation. It can be seen that the Z42,Z51-route is most common. This is the standard route of cleaning and inspection (Z42) and inhouse repairs (Z51). Other options are that the fanblades are only repaired (Z51) or that the standard route is combined with an external repair (Z03). Besides it is possible that the standard route is preceded by a light version of the cleaning and inspection (Z41).

The other options are not taken into account as the routes only containing cleaning and inspection (Z41 and Z42) are not yet complete because these are the last data points in the dataset. Moreover the route including Z17 is not taken into account as this is a one time event.

So only the engines with routes inside the red circles, 25 in total, are included in the data analysis.

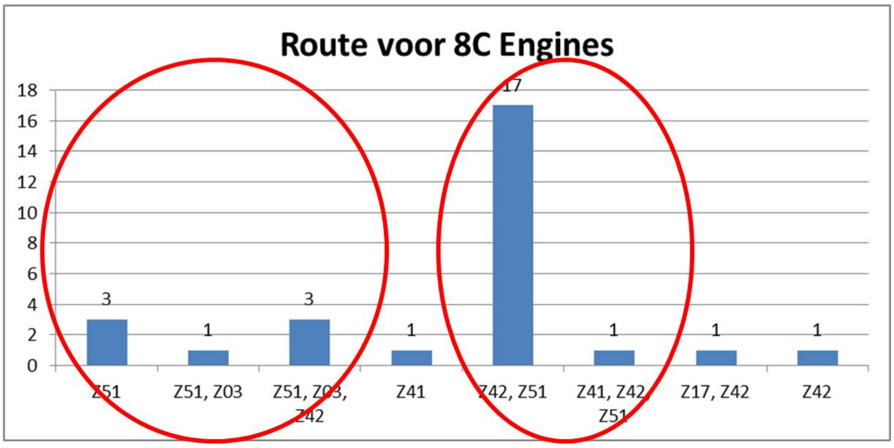


FIGURE 3.20: Routes of CF6-80C2 Engines

3.3.5.1 Tasks and Normative Times

The heavy cleaning and inspection phase (Z42) of a complete set of fanblades on average consists of 15.8 tasks. Together these tasks take, based on the normative times, 23 hours on average. This is equal to 2.1 workdays. The in house repair phase (Z51) of a complete set of fanblades on average consists of 76.8 tasks. The normative times of these tasks add up to 50.3 hours on average. This phase thus takes 4.7 workdays.

3.3.5.2 Handshakes

Figure 3.21 shows the share of phases delivered on time. It can be seen that phase Z42 performances worst, only 14% on time. Phase Z51 performs better, but still performs bad as only half of the work is delivered on time. When adding up the handshakes and the TAT of the phases, only 28% of the complete sets of CF6-80C2 fanblades is delivered on time.

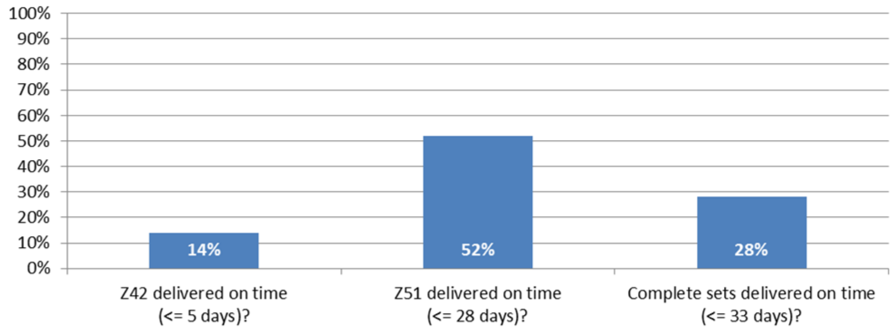


FIGURE 3.21: % Delivered on Time

3.3.5.3 Waiting Times

Based on the TAT and the normative times of all tasks, the waiting times can be calculated via this formula: *Waiting Time = Turnaround Time - Normative Time*.

Figure 3.22 shows the sum of the duration and waiting times of all tasks per techniekcode. The data is presented per techniekcode because the starting dates of the operations are not precise enough to present reliable data on the specific tasks in the process. Moreover the data is presented per techniekcode in order to present a clear overview. Presenting the data per task will result in an enormous overview that is hard to read.

The blue part of the columns shows the duration while the red part presents the waiting time. It can be seen that four of the techniekcodes causes the most waiting time. These outliers are:

- Q504: Shotpeening Overall
- Q810: Benchwork Airfoils
- Q811: Seal Replacement
- Q813: Insp/prts/rep Fanblades

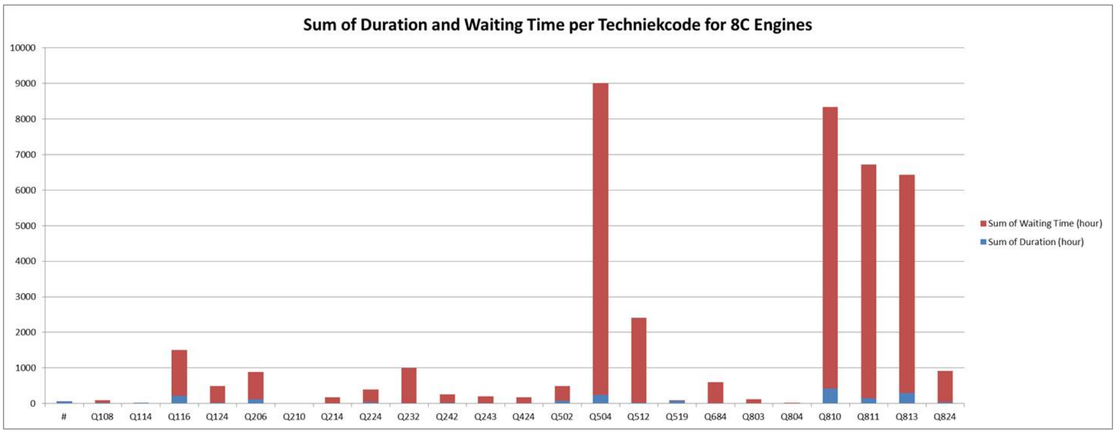


FIGURE 3.22: Sum of Duration and Waiting Time per Techniekcode for CF6-80C2 Engines

As can be seen in figure 3.23, these four techniekcodes together cause 76% of all waiting times.

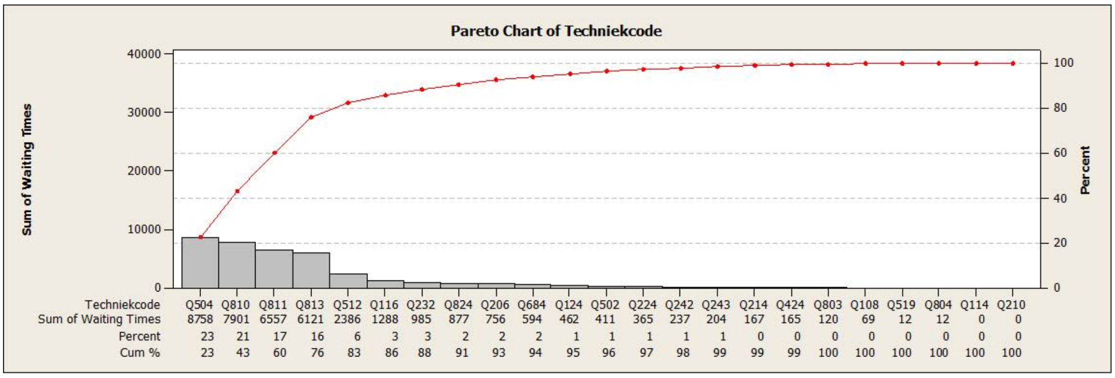


FIGURE 3.23: Pareto Distribution of Waiting Times per Techniekcode for CF6-80C2 Engines

Next, it is interesting to take a closer look at these techniekcodes. Figure 3.24 shows all tasks for these techniekcodes sorted per techniekcode. The figure shows the sum of the duration and waiting times per taaknummer of all tasks. Again the blue part of the column shows the duration while the red part presents the waiting time.

It can be seen that the first three techniekcodes all have one clear outlier:

- Q504: task 1120 - Shotpeening Overall
- Q810: task 820 - Benchwork Airfoils
- Q811: task 160 - Removing Seals

Together these three tasks cause 42% of all waiting times.

The last techniekcode, Q813, does not have a clear outlier. Here all tasks cause a bit waiting time and together these waiting times form the outlier of techniekcode Q813. So for this techniekcode not one specific task is the main cause of the waiting time, but the amount of tasks is the problem.

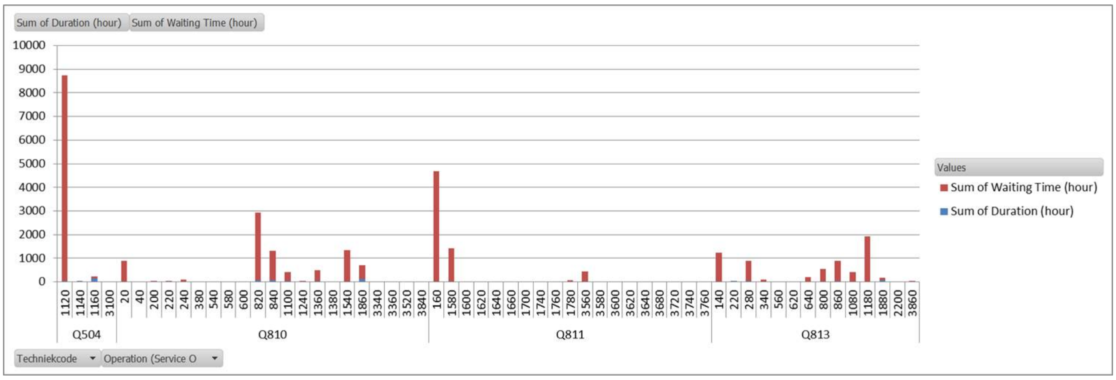


FIGURE 3.24: Sum of Duration and Waiting Time per Taaknummer for CF6-80C2 Engines

3.3.6 CF6-80E1 Engines

Figure 3.25 shows the routes of the analyzed CF6-80E1 engines through the fanblades workstation. It can be seen that again the Z42,Z51-route is most common. This is the standard route of cleaning and inspection (Z42) and inhouse repairs (Z51).

The other routes are not taken into account. The Z41,Z51-route and the Z51-route are based on old shop travelers. This causes that the task numbers and the duration of the tasks do not match with the other engines. The same counts for one of the Z42,Z51-routes. Therefore these engines are not taken into account. The Z41-route and the Z42-route are not taken into account because these are the last data points in the dataset and these are not yet complete. The Z59-route is not taken into account as this is a one time event.

So only 20 of the engines within inside the red circle are included in the data analysis.

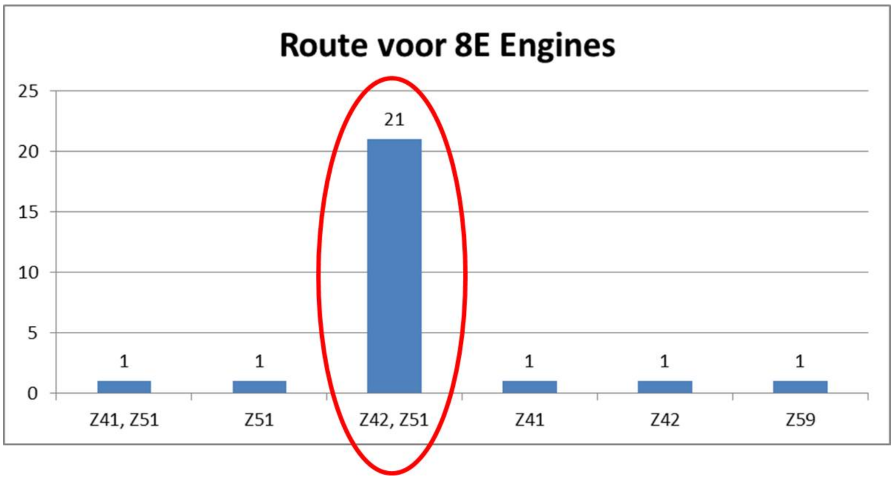


FIGURE 3.25: Routes of CF6-80E1 Engines

3.3.6.1 Tasks and Normative Times

The heavy cleaning and inspection phase (Z42) of a complete set of fanblades on average consists of 11.8 tasks. Together these tasks take, based on the normative times, 40.5 hours on average. This is equal to 3.8 workdays. The inhouse repair phase (Z51) of a complete set of fanblades on average consists of 61.0 tasks. The normative times of these tasks add up to 60.5 hours on average. This phase thus takes 5.6 workdays.

3.3.6.2 Handshakes

Figure 3.26 shows the share of phases delivered on time. It can be seen that phase Z42 performances worst, only 25% on time. Phase Z51 performs better, but still performs bad as only 40% of the work is delivered on time. When adding up the handshakes and the TAT of the different phases on the route of the engines, only 30% of all sets of CF6-80E1 fanblades is delivered on time.

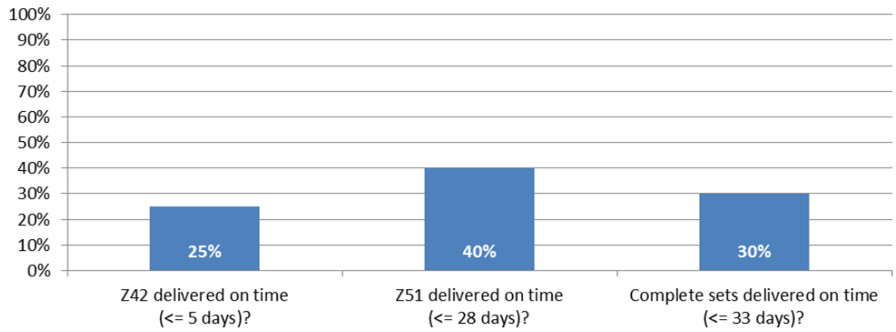


FIGURE 3.26: % Delivered on Time

3.3.6.3 Waiting Times

Based on the TAT and the normative times of all tasks, the waiting times can be calculated via this formula: *Waiting Time = Turnaround Time - Normative Time*.

Figure 3.27 shows the sum of the duration and waiting times of all tasks per techniekcode. The data is presented per techniekcode because the starting dates of the operations are not precise enough to present reliable data on the specific tasks in the process. Moreover the data is presented per techniekcode in order to present a clear overview. Presenting the data per task will result in an enormous overview that is hard to read.

