Operational excellence by continuous improvement of the integral engine MRO chain

A case study at KLM Engineering & Maintenance Engine Services

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Preface

Dear reader,

When I was a kid, every day I cycled past the former headquarters of KLM in The Hague. Next to the building was a statue of Albert Plesman, who was looking into the sky. Not knowing he was the founder of the biggest airline of The Netherlands. The past seven months I was able to explore the world of aircraft Maintenance, Repair and Overhaul during my graduation internship at KLM Engineering & Maintenance.

The work lying in front of you represents the result of my master thesis project to complete my master studies Transport, Infrastructure & Logistics (TIL) at the Delft University of Technology. The aim of this project was to improve and shorten the performance of the integral engine MRO chain at KLM Engineering & Maintenance Engine Services to contribute to the goal of a turnaround time of 45 days.

Naturally, I could not have completed this master thesis project with help of many others, I would like to use this opportunity to express my gratitude to these people.

First of all, I want to thank Guus Philips van Buren and Alex Gortenmulder for the opportunity to conduct my thesis project at KLM Engineering & Maintenance at the Lean Six Sigma Office. Their enthusiasm, knowledge and feedback helped and challenged me to get the most out of my internship period. Next, I want to thank all colleagues at Engine Services for sharing their time, knowledge and data with me. A especial thanks to Nienke Klinkhamer for the pleasant cooperation, which led to a successful master thesis and a solid basis for TAT45. Thirdly, I want to express my thanks to my graduation committee: Dr. Wouter Beelaerts van Blokland, whose expertise elevated this research to a higher level than I could have anticipated. Dr. John Baggen, for helping me with the approach of the research and with structuring the report in a scientific way. Lastly, dr. ir. Dingena Schott, many thanks for your critical but fair (scientific) questions and additions during the meetings. All three professors have helped me a lot to bring this thesis on a scientific level.

And finally, I want to thank all my fellow interns, friends, family for their patience, support and input.

Enjoy!

Amsterdam, 10th of July 2017

Govert Soeters

Executive summary

Travelling by air has become the safest transport mode of all (Mouawad & Drew, 2013). To ensure this high level of safety it is important to make sure the aircraft is checked regularly and maintenance is performed when needed.

To win market share in the Maintenance, Repair and Overhaul (MRO) sector of the airline industry, maintenance providers should compete on cost, throughput time or quality of the delivered services (Ayeni, Baines, Lightfoot, & Ball, 2011).The average turnaround time (TAT) of the total engine MRO chain at KLM E&M Engine Services (ES) is 71 days. The goal of KLM E&M ES is set at a total TAT of 45 days. Therefore, it is clear there is a big gap between the current situation at KLM E&M ES and the desired situation. In addition to this performance gap, KLM E&M ES does not know which process step needs to be improved first. The reason for this, is that KLM E&M ES does not know what the impact of a performance change of one individual process step is, on the total integral engine MRO chain. The objective of this research is to improve the integral aircraft engine MRO chain to contribute to the aim of lowering the integral engine MRO chain to at least the desired 45 days.

To work towards this goal, a continuous improvement framework is used. To apply this framework at KLM E&M ES, the levels of planning and control for an engine MRO environment need to be identified. These levels require various management decisions. Decisions can influence the performance of that process step, and thus on the whole integral chain. Besides the levels of planning and control, a performance measurement model needs to be developed that represents the performance of all the individual process steps as well as the performance of the integral engine MRO chain. This leads to the following research question:

"Which management decisions must be taken to improve the performance of the integral engine MRO chain at KLM E&M Engine Services?"

To answer the main research question, three definitions should be clarified. Firstly, the integral engine MRO chain at KLM E&M ES needs to be clear. Secondly, the management decisions that could be taken in the engine MRO process should be known. And thirdly, it should be clear what the improvement of the performance means.

Firstly, the integral engine MRO chain consists of four major stages; the work scope determination, the disassembly of the engine, the repair stage of the parts and the assembly of the engine. All the stages consist of more detailed process steps. The disassembly stage contains the disassembly, and the cleaning and inspection of parts. The repair stage consists of the in-house repairs, the outsourced repairs, the inbound and the outbound transport process steps. The assembly stage includes the assembly, the testing of the engine and remaining rework that has to be done.

Secondly, to find out what management decision can be taken to improve the integral engine MRO chain and to determine the definition of the word improvement, a literature study must be conducted. In literature four levels of management decision making have been found for planning and control. Level 1, the Strategic Business Plan. Level 2, the Production Plan. The first part of level 3 is the Master Production Schedule. The second part of level 3 is the Material Requirements Planning. Level 4, the Production Activity Control.

Depending on the kind of environment, different decisions can to be taken on the various levels of planning and control. In literature, the engine MRO environment was not known yet. Literature review shows that it is very closely related to the remanufacturing environment. In a typical remanufacturing environment, the company disassembles various products that have no owner anymore, uses several parts of the different products and combines those to produce their new product. The big difference for engine MRO is that the engine will always be the property of the client, which means that the majority of the parts need to be back on the same engine. This makes the engine MRO process very complex.

Understanding the levels of planning and control and the type of environment, the management decisions that can be taken at various levels can be defined, seeFigure 1.

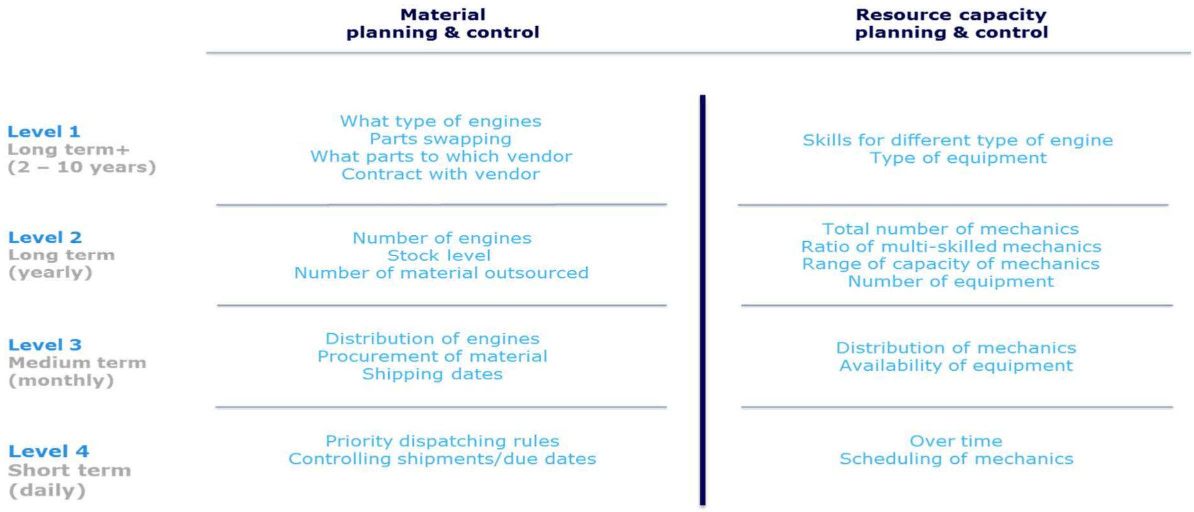

Figure 1. Management decisions for an engine MRO process

Thirdly, to improve the process, it should be known what improvement means in the context of engine MRO. In the literature, six Key Performance Indicators (KPIs) have been determined which are useful to measure the performance of the engine MRO process; waiting time, process time, average turnaround time, turnaround time, standard deviation and on-time performance. Thus, improvement in the engine MRO environment means, to score better on at least one of these six KPIs. With these KPIs it is clear what needs to be measured, but how it can be measured is also very important in engine MRO. Because the majority of the disassembled parts need to return to the same engine, the moment to start reassembling is when all the parts are serviceable again. This has influence on two events; the method of measuring the repair process step and the general overview of the integral engine MRO chain. In the repair process step, the TAT of individual parts should not be measured per individual part, however it should be measured from the time the first part is sent out for repair until the last part of that assy is returned. Secondly, at KLM E&M ES, the engine MRO process is only measured as individual process steps. There is no combined overview of the integral engine MRO chain at KLM E&M ES. A total overview from an integral perspective should be provided, to measure the integral engine MRO performance at KLM E&M ES.

With these KPIs, a change in management decision can be measured. To find out what kind of management decisions must be taken to improve the engine MRO process, various process improvement theories have been found in the literature. In this research, the main process improvement theories which are used are; lean manufacturing, six sigma and the theory of constraints.

By combining the several findings, a continuous improvement framework is built which works as a guideline to improve the integral engine MRO process. The base of the framework is the five steps of the theory of constraints. The steps have been adjusted to be suitable to improve the engine MRO process;

1. Identify the constraint of the integral engine MRO chain.
2. Exploit and elevate every process step of the constraint.
3. Compare the solutions and choose the most efficient.

4. Implement the solution, if anything changes in the performance go back to step 1.

In theory, this is an on-going process, but in this research the process ends when there is not enough information available anymore to determine which solution is best to implement.

Now the definitions of the main research question are clear, it can be answered. First, a performance measurement model is developed. This model represents the performance of the individual process steps and the performance of the integral engine MRO chain. After gathering the necessary data, the current performance of the engine MRO chain at KLM E&M ES is modelled, see Figure 2. The TAT of the integral engine MRO chain at KLM E&M ES is on average 71 days, with a standard deviation of 31 days and an on-time performance of 31%.

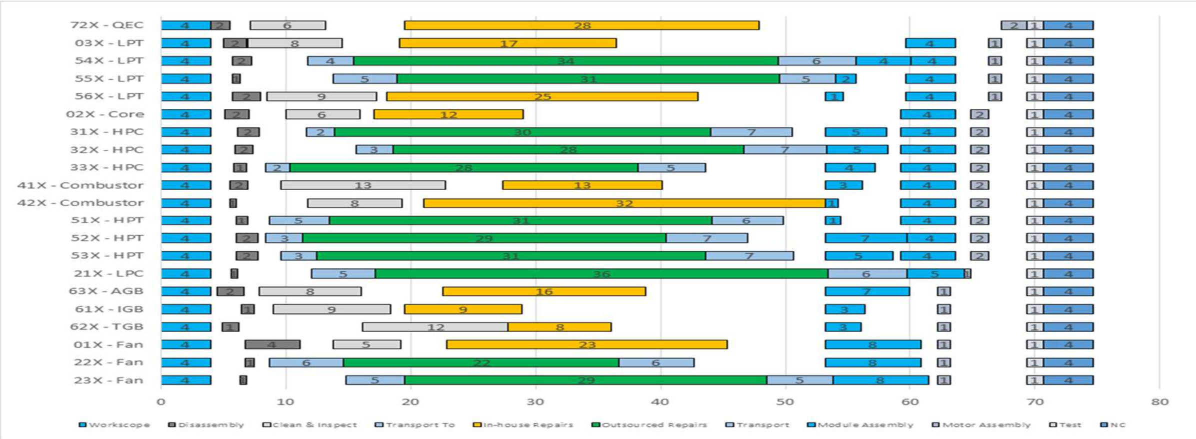

Figure 2. Current performance of the engine MRO chain at KLM E&M ES

To improve the performance, first of all the constraints and the root causes need to be identified. As found in literature, the constraints are assy's of the engine. Because of this, individual process steps should be improved to solve them. For all the process steps the major root causes were*: the distribution and scheduling of mechanics, the priority dispatching rules, the distribution of engine injections, exceeding contract TAT, batching and missing material.*

The root causes can be solved by taking management decisions which influence the process step. With the various decisions that can be taken, solutions to improve a process step are designed. For every process step an exploit and an elevate solution must be designed. In this research, 13 solutions have been designed. The effectiveness of these solutions are determined by evaluating the impact on the TAT with the level of planning and control on which the decision needs to be taken.

To improve the integral engine MRO chain at KLM E&M ES, the continuous improvement framework is applied. At every iteration, a new constraint appears that needs to be eliminated. This research has conducted six iterations that improve the integral engine MRO chain at KLM E&M ES. Below, the six iterations, with the solution that is implemented, and the underlying management decision that must be taken, are shown. Inside the brackets, the performance of the iteration is given (TAT – SD – OTP).

Iteration 1
Solution: exploit waiting times before transport and cleaning
Management decision: use least slack policy (65 days – 31 days – 36%)
Iteration 2
Solution: exploit contract outsourced repairs
Management decision: apply proactive vendor management (59 days – 20 days – 47%)
Iteration 3
Solution: exploit outbound and inbound transport

Management decisions: combine DGO and IIG manpower and prioritise parts based on the flight cut-off times (55 days – 18 days – 60%)

Iteration 4

Solution: elevate in-house repairs

Management decisions: less batching, better scheduling and distributing of manpower and more multi-skilled mechanics (especially skill P for combustor) (54 days – 13 days – 71%)

Iteration 5

Solution: elevate Assembly

Management decisions: better scheduling and distribution of manpower (47 days – 11 days – 86%)

Iteration 6

Solution: elevate outsourced repairs

Management decision: renew contract with vendors to TAT 21 days (42 days – 11 days – 92%)

It is not necessary to start all projects, to improve the performance, right away. It depends on the iterations, which project has priority over others. There should be one coordinator that manages the total project and updates the measurement performance model regularly to see how the implementation of the various projects is working. The implementation plan will be controlled based on the performance measurement model.