The blue part of the column shows the duration while the red part presents the waiting time. It can be seen that five of the techniekcodes causes the most waiting time. These outliers are:

- Q116: NDT-1-PEN
- Q504: Shotpeening Overall
- Q810: Benchwork Airfoils
- Q811: Seal Replacement
- Q813: Insp/prts/rep Fanblades

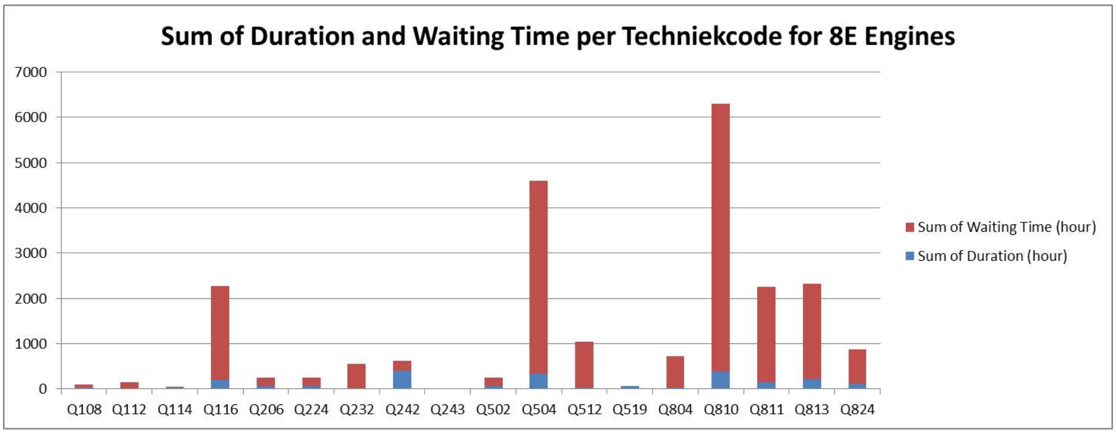


FIGURE 3.27: Sum of Duration and Waiting Time per Techniekcode for CF6-80E1 Engines

As can be seen in figure 3.28, these five techniekcodes together cause 80% of all waiting times. It is interesting to remark that four of these techniekcode correspond with the techniekcodes causing the most waiting times for the CF6-80C2 engines. These four techniekcodes, Q504, Q810, Q811 and Q813, together cause 70% of all waiting times.

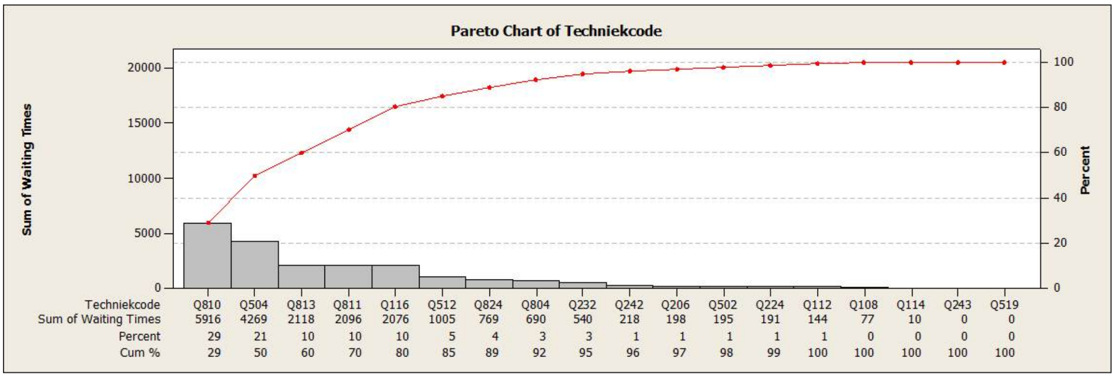


FIGURE 3.28: Pareto Distribution of Waiting Times per Techniekcode for CF6-80E1 Engines

Again, it is interesting to take a closer look at these four techniekcodes. Figure 3.29 shows all tasks for these techniekcodes sorted per techniekcode. The figure shows the sum of the duration and waiting time per taaknummer of all tasks. Again the blue part of the column shows the duration while the red part presents the waiting time.

It can be seen that the first three techniekcodes all have one clear outlier:

- Q504: task 600 - Shotpeening Overall
- Q810: task 300: Benchwork Airfoils
- Q811: task 20 - Removing Seals

These tasks correspond with the tasks causing the most waiting times for the CF6-80C2 engines. Together these three tasks cause 47% of all waiting times.

The last techniekcode, Q813, does not have a clear outlier. Here all tasks cause a bit waiting time and together these waiting time form the outlier of techniekcode Q813. So for this techniekcode not one specific task is the main cause of the waiting time, but the amount of tasks is the problem. This also corresponds with the finding for the CF6-80C2 engines.

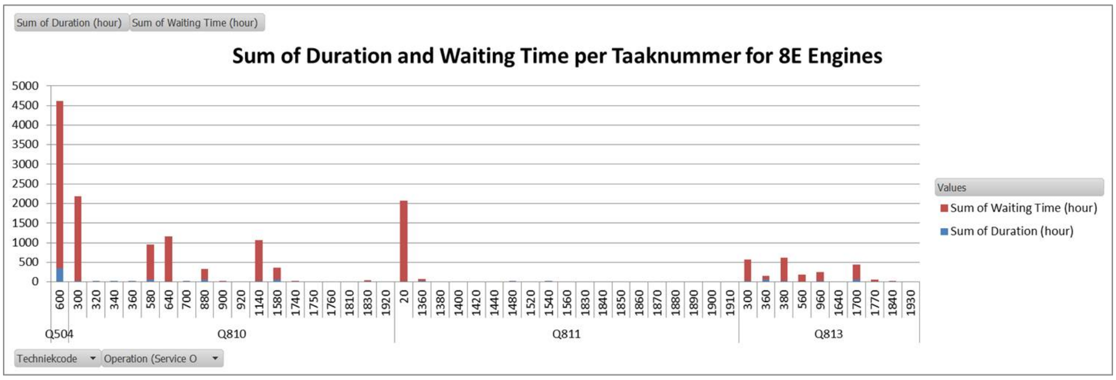


FIGURE 3.29: Sum of Duration and Waiting Time per Taaknummer for CF6-80E1 Engines

3.3.7 Conclusions Data Analysis

The data analysis shows that 29% of the complete sets of fanblades are delivered on time. The average TAT is 40 days. The fanblades of the CF6-80E1 engines on average are delivered slightly earlier than the fanblades of the CF6-80C2 engines. The average turnaround time of the fanblades of the CF6-80E1 engines is 40 days where the turnaround time of the fanblades of the CF6-80C2 engines is 42 days.

Next, it can be concluded that the findings from the data analysis for the fanblades of the CF6-80C2 engines correspond to the findings for the fanblades of the CF6-80E1 engines. The data analysis shows that 74% of all waiting times is caused by four techniekcodes, namely:

- Q504: Shotpeening Overall
- Q810: Benchwork Airfoils
- Q811: Seal Replacement
- Q813: Insp/prts/rep Fanblades

Three of these techniekcodes contain of one specific task causing most of the waiting times. These three tasks cause 44% of all waiting times. These tasks are:

- Q504: Shotpeening - 1120 (CF6-80C2) and 600 (CF680E1)
- Q810: Blending - 820 (CF6-80C2) and 300 (CF680E1)
- Q811: Removing Seals - 160 (CF6-80C2) and 20 (CF680E1)

The last techniekcode, Q813, does not have one specific task that is the main cause of the waiting time. All inspections cause a bit of the waiting times and the sum of all these waiting times is the problem.

3.4 Observations

Now the main problem areas are defined based on the system analysis and the data analysis, more in depth knowledge is needed in order to find the cause of the waiting times at these problem areas. In order to gain this in depth knowledge the process at the fanblades workstation is further analyzed by observations. These observations are presented in this section.

3.4.1 General Observations

Next to the observations on the main problem areas, there are also more general observations that provide insights in the waiting times at the fanblades workstation.

First, the priorities of the work to be done are not clear. Engine Services uses the 'dagnummersysteem' in order to show which part needs to be delivered first. The 'dagnummersysteem' assigns a number to each part. The number stands for the day that the part needs to be delivered to aprep. This way employees know which part should be operated first. Next to the 'dagnummersysteem', the employees get a list of work at the start of their shift. This list contains the tasks the employees needs to fulfill during the shift. Most of the tasks on this list correspond to the priorities following the 'dagnummersysteem'. However, the skillmanager corrects the priorities following from the 'dagnummersysteem' based on his experience from the past. Lastly, there are emergency parts that get the highest priority. Most of the time these parts are not included in the list the employee gets at the start of the shift as these emergency parts are ad hoc incidents. Due to the combined existence of the 'dagnummersysteem', the list at the beginning of the shift and the emergency parts, the priorities of the work to be done are not clear.

Secondly, there is a lack of flow in the system. The lack of flow is caused by the waiting times before almost every step in the process. This way there is a lot of work in progress in the system and the turnaround time of the process is high. For example, fanblades leaving the shotpeen machine, one of the constraints, are parked for a while before the next task is performed. In an ideal situation an employee is present to receive the fanblades and directly perform the next task. Currently this is not the case and the waiting times in the system cause a lack of flow in the system.

Lastly, the work is moved through the process in large batches. These batches contain a complete set of fanblades. So the fanblades are moved through the process per 34 or 38 fanblades. However, as stated in the process analysis, most tasks can handle only one blade at a time. Most of the machines can handle multiple fanblades per operation, but none of them can handle a complete set at the same time. Therefore the batch size causes a lot of waiting times in the process as the rest of the fanblades is waiting as only a part of them is being processed.

3.4.2 Observations Shotpeening

Observations on shotpeening show that the shotpeen machine processes parts from multiple workstations as the shotpeen machine is a shared resource. This causes a queue of parts needed to be shotpeened in front of the machine. The shotpeen machine is operated by two operators who both fulfill one shift per day. The fanblades are delivered to the shotpeen machine as a complete set and are shotpeened one after another without interruptions from other parts. Shotpeening of a complete set of fanblades takes a lot of time and therefore the fanblades are postponed and shorter operations are performed first. So the waiting times are caused by inventory due to the queue and by batching of the fanblades.

Moreover observations show that there is a second shotpeen machine available in the engine shop at the plating workstation. The plating shotpeen machine is also a shared resource but does not operate as much parts as the PW1 shotpeen machine does. Therefore the shotpeen machine of the plating workstation is operated by only one operator fulfilling one shift per day. The plating machine is capable of all work performed at the PW1 shotpeen machine, but the needed programs needed to be installed first. So there is unused shotpeen capacity at the plating workstation.

Waiting times also arise because of the absence of the shotpeen operator. At the moment the PW1 shotpeen machine is operated by two operators and the plating machine is operated by one operator. This regularly causes that the shotpeen machine is not operated due to for example operators having a break, being sick of having a holiday. This causes waiting times as the machine is not available when no operator is available. However, seven employees are trained in order to operate the shotpeen machine. So there is a lot of unused operator capacity.

At the moment the shotpeen machine of PW1 is used 61% of the time. This number is based on five days a week, two shifts per day and 5.4 productive hours per shift. The utilization of the plating shotpeen machine is 16%. When looking at the utilization of both machines based on 8 productive hours per shift, the results are even worse. This results in a utilization of 41% for the PW1 shotpeen machine and a utilization of 14% for the plating shotpeen machine.

When looking at the PW1 shotpeen machine almost half of the work, 45%, is devoted to the fanblades department. The other half of the work, 55%, is devoted to the parts from the PW1 workstation.

3.4.3 Observations Benchwork

The observations on benchwork focus on the blending activities at the start of the repair process as this task causes most of the benchwork waiting times.

Blending makes sure the curvature of the front edge and the tip of the fanblades are optimal and minor cracks are removed. The waiting times arise because the amount of rework caused by blending. By blending minor cracks are removed, however these cracks are not visible to the naked eye. Therefore a crack test is performed afterwards. It frequently occurs that not all cracks are removed from the blades at the first time blending. The fanblades then have to be blended again in order to remove the remaining cracks. This rework takes extra time and thus causes waiting times. However, the rework is hard to prevent as blending is an iterative process.

Next to rework also waiting times are caused by employees postponing the blending tasks for as long as possible because it is physical and heavy work. Employees postponing the blending tasks causes waiting times for the fanblades.

3.4.4 Observations Seals Replacement

When observing the removing of the seals it is noticeable that waiting times are not caused by the process of removing seals. The waiting times are caused because the removing of the seals for most sets of fanblades is the first task of the repair phase (Z51). The task is started when the cleaning and the inspection pahse (Z42) is finished. However, the pace of the Z42 phase is higher than the pace of the Z51 phase. Therefore a buffer arises at the start of the Z51 phase; the removal of the seals. So the waiting times at seals replacement are due to differences in the pace of the Z42 and Z51 phase causing inventory at the seals removal.

3.4.5 Observations Inspections

The waiting times for the inspections are not caused by one specific inspection but by the sum of the waiting times of all inspections. These waiting times are caused because the inspector is not always available when needed. The inspections are performed by the inspector of the fanblades workstation or by the inspector of the airfoils workstation. The inspectors need to do all inspections on both workstations and thus are not directly available. This causes waiting times.

Next to the availability of the inspections, the necessity of the inspections is discussed. Not all inspections are required according to the manual and not all inspections need to be performed by a qualified inspector. In collaboration with engineering the necessity of inspections must be further explored, because doing inspections that are not required does not add value for the customer and is a form of overprocessing.

3.4.6 Conclusions Observations

The observations provide an overview of the causes of waiting times in the process. General causes of waiting times are the unclear priorities, the lack of flow and the large batches.

Observations show that the waiting times from shotpeening haves multiple causes. Waiting times are caused due to the queue in front of the shotpeen machine. Moreover waiting times are caused due to the large batches of fanblades. Next, waiting times arise because of the absence of the operator causing the shotpeen machine being unavailable. Furthermore both the PW1 and the plating shotpeen machines are not operated to full capacity.

The waiting times for benchwork are caused by rework activities and the employees postponing the blending tasks.

At seals replacement waiting times arise due to differences in the pace of the cleaning and inspection phase (Z42) and the repair phase (Z51) phase causing inventory at the seals removal.

Observations on the inspections show that the waiting times are caused by the inspector not being directly available and inspectors performing inspections that are not required according to the manual.

3.5 Conclusions Case Study at KLM E&M

Research question 3: How is the current process of the in house repairs at Engine Services structured?

The engine MRO process consists of four stage. Stage 0 covers the determination of the workscope. During stage 1 the engine is disassembled. Stage 2 consists of the actual repairs. The last stage, stage 3, covers the assembly of the engine. Most of the repairs are performed in house. These in house repairs are performed on several specialized workstations. The fanblades workstation performs worst based on the turnaround time of the repairs. The repair of the fanblades consists of two main phases: the cleaning and inspection phase (Z42) and the in house repair phase (Z51). At the moment only 29% of the complete sets of fanblades are delivered on time. The average TAT is 40 days. 74% of all waiting times is caused by four techniekcodes, namely:

- Q504: Shotpeening Overall
- Q810: Benchwork Airfoils
- Q811: Seal Replacement
- Q813: Insp/prts/rep Fanblades

Research question 4: What factors influence the turnaround time of in house repairs of engine MRO services according to the case study?

The main constraints in the fanblades workstation (shotpeening, blending, removing seals and inspections) are mainly caused by *inventory*, *waiting*, *overprocessing*, *rework*, the lack of *availability of machines*, the lack of *availability of man* and the *batch size*.

Together with the factors found in literature, the factors influencing the turnaround time found in the case study are the input for the synthesis presented in chapter 4. These factors will be compared and a current state framework of the turnaround time of in house repairs of engine MRO services is presented.

Part II

Analyze Phase

Chapter 4

Synthesis

This chapter contains a comprehensive synthesis of the literature review and the case study. This synthesis combines the knowledge from the literature on the conditions and the factors reducing the turnaround time of engine MRO services with the findings of the case study at KLM E&M Engine Services. The goal of this synthesis is to identify the main factors of influence on the turnaround time specifically for in house repairs of engine MRO services and to present the main problem areas of the process at the fanblades workstation. This chapter thus answers research question 5, *"do the factors found in literature correspond with the factors found in the case study?"*.