The answer to the main research question *"Which management decisions must be taken to improve the performance of the integral engine MRO chain at KLM E&M Engine Services?"* is: use least slack policy, apply proactive vendor management, combine DGO and IIG manpower and prioritise parts based on the flight cut-off times, less batching, better scheduling and distributing of manpower and more multi-skilled mechanics, better scheduling and distribution of manpower, renew contract with vendors to TAT 21 days. After taking these decisions and implementing the , the TAT will be reduced to 42 days. This is lower than the initial goal of 45 days of KLM E&M ES.

Thus for KLM E&M ES, it is strongly recommended to take these decisions and implement the associated solutions. Subsequently, it is strongly recommended to use the performance measurement model to have an integral overview of the performance of the current situation. Associated with this model, it is also recommended to measure the repair process step on set level. This will give a realistic representation of the real world. Next to that, to have an even more realistic representation of the real world, it is recommended to use better data. Finally, it is recommended to use the continuous improvement framework and the levels of planning and control for an engine MRO environment, when further improvement of the engine MRO process is required.

Further research should be done to identify the root causes that have not been examined in detail. For example, the cleaning and inspection process step. Finally from a scientific point of view, it is recommended to test the continuous improvement framework in other industries to make it more reliable and robust.

Contents

List of figures and tables

List of abbreviations

Abbreviation	*Explanation*
4M	Method, Machine, Manpower and Material
5x2	2 shifts a day, 5 days a week
7x2	2 shifts a day, 7 days a week
Aprep	Warehouse for serviceable parts
ATO	Assembly-to-order
BOM	Bill of Material
DBR	Drum-Buffer-Rope
DGO	Decentralized Goods Receipt
DMADC	Define-Measure-Analyse-Design-Control
DMAIC	Define-Measure-Analyse-Improve-Control
ES	Engine Services
ETO	Engineer-to-order
FIFO	First-in First-out
HPC	High Pressure Compressor
HPT	High Pressure Turbine
ICAO	International Civil Aviation Organization
IIG	Inspection Incoming Goods
JIT	Just-In-Time
KLM	Koninklijke Luchtvaart Maatschappij
KPI	Key Performance Indicator
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
MPS	Master Production Schedule
MRO	Maintenance, Repair and Overhaul
MRP	Material Requirements Planning
MTO	Make-to-order
MTS	Make-to-stock
OEM	Original Equipment Manufacturers
OTD	On-Time Delivery
OTP	On-Time Performance
OTS	On-Time Start
PDAC	Plan-Do-Act-Check
PDR	Priority Dispatching Rule
PT	Process Time
QEC	Quick Engine Change
SD	Standard Deviation
TAT	Turnaround Time
TIMWOOD(S)	Type of wastes: Transport, Inventory, Motion, Waiting, overprocessing, overproduction, defects, (skills)
TOC	Theory of Constraints
WT	Waiting Time

1 Introduction

The first chapter serves as an introduction of the research performed in this thesis. After the introduction, the following topics will be clear; the context and the problem of what the reason was to conduct this thesis at KLM Engineering & Maintenance Engine Services is elaborated in section 1.1. After that in section 1.2, the research scope and the objectives of the research will be described. Next in section 1.3, the main research question and the sub-questions are presented. In section 1.4, the scientific and the societal research relevance are elaborated and as last in section 1.5, the research approach is described. Figure 2 shows the schematic overview of chapter 1.

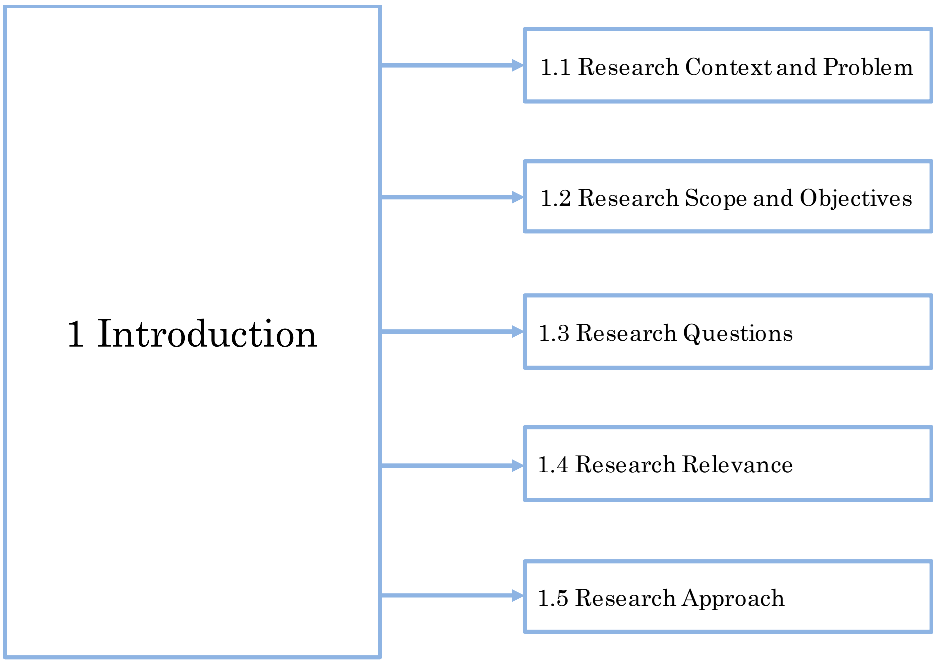

Figure 2. Schematic overview of chapter 1

1.1 Research Context and Problem

1.1.1 Research Context

This research is conducted to enrich the science with more knowledge about the integral engine Maintenance, Repair and Overhaul (MRO) supply chain and on how to improve this supply chain on basis of planning and control. Engine MRO is a part of the aircraft MRO industry.

There are various MRO providers, a distinction can be made between these providers. There are Original Equipment Manufacturers (OEMs) that provide MRO for their own products, like Airbus, GE and Rolls-Royce. There are airlines that provide MRO, like KLM E&M, Lufthansa Technik and Delta Tech Ops. And there are non-OEMs that provide MRO, like Hong Kong Aircraft Engineering and SR Technics. The total market share of MRO in 2015 was $67.1 Billion (Doan, 2015). MRO services can be divided in four types; Airframe, Components, Line Maintenance and Engine. The share of engine services is the highest with 42 per cent and the share of line maintenance the lowest with 18 per cent (Doan, 2015).

Engine MRO service is very important in the aviation sector, since safety is at the core of ICAO's fundamental objectives (ICAO, n.d.). An aircraft engine needs maintenance after a certain amount of flight hours, a certain amount of cycle times or when a signal is given at the dashboard. The engine MRO market is becoming increasingly competitive and its dynamics more complicated. Since decades the OEMs are dominating the market with a large share of the MRO business. It looks like that this trend will set to continue and will make life harder for the other MRO providers. This domination comes forth from the issue that OEMs sell their engines to clients together with a long-term service agreement (Chellappa, 2015). Another reason that will make it more difficult in the future for non-OEMs to compete, is that new engines, that require less maintenance, are introduced. For the non-OEMs to win some market share, maintenance providers should compete on cost, throughput time or quality of the delivered services (Ayeni, Baines, Lightfoot, & Ball, 2011).

In general engine MRO consists of four stages. To start the determination of the work scope, the disassembly stage, the repair stage and the assembly stage. See Figure 3 for a schematic overview of the stages of engine MRO. These four stages are in their turn divided in several other process steps. The complete engine MRO description will be elaborated in section 2.2.

Figure 3. Engine MRO supply chain

KLM E&M – Engine Services

KLM E&M is an airline that provides MRO. Due to the different MRO services, KLM E&M is divided in various departments, such as: Component Services, Engine Services (ES), Engineering, Line Maintenance, Maintenance Control Centre Office and Base Maintenance. In this thesis, the focus will be on the Engine MRO services. The goal of KLM E&M for Engine MRO is to deliver total engine care, this includes services from on-site support to MRO and from material services to engine availability (Air France KLM, n.d.).

1.1.2 Research Problem

As stated above, for engine MRO providers to win market share it must compete on cost, throughput time or quality. In this research, the aim is on reducing the throughput time. At KLM E&M, in the current situation the turnaround time (TAT) of the integral Engine MRO chain is on average 71 days per engine. The on-time performance (OTP) of all engines 2016 was a miserable 31%. That means that just 19 engines of the 62 engines were delivered back on time at the client. Previous researches (Mogendorff, 2016) (Meijs, 2016) at the engine department have shown that there is a lot of potential to achieve improvements in various parts of the integral engine MRO chain.

Rozenberg did research to the engine MRO chain, with the focus on the outsourced repairs, from an integral perspective and tried to connect all different stages to each other (Rozenberg, 2016).

At the moment, the engine department of KLM E&M is working on the poor OTP problem, a current project is running on reducing the TAT of the integral engine MRO chain. The name of the project is 'TAT45' and aims on reducing the TAT to 45 days. That is a reduction of 26 days, compared to the current average situation with a TAT of 71 days. Besides the results of (Meijs, 2016) and (Mogendorff, 2016) various other projects are on the TAT45-list. Meijs (2016) and Mogendorff (2016) did research to improve the actual processes, Rozenberg (2016) did research to the performance of the integral supply chain with focus on the outsourced repairs. In Rozenberg's research is shown that simple changes can have a major impact on TAT of the integral engine MRO chain. But still more areas remain unexplored and unknown in detail. What not have been researched yet, are the disassembly and assembly stage. A more detailed view of these phases and the relation between several process steps has not been given yet.

After the integral engine MRO chain is brought into more detail, and all the sub-process and the performance of those processes are clear and known, improvements can be made. But what kind of improvements could be done and how could these improvements be implemented, are relevant questions. The answers will be found in the planning and control of the whole system.

So, it is clear that there is a gap in the desired performance and the current performance of the engine MRO service. In some areas it is also clear what this gap is, but in others it is not. In the assembly stage for example, it is clear that there is a gap between current and desired performance. But how improvements can be made to get to this desired performance is unclear, because it is not known what (sub)processes have potential to improve and can increase the performance.

Problem statement

From the information in the research context and the research problem the following problem statement can be formulated:

Within the aircraft engine MRO industry, there is limited knowledge of the impact of the performance of individual process steps on the performance of the integral engine MRO chain, because of this there is a gap between the current performance and the desired performance of the integral engine MRO chain.

1.2 Research Scope and Objectives

1.2.1 Research Scope

The research focuses on the integral chain of the aircraft engine MRO process. The MRO process of only one engine type, the CFM56-7B, is taken into account. The main focus lies on the levels of planning and control of the integral engine MRO supply chain, which controls the performance of the engine MRO chain. The only process step of the engine MRO chain that is not analysed and in that way left out of scope, is the work scope.

1.2.2 Research Objective and Deliverables

The objective of the research is that it has academic value and contribute to the science as well that is has practical value for KLM E&M. In the ideal world, the academic value will support the practical value of the research and vice versa. In the problem analysis is shown that there are a lot of potential areas that could be improved, and where the practical value can show its worth. With validated solutions to improve the integral MRO chain, the practical value can give its justice.

To show the practical value of the academic invented theories, it is tested on the basis of a case study. The conceived continuous improvement framework will be tested in the environment of KLM E&M Engine Services. Therefore the research objective can be stated as follows:

Improve the integral aircraft engine MRO chain at KLM E&M Engine Services to contribute to the aim of shortening the current TAT to 45 days.

Based on this research objective a number of deliverables will follow:

- The levels of planning and control for an engine MRO environment
- A continuous improvement framework to improve the performance of the integral aircraft engine MRO chain
- A performance measurement model to show the current performance and simulate the impact of proposed improvements on the performance of the integral aircraft engine MRO chain

1.3 Research Questions

Based on the described research problem, the context and the research objective, the main research question can be defined as:

"Which management decisions must be taken to improve the performance of the integral engine MRO chain at KLM E&M Engine Services?"

Sub-questions are formulated to get to the answer of this main research questions. The ten sub questions are:

i. How is the current engine MRO supply chain organized at KLM E&M ES?

ii. What planning and control levels are known from literature?

iii. Regarding planning and control, how can the engine MRO environment be defined?

iv. What are the performance measures for an engine MRO process?

v. What framework can be proposed to improve the performance of the integral engine MRO chain?

vi. What is the current performance of the individual process steps and how does this form the current performance of the integral engine MRO chain at KLM E&M ES?

vii. What constraints become visible by analysing the performance of the engine MRO chain at KLM E&M ES and what are the root causes of these constraints?

viii. Which solutions can be used to solve the root causes?

ix. What would be the impact of applying the continuous improvement framework on the performance of the integral engine MRO chain at KLM E&M ES?

x. What implementation plan can be made to translate the iterations of the framework into practice, and how can these implementations be sustained?