Therefore this synthesis discusses the main problem areas at the fanblades workstation (section 4.1), the factors of influence (section 4.2) and the performance measurement (section 4.3).

4.1 Main Problem Areas at Fanblades Workstation

The case study identified the main problem areas at the fanblades workstation. For each problem area different reasons were found that influenced the turnaround of the in house repairs of the engine MRO services. This section presents how these reasons influence the factors in the literature framework presented in chapter 2 and thus the turnaround time of the in house repairs of the engine MRO services. These reasons are the starting point for designing alternatives in order to reduce the turnaround time of the process.

- **Batching**
  Batching is a general reason for the appearance of waiting times. At the moment all fanblades of a set are moved through the system as one large batch. Batching influences the factor *batch size*. The large batches in the system result in a lot of work in progress and a lot of fanblades waiting while only one fanblade is repaired at a time. Therefore batching also influences the factors *inventory* and *waiting*.
- **Shotpeen Machine**
  The waiting times at shotpeening have multiple reasons. First of all waiting times are caused by fanblades waiting in the queue in front of the shotpeen machine. This queue is caused by the amount of work that is processed by the shotpeen machine, the absence

of the operator and both the PW1 and the plating shotpeen machines not being operated to full capacity. In summary, these reasons influence the factors *inventory*, *waiting* and *availability of the machine*.

- **Benchwork**
  The waiting times for benchwork are caused because the cracks in the fanblades are not removed the first time. This causes that fanblades needs to be blended again in order to remove the remaining cracks. These extra blending activities take extra time and thus cause waiting times. So, the reason for waiting times at benchwork influences the factor *rework*.

- **Seals Replacement**
  At seals replacement waiting times arise due to differences in the pace of the cleaning and inspection phase (Z42) and the repair phase (Z51) phase causing fanblades waiting in an input buffer in front of the seals removal. The reason for waiting times at the seals replacement thus influences the factors *inventory* and *waiting*.

- **Inspections**
  The waiting times for the inspections are caused by the inspector not being directly available when needed. Moreover waiting times are caused by inspectors performing inspections that are not required according to the manual. Therefore inspections influence the factors *overprocessing* and *availability of man*.

4.2 Current State Framework for Reducing Turnaround Times

As stated before, the main constraints in the fanblades workstation arise at batching, shotpeening, benchworking, replacing seals and inspections. These constraints are mainly caused by *inventory*, *waiting*, *overprocessing*, *rework*, the lack of *availability of machines*, the lack of *availability of man* and the *batch size*.

When combining these findings from the case study at KLM E&M with the literature framework presented in section 2.6, it can be concluded that not all factors that influence the turnaround time according to the literature actually have a strong impact on the turnaround time of these specific in house repairs of engine MRO services.

As only the factors that have a strong influence on the turnaround time of the in house repairs of engine MRO services are interesting for further research, the literature framework is updated into a current state framework, see figure 4.1. The factors on waste are presented on the left side of the framework and the factors on assets and resources are on the right side. It can be seen that only seven factors of influence are included in the current state framework. These factors are still a combination of Lean, Six Sigma, LSS and the TOC. Therefore this current state framework can still function as a tool for a combined implementation of the different process improvement methods.

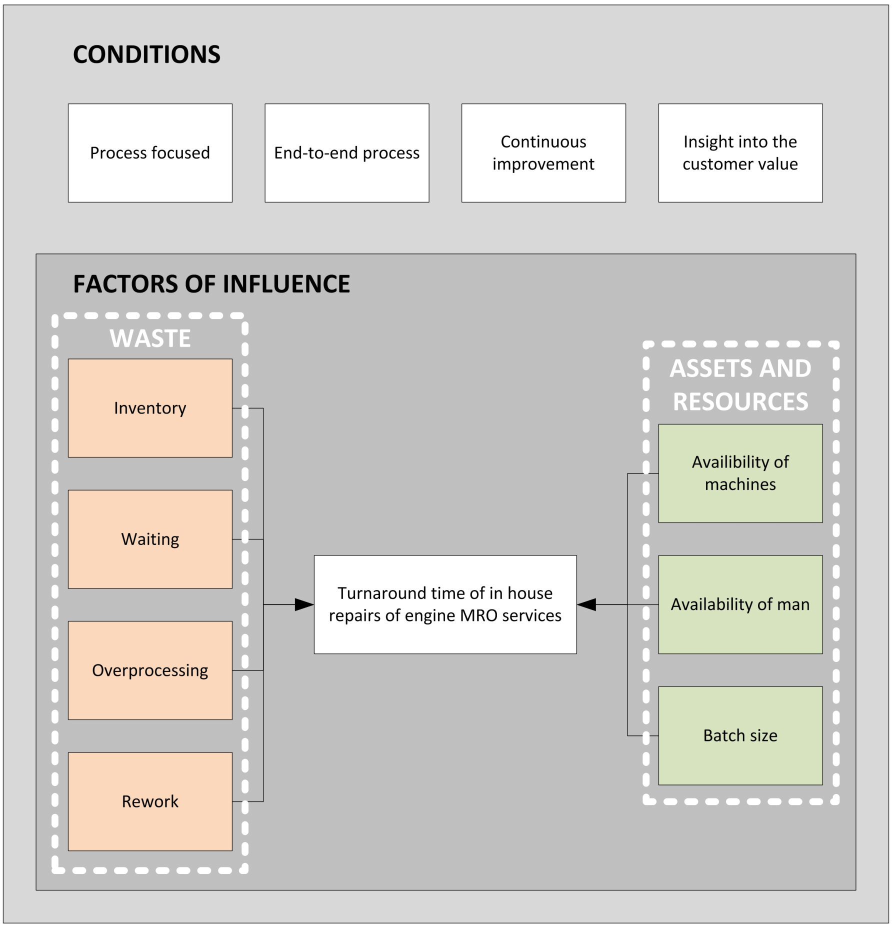


FIGURE 4.1: Current State Framework: Conditions and Factors of Influence

4.3 Performance Measurement

The case study shows that the performance measurement of the in house repairs of engine MRO services at KLM E&M is currently only based on the turnaround time of the different repair orders. However, the case study showed that this performance indicator does not provide a good and complete indication of the performance of the workstation. This has two reasons.

First, not the complete process is taken into account as the current performance indicator only takes the in house repair phase (Z51) into account. The performance of the cleaning and inspection phase (Z42) is not measured at the moment, but this phase surely is part of the repair process.

Moreover the current performance indicator measures the performance of one repair order at a time. A set of fanblades consists of multiple repair orders and therefore this performance indicator does not measure the performance for complete sets of fanblades.

The current performance indicator therefore is not sufficient for measuring the performance of the fanblades workstation. A new performance indicator should be introduced in order to measure the performance of the complete process for a complete set of fanblades.

The new performance indicator for the turnaround time of the in house repairs of the engine MRO services focuses on the result of the process and is therefore called a result performance indicator. Next to this result performance indicator, also performance indicators within the process are needed in order to early notice deviations in the process and to be able to localize the problems in the process. These new process performance indicators should be based on the factors of influence presented in the current state framework in figure 4.1.

At the moment there are no performance indicators measuring the process of the fanblades workstation. Therefore a new set of performance indicators needs to be defined. Together with the new result performance indicator for the turnaround time, these performance indicators provide managers the tools to control the process at the workstation. This new set of performance indicators must contain measurements for:

- The turnaround time of the complete process for the complete sets of fanblades,
- Inventory,
- Waiting,
- Overprocessing,
- Rework,
- Availability of Machines,
- Availability of Man, and
- Batch Size.

4.4 Conclusions Synthesis

Research question 5: Do the factors found in literature correspond with the factors found in the case study?

The factors found in the case study partly correspond with the factors found in literature. Therefore the literature framework is updated into the current state framework, see figure 4.1. The factors of influence in this framework are *inventory*, *waiting*, *overprocessing*, *rework*, *availability of machines*, *availability of man* and *batch size*.

Part III

Improve Phase

Chapter 5

Performance Measurement

This fifth chapter of the report presents the proposal for the new way of performance measurement. As stated in chapter 4, the current indicator for performance measurement is not sufficient for measuring the performance of the fanblades workstation. A new performance indicator need to be introduced in order to measure the performance of the complete process for a complete set of fanblades.

Next, also new performance indicators are needed in order to measure the performance of the factors of influence presented in chapter 4. Currently there are no performance indicators that measure the performance within the process. So, new process performance indicators need to be introduced.

Both the new result performance indicator on TAT and the new process performance indicators on the factors of influence are presented in this chapter. This chapter thus answers research question 6, *"how can the performance of the turnaround time of in house repairs of engine MRO services be measured?"*.

5.1 New Result Performance Indicator

The case study shows that the performance measurement of the in house repairs of engine MRO services at KLM E&M is currently not sufficient for measuring the performance of the fanblades workstation.

First, not the complete process is taken into account as the current performance indicator only takes the in house repair phase (Z51) into account. Moreover the current performance indicator does not measure the performance of a complete set of fanblades. A new performance indicator is needed in order to measure the performance of the complete process for a complete set of fanblades. The differences between the current and the new performance indicator are depicted in figure 5.1.

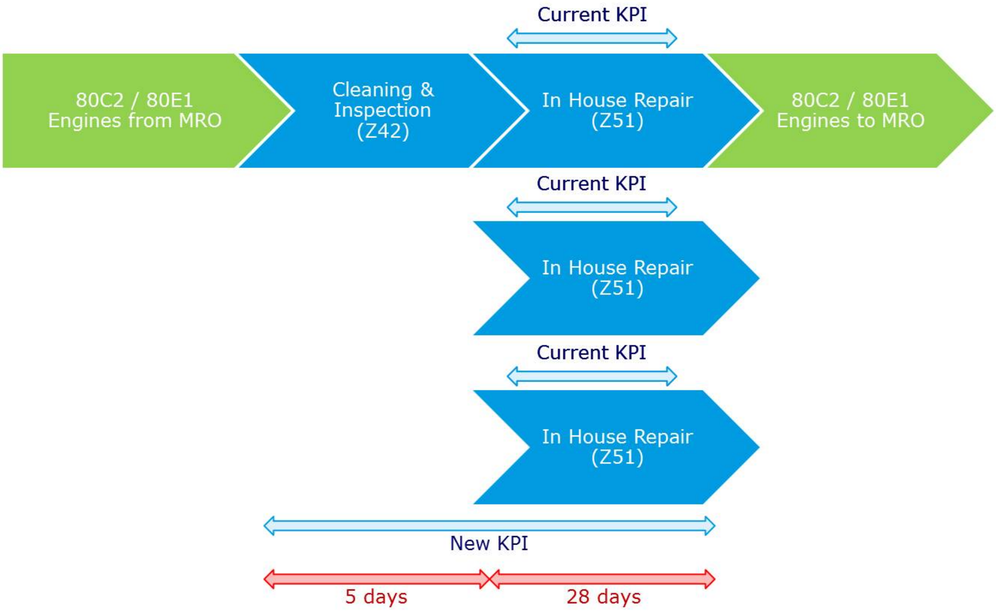


FIGURE 5.1: New KPI versus Current KPI

It can be seen that the new performance indicator provides insight in the performance of the complete set for the complete process. This way the real performance of the workstation is presented and this provides managers insight in the process. The performance of the workstation can be calculated by the formulas presented below.

$$TAT^{i}_{CompleteSet} = CompleteSet^{i}_{end} - CompleteSet^{i}_{start} \tag{5.1}$$

$$CompleteSet^{i}_{OnTime} = \begin{cases} 1, & \text{if } TAT^{i}_{CompleteSet} \leq 33 \\ 0, & \text{otherwise} \end{cases} \tag{5.2}$$

$$TAT_{performance} = \frac{\sum_{i \in I} CompleteSet^{i}_{OnTime}}{n} * 100\% \tag{5.3}$$

with:
$TAT^{i}_{CompleteSet}$ = Turnaround Time of the complete set i [day]
$CompleteSet^{i}_{end}$ = Finish day of a set i [day]
$CompleteSet^{i}_{start}$ = Start day of a set i [day]
$TATperformance$ = % of complete sets of fanblades delivered on time [%]
I = Set of all sets of fanblades
n = Number of complete sets in set I [#]

The current performance indicator for the turnaround time shows that 52% of the repair orders is delivered on time from the repair phase (Z51). The new performance indicator for the turnaround time shows that only 29% of the complete sets is delivered on time from the complete process.

5.2 New Process Performance Indicators

Next to the result performance indicator on the turnaround time, also performance indicators within the process are needed in order to early notice deviations in the process and to be able to localize the problems in the process. These new process performance indicators are based on the factors of influence presented in the current state framework in chapter 4.

At the moment there are no performance indicators measuring the process of the fanblades workstation. Therefore a new set of performance indicators is defined. This new set of performance indicators is presented in the sections below.

5.2.1 Inventory Performance Indicator

The performance of the inventory is equal to the amount of work in progress, see equation 5.4. This calculated by the amount of sets within the process excluding the sets in the input buffer. The ideal amount of sets in the process needs to be calculated based on more precise data on the set-up times, processing times, waiting times and the amount of input. The value of the inventory performance indicator needs to be compared with the ideal amount of sets in the process. In an ideal situation these numbers are equal.

$$Inventory_{Performance} = Work\ In\ Progress \tag{5.4}$$

5.2.2 Waiting Performance Indicator

The waiting times in the system need to measured in different three different ways. This way a complete overview of the waiting times is provided. All three performance indicators are presented below.

Waiting Times in Input Buffer
First, the waiting times of the sets in the input buffer need to be determined. This waiting time equals the time between the end of the cleaning and inspections phase (Z42) and the start of the repair phase (Z51) of all sets of fanblades *i*, see equation 5.5.

$$WaitingInput_{Performance} = \sum_{i \in I} Z51_{start} - Z42_{end} \tag{5.5}$$

Waiting Times in Process
Next, the percentage of the waiting times within the process need to be measured. This percentage is calculated by dividing the waiting times by the available time, see equation 5.6. The waiting times are equal to the turnaround time minus the weekends and the normative times of all sets of fanblades i. The available time is equal to the turnaround time minus the weekends of all sets of fanblades i.

$$WaitingProcess_{Performance} = \frac{\sum_{i \in I} TAT^{i}_{CompleteSet} - Weekend^{i} - Norm^{i}}{\sum_{i \in I} TAT^{i}_{CompleteSet} - Weekend^{i}} * 100\% \tag{5.6}$$

Waiting Times per Techniekcode

The third performance indicator on waiting times provides insight in the location of the waiting times within the process. The numbers are calculated the same way as the waiting times in the process. However, here the turnaround times and the normative times of one techniekcode k are used, see equation 5.7.

$$WaitingTechniekcode^{k}_{Performance} = \frac{\sum TAT^{k}_{Techniekcode} - Weekend^{k} - Norm^{k}}{\sum TAT^{k}_{Techniekcode} - Weekend^{k}} * 100\% \quad (5.7)$$

5.2.3 Overprocessing Performance Indicator

The performance indicator on overprocessing provides insight in the amount of unnecessary inspections within the process, see equation 5.8. The goal is maintain zero of these tasks. Therefore this number must be minimized.

$$Overprocessing_{Performance} = \#\ of\ unnecessary\ inspections\ within\ the\ process \quad (5.8)$$

5.2.4 Rework Performance Indicator

The rework performance indicator shows the amount of rework activities in the process, see equation 5.9. The goal is maintain zero of these activities. Therefore this number must be minimized.

$$Rework_{Performance} = \#\ of\ rework\ tasks\ within\ the\ process \quad (5.9)$$

5.2.5 Availability of Machines Performance Indicator

The availability of the machines is measured in two different ways. This way there is insight in both the technical and the human side of the availability of the machines. Both performance indicators are presented below.