1.4 Research Relevance

The research that is conducted has initially two purposes. On the one hand, there is a scientific relevance which will broaden the knowledge of planning and control regarding engine MRO environment. On the other hand, this research has a societal relevance which will contribute to the engine MRO process at KLM E&M ES in practice.

1.4.1 Scientific Relevance

This research is done to provide a continuous improvement framework for the integral engine MRO chain. This framework contents management decisions of planning and control that should be considered when offering engine MRO services. The framework is tested by means of a case study at KLM E&M Engine Services in combination with a performance measurement model. This model is developed to show the current state and simulate the impact of possible improvements on the integral engine MRO chain. The framework also uses the levels of planning and control of an engine MRO environment, but since this environment is not very common, few is known about it in literature. This research will enrich the science with more knowledge about the engine MRO environment and associated levels of planning and control.

1.4.2 Societal Relevance

On the short term this research is of societal relevance for KLM E&M. The framework will be tested at the engine MRO department of KLM E&M. At first, it will give the department a better overview of the integral supply chain. With this more detailed view, constraints can be identified and the root causes can be determined. As last, based on the designed framework, these root causes can be solved. With solving these bottlenecks, the total TAT of the engine MRO process could be reduced and thus the on-time performance towards the client will be improved. This research is not only meant to solve problems at KLM E&M, in the end it could be of societal relevance for more companies in the MRO industry.

1.5 Research approach

The main focus of the research is to improve the integral engine MRO process at KLM E&M ES. There are several approaches to conduct such researches. Three research approaches for process improvements are compared and one of these three is chosen for this research.

1.5.1 Engineering Design

According to Dym and Little (1994), the engineering design approach is a systematic, intelligent process in which designers generate, evaluate and specify designs for devices, systems or processes whose form and function achieve clients objective users' needs while satisfying a specified set of constraints. The progress from the design problem to the final product is performed step by step, by design decisions, each of which changes the design rate (Grigoras & Hoede, 2007). During the design process, the initial problem statement evolves into an entire framework of knowledge, drawings and models. Which are gathered using various analyses during this process. The iterative process steps are as followed: Problem definition, defining scope and formulate criteria, identifying constraints, generate concepts, develop and test predictive models, conceive best possible solution, final solution and evaluate solution.

1.5.2 DMADC cycle

This approach is derived from the Six Sigma methodology, Beelaerts van Blokland (2017) transformed the cycle to DMADC – Define Measure Analyse Design Control. The cycle consists of a study part (DMA) and an improve part (DC). Each phase builds on the previous one, with the goal of implementing long-term solutions to problems. In Figure 4 the cycle is shown schematically. Each step of the DMADC cycle, in relation to this research, is explained below.

Define

In the first phase the research is defined. At first the context and research problem are described. After the problem definition is clear, the objective and scope of the research are determined. Furthermore, the approach to solve the problem must be defined (Reid & Sanders, 2010). After the creation of the scientific methodology, the methodology will be tested by means of a case study. To test the methodology, the environment of the case study needs to be defined as well. In the description of the environment it becomes clear that the field of research will be high-bypass turbofan engines in an aircraft engine MRO environment.

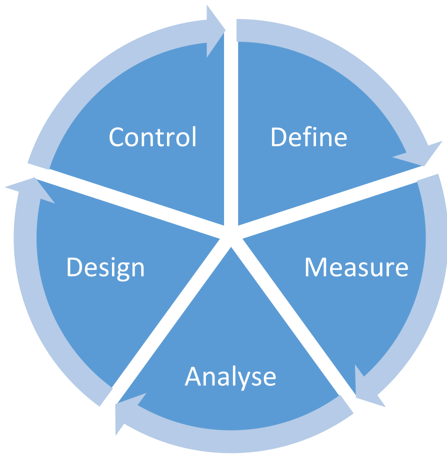

Figure 4. DMADC approach cycle

Measure
The goal of the second phase is to gather all the data and information that is needed to analyse the problem. At first the way of how the process is measured needs to be determined and the applicability of these measurements have to be researched. To identify the size of the problem in the different stages, probability plots are made and it can be seen that in most stages the TAT performance is not normally distributed, which indicates that there is waste in the system. The next step is to understand and map the current process in detail. To map the process it helps to identify constraints that effect the performance (Reid & Sanders, 2010). A value stream map is therefore a good method to map the process and identify the constraints in the system (George, 2002).

Analyse
The goal of the Analyse phase is to find the main constraints and determine the root cause of this main constraint (Reid & Sanders, 2010). This will be done by analysing the assembly process steps and the corresponding gathered data from the previous phase.

Design
The Design phase of the cycle has the goal to eliminate the root cause of the main constraints (George, 2002), as found in the Analyse phase. Solution scenarios are created in a systematic way, using methodologies from the framework. Next, the effects of the different scenarios on the engine MRO chain are modelled.

Control
In the control phase methods to sustain the future state of the system are given. In this research this phase will only be described in words and an advice will be given on how to implement and sustain the future state without executing the step.

1.5.3 Plan-Do-Act-Check

Plan-Do-Act-Check is an iterative management method that consists four steps, it is used in business for the control and continual improvement of processes and products. The concept is based on the scientific method of Francis Bacon (Novum Organum, 1620). The fundamental principle of this scientific method is iteration, once a hypothesis is confirmed or negated, the next cycle will start again at 'plan' and will extend the knowledge further. To reach a perfect operation and output, the PDCA cycle will bring the process owner closer to its goal by repeating it continuously (Moen & Clifford, 2009). PDCA is also known as a system for developing critical thinking. The four steps of the PDCA cycle are elaborated in Appendix A.

1.5.4 Conclusion research approach

A derivation of the DMAIC cycle from the Lean Six Sigma theory is used. In literature and at KLM E&M, DMAIC is an often-used method for process improvements and it provides a clear structure to analyse and solve operational problems. The reason for choosing the DMADC approach is because it is a structured problem-solving method and is an often-used improvement method. This approach is very suitable to test the proposed continuous improvement framework with simulation of the iterations. In this research, the improvement step is replaced for the design part. The reason for this change is that this research is limited in doing actual practical implementations, because of the limited research time. The focus of this research is to design future states that could improve the process in practice and find solutions that contribute to these improved scenarios.

In theory it may look like a linear process of following the DMADC steps, but in practice this whole process is iterative. The research build-up is shown in Figure 5, as can be seen there are some feedback loops present, because every new insight could lead to a change in the former steps.

Chapter 1 is part of the **define phase** of this research, it contains; the research context, research problem, research objective, research scope, deliverables, main research question and sub-questions.

In chapter 2 the **define phase** continues with the description of the research field. Here the working of the high-bypass turbofan is elaborated in a nutshell and the meaning of aircraft engine MRO is described. In chapter 2 sub-question i will be answered.

Chapter 3 describes the performed literature study, which is still part of the **define phase**. This chapter focusses on the literature review. The literature review contains the literature study on planning and control in operational production processes, the identification of the type of environment of aircraft engine MRO, the key performance indicators (KPIs) of the engine MRO process will be defined and process improvement theories from literature will be described. In chapter 3, sub question ii, iii and iv will be answered.

In the next chapter of the **define phase**, chapter 4, found literature is adjusted for the use in an engine MRO environment. This literature review results in a continuous improvement framework to improve the performance of engine MRO chain. This continuous improvement framework is based on the theory of constraints, the levels of planning and control for an engine MRO environment and the process improvement theories. In this chapter sub-questions v will be answered.

Chapter 5 contains the currents state analysis of the case study at KLM E&M ES, which consists of the **measure phase**. In this chapter, the process itself and the process measurements will be defined. Sub question vi will be answered in this chapter.

The constraints of the process and the root causes of the constraints will be determined in the **analyse phase** in chapter 6. Sub-question vii will be answered in chapter 6.

Chapter 7 contains the **design phase**, here the continuous improvement framework will be used to design possible future states of the current performance of the engine MRO chain at KLM E&M ES in theory. The various future states will be evaluated on its performance in the performance measurement model. In this chapter, sub-question ix will be answered.

In chapter 8 the **control phase** of this research will be described. There will be only given an advice of an implementation plan and how this implementation can be at KLM E&M ES. Sub-question x will be answered in this chapter.

The last chapter, chapter 9, contains conclusions of the results of the case study. Here the research questions will be answered and the contribution of this research will be evaluated. As last, recommendations to KLM E&M and further research will be given.

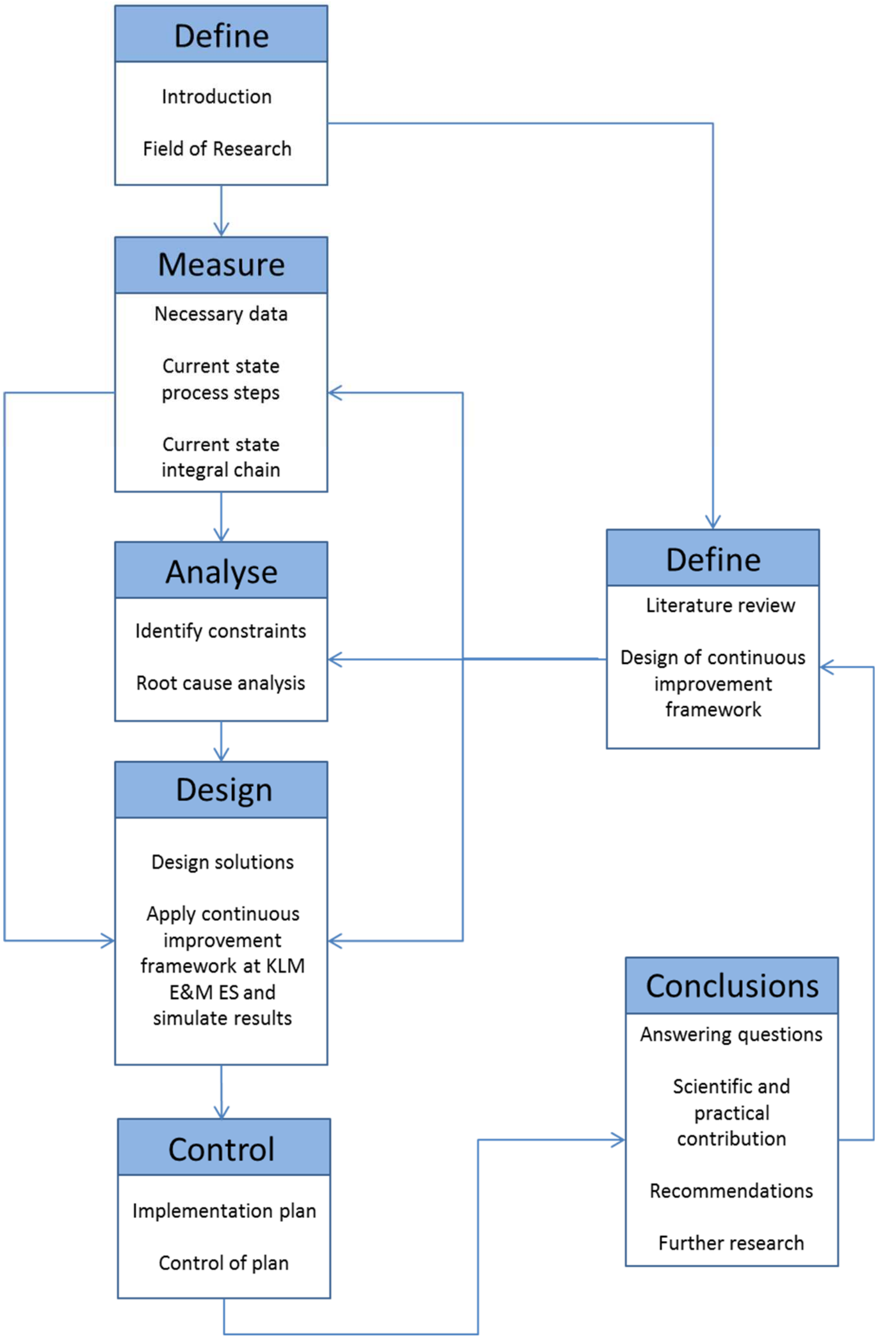

Figure 5. Approach of this research

2 Research Field: Aircraft engines

In this chapter the field of research is described. The product that this thesis is about, and what is the service that is provided for this product will be clear. There will be explained what the process, that is performed to realise the service that is provided, contains and how this is executed. The focus in this chapter is on answering the sub question; *"How is the current engine MRO chain organized at KLM E&M ES and what are its limitations?"* First a brief explanation of the high by-pass turbofan engine will be given in section 2.1. The high by-pass turbofan engine is the engine of which KLM E&M ES is capable of providing MRO. How this MRO is executed, all the process step that an engine passes, will be elaborated in section 2.2. Besides that all the process steps will be clear, also the governance and accountability, the planning and control and the performance control at KLM E&M ES will be described in section 2.2. Figure 6 shows the overview of chapter 2.