Availability of the Shotpeen Machines

The availability of the machines presents the technical side. This is measured by dividing the amount of hours the machine is available by the amount of work in hours, see equation 5.10. The amount of hours the machine is available is calculated by the number of working days minus the number of days the machine is out of order times the amount of hours worked per day. When the value is above 100%, the amount of hours the machine is available is higher than the amount of work. This should not result in waiting time. When the value is below 100%, the amount of work exceeds the amount of hours the machine is available. This will result in waiting times.

$$AvailabilityOfMachines_{Performance} = \frac{\#\ of\ hours\ machine\ is\ available}{\#\ of\ hours\ work} * 100\% \quad (5.10)$$

Utilization of the Shotpeen Machines
The utilization of the machines shows the human side of the availability. This is measured by dividing the amount of hours the operators are working by the amount of work in hours, see equation 5.11. When the value is above 100%, the amount of hours worked by the operator is higher than the amount of work. This should not result in waiting time. When the value is below 100%, the amount of work exceeds the amount of hours the operator is working. This will result in waiting times.

$$UtilizationOfMachines_{Performance} = \frac{\#\ of\ hours\ worked\ by\ operator}{\#\ of\ hours\ work} * 100\% \tag{5.11}$$

5.2.6 Availability of Man Performance Indicator

The performance of the availability of man is measured by dividing the amount of hours the inspector is working by the amount of work in hours, see equation 5.12. When the value is above 100%, the amount of hours worked by the inspector is higher than the amount of work. This should not result in waiting time. When the value is below 100%, the amount of work exceeds the amount of hours the inspector is working. This will result in waiting times.

$$AvailabilityOfMan_{Performance} = \frac{\#\ of\ hours\ worked\ by\ inspector}{\#\ of\ hours\ work} * 100\% \tag{5.12}$$

5.2.7 Batch Size Performance Indicator

The performance on the batch size can be calculated by dividing the total number of fanblades repaired by the number of batches. The ideal number of fanblades per batch needs to be calculated based on more precise data on the set-up times, processing times and waiting times. The value of the batch size performance indicator needs to be compared with the ideal amount of fanblades per batch. In an ideal situation these numbers are equal.

$$BatchSize_{Performance} = \frac{\#\ of\ blades}{\#\ of\ batches} * 100\% \tag{5.13}$$

5.3 Conclusions Performance Measurement

Research question 6: How can the performance of the turnaround time of in house repairs of engine MRO services be measured?

The performance can be measured with the new result performance indicator on turnaround time. This performance indicator takes both the complete process and the complete set of fanblades into account. The performance within the process can be measured using a set of process performance indicators on *inventory*, *waiting*, *overprocessing*, *rework*, *availability of machines*, *availability of man* and *batch size*.

Chapter 6

Alternatives:
Design and Assessment

This chapter presents the alternatives in order to improve the current state of the system at the fanblades workstation. First the alternatives are designed, described and their impact on the turnaround time of in house repairs of the engine MRO services is determined in section 6.1. Afterwards the alternatives are assessed using a Multi-Criteria Analysis (MCA) in section 6.2. The MCA assesses the alternatives on their impact on different criteria.

Therefore this chapter answers research question 7, *"which alternatives can influence the factors that influence the turnaround time of in house repairs of engine MRO services?"*, and research question 8, *"what is the impact of these alternatives on the performance of the system?"*.

6.1 Design of the Alternatives

As stated before, this sections introduces the different alternatives for reducing the turnaround time at the fanblades workstation. Multiple alternatives are designed for the identified main problem areas in the process. These alternatives are designed based on the steps of the Theory of Constraints (TOC). Within the TOC there are two options when eliminating the constraints (Goldratt, 2013, Carl Pegels, 2005, Ehie, 2013, van Ede, 2013, Rand, 2000):

1. **Exploit the constraint at its maximum.**
   The constraint must produce its maximum output by removing the limitations on the constraint in order to fully use the capacity of the bottleneck (van Ede, 2013, Şimşit, 2014).
2. **Elevate the constraint in the system.**
   The capacity of the constraint is increased by investments in terms of, for example, time, effort and money (Şimşit, 2014, Rand, 2000). There are two options, namely:
   - Increase the capacity by investing in new, extra machines and men.
   - Increase the capacity by shifting work to other, already existing machines or men.

These options for eliminating the constraints are translated into different alternatives for the constraints identified in the case study. The alternatives are designed for the main problem areas *shotpeening*, *inspections*, *benchwork* and *batching*. For the main problem area *seal replacement* no alternatives are designed due to the fact that the waiting times are caused by an input buffer. It is assumed that this input buffer and the associated waiting times will automatically decrease when the alternatives on the other problem areas ensure a shorter TAT and a more predictable process.

6.1.1 Alternatives for Shotpeening

As stated before the waiting times at the shotpeen machine are a result of the amount of work passing through the shotpeen machine and the availability of the operator of the machine. Three alternatives are designed in order to reduce these waiting times.

6.1.1.1 Exploit the Constraint at its Maximum

Alternative 1: Advanced Operator Planning
The first alternative, A1, is focused on exploiting the full capacity of the shotpeen machine. This means that the shotpeen machine should be operated non-stop when there is work in line for the machine. In order to realize this, there should always be an operator controlling the machine. Here it is important to make sure that there is always at least one operator available, so the operators cannot have breaks together and their holidays should be aligned to each other. As at the moment only two people are working as shotpeen operator, more employees should be trained to control the machine.

Effect on the Turnaround Time
This alternative affects the waiting times at the shotpeen machine. The data analysis shows that shotpeening covers 22% of the total waiting times in the system. Based on the fact that the shotpeen machine currently is used for only 61% of the time, an advanced operator planning should result in no waiting times for shotpeening. However, it is unlikely that the planning will eliminate all waiting times. Therefore this alternative results in 75% less waiting times and this results in 16.5% less waiting times for the complete system. This equals a reduction of the TAT of 5.1 days.

6.1.1.2 Elevate the Constraint in the System

Alternative 2: Extra Shotpeen Machine
The second alternative, A2, focuses on increasing the shotpeen capacity. In order to increase this capacity an extra shotpeen machine is purchased. This way the shotpeen capacity at the PW1 workstation increases with 50%. The new shotpeen capacity is high enough to eliminate the queue in front of the machines. As at the moment only two people are working as shotpeen operator, more employees should be trained to operate both machines.

Effect on the Turnaround Time
This alternative affects the waiting times at the shotpeen machine. The data analysis shows that shotpeening covers 22% of the total waiting times in the system. By purchasing an extra shotpeen machine the total shotpeen capacity will be high enough to reduce the waiting times

to zero even if the shotpeen machines are not used to full utilization. Therefore this alternative results in 22% less waiting times. This equals a reduction of the TAT of 6.8 days.

Alternative 3: Combining PW1 and Plating Shotpeen Capacity
The third alternative on shotpeening also aims to increase the shotpeen capacity. Here the capacities of both shotpeen machines are combined. This can be realized by combining the queues of both machines into one queue. Next, it is important that all work can be performed on both machines. Therefore all shotpeen programs should be available on both machines. Moreover all operators must be able to operate both machines. This way all work can be performed by all operators on both machines. The combined queue results in less waiting times as in the new situation much more flexibility is built into the process. This way waiting times can be removed from the shotpeen activities.

Effect on the Turnaround Time
This alternative affects the waiting times the shotpeen machine. The data analysis shows that shotpeening covers 22% of the total waiting times in the system. Based on the fact that the shotpeen machines are used for only 61% and 16% of the time, this alternative should result in no waiting times for shotpeening. Therefore this alternative will result in 22% less waiting times. This equals a reduction of the TAT of 6.8 days.

6.1.2 Alternatives for Inspections

This sections presents the alternatives designed for reducing the waiting times caused by the inspections. These waiting times are mainly caused by overprocessing and the lack of availability of the inspector. The alternatives influence these factors in order to reduce the turnaround time.

6.1.2.1 Exploit the Constraint at its Maximum

Alternative 4: Digitized Documentation
The first alternative for the inspections, A4, focuses on making sure that the inspector is inspecting all the time and that he does not have to spend time on other tasks like documentation. In order to make sure that the time spent on documentation is minimized, the documentation needs to be digitized. In an ideal situation the inspector checks the fanblades and approves this by one click on a mobile device instead of the approving it with the current amount of paperwork.

Effect on the Turnaround Time
Currently the waiting times caused by inspections equal 14% of the total waiting times in the system. Digitized documentation reduces these waiting times with 50% as the documentation at the moment consumes a lot of time. Therefore this alternative results in 7% less waiting times for the complete system. This equals a reduction of the TAT of 2.2 days.

6.1.2.2 Elevate the Constraint in the System

Alternative 5: Remove Non Required Inspections
This alternative, A5, focuses on removing the inspections from the process that are not required according to the manual. This way overprocessing is removed from the system and the tasks of the inspector are reduced. This way the availability of the inspector increases. This alternative

thus influences waiting and the availability of man. However, it should be taken into account that removing these inspections from the process increases the risk of rework later on in the process. These rework activities increase the turnaround time.

Effect on the Turnaround Time
This alternative causes that the waiting time caused by inspections equals zero for the inspections that are not required according to the manual. It is assumed that these inspections account for around half the waiting times. Therefore the waiting times for the inspections decrease with 50%. Moreover the removing the inspections affects the waiting times of the other inspections by reducing the workload of the inspectors. This will decrease the waiting times of the remaining inspections with 50%. Next, the risk of the rework later on in the process causes extra waiting times that increase the TAT. Currently the waiting times caused by inspections equal 14% of the total waiting times in the system. After implementing this alternatives the waiting times are reduced to 7% of the total waiting times. This equals a reduction of the TAT of 2.2 days.

Alternative 6: Self-Inspections
Another way for elevating the constraint of the inspections is to introduce self-inspections for the inspections that are not required according to the manual, A6. This way the employees are allowed to inspect their own work or the work of a direct colleague. These self-inspections make sure that the work is inspected directly after finishing the task. The waiting times will thus be minimized. Here it is important to standardize the way of working in order to control the quality of the inspection. Another advantage of this alternative is that the workload of the inspectors will decrease and thus the waiting times for the other inspections also will decrease.

Effect on the Turnaround Time
The implementation of the self-inspections ensures that the waiting time caused by inspections equals zero for the inspections that are not required according to the manual. It is assumed that these inspections account for around half the waiting times. Therefore the waiting times for the inspections will decrease with 50%. Moreover the self-inspections affect the waiting times of the other inspections by reducing the workload of the inspectors. This will decrease the waiting times of the remaining inspections with 50%. Currently the waiting times caused by inspections equal 14% of the total waiting times in the system. After implementing this alternatives the waiting times are reduced to 4% of the total waiting times. This equals a reduction of the TAT of 3.1 days.

6.1.3 Alternatives for Benchwork

The alternatives for reducing the waiting times at benckworking are presented in this section. These alternatives aim to minimize the rework activities in order to reduce the turnaround time.

6.1.3.1 Exploit the Constraint at its Maximum

Alternative 7: Expand Blending Activities
The first alternative on benchwork, A7, focuses on expanding the blending activities. This means that the employee blends a somewhat thicker layer from the edge of the blade. This way the employee knows for sure that all cracks are removed from the blade and no rework activities are needed.

Effect on the Turnaround Time
This alternative makes sure that the waiting times for rework are removed from the system. However, the normative times of the blending tasks are increased for all blades of the set. Therefore this alternative does not affect the turnaround time. Currently the benchwork waiting times cover 23% of all waiting times. After implementing this alternative, the benchwork waiting times still cover 23% of all waiting times. So the TAT is not reduced.

6.1.3.2 Elevate the Constraint in the System

Alternative 8: Automation of Blending
The next alternative on blending, A8, focuses on increasing the blending capacity by purchasing a blending machine. This way the blending activities are automated and all rework activities are removed from the system. Moreover automation of blending will ensure that the blending activities take less time and the employee is not longer needed and thus available for fulfilling other tasks.

Effect on the Turnaround Time
The automation of blending makes sure that the waiting times are removed from the system. Moreover this alternative reduces the process times. Currently the benchwork waiting times cover 23% of all waiting times. After implementing the automation of blending, these waiting times are zero. This equals a reduction of the TAT of 7.1 days.

Alternative 9: Combine Forces
The third alternative on benchwork waiting times, A9, also focuses on increasing the capacity. Here the employees of other workstations assist in the blending activities as no specific training is required to fulfill these tasks. This way the capacity available for the blending activities is increased. It is important to note that this is only possible if the employees do not have to fulfill tasks at their primary workstation.

Effect on the Turnaround Time
The implementation of this alternative results in less waiting times as more employees fulfill the blending activities. However, these extra employees are not available all the time. Therefore only a quarter of the waiting times will be removed from the system. Currently the waiting times of the benchwork activities cover 23% of all waiting times in the system. After implementing A9, the waiting times for benchwork are 17.3% of all waiting times in the system. This equals a reduction of the TAT of 1.8 days.

6.1.4 Alternatives for Batching

This section presents the different alternatives on batching. As batching is not a constraint like shotpeening, inspections and benchwork, another way of designing alternatives is used. First, two alternatives are designed that introduce an alternative batch size to the system. More specifically, batches of 4 or 8 fanblades are introduced, since these numbers are most logical given the capacities of the various machines in the system. Next to these smaller batches, also an alternative focusing on introducing flow to the system is presented as more flow increases the throughput of the batches in the system. This way the capacity of the system is better utilized. This third alternative on batching introduces the drum, buffer, rope technique.

Alternative 10: Batch Size of 8 Fanblades
The first alternative on batching, A10, presents a new and smaller batch size, namely eight fanblades per batch. This way the amount of work in progress and thus the waiting times in the process are minimized.

Effect on the Turnaround Time
Calculations in appendix C show that batches of 8 fanblades almost halve the time needed to repair a complete set of fanblades. This reduces the turnaround time with 2.5 days.

Alternative 11: Batch Size of 4 Fanblades
The concept of this alternative, A11, is the same as the previous alternative, but here a batch contains four fanblades instead of eight. Again a smaller batch size ensures less work in progress and thus less waiting times in the process.

Effect on the Turnaround Time
Calculations in appendix C show that batches of 4 fanblades will more than halve the time needed to repair a complete set of fanblades. This reduces the turnaround time with 3.1 days.

Alternative 12: Drum, Buffer, Rope
The third alternative on batching, A12, introduces the drum, buffer, rope technique. This technique is already explained in section 2.5.2. This technique introduces flow to the system resulting in less inventory and waiting times in the process. The results are realized because the inventories are removed from the system by just-in-time deliveries and the flow will be balanced in order to ensure a predictable process.

Effect on the Turnaround Time
The result of this alternative depends on the size of the batch. A reduction of the batch size with factor X results in a reduction of the waiting times with factor X. This is because smaller batches result in more flow through the system.