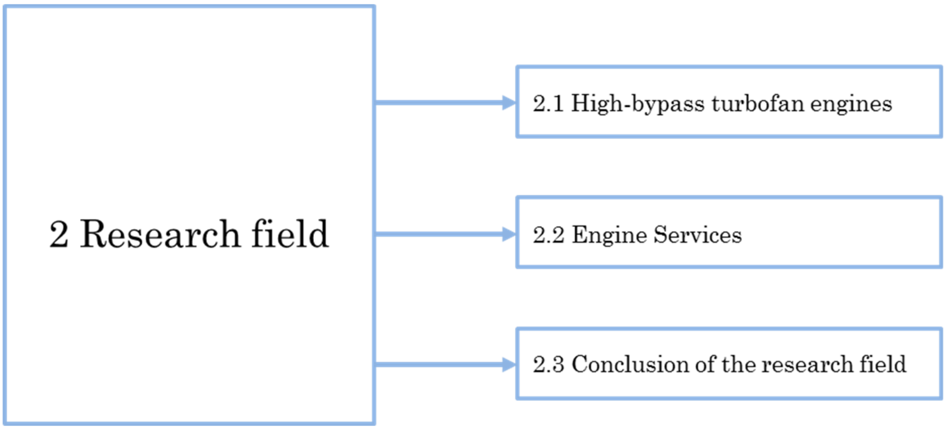

Figure 6. Schematic overview of chapter 2

2.1 High-bypass turbofan engines

A turbofan engine is a trade-off between the concepts of a pure turbojet and a propeller engine (Anderson, 2008), as it combines the high thrust of a turbojet engine with the higher efficiency of a piston engine-propeller combination. At high-bypass turbofans a large share of all the air that flows through the engine, at least 80%, flows through the bypass duct.

As can be seen in Figure 7, the engine consists of multiple parts. A turbofan engine consists of a number of main modules: the fan, the compressor (LPC, HPC), the combustor, the turbine (HPT, LPT) and the exit nozzle. Each part has its own task within the engine. The turbine drives both the fan and the compressor, while the fan accelerates a large mass of air that flows through and outside of the engine core. The ratio between flow through and around the core is called the 'Bypass Ratio'. 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 of a Turbofan engine is a combination of the airflow from the exhaust nozzle and the thrust produced by the fan (Anderson, 2008).

The primary airflow enters the engine through the fan. The fan functions like a propeller as it accelerates the air into the engine. The airflow enters the low- and high-pressure compressors after the fan. The compressors compress the air and it can reach temperatures of 450 ^{o}C. The optimal conditions of the airflow for combustion is generated by the compressor. When the air is compressed, the airflow enters the combustion chamber, where the airflow is mixed with fuel and got burnt. By burning the mixture of air and fuel, the temperature rises and can reach 1700 ^{o}C. After the combustion, 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 primary duct and nozzle eject the airflow where it will join the secondary airflow, the airflow that bypasses the core engine. 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).

Aircraft maintenance represents more or less 10 to 15 per cent of an airline's operating budget. 35 to 40 per cent of these costs are engine related maintenance (Ackert, 2011). There are three main reasons for engine maintenance: Operational, Value Retention and Regulatory Requirements. Operational maintenance is needed to keep the engine in a serviceable and reliable condition. Value Retention is done to maintain the current and future value of the engine. As last, Regulatory Requirement maintenance is executed due to the fact that engines need to meet minimum required demands and standards of inspection and maintenance. There are several indicators that generally measure the health of an engine (Ackert, 2011);

EPR (Engine Pressure Ratio)
This indicator is sometimes used to measure the thrust of the engine.

EGT (Exhaust Gas Temperature)
This indicator is a common condition or health parameter. A high EGT can indicate degraded engine performance. The manufacturer gives a maximum allowed temperature; the temperature is measured at the engine exhaust in degrees Celsius.

N1-Speed
The N1-speed measures the rotation speed of fan.

EGT Margin
The EGT margin is the difference between maximum allowed EGT and peak EGT during takeoff. The required margin after repair is part of the contract with the client.

2.2 Engine Services

"The aviation MRO industry is responsible for the retaining or restoring of aircraft parts in or to a state in which they can perform their required design function(s). This includes the combination of

all technical and corresponding administrative, managerial, supervisory and oversight activities." is the given definition by (Ayeni, Baines, Lightfoot, & Ball, 2011) of the aviation MRO industry. This section will discuss the type of MRO relevant to this research: the engine MRO.

2.2.1 Engine MRO chain at KLM E&M ES

An aircraft engine consists of more than 10,000 parts. And all these parts have their unique position on the engine. The system of the engine can be divided in four levels. There is the engine level, which consists of one part, the engine. When disassembling the engine, the engine is disassembled in seven parts, called modules. These individual modules consist in their turn of several other parts, called assy's. It depends on the type of engine of in how many assy's the engine can be divided. All these assy's can be disassembled in the 10,000 individual parts. See Figure 7 and Figure 8 for the visualisation of an aircraft engine.

The second stage is the disassembly stage. Here the engine will be disassembled and be cleaned and inspected on damages per part. It depends on the work scope, to the extent to which the engine will be disassembled. For a full shop visit, the whole engine needs to be disassembled. In contrary to a light shop visit, where only a few parts will be disassembled. For the disassembly of a full shop visit engine, the engineers always follow the same sequence of disassembly. The engineers start with disassembling the QEC, which are all the small parts that are on the outside of the engine, like tubes, brackets and wires. Then the first module that will be disassembled is the LPT, on the backside of the engine. After the LPT, three modules that are combined will be disassembled at once. These three modules are the HPT, Combustor and the HPC, together they are called the Core. After the Core is disassembled, the LPC is removed and as last the Fan and Gearbox remain to be disassembled. All the modules are brought to a designated workstation, where the modules first will be disassembled in assy's and the assy's will be disassembled in their turn into the individual parts. When the engine is disassembled in parts, some parts are brought to the cleaning and inspection area. Here the parts are cleaned and inspect on any damages. The parts that do not need to be cleaned and inspected are moved directly to the repair stage.

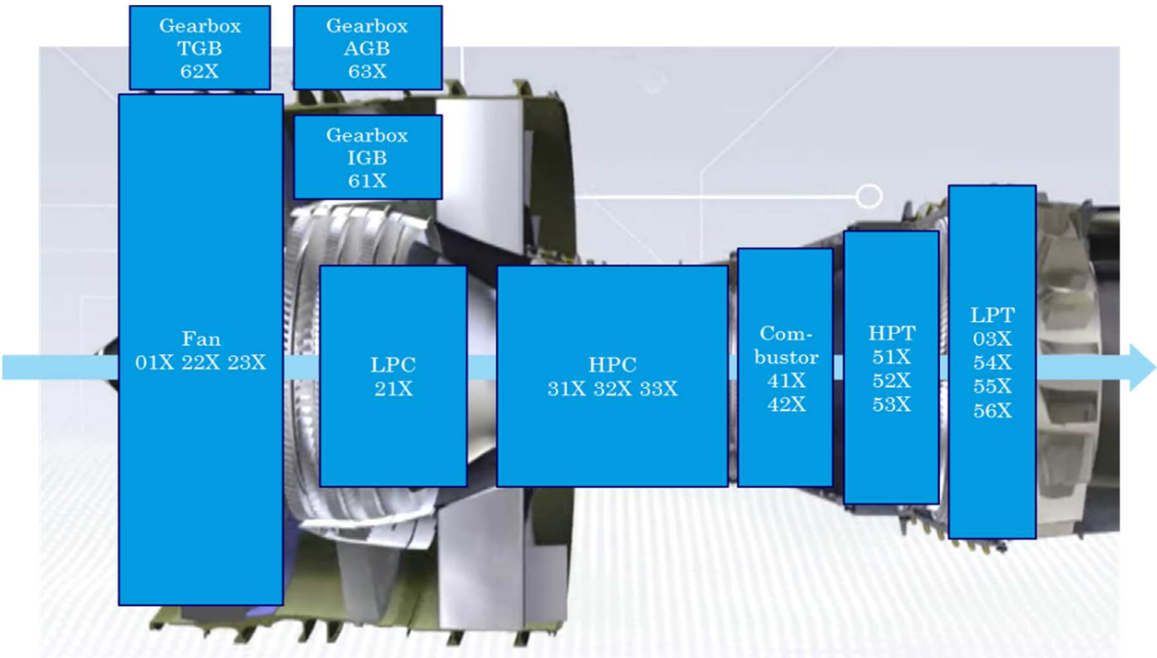

Figure 7. Aircraft engine (type CFM56-7B)

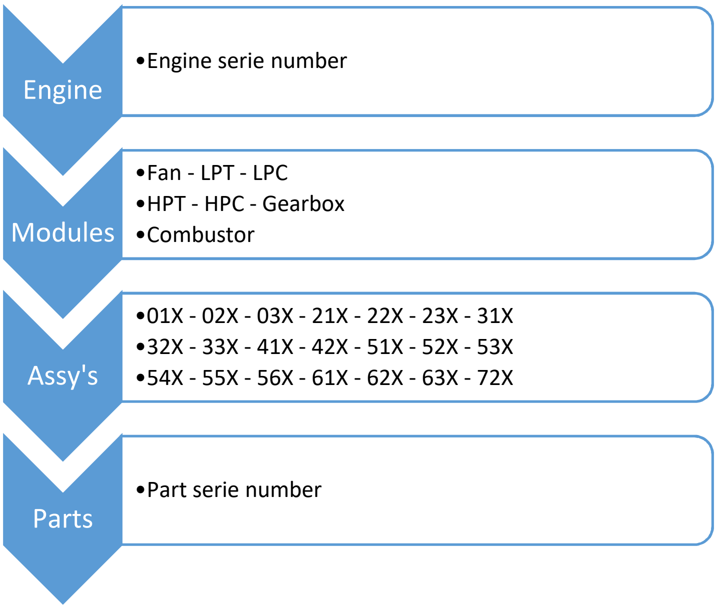

Figure 8. Engine build-up

If there is damage found on parts at the inspection phase, it proceeds in the MRO chain to the repair stage. If not, it will be replaced or the repair stage is skipped because the part is already serviceable. In the repair stage all the repairs will be performed, both intern and extern. 60% of all the parts is repaired intern at KLM E&M. The external parts first go to the logistics area where they will be sent to the particular vendor. The vendor will repair the parts and sends them back when ready. When the parts are returned at KLM E&M, first an incoming check will take place. Here the parts are inspected on the fact if the parts are repaired correctly. If so, the parts will be brought to Aprep, Aprep is the warehouse where a part goes to when it is declared serviceable and is being kept until all the parts of the same engine are complete. Serviceable means, the part is not damaged or broken and can be safely used. This means for any level of speaking, it can be a part, a module or the whole engine, that is serviceable or unserviceable.

After all parts have been repaired or are replaced and are back in the shop, the assemble phase will start. The carts with all the parts of that particular engine are brought from Aprep to the designated work centres to start with the assembly of the modules. When the HPT, HPC and the combustor are assembled, then first these three modules are assembled together as the core. And then when all the modules are assembled, there is a particular building sequence that should be followed to build the whole engine. First the fan should be placed in the overhead stand, then inside the fan, the LPC and a part of the gearbox are assembled. After that the core is assembled and the last module that will complete the engine is the LPT. The gearbox that is positioned on the outside of the engine is flexible in assembling, it can be assembled as first or as last. When all the modules are assembled together, the only parts that are left are the QEC. The QEC are all the brackets, tubes and wires etc. that are installed on the outside of the engine.

At KLM E&M there is a rule that whatever part comes of a particular engine, the same part will be returned back on that same engine. High exceptions can be made for Air France-KLM engines, because the parts will than stay within the companies' engines.

When the engine is completely assembled, it first needs to be tested before it can be returned to the client. Testing the engine is done in a so called test cell. If there have been found any implications, rework has to be done, if not, the engine can be returned serviceable to the client. See Figure 9 for the schematic view of the engine MRO chain.

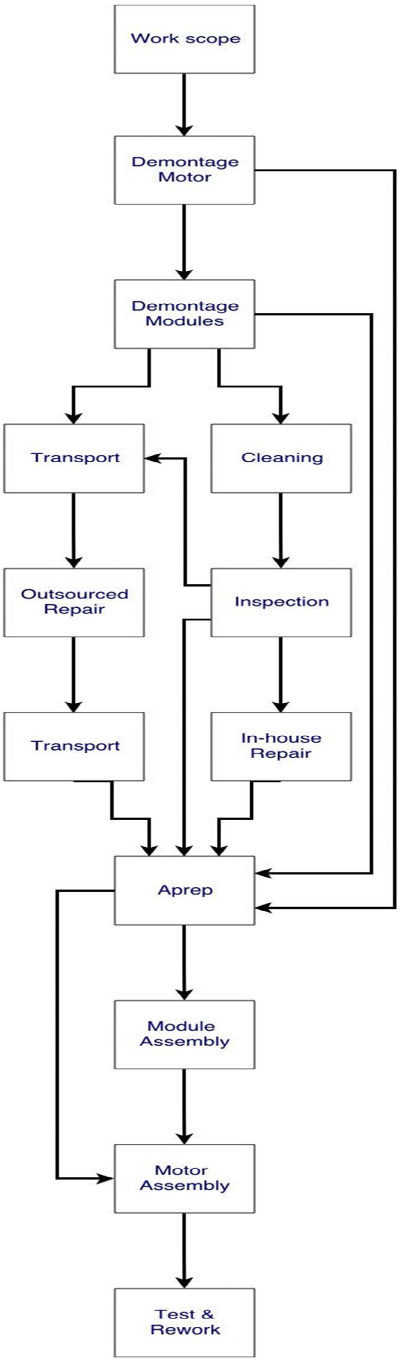

Figure 9. Flow chart of supply chain process at KLM E&M ES

2.2.2 Governance and Accountability at KLM E&M ES

As described the whole engine MRO chain consists of four stages; work scope, disassembly, repair and assembly. These four stages are in divided in more phases. Disassembly stage consists of disassembly, cleaning and inspection. Repair stage consists of in-house repairs and outsourced repairs. And the assembly stage consists of assembly, testing and rework. From the just mentioned phases, there are three layers of management. One manager, the VP of Engine Services, is accountable for the whole engine MRO chain. One layer below him, there is a MRO manager accountable for the work scope, disassembly and assembly stages. And there are two managers for the repair stage, one for the outsourced repairs and one for the in-house repairs. And the third layer consists of managers of the phases like, assembly, disassembly, cleaning and inspection.

Between the four stages agreements are made of what the TAT per stage may be. The handshake that is made for the disassembly stage is 11 days. This 11 days begin from the moment a mechanic starts with disassembling a part from the engine and the disassembly stage is completed when the last part is handed over to the repair stage. From the moment the last part is handed to the repair department, the repair stage begins. For in-house repairs a handshake is made for 28 days and for outsourced repairs a handshake is made for 35 days. The repair stage is completed when the last part is declared serviceable and is at Aprep. The handshake that is made for the assembly stage is 13 days and starts when the carts with parts is brought to the mechanics to start assembling. This stage is completed when the engine is serviceable released and can be returned to the client. Table 1 shows the agreed handshakes per process step and appendix I shows more detail, the norm times of the disassembly and assembly per assy are shown there.

Table 1. Agreed handshakes of process steps

Disassembly	*Cleaning & Inspection*	*Transport (Inbound – Outbound)*	*Repair*	*Assembly*	*Test & Rework*
6 days	5 days	3 – 4 days	28 days	11 days	2 days

2.2.3 Planning and control at KLM E&M ES

As been stated in 1.1, the ES MRO market has become very competitive. There is a high demand for low prices, high quality and low turnaround times. Demand for capabilities that would have been impossible to meet under the more dichotomous strategies of the not too distant past have become the norm for competition in today's manufacturing environment (Newman & Sridharan, 1995). And the same is valid for the MRO environment. The available process technologies within the firm determines its flexibility and ability to support the competitive priorities. A planning and control system is a major component of the infrastructure that supports the production process selected for the specific environment (Newman & Sridharan, 1995).

The planning of the engines is regulated by the planning department of Engine Services. This department decides when engines are coming to the shop from the client. Usually the planning department accepts all requests of clients for engine MRO and the incoming engines are not really regulated on resource capacity on the shop floor. Once in the shop, the department keeps track on the progress of the engine. The planning department uses a self-made excel tool to keep track on the progress. When an engine is behind schedule, the colour of this engine becomes red in the excel sheet. At the shop floor, the first-in first-out is used at every process step.

2.2.4 Performance control system at KLM E&M ES

Currently, the performance of the engine MRO supply chain is controlled with the use of the Connected Business Balanced Score Card (CBBSC). This CBBSC consists of a flow chart with the main sub-processes of engine MRO. There are four main KPI's that measure the performance of engine MRO; on time performance (TAT), product quality (EGT), test cell and productivity. The current control system of the performance at KLM E&M ES is shown at Figure 10.

The control system measures four performance indicators of the engine MRO. For each indicator, the definition as used by KLM E&M ES is given in Table 2. The on-time performance is measured on several processes; for the overall on time performance of engines, for the in-house repair stage on time performance and for the outsourced repair stage on time performance.

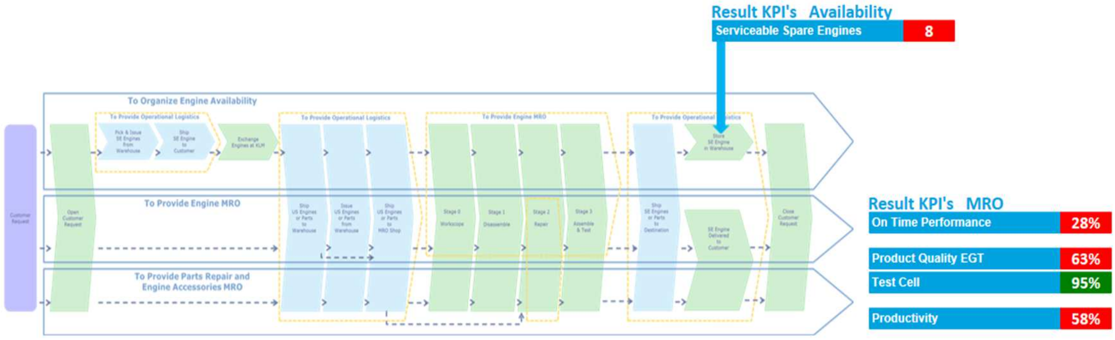

Figure 10. Current control system KLM E&M ES

Table 2. Current key performance indicators of engine MRO at KLM E&M ES

Key performance indicator (KPI)	***Description***
On time performance (TAT) %	Percentage of engines/parts that is delivered within the agreed TAT. Depending on the level of detail (overall MRO or repair stage)
Product Quality (EGT) %	Percentage of engines with EGT that matches the contract EGT (if included in contract)
Test Cell %	Percentage of engines that pass the test cell's final test the first time.
Productivity %	Planned man-hours versus spent man-hours

2.3 Conclusion research field

In chapter 2 the first sub question, *"How is the current engine MRO chain organized at KLM E&M ES?"*, has become clear. The MRO chain consists of four main stages, the work scope determination (which is left out of scope in this thesis), the disassembly stage, the repair stage and the assembly stage. The last three stages contain several other process steps. The disassembly stage consists of the disassembly and the cleaning and inspection. The outsourced repairs, have also a transport process step in the repair stage. And the assembly stage consists of the assembly, testing the engine and rework that needs to be done. The engine itself consists of four levels of detail, it differs on which level of detail the engine passes a process step. The highest level of detail is the engine as a whole, then a whole engine consists of seven modules and these seven modules contain 21 assy's in total. These assy's can be disassembled into more than 10,000 parts.

The engine passes the process steps on different levels of detail and for every process step agreements have been made of how long a process step may take for a part of the engine. The six agreements that are made for the process steps are; six days for the disassembly, five days for cleaning and inspection, three days for the outbound transport, four days for the inbound transport, 28 days for the repair, eleven days for the assembly and two days for test and rework.

The planning and control is done by a separate department. The engines are tracked in a self-made excel and when an engine is behind schedule, this will be highlighted in red on the planning, but not much will be done about it. Unless the due date will be met soon. At the shop floor the first-in first-out rule is used at every process step. The planning and control at KLM E&M ES should be optimized in order to let the engine MRO chain perform better.

At KLM E&M ES the performance of the engine MRO chain is measured on four KPIs; On-Time Performance, Product quality, Test cell and productivity. These KPIs are not the best to control the engine MRO chain.

3 Literature review

In the previous chapter the current process of the integral engine MRO supply chain at KLM E&M is discovered. It has been found that the process measurement is not done properly, which leads to an ineffective and inefficient process control. And if it is not known how the MRO process can be controlled, it is not known how to adjust the planning in a way that the process can be led into the right direction. Now all the supply chain process steps are clear, the next step is to do literature review to find theories and studies to counter the limitations on measurement, control and planning. The result of this literature review is a framework that can be proposed and applied in engine MRO processes, with the goal of improving the integral engine MRO supply chain. First, to get to know what should get measured and controlled, the type of environment of the integral engine MRO supply chain should be clear. In section 3.1 an answer on the second sub question will be found; "*What planning and control levels are known from literature?"* Here the focus will be on planning and control methods in different environments. After that is clear, the type of an engine MRO environment should be defined by answering sub question three "*Regarding planning and control, as what can the engine MRO environment be defined?"*. After that, it has to be known how the whole process should be measured. Section 3.2 will focus on how the process should be measured. Sub question four will be the main focus in that section; *"What are the performance measures for an engine MRO chain?"* When the performance of the system is known, it can be controlled. Section 3.3 will focus on theories that can improve the processes. Section 3.4 will give an overview of the findings of the literature review. See Figure 11 for an overview of chapter 3.

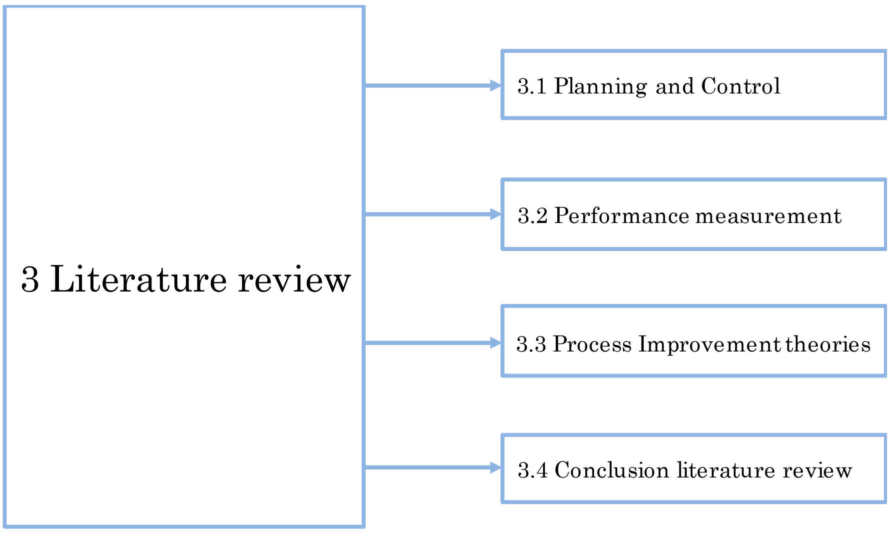

Figure 11. Schematic overview of chapter 3

3.1 Planning and Control

3.1.1 What is P&C

To determine how much of the end-product is needed, based on customer orders or demand forecasts, is one of the two main functions of planning and control systems. The other is to plan the requirements for materials, including the lot sizing and the determination of time-phased sets of component and raw material requirements. Like, inventory accounting, scheduling and sequencing jobs, planning and balancing capacities, order release and controlling the goal performance and taking action if deviations occur (Zäpfel & Missbauer, 1993). It is essential to integrate these activities into a planning and control system, to have an efficient, effective and economical operation in a manufacturing unit of an organization.

3.1.2 Levels of planning and control

Various planning horizons and levels of detail are used for planning methods. On the more detailed material planning level and the manufacturing operations on shop floor level, the planning object is the individual dependent items. While in long-term planning, the planning object is often the end product or product group. At each level, there are several planning decisions and each level varies in purpose, time span and level of detail. Due to these differences, each level has its own; purpose of the plan, planning horizon, level of detail and planning cycle.

Figure 12. Five levels of detail in manufacturing planning and control (Apics, 2011)

Level 1 – Strategic Business Plan (2 – 10 years)

The strategic business plan is a long-term plan of the major goals and objectives the company expects to achieve over the next 2 to 10 years or more. It is a plan of the broad direction and shows the kind of business the firm wants to do in the future (Management & Development Center, sd). The development of the Strategic Business Plan is the responsibility of senior management. Each department produces its own plans to achieve the objectives set by the Strategic Business Plan. The level of detail is not high and it is concerned with general market and production requirements and not sales of individual items. Strategic business plans are usually reviewed every six months to 1 year.