6.2 Assessment of the Alternatives

This section discusses the assessment of the alternatives. The alternatives are assessed on different criteria using a multi-criteria analysis (MCA). First, the criteria are presented in section 6.2.1. These criteria take both the customers wishes and the factors influencing the turnaround time into account. Next, the assessment methodology MCA is further explained in section 6.2.2 and the results of the MCA are presented in section 6.2.3. Lastly, this section presents the validation of the results of the MCA in section 6.2.4.

6.2.1 Assessment Criteria

As stated before, the assessment criteria are based on both the wishes of the customers and the factors in current state framework. This way the criteria cover all aspects that influence the potential of the different alternatives and provide an overview of the impact of the alternatives on the performance of the complete system.

In section 1.7 the criteria following from the wishes of the customer are presented. The customers want faster and cheaper MRO services of high quality. Therefore the *turnaround time*, the *costs of a repair* and the *quality of the product* need to be taken into account. Moreover this section introduced the criterion *ease of implementation* as this is important for KLM E&M next to the criteria focusing on the customer needs.

Next to these criteria presented before, the factors in the current state framework should be taken into account. These factors are inventory, waiting, overprocessing, rework, availability of machines, availability of man and batch size. When implementing alternatives that influence one or more of these factors, the turnaround time of the system is affected. Therefore the *turnaround time* should be included as a criterion. Moreover these alternatives will require changes in the system and these changes cost money. Most of the alternatives require only changes of the process. These changes lead to *implementation costs*. For some alternatives some larger investments are needed. These investments lead to *investment costs*. Both the implementation costs and the investment costs can influence the *process costs*, the costs of a repair.

So when combining the criteria following from both the wishes of the customers, the wishes of KLM E&M and the factors in current state framework, five criteria can be identified, namely:

1. **Turnaround Time**
   The turnaround time (TAT) is the time needed for the in house repair of a complete set of fanblades. This is measured in days and the lower the TAT, the better.

2. **Process Costs**
   The process costs present the costs of a in house repair of a complete set of fanblades. These process costs are measured in euros. In order to offer the customer cheaper MRO services the goal is to reduce the process costs.

3. **Implementation Costs**
   The implementation costs cover the costs of the implementation of the alternative and the associated investments. These costs are measured in euros.

4. **Quality of the Product**
   The quality of the product is based on two aspects. First it is important that the fanblades meet the requirements according to the manual. This is checked during the final inspection. So the results of this inspection are important. Next, the expected remaining lifetime of the fanblades affects the quality of the product. So the quality of the product is measured by the results of the final inspection and the expected remaining lifetime of the fanblades.

5. **Ease of Implementation**
   The ease of the implementation indicates the amount of changes needed for the implementation. The more changes needed, the lower the ease of implementation. So the ease of the implementation is measured by the amount of changes needed for the implementation of the alternative.

6.2.2 Multi-Criteria Analysis

This section explains the assessment methodology multi-criteria analysis (MCA). The MCA methodology is applicable for this research as it is a helpful tool for decision making. The MCA makes it possible to compare the effects of multiple alternatives on a set of criteria. Moreover it is possible the assign weights to the criteria in order to include the importance of the criteria in the analysis. Next, the MCA can be used for both quantitative and qualitative scores and the scores do not need to be monetized. This way the MCA provides a clear overview of the impact of the alternatives on the performance of the complete system.

The multi-criteria analysis consists of three steps. All three steps are discussed in this section.

First, the weights of the different criteria are determined. Here it is important to make sure the weights and thus the importance of the criteria correspond with the ideas of the decision maker. In order to achieve this, the decision maker should be involved in the determination of the weights of the criteria. The weights of the criteria are found by an one-on-one comparison of the criteria. This method is easy to understand and is therefore a useful tool when involving the decision maker in the process. Moreover this method makes it possible to set up nuanced weights which provide a better understanding of the differences in terms of importance. The one-on-one comparison of the criteria compares the importance of the criteria in pairs. The comparison of all pairs leads to the weights of the different criteria. The most important criterion has the highest weight while the least important criterion has the lowest weight. This way the importance of the criteria is taken into account in the assessment of the alternatives. The one-on-one comparison of the criteria can be found in appendix D. The weights of the criteria are determined in consultation with the decision makers at KLM E&M. This comparison shows that the turnaround time is the most important criterion. The quality of the product and the process costs have the same rank and are ranked slightly less important than the turnaround time, but still more important than the implementation costs. The least important criterion is the ease of implementation.

Second, the alternatives are assessed on the five criteria. Here a score is given for all alternatives on the different criteria. These scores vary from 1, worst, to 5, best. The measurement level is ordinal meaning that the scores have a clear order but the differences between the scores are not all equal. This is caused by the fact that the exact effects of the alternatives on the criteria are not known and therefore estimates are used. If the exact effects are determined in further research, it is possible to change the measurement level to an interval and ratio measurement level. Here the differences between the scores are all equal. When assigning the scores to the alternatives, first the best and the worst alternative are scored. The best alternative is scored 5 and the worst alternative is scored 1. Next, the other alternatives are ranked in the range between the best and worst alternatives. The explanation and the results of the ranking can be found in appendix D.

Last, the weights from the first step are multiplied by the scores from the second step. This results in the final scores for the MCA. The summation of the scores for the different criteria shows the total score of the alternative. This score presents the impact of an alternative on the performance of the complete system taking the importance of the criteria into account. The higher the score, the more attractive an alternative is.

6.2.3 Results of the Multi-Criteria Analysis

This section presents the results of the multi-criteria analysis (MCA), see figure 6.1. The highest scores are colored dark green. Slightly less scoring alternatives are colored light green. The alternatives that are colored yellow or red score worse.

It can be seen that three alternatives are most attractive as these alternatives have the highest scores. These alternatives are colored dark green. Three alternatives have a slightly less high scores, but are still attractive. These alternatives are colored light green. The other six alternatives score worse and are not taken into account. These alternatives are colored yellow and red.

		C1 Turnaround Time	C2 Process Costs	C3 Implementation Costs	C4 Quality of the Product	C5 Ease of Implementation	Sum
A1	Advanced Operator Planning	1,22	1,10	0,76	0,66	0,51	4,25
A2	Extra Shotpeen Machine	1,53	0,22	0,15	0,66	0,10	2,66
A3	Combining Shotpeen Capacity	1,53	1,10	0,76	0,66	0,31	4,36
A4	Digitized Documentation	0,61	0,22	0,15	1,10	0,10	2,19
A5	Remove Non Required Inspections	0,61	0,66	0,76	0,66	0,41	3,10
A6	Self-Inspections	0,92	1,10	0,46	0,66	0,31	3,44
A7	Expand Blending Activities	0,31	1,10	0,46	0,22	0,20	2,29
A8	Automation of Blending	1,53	0,22	0,15	0,66	0,10	2,66
A9	Combine Forces	0,61	1,10	0,61	0,44	0,10	2,86
A10	Batch Size of 8 Fanblades	0,92	1,10	0,61	0,66	0,31	3,59
A11	Batch Size of 4 Fanblades	0,92	1,10	0,61	0,66	0,20	3,49
A12	Drum, buffer, rope	1,53	1,10	0,76	0,66	0,41	4,46

FIGURE 6.1: Scores of the Alternatives Including Weights for the Multi-Criteria Analysis

The MCA shows that six alternatives are attractive to implement. However, A10 and A11 cannot be implemented simultaneously. Therefore only the best scoring alternative, A10, is selected. Thus, based on the results of the MCA five alternatives are selected:

- A1: Advanced Operator Planning
- A3: Combining Shotpeen Capacity
- A6: Self-Inspections
- A10: Batch Size of 8 Fanblades
- A12: Drum, buffer, rope

Together these alternatives reduce the average turnaround of a set of fanblades from 41 days to 16.4 days, for calculations see appendix C. So, on average all sets of fanblades will be delivered on time. Looking at the data set used for this research, at the moment only 29% of the sets of fanblades is delivered on time. After implementing the alternatives, 98% of all sets of fanblades is delivered on time, for calculations see appendix C.

6.2.4 Validation of the Results

In order to validate the results of the MCA a sensitivity analysis is performed. This sensitivity analysis tests the sensitivity of the results by changing the weights of the criteria. If different sets of weights result in the same outcomes, the results of the MCA are valid.

The sensitivity analysis consists of two parts. First, the MCA is performed with equal weights for all criteria. Here all five criteria have the weight 0.2. Next, the MCA is performed multiple times and every time one of the original weights is increased with 50%. The outcomes of the different MCA are compared to the results of the original MCA with the original set of weights. The weights used for the validation and the results of the new MCA are presented in appendix D. This appendix also includes an extensive discussion of the findings of the sensitivity analysis.

Almost all results of the original MCA match with the results of the new MCA. However, it should be noted that alternatives A2 and A8 should be taken into account in situations with a very high importance of the turnaround time. So based on this sensitivity analysis it can be concluded that the results of the MCA are valid.

6.3 Conclusions Alternatives

Research question 7: Which alternatives can influence the factors that influence the turnaround time of in house repairs of engine MRO services?

A set of 12 different alternatives is designed in order to reduce the turnaround time. A MCA selected five alternatives that influence the performance of the system best. These alternatives are:

- A1: Advanced Operator Planning
- A3: Combining Shotpeen Capacity
- A6: Self-Inspections
- A10: Batch Size of 8 Fanblades
- A12: Drum, buffer, rope

Research question 8: What is the impact of these alternatives on the performance of the system?

At the moment the average turnaround time of the system is 41 days. The implementation of the selected alternatives results in a turnaround time of 16.4 days. So, on average all sets of fanblades are delivered on time. Looking at the data set used for this research, at the moment only 29% of the sets of fanblades is delivered on time. After implementing the alternatives, 98% of all sets of fanblades is delivered on time.

Chapter 7

Implementation at KLM E&M Engine Services

This chapter discusses the implementation of the alternatives at KLM E&M Engine Services. Here a distinction if made between the implementation at the fanblades workstation (section 7.1) and the other workstations at the engine shop (section 7.2). This chapter thus answers research question 9, *"which alternatives should be implemented at KLM E&M Engine Services and how?"*, and research question 10, *"to what extent are these alternatives applicable at other processes within KLM E&M Engine Services?"*.

7.1 Implementation at Fanblades Workstation

The implementation at the fanblades workstation consists of two parts: the implementation of the new way of performance measurement and the implementation of the set of alternatives. Both are discussed below.

7.1.1 Implementation Performance Measurement

This section discusses the implementation of the new way of performance measurement. It is advised to start with this new way as soon as possible. This way the data can provide an overview of the current state of the system before the alternatives are implemented. The new performance indicators should be included into the Connected Business Balance Score Card in order to ensure managers are confronted with the numbers. Moreover it is advised to update the numbers at least every day in order to quickly notice and localize irregularities in the process. This way managers can intervene fast and effective.

The new way of performance measurement can only be implemented when the way of data collection is more precise. It is required to note the exact starting and finish moment of the task. Moreover the precise set-up times, processing times and waiting times are required. Also the rework activities need to be measured.

7.1.2 Implementation Alternatives

The multi-criteria analysis selected a set of five alternatives that score best on the criteria. This section advises on the implementation of these alternatives.

- **A1: Advanced Operator Planning**
  The advanced operator planning can be implemented right away. Here it is very important to show the operators of the shotpeen machine the importance of this planning as this alternative requires a change in the behavior of the operator. Therefore it is very important to involve the operators in the new planning. The skill-managers need to verify that it is actually put into practice. Moreover extra shotpeen operators should be trained.
- **A3: Combining Shotpeen Capacity**
  In order to implement the combined shotpeen capacity it is important that both machines contain all programs needed for the different parts. The installation of the programs can be done by the shotpeen operators. The largest share of the work is to install programs on the plating shotpeen machine. As this machine is only used one shift per day, this should not cause any problems. Moreover the existing and the new operators should be trained to operate on both machines. Next, the shotpeen activities should be sent to one queue. Here a change in the shop travelers is needed. This should be changed by the engineering department. After these preparations are done, the combined shotpeen capacity can be implemented.
- **A6: Self-Inspections**
  Before the self-inspections can be implemented it is needed to define which inspections are not required according to the manual. Next, a standard way of working should be introduced in order to ensure that all employees inspect the fanblades the same and the right way. Also the shop travelers should be updated so the self-inspections are a true part of the repair route. All three tasks should be done in close cooperation with the engineering department.
- **A10: Batch Size of 8 Fanblades**
  It is advised to directly start to work with batches of eight fanblades. In order to make this possible, the carts of the fanblades need to be updated. The new carts can be made from the current carts by the employees working at the fanblades department. Moreover it is important to make sure that the fanblades can always be traced in the shop in order to ensure that all fanblades return to the same engine. Next, a shop traveler should be printed for each batch of fanblades.
- **A12: Drum, buffer, rope**
  Lastly, it is advised to implement the drum, buffer, rope technique. The implementation of this alternative should start after the other alternatives are implemented. This way the system can be balanced for the future state of the system. In order to implement the drum, buffer, rope technique more precise set-up times, processing times and waiting times are required. These times can simply be found by measuring all activities at the workstation.

Next to these recommendations on the implementation of each of the alternatives, it is recommended to organize an action-workout session. This session should take around three or four days in order to kick-start the transition of the workstation. During this session a combination of theory and practice is discussed. The theory is important in order to explain the employees why these alternatives are useful and to provide them insights in the potential of the future state of the workstation. Next the theory is translated into practice and the employees immediately start the implementation process by for example measuring the process times of the activities at the workstation or updating the carts for the new batches of fanblades. This way the action-workout session contributes to the acceptance of the alternatives by the employees and it helps to quickly introduces the future state of the workstation.

7.2 Implementation at Other Workstations

For the other workstations it is advised to implement the new way of performance measurement. Here the same counts as for the implementation at the fanblades workstation, the data collected from the system needs to be more precise.

Besides it is interesting to look for opportunities to introduce the set of alternatives at the other workstation. It is expected that the alternatives will be applicable at other workstations as the waiting times at other workstations are high as well. The alternatives will be specifically interesting for the workstations that contain shared resources, that work with large batches of parts and that have similar repair workscopes.

7.3 Conclusions Implementation

Research question 9: Which alternatives should be implemented at KLM E&M Engine Services and how?

Next to the new way of performance measurement, it is advised to first implement alternatives A1, A3, A6 and A10. Alternative A12 should be implemented after the other alternatives are implemented.

Research question 10: To what extent are these alternatives applicable at other processes within KLM E&M Engine Services?

For the other workstations it is advised to implement the new way of performance measurement. Besides it is interesting to look for opportunities to introduce the different alternatives. The alternatives will be specifically interesting for the workstations that contain shared resources, that work with large batches of parts and that have similar repair workscopes.

Part IV

Control Phase

Chapter 8

Evaluation and Control

After implementing the alternatives it is important to maintain the new state, the future state of the system. In order to maintain the future state of the system, managers need tools to evaluate and control of the performance of the system. This chapter answers the final research question, research question 11, *"how can the future performance of the system be monitored and controlled?"*.

Managers need tools to evaluate and control performance. These tools should provide the manager insights in the results of the system, but also in the performances within the process. Therefore the current state framework presented in chapter 4 is used as a starting point for the design of these tools. After the implementation of the alternatives not all factors of influence still need to be measured. Overprocessing can be excluded, because the alternatives make sure that all overprocessing tasks are removed from the system. Moreover batch size is excluded as the future state of the system only contains smaller batches of eight fanblades. Therefore the current state framework needs to be updated in order to provide the managers tools for the evaluation and control of the future state of the system. The future state framework is presented in figure 8.1. Again the factors on waste are presented on the left side of the framework and the factors on assets and resources are on the right side. It can be seen both overprocessing and batch size are removed from the framework. The performance of the remaining factors is measured using the performance indicators presented in chapter 5. These performance indicators are needed in order to quickly notice and localize irregularities in the process. This way managers can intervene fast and effective.

> *Research question 11: How can the future performance of the system be monitored and controlled?*
>
> The future performance of the system can be monitored and controlled using the future state framework, see figure 8.1. The performance indicators of the factors of influence within this framework are used in order to quickly notice and localize irregularities in the process. This way managers can intervene fast and effective.

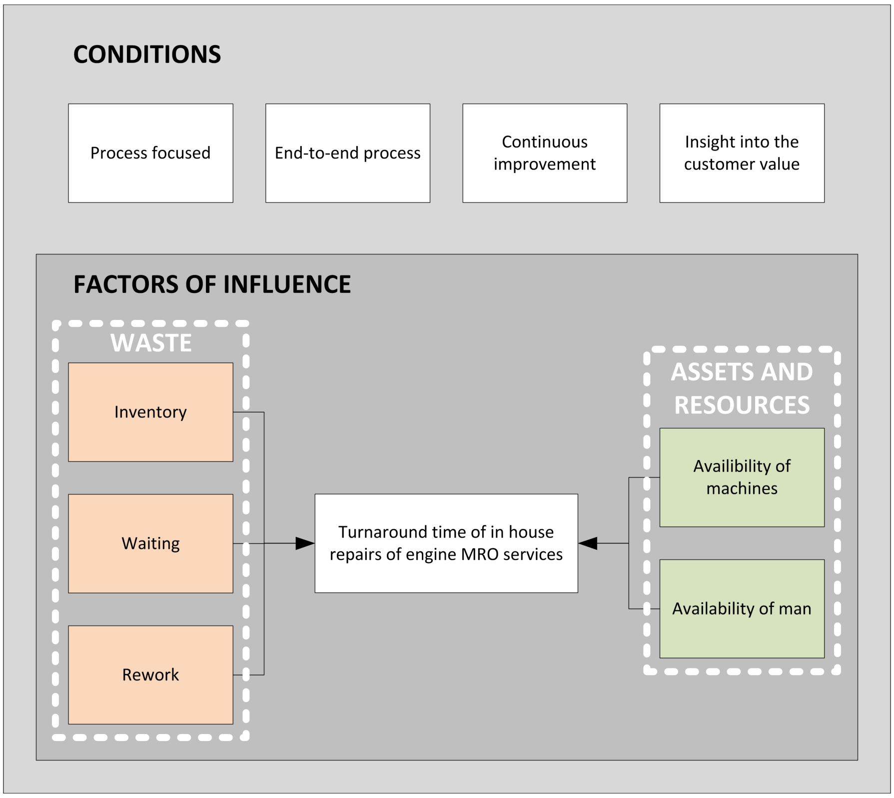


FIGURE 8.1: Future State Framework: Conditions and Factors of Influence

Chapter 9

Conclusions and Recommendations

The ninth chapter of this report consists of the conclusions (section 9.1) and the recommendations (section 9.2) of the research. Moreover this chapter discusses the limitations of the research (section 9.3).

9.1 Conclusions

This section answers the main research question of the research: *"Which alternatives can be identified in order to reduce the turnaround time of the in house repairs of aircraft engine MRO services and what is the impact of these alternatives on the performance of the system?"*. The answer to this question is based on the sub research questions answered earlier in this report. The conclusions can be divided in three main conclusions. First of all, the turnaround time of in house repairs of engine MRO services is influenced by seven factors, namely *inventory*, *waiting*, *overprocessing*, *rework*, *availability of machines*, *availability of man* and *batch size*. Next, the performance measurement needs to be updated in order to measure the turnaround time of a complete set of fanblades and the values of the factors of influence. Finally, a set of five alternatives needs to be implemented in order to reduce the turnaround time of in house repairs of engine MRO services. All three main conclusions are discussed in more detail in the three subsections below.

9.1.1 Factors of Influence

Business Process Management, Lean, Six Sigma, Lean Six Sigma and the Theory of Constraints are widely known methods for process improvement. These methods all highlight multiple factors influencing the turnaround time. These factors are *transport*, *inventory*, *motion*, *waiting*, *overprocessing*, *overproduction*, *defects and rework*, *availability of machines*, *availability of man*, *availability of material*, *availability of methods* and the *batch size*.

The case study at the KLM E&M Engine Services shows that in practice *inventory*, *waiting*, *overprocessing*, *rework*, the lack of *availability of machines*, the lack of *availability of man* and the *batch size* are the main factors influencing the turnaround time of in house repairs of engine MRO services.

When combining these findings from the case study with the findings from literature, it can be concluded that not all factors that influence the turnaround time according to the literature, actually have a strong impact on the turnaround time of the in house repairs of engine MRO services.

As only the factors that have a strong influence on the turnaround time of the in house repairs of engine MRO services are interesting for further research, only the seven factors of influence found in the case study at KLM E&M Engine Services are taken into account. These factors are still a combination of Lean, Six Sigma, Lean Six Sigma and the Theory of Constraints.

9.1.2 Performance Measurement

The second main conclusion focuses on the measurement of the performance. The case study shows that currently the performance measurement of the in house repairs of engine MRO services at KLM E&M is only based on the turnaround time of the different repair orders. However, the case study showed that this performance indicator does not provide a good and complete indication of the performance of the workstation as this performance indicator does not take the complete process and not the complete set of fanblades into account. Therefore a new performance indicator is introduced in order to measure the performance of the complete process for a complete set of fanblades. The new performance indicator can be calculated by the formulas below.

$$TAT^{i}_{CompleteSet} = CompleteSet^{i}_{end} - CompleteSet^{i}_{start} \tag{9.1}$$

$$CompleteSet^{i}_{OnTime} = \begin{cases} 1, & \text{if } TAT^{i}_{CompleteSet} \leq 33 \\ 0, & \text{otherwise} \end{cases} \tag{9.2}$$

$$TAT_{performance} = \frac{\sum_{i \in I} CompleteSet^{i}_{OnTime}}{n} * 100\% \tag{9.3}$$

with:
$TAT^{i}_{CompleteSet}$ = Turnaround Time of the complete set i [day]
$CompleteSet^{i}_{end}$ = Finish day of a set i [day]
$CompleteSet^{i}_{start}$ = Start day of a set i [day]
$TATperformance$ = % of sets of fanblades delivered on time [%]
I = Set of all sets of fanblades
n = Number of complete sets in set I [#]

The new performance indicator for the turnaround time focuses on the result of the process and is therefore called a result performance indicator. Next to this result performance indicator, also performance indicators within the process are needed in order to early notice deviations in the process and to be able to localize the problems in the process. Currently, there are no performance indicators measuring the performance of the process. The new process performance indicators measure the values of the factors presented in section 9.1.1.

9.1.3 Set of Alternatives

A set of 12 different alternatives is designed in order to reduce the turnaround time. Based on a multi-criteria analysis (MCA) the best alternatives are selected in order to improve the performance of the system. The MCA assesses the alternatives based on five criteria, namely turnaround time, process costs, implementation costs, quality of the product and ease of the implementation.

The MCA selected five alternatives to be the most attractive, namely:

- A1: Advanced Operator Planning
- A3: Combining Shotpeen Capacity
- A6: Self-Inspections
- A10: Batch Size of 8 Fanblades
- A12: Drum, buffer, rope

Together these alternatives ensure that in the future state of the system 98% of all sets of fanblades are delivered on time with an average turnaround time of 16.4 days.

9.2 Recommendations

This section presents the recommendations that emerge from this research. These recommendations are divided into two kinds of recommendations: the recommendations for science (section 9.2.1) and the recommendations for KLM E&M Engine Services (section 9.2.2).

9.2.1 Recommendations for Science

From a scientific perspective it is recommended to perform multiple case studies in order to validate the framework containing the factors of influence as currently the framework is based on the findings of only one case study. First of all it is interesting to perform another case study within KLM E&M Engine Services. Next, it is also interesting to perform a case study at another engine MRO service provider or a company in another MRO business. It is expected that the framework will be specifically useful for processes that contain shared resources, that work with large batches of parts and that have similar workscopes.

9.2.2 Recommendations for KLM E&M Engines Services

For KLM E&M Engines Services it is recommended to directly implement the new way of performance measurement at all workstations in the engine shop. This way managers can quickly notice and localize irregularities in the process and thus intervene fast and effective. The new way of performance measurement can only be implemented when the way of data collection is more precise. It is required to note the exact starting and finish moment of the task. Moreover the precise set-up times, processing times and waiting times are required.

Next to the new way of performance measurement, it is advised to first implement alternatives A1, A3, A6 and A10. Alternative A12 should be implemented after the other alternatives are implemented. However, before the alternatives are implemented, it is important do more in depth research on the costs and the benefits of the alternatives as the current numbers are based on estimates. Moreover it is advised to organize an action-workout session when implementing the alternatives. This way the employees can be involved in the process and the implementation can be kick-started. This workout session can also be used to organize a pilot for the alternatives in order to test the potential of the alternatives again.

Finally, it is interesting to look for opportunities to introduce the alternatives at other workstations. The alternatives will be specifically interesting for the workstations that contain shared resources, work with large batches of parts and have similar workscopes.

9.3 Limitations

Next to the conclusions and the recommendations it is important to present the limitations of the research. These limitations should be taken into account when considering implementing the results of the research.

- The data used for the data analysis of the research has two limitations. First the moment a task starts and ends is only given in days and not the exact time. This causes that the turnaround times used in the research are not accurate. Moreover it is expected that the normative times do not exactly comply with reality. Therefore additional research is needed in order to find the exact data for the set-up times, processing times and waiting times. Based on this data the conclusions can be presented with higher certainty. However, it is not expected that these more exact data have a strong impact on the results of the research as the results are so clear.
- Next, the process costs and the implementation costs are based on estimations. In order to determine the financial feasibility more in-depth, further financial research is needed on the costs and the profits of the alternatives.
- Finally, there is no documentation on the reasons for sets of fanblades being delivered late. Therefore the conclusions are based on the data of the last year and a limited set of observations and interviews. Therefore the findings of the research may be questionable. More data and observations are needed in order to underline and confirm the results of this research.

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Appendix A

Extensive Company Profile

This appendix gives an extensive company description of KLM in order to create an overview of the organization, the context of the research.

The 'Koninklijke Luchtvaartmaatschappij' (KLM) is founded on October 7, 1919 (KLM, 2015d) and is the oldest airline still operating under its original name (KLM, 2015b). Queen Wilhelmina granted the designation 'Royal' to KLM even before it was founded in September 1919 (KLM, 2015d). The first KLM flight departed from London in May 1920 heading for Schiphol (KLM, 2015d). The first intercontinental KLM flight departed four years later in October 1924 (KLM, 2015d). This first intercontinental flight headed to Batavia on Java, now Jakarta, and took 54 days (Luchtvaartnieuws, 2009).

Nowadays KLM is a large worldwide carrier. In 2014, KLM transported 27,740,000 passengers and 759,732 tons of cargo (KLM, 2014a). KLM now serves 135 destinations, of which 67 are long-haul destinations and 68 are medium-haul destinations (KLM, 2015f). These destinations are served using a hub-and-spoke network. The hub-and-spoke principle originates from the USA and was introduced during the 80's. KLM was the first European airline that used a hub-and-spoke network (KLM, 2015g).

The vision of KLM for the future is 'to become the most customer centric, innovative and efficient European network carrier' (KLM, 2015b). 'KLM wants to be the customers' first choice, to be an attractive employer for its staff and, a company that grows profitably for its shareholders' (KLM, 2015b). In order to realize this vision KLM offers services in three different areas: the passengers business, the cargo business and the engineering and maintenance business. To serve all three areas, KLM cooperates with different parties and in various ways. Below more information is given on the KLM Group, the Air France - KLM Group and the Skyteam.

A.1 KLM Group

KLM is the core of the KLM Group. Besides KLM also KLM Cityhopper, Transavia en Martinair are part of this group (KLM, 2015b). All three airlines are 100% owned by KLM and thus are full daughter companies of KLM.

KLM Cityhopper
KLM Cityhopper is a regional airline only serving routes within Europe. On these routes the passenger may expect the same service and hospitality as on a ”normal” KLM flight. KLM Cityhopper does not sell the tickets for its flights, but these tickets are sold by KLM. (KLM Cityhopper, 2015)

Transavia
Transavia is a low cost airline and offers flights within Europe and to countries around the Mediterranean Sea. This way Transavia connects its bases in the Netherlands, Amsterdam Airport Schiphol, Rotterdam-The Hague Airport and Eindhoven Airport, with popular summer and winter holiday destinations. (Transavia, 2015)

Martinair
Martinair is specialized in air cargo transportation and offers routes worldwide. Until the end of 2011, Martinair also offered passenger flights, but nowadays Martinair is only focused on the air cargo business. For this reason Martinair now cooperates closely with KLM Cargo. (Martinair, 2015)

A.2 Air France - KLM Group

In 2004 KLM merged with Air France and the Air France - KLM Group was founded. With this merger Air France - KLM became the largest European airline group. Together they own 573 aircraft and carry more than 77 million passengers per year. Combining the networks of the two airlines offers passengers 243 destinations. (KLM, 2015a)

A.3 Skyteam

The Skyteam is an worldwide alliance of 20 airlines. The Skyteam is founded in 2000 and KLM joined the alliance in 2004 (Skyteam, 2015b). Joining the Skyteam benefits both KLM and the passengers. KLM can offer more destinations through alliance partnerships. An example of these partnerships is a code share agreement (Skyteam, 2015c). This means that two or more airlines offer seats on the same flight using different flight codes (Aeroflot, 2015). This way airlines can offer seamless transfers and more destinations and this results in an increased market position of the airline (Skyteam, 2015c). The alliance also benefits the passengers as this eases the process of booking, checking in, traveling and transferring on flights with a transfer (Skyteam, 2015c). Moreover the passengers can fly to more destinations. Together the alliance flies more than 665 millions passengers to over a 1,000 destinations in 179 countries (Skyteam, 2015a).

Appendix B

Value Stream Map

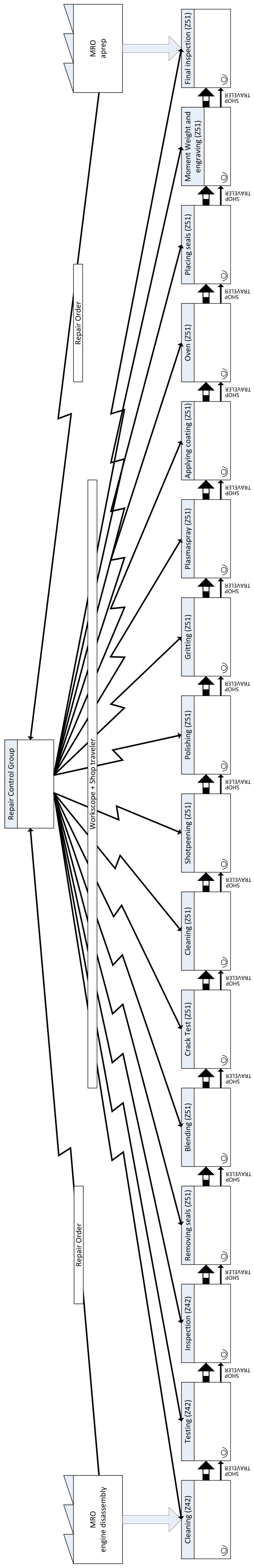

FIGURE B.1: Value Stream Map In House Repairs Fanblades Workstation

Appendix C

Alternatives

C.1 Alternatives on Batching

The TAT based on the normative times of a complete set with batches of 34 or 38 fanblades is calculated by adding up all normative times. This results in a TAT of 67.5 hours. This equals 6.3 days based on 2 shifts per day of 5.4 productive hours.