Level 2 – Production Plan (yearly)

Given the objectives set by Strategic Business Plan, production management is concerned with the following: the quantities of each product group that must be produced in each period, the desired inventory levels, the resources of equipment, labour, and material needed in each period and the availability of the resources needed. The level of detail is not high. The production plan will show major product groups or families. Production planners must devise a plan to satisfy market demand within the resources available to the company. For effective planning, there must be a balance between priority and capacity. Along with the market and financial plans, the production plan is concerned with implementing the strategic business plan. The planning horizon is usually 6 to 18 months and is reviewed each month or quarter (Management & Development Center, sd).

Level 3 – Master Production Schedule (monthly)

The Master Production Schedule specifies the timing and size of production quantities for each product. The master production schedule links the firm's broad strategies, as expressed in the aggregate production plan, to more specific tactical plans that will enable the firm to balance the product demands of customers with the supply of products made available by plant schedules and inventory (Hill, Berry, & Schilling, 2003). The level of detail is higher and the planning horizon usually extends from 3 to 18 months but depends on purchasing and manufacturing lead times. Usually the plans are reviewed and changed weekly or monthly.

Level 3 – Material Requirements Planning (monthly)

MRP is a set of logical planning techniques which better enables management to operate in a manufacturing environment. It is a network scheduling concept which integrates company-wide information to plan the activities of the manufacturing function (Wong & Kleiner, 2001). MRP offers management the capability to identify the products that are actually going to be produced. These items come from the production plan which is an extension of the material requirements plan. The material requirements plan in turn, identifies what the designated work centres and/or the factory floor, including vendor, requirements are going to be over a designated period of time. The material requirements plan is a sophisticated computer generated calculation quantifying procurements and production requirements from the relationships of the above four reference questions. Specifically, these interrelationships are generated from the master production schedule, the inventory records and the bill of material. The level of detail is high and the planning horizon is at least as long as the combined purchase and manufacturing lead times. It usually extends from 3 to 18 months.

Level 4 – Production Activity Control (PAC) (daily)

In a synthetic way, PAC can be defined as the group of activities directly in charge of managing the transformation of planned orders into a set of outputs (Grabot & Geneste, 1998). It governs the very short-term detailed planning, execution and monitoring activities required to control the flow of an order from the time when the order is released by the planning system for execution until the point that the order is filled and its disposition is completed (Melnyk & Carter, 1986). The production activity control system is essential to ensure reactivity along with optimization of resource use, since it applies middle-term decision making of the upper levels with the adaptations required by short-term or real-time disturbances. The application of the middle-term decision making with as few modifications as possible is important since these decisions aim at optimizing the use of the resources. The level of detail is high since it is concerned with individual components, workstations and orders. Plans are reviewed and revised daily.

Resource capacity Management

At each level in the manufacturing planning and control system, the plan must be tested against the available resources and the capacity of the manufacturing system. If the capacity cannot be made available when needed, the planning must be changed. There can be no valid, workable production plan unless these changes are done (Management & Development Center, sd).

Over several years, machinery, equipment and plants can be added to or taken away from the shop floor, which relates to level 1 of the planning and control overview. But, in the planning and control levels from production plan to production activity control, other kind of changes are related to the different levels. The capacity changes that can be accomplished on these levels are for example, changing the number of shifts, working overtime, subcontracting the work.

Vendor management

Managing the relation with the vendor of raw material or components is very important for the production process of a company. In the end a company expects from a vendor that all parts will be delivered on the agreed due date and with good quality. But the better the control over this vendor the more likely it will be that the vendor will comply on the agreed terms. Vendor management is, just like capacity management, active in various levels of the planning and control model. Below, the levels are elaborated in more detail.

3.1.3 Operational process environments

For every type of manufacturing firm, other planning and control methods could be applicable. There is no 'best' planning and control system for all instances. It depends on the demand, products and manufacturing characteristics to say which planning and control method is the most suitable. A method that works perfectly well in one situation can be a completely wrong approach in another (Jonsson & Mattsson, 2003) (Van Dierdonck & Miller, 1980). Having a good fit between the production and planning system and the production environment facilitates better execution of activities that add value (Newman & Sridharan, 1995).

First, a distinction will be made between two main environments. The most common environment is the production process manufacturing environment, which contains the production process from raw material or sub-assemblies to the final product. The other is the remanufacturing environment, which contains a disassembly process of old or defect products, a repair process and the assembly process into the final product. Both types of these main environment can have its own variances characterized by the same variables. In the next paragraph the variety of differences within these two main environments can be made clear.

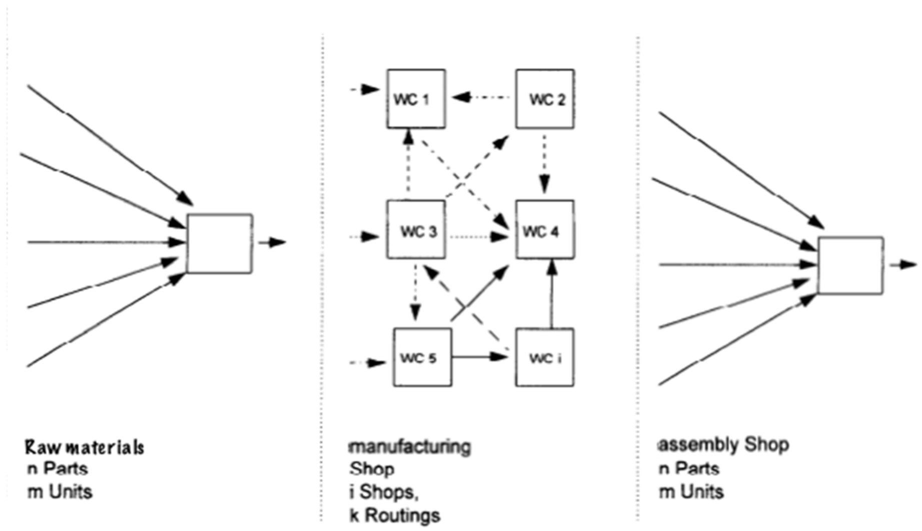

Figure 13. Typical elements of a manufacturing shop

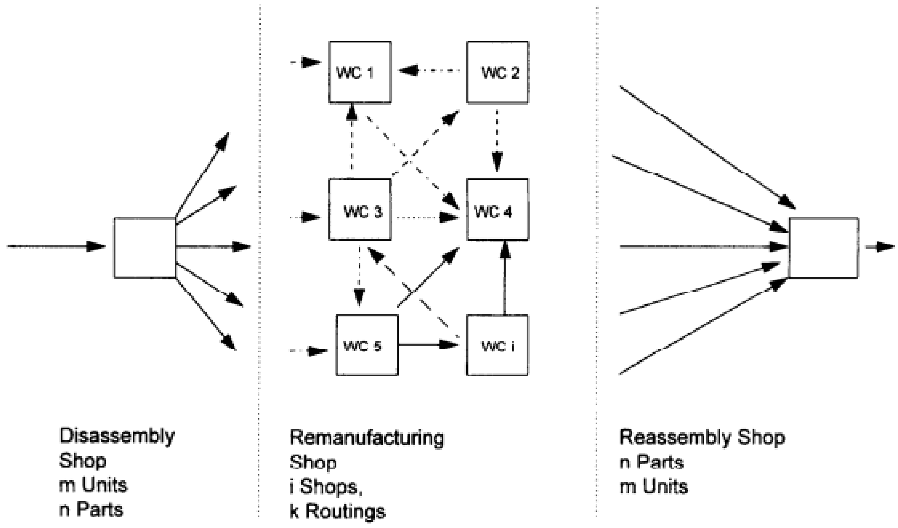

Figure 14. Typical elements of a remanufacturing shop (Guide Jr., Kraus, & Srivastrava, 1997)

Jonsson and Mattsson (2003) state that the planning environment can be characterized by several variables related to the product, the demand and the manufacturing process. No matter if the main environment is the production process or the remanufacturing environment. There are six different variables that characterize the product. The eight demand-related variables characterize demand and material flow from a planning perspective. The third group distinguishes six variables that characterize the manufacturing process from a planning perspective. Table 3 summarizes the detailed sub-variables of the three environmental characteristics.

As stated earlier, in each combination with different environmental characteristics another method of planning and control should be used. Four common environmental combinations will be used to give examples of how various environments look like; complex customer products (type 1), Configure to order products (type 2), Batch production of standardized products (type 3) and Repetitive mass production (type 4) (Jonsson & Mattsson, 2003). Hill (1995) used four similar types, i.e. project, jobbing, batch, line and continuous. The more detailed description of these environment types can be found in Appendix B.

Table 3. Environmental variables (Jonsson & Mattsson, 2003)

Product related	Definition
BOM complexity	The number of levels in the bill of material and the typical number of items on each level
Product variety	The existence of optional product variants
Degree of value added at order entry	The extent to which the manufacturing of the products is finished prior to receipt of customer order
Proportion of customer specific items	The extent to which customer specific items are added to the delivered product, e.g. the addition of accessories
Product data accuracy	The data accuracy in the bill of material and routing file
Level of process planning	The extent to which detailed process planning is carried out before manufacture of the products
Demand-related	
P/D ratio	The ratio between the accumulated product lead time and the delivery lead time to the customer
Volume/frequency	The annual manufactured volume and the number of times per year that products are manufactured
Type of procurement ordering	Order by order procurement or blanket order releases from a delivery agreement
Demand characteristics	Independent or dependent demand
Demand type	Demand from forecast, calculated requirements or from customer order allocations
Time distributed demand	Demand being time distributed or just an annual figure
Source of demand	Stock replenishment order or customer order
Inventory accuracy	Accuracy of stock on hand data
Planning perspective	
Manufacturing mix	Homogeneous or mixed products from a manufacturing process perspective
Shop floor layout	Functional, cellular or line layout
Batch size	The typical manufacturing order quantity
Through-put time	The typical manufacturing through-put routings
Number of operations	Number of operations in typical routing
Sequencing dependency	The extent to which set-up times are dependent on manufacturing sequence in work centres

3.1.4 Remanufacturing structure

Aircraft engine MRO is not a normal manufacturing process as discussed in the previous paragraphs. An addition to the process is that the disassembly activity is present in the process. After literature review, the engine MRO can be described as very close related to the remanufacturing process. As stated by Lund (1983) remanufacturing is *"…an industrial process in which worn-out products are restored to like-new condition. Through a series of industrial processes in a factory environment, a discarded product is completely disassembled. Useable parts are cleaned, refurbished, and put into inventory. Then the new product is reassembled from the old and, where necessary, new parts to produce a fully equivalent- and sometimes superior- in performance and expected lifetime to the original new product."*

A typical remanufacturing system consists of three distinct sub-systems: disassembly, processing and reassembly (Guide Jr., 2000). Because of the use of general-purpose equipment and the need for flexibility, remanufacturing operations layouts are most commonly in a job-shop form (Nasr, Hughson, Varel, & Bauer, 1998). Remanufacturing firms have a more complex shop structure to manage, control and plan. Highly variable material processing equipment, disassembly operations and stochastic product returns causes thus additional complexity (Guide Jr. & Srivastava, 1998) (Guide Jr. & Kraus, 1997b). The first step in remanufacturing is disassembly, in this process the product is fully disassembled in all individual components. In the processing step, the components will be cleaned, checked and repaired/refurbished. When it is known that a new product is needed, the product will be assembled from all the individual components in the last step of the remanufacturing system.

The disassembly process provides input for many other decision; including disposal requirements, quantities of recovered material, release of parts to the repair and/or remanufacturing shops, and purchase requirements for replacement materials.

3.1.5 Complexity of remanufacturing

With respect to the normal manufacturing process, the remanufacturing process has some complex elements. The characteristics that are the main differences and which makes the remanufacturing more complex between the two types of environment are the material recovery rate, the stochastic routings and processing times, the serial number specific parts matching, the disassembly and the outsourced repairs. For a full description of these characteristics see Appendix B.

The material recovery rate is described by Guide Jr. *et al.* (1999) as: *"how often a part is in a suitable condition to be remanufactured."* In a remanufacturing environment the recovery of material is unknown, and that is what makes the process more complex.

Highly variable process times and stochastic routing are common in a remanufacturing environment, because the condition of the disassembled parts are unknown on forehand. This causes a shifting in bottlenecks with every other product that is handled, which is making the whole process more complex.

It could be a desire of the client, to reassemble certain parts back on the same disassembled product. Thus, these serial number specific parts must be tracked to be back on the same time and that process is very complex (Guide Jr., 2000). With the presence of any serial number specific items coordination between disassembly and reassembly becomes critical if customer due dates are to be met (Guide Jr., Jayaraman, & Srivastava, 1999).

The effects of the disassembly operations has impact on a large number of areas, including, shop floor control, production control, scheduling, and materials and resource planning. The disassembly and subsequent release of parts to the processing activities require a high degree of coordination with reassembly to avoid high inventory levels or poor customer service (Guide Jr., Jayaraman, & Srivastava, 1999). This makes the remanufacturing process more complex than a typical normal production process.