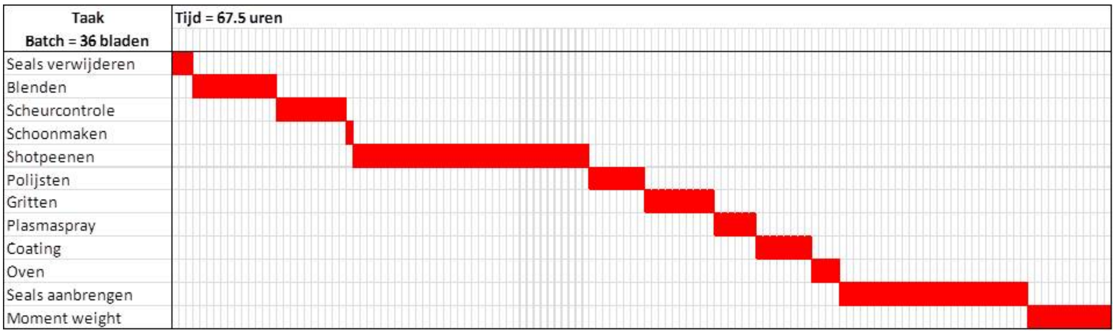

FIGURE C.1: TAT based on the normative times of a complete set with batches of 34 or 38 fanblades

The normative times for batches of 4 or 8 fanblades are calculated by:

$$\frac{normative\ times\ for\ a\ complete\ set}{34\ or\ 38} * 4\ or\ 8 \tag{C.1}$$

The TAT based on the normative times of a complete set with batches of 4 or 8 fanblades is calculated by pushing the normative to each other as close as possible. This is visualized in figures C.3 and C.2. As can be seen in the figures, the smaller batches result in lower TAT. Batches of 4 fanblades result in a TAT of 24.5 hours. This equals 2.3 days. The batches of 8 fanblades results in a TAT of 31.5 hours. This equals 2.9 days.

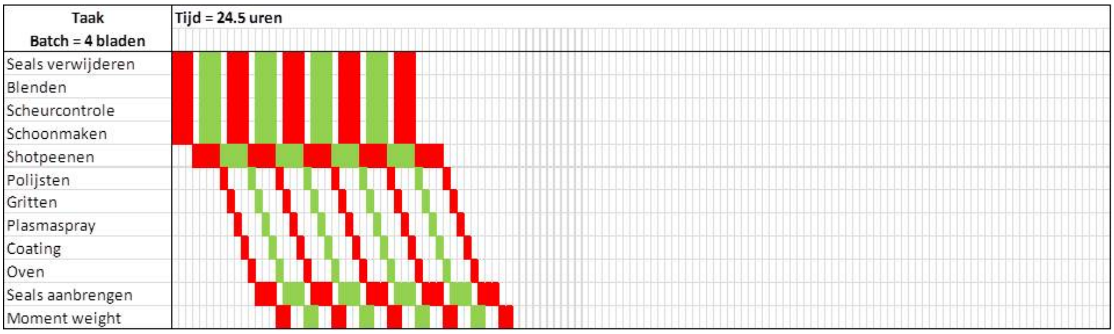

FIGURE C.2: TAT based on the normative times of a complete set with batches of 4 fanblades

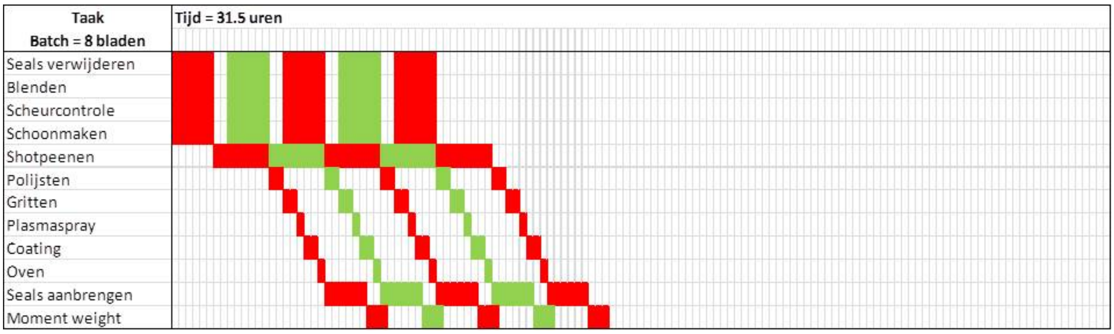

FIGURE C.3: TAT based on the normative times of a complete set with batches of 8 fanblades

C.2 Combining the Selected Alternatives

This section presents the effect of the combined implementation of the selected alternatives on the turnaround time of the in house repairs. The individual effects of the alternatives are already presented in chapter 6. These effects are:

- **A1:** a reduction of the TAT with 5.1 days.
- **A3:** a reduction of the TAT with 6.8 days.
- **A6:** a reduction of the TAT with 3.1 days.
- **A10:** a reduction of the TAT with 2.5 days.
- **A12:** the batch size decreases with a factor of approximately 5 (38:8), the waiting times will therefore also reduce with a factor 5.

It is important to note that the effects of alternatives A1, A3 and A6 come at their best when there is flow in the process. This flow can be created by the implementation of alternatives A10 and A12. Moreover it should be noted that alternatives A10 and A12 do not come at their best when there is a lot of waste in the process, because waste hinders the throughput of the batches through the process. Therefore it is concluded that all alternatives are needed in order to achieve the best results as the reduction of the TAT depend on each other.

So, the individual effect of the alternatives cannot simply be summed. Therefore it is assumed that A1, A3, A6 and A10 remove waste from the process in order to ensure that A12 comes at its best. The reduction of the waiting times is then calculated by the effect of A12. This effect is calculated below.

The current waiting times of the repair phase (Z51) are:

$$Current\ TAT\ Z51 - Current\ Normative\ Times\ Z51 = 31.5 - 6.3 = 25.2\ days \tag{C.2}$$

The new waiting times of the the repair phase (Z51) are:

$$Current\ Waiting\ Times\ Z51\ /\ 5 = 25.2\ /\ 5 = 5.0\ days \tag{C.3}$$

The new TAT of Z51 is:

$$New\ Normative\ Times\ Z51 + New\ Waiting\ Times\ Z51 = 2.9 + 5.0 = 7.9\ days \tag{C.4}$$

The new complete TAT is:

$$New\ TAT\ Z51 + Current\ TAT\ Z42 = 7.9 + 8.5 = 16.4\ days \tag{C.5}$$

Together these alternatives reduce the average turnaround of a set of fanblades from 41 days to 16.4 days. So, on average all sets of fanblades are delivered on time. Looking at the data set used for this research, at the moment only 29% of the sets of fanblades is delivered on time. After implementing the alternatives, 98% of all sets of fanblades are delivered on time.

Appendix D

Multi-Criteria Analysis

As explained in chapter 6, the multi-criteria analysis (MCA) consists of three parts. First, the weights of the criteria are determined using an one-on-one comparison of the criteria. Second, the alternatives are assessed on all five criteria. Here a score varying from 1 to 5 is assigned to all alternatives on all criteria. Last, the scores of the alternatives are multiplied by the weights of the criteria. This way the final scores of the MCA are found. These final scores represent the attractiveness of the alternatives. All three steps of the MCA are described below.

Weights of the Criteria

As stated before, the weights of the criteria are found using an one-on-one comparison of the criteria. Here all pairs of criteria are compared on the importance of the criterion. The most important criterion of the pair gets the score 2. The least important criterion gets the score 1/2. If both criteria have the same importance, both criteria get the score 1. The scores of the criteria can be found in figure D.1.

		C1 Turnaround Time	C2 Process Costs	C3 Implementation Costs	C4 Quality of the Product	C5 Ease of Implementation	Sum	Weight
C1	Turnaround Time	1	2	2	2	2	9,00	0,31
C2	Process Costs	0,5	1	2	1	2	6,50	0,22
C3	Implementation Costs	0,5	0,5	1	0,5	2	4,50	0,15
C4	Quality of the Product	0,5	1	2	1	2	6,50	0,22
C5	Ease of Implementation	0,5	0,5	0,5	0,5	1	3,00	0,10

FIGURE D.1: Weights of the Criteria for the Multi-Criteria Analysis

It can be seen that the turnaround time is more important than all other criteria. This is due to the fact that reducing the turnaround time is the main goal of this research. Moreover the turnaround time is important as this is one of the main agreements with the customer and a low turnaround time is an important competitive advantage for KLM E&M.

Next, it can be seen that both the process costs and the quality of the product are more important than the implementation costs and the ease of the implementation. This is due to the fact that both the process costs and the quality of the product are part of the customer agreements and it is important for KLM E&M to meet these agreements. Moreover, as these criteria are part of the customer agreements, low process costs and high quality of the products are an important competitive advantage for KLM E&M. Besides, the process costs are important for KLM E&M in order to make sure the process is still profitable.

Moreover figure D.1 shows that the implementation costs are more important than the ease of the implementation, but less important than all other criteria. KLM E&M preferably does not spend a lot of money on the implementation of the alternatives, but if the effects on the turnaround time, the process costs and the quality of the products are very positive, then high implementation costs are definitely worth considering.

Finally, the ease of the implementation is less important than all other criteria. In an ideal situation the implementation of the alternatives is very easy, but if an alternative has a positive effect on the other criteria, it is not a deal-breaker if the alternative not that easy to implement.

After the one-on-one comparison of the criteria, the scores are summed. The weights are determined by dividing the sum of the scores of one criteria by the sum of the scores of all criteria. This way the weights add up to 1.

It can be seen in the most right column of figure D.1 that the turnaround time is the most important criterion. The quality of the product and the process costs have the same rank and are ranked slightly less important than the turnaround time, but still more important than the implementation costs. The ease of implementation is the least important criterion.

Scoring the Alternatives

The next step of the MCA is the assessment of the alternatives on all five criteria. Here all alternatives are scored on the different criteria. These scores vary from vary from 1, worst, to 5, best. When assigning the scores to the alternatives, first the best and the worst alternative are scored. The best alternative is scored 5 and the worst alternative is scored 1. Next, the other alternatives are ranked in the range between the best and worst alternatives. The scores can be found in figure D.2 and are discussed below.

Turnaround Time

First all alternatives are scored on the turnaround time. The effects of the alternatives on the turnaround time are already presented in chapter 6. These effects are translated in a score between 1 and 5 in order to be able to compare these effects with the scores on the other criteria.

- A1 - Advanced Operator Planning: reduction of 5.1 days, this leads to a score of 4.
- A2 - Extra Shotpeen Machine: reduction of 6.8 days, this leads to a score of 5.

- A3 - Combining Shotpeen Capacity: reduction of 6.8 days, this leads to a score of 5.
- A4 - Digitized Documentation: reduction of 2.2 days, this leads to a score of 2.
- A5 - Remove Non Required Inspections: reduction of 2.2 days, this leads to a score of 2.
- A6 - Self-Inspections: reduction of 3.1 days, this leads to a score of 3.
- A7 - Expand Blending Activities: reduction of 0 days, this leads to a score of 1.
- A8 - Automation of Blending: reduction of 7.1 days, this leads to a score of 5.
- A9 - Combine Forces: reduction of 1.8 days, this leads to a score of 2.
- A10 - Batch Size of 8 Fanblades: reduction of 2.5 days, this leads to a score of 3.
- A11 - Batch Size of 4 Fanblades: reduction of 2.5 days, this leads to a score of 3.
- A12 - Drum, buffer, rope: reduction of 7.8 days based on a batch size of 8 fanblades, this leads to a score of 5.

Process Costs
The process costs present the costs of a in house repair of a complete set of fanblades. In order to offer the customer cheaper MRO services the goal is to reduce the process costs. The scores of the alternatives on these costs are presented below.

- A1 - Advanced Operator Planning: the implementation of A1 is based on a change of the way of working and reduce the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A2 - Extra Shotpeen Machine: this alternative requires the purchase of a new shotpeen machine. Due to the depreciation of the machine, the process costs will increase. Therefore this alternative scores a 1 on this criterion.
- A3 - Combining Shotpeen Capacity: the implementation of A3 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A4 - Digitized Documentation: this alternative requires the purchase of a new digitized documentation system. The high investment costs will increase the process costs. Therefore this alternative scores a 1 on this criterion.
- A5 - Remove Non Required Inspections: the implementation of A5 removes the non required inspection from the process and therefore increases the risk of rework later on in the process. As this rework is detected at the end of the process, a lot of work needs to be redone. This causes a extra process costs. Therefore this alternative scores a 3 on this criterion.
- A6 - Self-Inspections: the implementation of A6 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.

- A7 - Expand Blending Activities: the implementation of A7 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A8 - Automation of Blending: this alternative requires the purchase of a new blending machine. Due to the depreciation of the machine, the process costs will increase. Therefore this alternative scores a 1 on this criterion.
- A9 - Combine Forces: the implementation of A9 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A10 - Batch Size of 8 Fanblades: the implementation of A10 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A11 - Batch Size of 4 Fanblades: the implementation of A11 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.
- A12 - Drum, buffer, rope: the implementation of A12 reduces the turnaround time without adding costs to the process. Therefore more work can be done in the same time and the process costs are reduced. This alternative scores a 5 on the process costs.

Implementation Costs
Next, the scores of the alternatives on the implementation costs are determined. Here both the investment costs and the implementation costs are taken into account. The scores are explained below.

- A1 - Advanced Operator Planning: the implementation of A1 is based on a change of the way of working of the shotpeen operators. This change can be reached without high implementation costs. Therefore A1 scores a 5 on this criterion.
- A2 - Extra Shotpeen Machine: this alternative requires the purchase of a new shotpeen machine. Therefore the implementation costs of this alternative are very high and this alternative is scored with a 1.
- A3 - Combining Shotpeen Capacity: the implementation of A3 does not require large investments. However all programs need to be installed on both machines, but this can be done by the existing shotpeen operators. Therefore A3 scores a 5.
- A4 - Digitized Documentation: this alternative requires the purchase of a new digitized documentation system. Therefore the implementation costs of this alternative are very high and this alternative is scored with a 1.
- A5 - Remove Non Required Inspections: the implementation of A5 does not require large investments. However all inspections need to be checked with the manual, but this can be done by the existing engineers. Therefore A5 scores a 5 on implementation costs.