With remanufacturing, besides the delivery of new/raw material, there is another process step where vendors might come into play. When the company is not able to repair some parts itself, a vendor is used to repair those specific parts for that company. Once the parts are shipped to the vendor, it is out of the companies control. A specific return date is agreed, but when the parts return exactly is most of the time not entirely sure. This makes the remanufacturing process more complex.

3.1.6 Planning and control methods

In this paragraph, the different kind of planning and control methods are elaborated briefly on the various levels of planning and control. On the three highest levels, the strategic business plan, the production plan and the master production schedule, there are no different methods of planning and control to be distinguished. On these levels, it is more about making strategic decisions. Where the production plan level performs the volume planning and the master scheduling plans the product mix (Olhager & Wikner, 2000) and the distribution of the production determined at the production plan. But at the material requirements planning, the shop floor control and the capacity management, different environments work best with different planning and control methods. In the paragraphs below, a brief explanation is given of all methods, a full description of all the various planning methods are given in Appendix B.

Material planning methods

Re-order point planning uses demand forecasts to decide when to order a new quantity to avoid dipping into safety stock. Re-order point planning suggests a new order for an item when the available quantity drops below the item's safety stock level plus forecast demand for the item during its replenishment lead time.

Material Requirements Planning is a concept of creating material plans and production schedules based on the lead times of a supply chain. It brings a maximum of planning ability to accommodate dynamic natures (Newman & Sridharan, 1995).

The opposite of material requirements planning is the *Kanban system*. Kanban is a way to organize the chaos by making a need for prioritization and focus clear, and Kanban is also a way to uncover workflow and process problems in order to deliver more consistently to the customer.

Drum-buffer-rope (DBR) has close relations with the Kanban approach. The DBR method is coming from the Theory of Constraints and is based on only scheduling the constraint, thus the data that is needed will be reduced drastically (Goldratt, 1984).

Order-based planning is the functionality that plans planned orders to cover components and end items. This functionality largely corresponds to Materials Requirement Planning and uses Bill of Materials to explode material requirements and the routings to calculate lead-time of planned production orders

Shop floor control

The shop floor control, or production activity control, consists of scheduling (order release) and sequencing (dispatching). Three order release methods and six dispatching priority rules will be elaborated briefly.

Order release methods

Infinite capacity scheduling basically means that orders are released to the shop floor, irrespective whether the current load is above available capacity.

F*inite capacity* makes it possible to more effectively avoid overload and underload situations on the shop floor.

The *input/output control method* is based on the availability of capacity in the gateway work centre for the release of orders to the shop floor (Vollmann, Berry, & Whybark, 1997).

Priority Dispatching Rules (PDRs)

From literature six PDRs will be elaborated that keep flow in the system by having focus on moving material to the assembly phase, because that is the objective of the remanufacturing system. The first PDR is *first-come first-serve* (FIFO), which means that the part that is waiting the longest, which was there the first of all waiting parts, is being processed at first. The second PDR is a rule where the part with the *shortest processing time* (SPT) is being processed first. Parts waiting for a resource are ranked (low to high) according to their processing times at the particular resource, that is what makes this PDR simple (Rose, 2001). The direct opposite of SPT is the *longest processing time* (LPT), which means that the part with the longest processing time is processed first. The fourth PDR is the *global shortest processing time* (GSPT), this rule is based on the SPT rule. For the GSPT, all the processing times of the resources that a particular part still needs to visit are accumulated. All parts that enter the system have a due date. In the *earliest due date* policy (EDD) the part in the buffer with the earliest due date will be processed first. The last PDR is the *least slack* (LS) rule, slack is the time from the moment of calculating until the due date minus the process time that still has to be done. The formula for slack for part π located in buffer b_i can be defined as:

$$s(\pi) = \delta(\pi) - \zeta i$$

Where $\delta(\pi)$ is the due date of part π and ζi is the estimate of remaining cycle-time in the plant for a part π located in buffer b_i. The part in the buffer with the least slack will be processed first. In essence the Least Slack Policy is a fair policy, it attempts to make every part equally late or equally early (Lu & Kumar, 1991). Which will reduce the standard deviation of lateness. Besides that, it will give priority to parts that are more critical because they have less slack. Which will lead to less expediting of parts.

Capacity planning

To use the *overall factors method* for capacity planning the products should be homogeneous from a manufacturing point of view. The method also assumes that the load from manufacturing a product is in the same planning period as the delivery date (Vollmann, Berry, & Whybark, 1997).

When using *capacity bills* as capacity planning method, manufacturing homogeneous products is of less importance. It employs detailed data on the time standards for each product. That is why poor time standards could become an obstacle when using this method (Fogarty, Blackstone, & Hoffmann, 1991).

Resource profiles rely on time standards and do not consider the stock-in-hand of components used in the products, as does the capacity bills method (Blackstone, 1989). The method allows for capacity planning prior to the conclusion of the detailed design and production planning phase, this is particularly relevant for engineer-to-order type of products (Jonsson & Mattsson, 2002b), like environment type 1.

The *capacity requirement planning method* is the most generally applicable capacity planning method. It can be used successfully in all four types of environment, but its relative strength is in environments with complex products that are custom built from standardized components or complex standard products (Jonsson & Mattsson, 2003). Capacity requirements planning has major advantages in environments where components are manufactured in batches to stock, like in the planning of stock-on-hand of components (Fogarty, Blackstone, & Hoffmann, 1991) (Vollmann, Berry, & Whybark, 1997) (Jonsson & Mattsson, 2002b).

3.1.7 Planning & control remanufacturing

The planning and control for a remanufacturing system is different than that of a normal manufacturing system. In this paragraph, this will be elaborated. Guide Jr., Jayaraman & Srivastava (1999) describe the situation as follows: *"The basic problem for production planning and control is to determine how much and when for a number of inter-related decision variables. Any coordinated production planning and control system must assist a manager in planning how much and when to disassemble, how much and when to remanufacture, how much to produce and/or order new materials, and coordinate disassembly and reassembly"*. There are four sections where the difference between a remanufacturing system and a normal production system differ significantly; the shop floor structure, the master production schedule, the part release control and the resource planning. The differences will be elaborated in the paragraphs below.

Shop structure

A large variety of shop structures ranging from highly repetitive work to large job-shop type structures are applicable for remanufacturing facilities. The most common type of remanufacturing facility will have both open and closed job shops with reassembly operations (Guide Jr., Jayaraman, & Srivastava, 1999). Repetitive flow remanufacturing facilities will still have reassembly and disassembly areas, but these will be more structured in a line flow organization. Control decisions must be linked to synchronize the entire system because all the processes in remanufacturing system is strongly dependent of each other.

Master Production Schedule

A make-to-order remanufacturing firm has little need with balancing core acquisition to demand, since a product must be returned before work may start. However, core acquisition and timing is a crucial concern that should be addressed in the MPS design. A function related to MPS is that of order release. Policies of releasing orders determine when and how to release jobs to the disassembly shops. To make shop loads more predictable and have an improved delivery performance, proper control of order release should be provided by managers (Guide Jr., Jayaraman, & Srivastava, 1999). Guide and Srivastava (1997) show that batching jobs at the order release stage produces increased variation in flowtimes and can significantly degrade delivery of orders.

Part release control

Priority control of parts to provide a predictable arrival of parts in the reassembly area is also a common concern among remanufacturers. Firms report using a set buffer size for common parts where service levels trigger replenishments. Parts that are more expensive are pushed to the reassembly area by the use of priority dispatch rules, or pulled by a final reassembly schedule. Purchase orders are often probabilistic for reasons discussed earlier, low volume and visibility (Guide Jr., 2000). Remanufacturing firms relying on a MTO strategy are less likely to use an MRP system for material procurement. The majority of the firms used simple re-order point systems for inexpensive parts, and ordered more expensive replacement parts as-needed.

To provide faster flowtimes and a better delivery performance schedulers should use specific priority dispatching rules for particular product structure types (Guide, Srivastava, & Kraus, 1997). A scheduler should pay close attention to the interactions between part type matching and disassembly release rules to provide a high degree of customer service and consistent flowtimes (Guide Jr. & Srivastava, 1998).

The dispatching rules explained in section 3.1.6 are also applicable at remanufacturing systems.

Resource Planning

Guide and Spencer (1997) present a resource planning model that operates well in a stable environment. The modified model takes stochastic routings and material recovery rates into account. Guide (1997) compared the modified planning techniques with traditional resource planning techniques and shows that the traditional techniques perform poorly in a remanufacturing environment and that methods that take into account all sources of variability produce more reliable results.

3.1.8 What type of environment is engine MRO

To discover the characteristics of the engine MRO environment the information in the previous paragraphs will be used. Figure 15 shows the overview of how the environment of the engine MRO process is determined. Based on the variables related to the product, the demand and the manufacturing process, the environment of the engine MRO process is determined. Below a summation and explanation of the characteristics of the engine MRO environment.

The engine MRO process had a disassembly, remanufacturing and reassembly stage.

The *Bill of Material (BOM) complexity* is high, because an engine is a very complex product with a lot of parts and a very specific way of how it should be build.

The *product variation* is low, because common engine MRO companies are in general specialized in just a few types of engines.

The *degree of value added at order entry* is like the Engineer-to-Order method. Where the process starts when the customer delivers the engine at the engine MRO company and the engine is exactly build how the customer wants to.

The *work scope determination* is mainly before the process starts. Before the engine will be disassembled the work scope will be determined with the help of a borescope. But in some cases the work scope has to be adjusted because there are findings during the disassembly or even the repair stage.

The *repair uncertainty* is present in the engine MRO process, because in most cases it is not known which parts need what kind of repairs.

The *parts are needed serviceable at the same time* is in some cases true. At least all the parts of the same assy need to be serviceable at the same time, otherwise the assy cannot be build. And on a bigger scale, all the parts of a module need to be serviceable at the same time, to start building a module.

The *serial number specific parts* is in theory a yes. Because for the quality of the engine it is better that all the original parts will be reassembled together on the same engine. But in some cases this rule will be violated by replacing some parts for others, to speed up the whole MRO process.

The *demand type* of the engine MRO market is based on customer orders, because a MRO process will only be commenced when a customer order has been taken place.

The *shop floor lay-out* is functional, because the different modules need different equipment. That is why the shop floor is divided in various departments where activities take place.

The *batch size* in general is low, because one engine/module/assy is dissembled or assembled individual. Inside some other processes it is possible that some batching occurs, but it is nog preferred.

The *number of operations* is high in the engine MRO process. Because the disassembly, remanufacturing and reassembly stages contain several other activities. Such as, cleaning, inspection, logistics and some other activities in the remanufacturing process.

Since it now is know what type of environment the engine MRO process is, the methods for planning and control can be determined. But first, to know where to apply or change the planning and control it is necessary to know the performance of the engine MRO system. How the performance will be measured for the various processes in the engine MRO process will be explained in the next section, section 3.2.