- A6 - Self-Inspections: the implementation of A5 does not require large investments. However a standard way of working needs to be developed for all inspections. This needs to be done by engineers, but this takes a lot of time and thus money. Therefore this alternative scores a 3 on implementation costs.
- A7 - Expand Blending Activities: the implementation of A6 does not require large investments. However all blending task descriptions need to be updated and the employees need to change their way of working. Together this takes a lot of time and thus money. Therefore this alternative scores a 3 on implementation costs.
- A8 - Automation of Blending: this alternative requires the purchase of a new blending machine. Therefore the implementation costs of this alternative are very high and this alternative is scored with a 1.
- A9 - Combine Forces: the implementation of A9 is based on a change of the way of working of all employees in the engine shop. This change can be reached without high implementation costs, but it takes a lot of time and effort. Therefore A9 scores a 4 on this criterion.
- A10 - Batch Size of 8 Fanblades: this alternative changes the number of fanblades per batch. The process remains the same, but the existing carts are updated. This can be done by the employees themselves. Therefore A10 scores a 4 on implementation costs.
- A11 - Batch Size of 4 Fanblades: this alternative changes the number of fanblades per batch. The process remains the same, but the existing carts are updated. This can be done by the employees themselves. Therefore A10 scores a 4 on implementation costs.
- A12 - Drum, buffer, rope: the implementation of A12 is based on a change of the way of working of the fanblades employees and on a change of the way of planning. These changes can be reached without high implementation costs. Therefore A12 scores a 5 on this criterion.

Quality of the Product
As stated in chapter 6, the quality of the product is based on two aspects, namely the quality of the product measured by the results of the final inspection and the expected remaining lifetime of the fanblades. The scores of the alternatives on this criterion are presented below.

- A1 - Advanced Operator Planning: this alternative does not affect the quality of the product. Therefore A1 scores a 3 on the quality of the product.
- A2 - Extra Shotpeen Machine: this alternative does not affect the quality of the product. Therefore A2 scores a 3 on the quality of the product.
- A3 - Combining Shotpeen Capacity: this alternative does not affect the quality of the product. Therefore A3 scores a 3 on the quality of the product.
- A4 - Digitized Documentation: this alternative does not affect the results of the final check or the remaining lifetime of the fanblades, but it provides a delighter to the customer as a digitized documentation system offers KLM E&M the opportunity to give the customers insight in the progress of their repairs. This influences the quality of the product experienced by the customers. Therefore A4 scores a 5 on this criterion.

- A5 - Remove Non Required Inspections: this alternative does not affect the quality of the product. Therefore A5 scores a 3 on the quality of the product.
- A6 - Self-Inspections: this alternative does not affect the quality of the product. Therefore A6 scores a 3 on the quality of the product.
- A7 - Expand Blending Activities: expanding the blending activities means that the employee blends a somewhat thicker layer from the fanblades. This causes that some of the fanblades are shorter than necessary. As the length of the fanblades is an important indicator of the lifetime of the fanblades, this alternative scores a 1 on this criterion.
- A8 - Automation of Blending: this alternative does not affect the quality of the product. Therefore A8 scores a 3 on the quality of the product.
- A9 - Combine Forces: this alternative is based on employees from other workstations helping out at the fanblades workstation. These employees do not need extra training for the blending activities. However, due to the fact that these employees are not experienced with the blending tasks, it is possible that these employees blend a somewhat thicker layer from the fanblades than necessary. This causes that some of the fanblades are shorter than necessary and this has a negative effect on the remaining lifetime of these fanblades. Therefore A9 scores a 2 on the quality of the product.
- A10 - Batch Size of 8 Fanblades: this alternative does not affect the quality of the product. Therefore A10 scores a 3 on the quality of the product.
- A11 - Batch Size of 4 Fanblades: this alternative does not affect the quality of the product. Therefore A11 scores a 3 on the quality of the product.
- A12 - Drum, buffer, rope: this alternative does not affect the quality of the product. Therefore A12 scores a 3 on the quality of the product.

Ease of Implementation
Finally, the alternatives are scored on the ease of the implementation. The ease of the implementation indicates the amount of change needed for the implementation. The more change needed, the lower the ease of implementation. The scores are explained below.

- A1 - Advanced Operator Planning: the implementation of A1 is based on a change of the way of working of the shotpeen operators. However, these changes are not major changes. Therefore A1 scores a 5 on the ease of implementation.
- A2 - Extra Shotpeen Machine: this alternative requires the purchase of a new shotpeen machine. This purchase costs a lot of money and therefore A2 is not easy to implement as enough budget needs to be released by the management. Therefore A2 scores a 1.
- A3 - Combining Shotpeen Capacity: the implementation of A3 requires all programs to be installed on both machines and moreover the shop travelers need to be updated. Due to these changes, this alternative scores a 3 on ease of implementation.

- A4 - Digitized Documentation: this alternative requires the purchase of a new digitized documentation system. This purchase costs a lot of money and therefore A4 is not easy to implement as enough budget needs to be released by the management. Therefore A4 scores a 1.
- A5 - Remove Non Required Inspections: in order to implement A5, all inspections need to be checked with the manual. Next the non required inspections need to be removed from the system. These are not major changes and therefore A5 scores a 4 on ease of implementation.
- A6 - Self-Inspections: in order to implement A6, all inspections need to be checked with the manual. Next for the non required inspections, a standard way of working needs to be developed and introduced to the employees. These are not minor changes to the process, but these changes will take a lot of time. Therefore A6 scores a 3 on this criterion.
- A7 - Expand Blending Activities: the implementation of A7 requires major changes in the way the employees work. As these changes are on existing tasks it is hard to implement these changes. Therefore A7 scores a 2 on ease of implementation.
- A8 - Automation of Blending: this alternative requires the purchase of a new blending machine. This purchase costs a lot of money and therefore A8 is not easy to implement as enough budget needs to be released by the management. Therefore A8 scores a 1 on this criterion.
- A9 - Combine Forces: the implementation of A9 requires major changes in the way the employees work. As these changes require the employees to do extra work, these changes are hard to implement. Therefore A9 scores a 1 on ease of implementation.
- A10 - Batch Size of 8 Fanblades: this alternative requires an update of the existing carts for the fanblades. Moreover the shop traveler must be compiled for each batch instead of for each repair order. Next, the employees need to work in batches of 8 instead of 34 or 38, so changes in the way they work are required. All changes are not major changes, but as it are a lot changes this alternative scores a 3 on the ease of the implementation.
- A11 - Batch Size of 4 Fanblades: the implementation of A11 requires the same changes as discussed for A10. However, some extra changes are needed as the batch size does not comply with the capacity of most of the machines in the process. Therefore employees for example need to combine batches in order to fill a machine to its capacity. This alternatives thus scores a 2 on the ease of implementation.
- A12 - Drum, buffer, rope: the implementation of A12 requires a new way of planning. However, this new way of planning does not affect the process, only the pace of starting a new repair. Therefore A12 scores a 4 on the ease of implementation.

All scores explained can be found in figure D.2. Here a complete overview of the effects of the alternatives on the set of criteria is presented.

		C1 Turnaround Time	C2 Process Costs	C3 Implementation Costs	C4 Quality of the Product	C5 Ease of Implementation	Sum
A1	Advanced Operator Planning	4	5	5	3	5	22
A2	Extra Shotpeen Machine	5	1	1	3	1	11
A3	Combining Shotpeen Capacity	5	5	5	3	3	21
A4	Digitized Documentation	2	1	1	5	1	10
A5	Remove Non Required Inspections	2	3	5	3	4	17
A6	Self-Inspections	3	5	3	3	3	17
A7	Expand Blending Activities	1	5	3	1	2	12
A8	Automation of Blending	5	1	1	3	1	11
A9	Combine Forces	2	5	4	2	1	14
A10	Batch Size of 8 Fanblades	3	5	4	3	3	18
A11	Batch Size of 4 Fanblades	3	5	4	3	2	17
A12	Drum, buffer, rope	5	5	5	3	4	22

FIGURE D.2: Scores of the Alternatives for the Multi-Criteria Analysis

Results of the MCA

As both the weights of the criteria and the scores of the alternatives on these alternatives are known, the results of the MCA can be calculated. In order to find these results, the scores of the alternatives are multiplied by the weights of the criteria. The summation of the new scores of an alternative for the different criteria shows the total score of the alternative. This score presents the impact of an alternative of the performance of the complete system taking into account the importance of the criteria. The higher the score, the more attractive the alternative.

The results of the MCA are presented in figure D.3. The highest scores are colored dark green. Slightly less scoring alternatives are colored light green. The alternatives that are colored yellow or red score worse.

It can be seen that three alternatives are most attractive as these alternatives have the highest scores. These alternatives are colored dark green. Three alternatives have slightly less high scores, but are still attractive. These alternatives are colored light green. The other six alternatives score worse and are not taken into account. These alternatives are colored yellow and red.

The MCA shows that six alternatives are attractive to implement. However, A10 and A11 cannot be implemented simultaneously. Therefore only the best scoring alternative, A10, is selected. Thus, based on the results of the MCA five alternatives are selected:

- A1: Advanced Operator Planning
- A3: Combining Shotpeen Capacity

- A6: Self-Inspections
- A10: Batch Size of 8 Fanblades
- A12: Drum, buffer, rope

	C1 Turnaround Time	C2 Process Costs	C3 Implementation Costs	C4 Quality of the Product	C5 Ease of Implementation	Sum
A1 Advanced Operator Planning	1,22	1,10	0,76	0,66	0,51	4,25
A2 Extra Shotpeen Machine	1,53	0,22	0,15	0,66	0,10	2,66
A3 Combining Shotpeen Capacity	1,53	1,10	0,76	0,66	0,31	4,36
A4 Digitized Documentation	0,61	0,22	0,15	1,10	0,10	2,19
A5 Remove Non Required Inspections	0,61	0,66	0,76	0,66	0,41	3,10
A6 Self-Inspections	0,92	1,10	0,46	0,66	0,31	3,44
A7 Expand Blending Activities	0,31	1,10	0,46	0,22	0,20	2,29
A8 Automation of Blending	1,53	0,22	0,15	0,66	0,10	2,66
A9 Combine Forces	0,61	1,10	0,61	0,44	0,10	2,86
A10 Batch Size of 8 Fanblades	0,92	1,10	0,61	0,66	0,31	3,59
A11 Batch Size of 4 Fanblades	0,92	1,10	0,61	0,66	0,20	3,49
A12 Drum, buffer, rope	1,53	1,10	0,76	0,66	0,41	4,46

FIGURE D.3: Scores of the Alternatives Including Weights for the Multi-Criteria Analysis

Validation of the Results

In order to validate the results of the MCA a sensitivity analysis is performed. This sensitivity analysis tests the sensitivity of the results by changing the weights of the criteria. If the different sets of weights result in the same outcomes, the results of the MCA are valid.

The sensitivity analysis consists of two parts. First, the MCA is performed with equal weights for all criteria. Here all five criteria have the weight 0.2. This set of weights is called W1: equal weights. Next, the MCA is performed multiple times and every time one of the original weights is increased with 50%. These new sets of weights are called W2 to W6. The outcomes of the different MCA are compared to the results of the original MCA with the original set of weights. This original set of weights is called W0: the reference weights.

All sets of weights are presented in figure D.4. The first column presents the original set of weights. The other columns present the new set of weights. The red colored cells contain the adjusted weights.

	W0 Reference Weights	W1 Equal Weights	W2 Increased Weight C1	W3 Increased Weight C2	W4 Increased Weight C3	W5 Increased Weight C4	W6 Increased Weight C5
C1 Turnaround Time	0,31	0,2	0,46	0,31	0,31	0,31	0,31
C2 Process Costs	0,22	0,2	0,22	0,33	0,22	0,22	0,22
C3 Implementation Costs	0,15	0,2	0,15	0,15	0,23	0,15	0,15
C4 Quality of the Product	0,22	0,2	0,22	0,22	0,22	0,33	0,22
C5 Ease of Implementation	0,10	0,2	0,10	0,10	0,10	0,10	0,15

FIGURE D.4: Weights of the Criteria for the Validation of the MCA

The results of the different MCA are found exactly the same as for the original MCA: the scores of the alternatives are multiplied by the weights of the criteria. The summation of the scores of an alternative for the different criteria shows the total score of the alternative. This score presents the impact of an alternative of the performance of the complete system taking into account the importance of the criteria. The higher the score, the more attractive the alternative.

Figure D.5 presents the results of all MCA performed in order to validate the results. The first column presents the original results of the MCA and the other columns present the results of the new MCA.

	W0 Reference Weights	W1 Equal Weights	W2 Increased Weight C1	W3 Increased Weight C2	W4 Increased Weight C3	W5 Increased Weight C4	W6 Increased Weight C5
A1 Advanced Operator Planning	4,25	4,40	4,86	4,81	4,64	4,58	4,51
A2 Extra Shotpeen Machine	2,66	2,20	3,42	2,77	2,74	2,99	2,71
A3 Combining Shotpeen Capacity	4,36	4,20	5,12	4,91	4,74	4,69	4,51
A4 Digitized Documentation	2,19	2,00	2,49	2,30	2,26	2,74	2,24
A5 Remove Non Required Inspections	3,10	3,40	3,41	3,43	3,48	3,43	3,31
A6 Self-Inspections	3,44	3,40	3,90	3,99	3,67	3,77	3,59
A7 Expand Blending Activities	2,29	2,40	2,44	2,84	2,52	2,40	2,39
A8 Automation of Blending	2,66	2,20	3,42	2,77	2,74	2,99	2,71
A9 Combine Forces	2,86	2,80	3,17	3,42	3,17	3,08	2,92
A10 Batch Size of 8 Fanblades	3,59	3,60	4,05	4,14	3,90	3,92	3,75
A11 Batch Size of 4 Fanblades	3,49	3,40	3,95	4,04	3,80	3,82	3,59
A12 Drum, buffer, rope	4,46	4,40	5,22	5,01	4,84	4,79	4,66

FIGURE D.5: Scores of the Alternatives Including Weights for the Validation of the MCA

It can be seen that most of the results of the MCA match with the results of the original MCA. Some important findings need to be mentioned:

- First of all, it can be seen that the three alternatives that scored best in the original MCA, also score best in other MCA. These are alternatives A1, A3 and A12.
- Next, the alternatives scoring second best in the original MCA, also score second best or even better in all other MCA. These alternatives are A6, A10, A11.
- Also alternatives A4, A7 and A9 have the same results for the new MCA as for the original MCA. These alternatives scored bad (red and yellow) in the original MCA and still perform bad in the new MCA.
- The alternatives A2 and A8 show some interesting results. Both alternative performed bad in the original MCA, but score good for the set of weights with increased importance of the turnaround time. Therefore it can be concluded that these alternatives can be interesting to implement when the turnaround time is very important. So for example, these alternatives can be interesting when further reducing the turnaround time of the repair.
- Finally, it should be noted that alternative A5 scored bad in the original MCA, but scores good for all the new MCA. Therefore it can be interesting to implement this alternative. However, this alternative cannot be implemented simultaneously with alternative A6 as both provide another solution for the waiting times of the inspections. As alternative A6 performs better than alternative A5 in all MCA and the alternatives cannot be implemented simultaneously, alternative A5 is not taken into account despite the fact that the alternative scores well in all new MCA.

So based on this sensitivity analysis it can be concluded that the results of the MCA are valid. Almost all results of the original MCA match with the results of the new MCA. However, alternatives A2 and A8 should be taken into account, next to the five selected alternatives, in situations with a very high importance of the turnaround time.