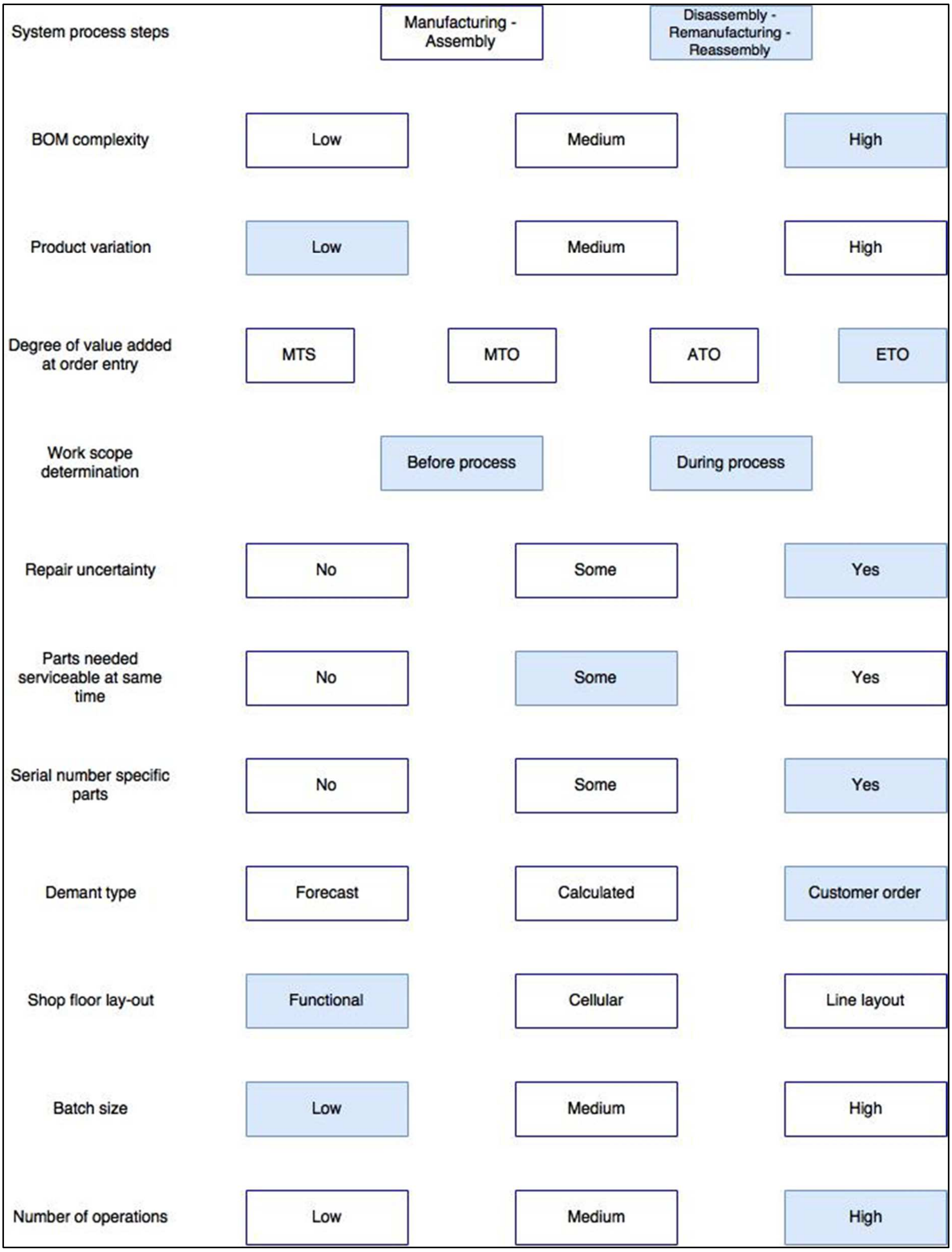

Figure 15. Determination of what type of environment the engine MRO process can be defined

3.2 Performance measurement

To get control over the whole process, it should be known how the process is performing at all the activities. To know how the activities perform, the activities have to be measured. But the activities should be measured on the right performances. What the right performances are, is the question in this section. A literature review is done to the kind of measurements that are relevant in the engine MRO supply chain.

3.2.1 Performance measurement indicators

The Key Performance Indicators (KPIs) that are relevant for the measurement of the performance in the engine MRO process are found in literature (Beelaerts van Blokland, De Waard, & Curran, 2008), (Meijs, 2016), (Mogendorff, 2016), (Van Rijssel, 2016) and (Van Welsenes, 2017). The relevant KPI's are elaborated in Table 4.

Table 4. Operational process KPI's (Van Welsenes, 2017)

KPI	***Description***	***Formula***
Turnaround time (TAT)	Measures the time it takes for one part to pass through a process of maintenance operations, repair and logistics	TAT = WT + PT
Average turnaround time (ATAT)	The average TAT of all parts that have been through the process in a certain time span	ATAT = ∑TAT / # parts
Standard deviation (SD)	Measures the variance of the measurements. The more variance in the process, the more instable it is.	
On time performance (OTP) %	Measures the amount of delivered items within the agreed time with respect to all deliveries.	OTP= 100 x (# parts that are finished within the transactional agreement/total amount of parts that is delivered)
On time start (OTS)	Measures the time when a certain activity starts	
On time delivered (OTD)	Measures the time when a certain activity is finished or delivered	
Waiting time (WT)	Measures the time when no value is added to a part because it is waiting to be processed	WT = TAT – PT
Process time (PT)	Measures the actual time spent developing a product with the ultimate goal being the addition of value to the end consumer	PT = TAT – WT or OTD – OTS

3.2.2 Performance measurement model

In the engine MRO environment the performance measurements are not all measured on the same level of detail from the engine perspective. As elaborated in section 2.2 there are four levels of detail in an engine; part, assy, module and engine. The various process steps in the engine MRO supply chain are measured on a different engine level. Table 5 shows what process steps are measured on which engine level. This is in general straight forward, for example, the cleaning step on part level; the part is measured when it enters the cleaning process until it leaves the cleaning process. And an example on engine level; the test phase is measured once the whole engine starts the testing phase until it completes this phase. The only process that is measured in a different way, takes place at the repair stage. How this works is elaborated below in the 'measurement repair process step' section.

Table 5. Process steps measured on what engine level

Engine level	***Process step***
Part	Cleaning, inspection, transport, repair
Assy	Assy disassembly, assy assembly
Module	Module disassembly, module assembly
Engine	Engine disassembly, engine assembly, test, rework

To measure the performance of the engine, it is necessary to put the measurements in a value stream. Because only measuring local performances will not give a clear view of what the performance is of the whole engine MRO supply chain together. By showing the performance in a value stream, it automatically shows the performance of the integral supply chain. Which is very important to get a clear and realistic view on the performance of the engine MRO supply chain. To do this, the KPIs as described in section 3.2.1 need to be measured and put together into a model. How this model is build-up, the validation and verification of the performance measurement model is further described in section 5.3.

Measurement repair process step

As can be seen in Table 5 the repair stage should be measured on part level, and as described in section 2.2.4 the repair process step is also already currently measured by KLM E&M ES using a BBSC system. The current method of measuring is dividing the OTP of all parts by the number of parts. Which means that it gives one performance measure for all the different parts that are repaired. Rozenberg (2016) used another method to measure the performance of the repair stage. Rozenberg measured the performance of the repair stage on part level per assy. This would give a repair performance measure per assy. But since it is known that an assy cannot be built before all parts of that assy are serviceable returned to Aprep, another method of performance measurement for the repair stage should be used (Guide, Srivastava, & Kraus, 1997). The repair stage should be measured per assy, with the performance measured on all the parts of that assy. That means, from the moment that the first part of a particular assy entered the repair stage until the last part of that assy completes the repair stage. Figure 16 visualises the proposed method of measuring the performance of the repair stage. In other words, the repair stage will be measured on part level per assy but for all the parts of an assy of that particular engine, with the earliest OTS of a part and the latest OTD of a part. Because the availability of all the parts of an assy is what is most important to continue the process.

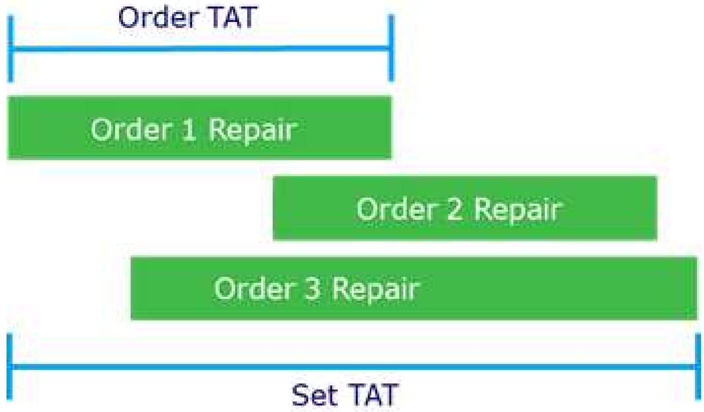

Figure 16.Difference between current performance measurement and proposed performance measurement

3.3 Process improvement theories

3.3.1 Lean

In the 1920s the basis of the lean theory was emerged, Henry Ford was the first to focus on eliminating waste of time and material where possible. He applied this techniques at the production plants of his company Ford. The CEO of Toyota, Taiichi Ohno, used the ideas of Ford and by adjusting and implementing them at the Toyota production plants, which lead to the Toyota Production System (TPS) (Ayeni, Baines, Lightfoot, & Ball, 2011). The actual term 'Lean' was popularized by Womack, Jones and Roos (1990) and they identified the five core principles:

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

Bendell (2005) summarized the lean philosophy very clear as:

"Lean (…) is the systematic pursuit of perfect value through the elimination of waste in all aspects of the organization's business processes. It requires a very clear focus on the value element of all products and services and a thorough understanding of the Value Stream"

Besides the five principles of Womack, Jones and Roos (1990), the other lean philosophy is TPS , as mentioned above. The TPS philosophy can be illustrated as a house and represents the basic principles of lean. The House is built on a strong foundation; Stability and Standardization. The system would collapse without these two conditions. The two pillars are formed by Jidoka (built-in-quality) and Just-in-Time. Jidoka is about detecting defects and repairing them early in the process, while Just-in-Time means getting the right amount of material at the right place at the right time. The base and the pillars carry the roof; the aim for highest quality, shortest lead time and lowest cost by continuous improvement: Kaizen (Stewart, 2011).

The "TPS House" can be built using Lean tools available for each element. The main drivers of a process taken from Lean, are waste – defined as TIMWOOD(S) – 4M and flow. These drivers can be investigated after the identification of the Value Stream.

Value Stream Mapping

To get insight in the performance of the current process, mapping the process is important. With analysing the current performance, the main constraint can be found. When the constraint is found, it is important to analyse the process of the constraint in more detail. To do that, VSM is a useful tool. A VSM helps to develop a good schematic view that captures information useful to help identify the root cause of the constraint (Smith & Hawkins, 2004). The advantage of VSM is that it depicts both the sequence of actions in a process and data on material flow, information flow, inventories, process times, setup times and delays (George, 2010). As a result of the VSM, the value-added and non-value-added processes can be deducted. A value-added process is a process step that does add value to the end-product and is valuable for the customer (George, 2010). A non-value-added process is a process that are not required to meet customer needs or run the business (George, 2010). Non-value-added process are mainly causes by the seven forms of waste.

7 forms of waste

To maximize customer value related to the effort put into the process, wastes have to be eliminated. The lean theory of Taiichi Ohno (1988) identifies seven types of waste. TIMWOOD(S) is an acronym for different forms of waste, namely Transport, Inventory, Motion, Waiting time, Overproduction, Over-processing, Defects and Skill. From previous research (Van Rijssel, 2016), (Rozenberg, 2016), (Meijs, 2016), (Mogendorff, 2016) and (Van Welsenes, 2017) it can be concluded that the number one form of waste is waiting time. This form of waste has significantly more influence on the process than all the other added up together.

4M

To execute a stable process, four types of resources are needed to accomplish that, namely manpower, machine, method and material. At first the 4Ms must be stable as the foundation for improvement (Art of Lean, Inc). The absence of one of the four Ms can be a cause of waste or variation in the process (Beelaerts van Blokland, De Waard, & Curran, 2008). The definitions of the 4Ms are elaborated below (Van Welsenes, 2017);

Manpower: stand for the right worker for the right job. Workers must be able to maintain good relations with other workers during operation, be qualified to do the work for which they are assigned and have appropriate experience, and workers must work there assigned hours.
Method: stands for the right way of working. Work must be standardized in order to maintain a consistent quality of the output and maximize the flow through the process.
Material: stands for the right amount of the right material needed to execute the process
Machine: stands for the right capacity and right capabilities of working equipment needed to execute the process.

3.3.2 Six Sigma

To describe the high level of quality the Motorial Corporation was striving for, the company developed the Six Sigma methodology (Reid & Sanders, 2010). The aim of Six Sigma is to decrease the number of defects and the variation in a process. The variability of number of defects in the output determines the quality of the process. The smaller the variability in the output of the system, the lower the chance of defects in the system, which in term reduces the chance of unsatisfied customers. Statistically six sigma means that 3.4 defects occur per million handlings. Motorola set this goal so that the process variability is ±6 S.D. from the mean (Linderman, 2003).
The principle of Six Sigma process improvement can be summarized in a straightforward formula:

$$Y = (X) + \varepsilon$$

In this formula, Y represents the output of a certain process. This output is a function f of value drivers X and a factor of uncertainty or error ε (International Six Sigma Institute, sd). Of course, a vast number of value drivers X have an influence on the process output Y. The aim of Six Sigma is to screen the value drivers until a selection of main value drivers (or root causes) remain that, upon improvement, positively influence the process output. This screening of value drivers is conducted following the DMAIC cycle.
As stated before in section 1.5.2, the DMAIC cycle stands for Define, Measure, Analyze, Improve and Control. In every step, there will be worked towards improving and controlling the future process performance. Several tools can be used to accomplish this improved future performance (iSixSigma, sd). Various of these tools will be discussed below.

Probability plot

A probability plot will help to analyse the variation of a process. It can show if the process is normally distributed or not. According to the Six Sigma theory there must be waste in the process when the variation of the process is high (Beelaerts van Blokland, De Waard, & Curran, 2008).

Root Cause Analysis

The Cause & Effect Diagram, also known as the Fishbone, is a useful way of mapping the input that effect the TAT performance. The diagram helps to find the root causes of problems that already have occurred (Department of Trande and Industry). The problems that occur are categorized by the 4Ms, as discussed in section 3.3.1.

The 5-Why method can help to determine the cause and effect relationship in a problem. This method is suitable when the real cause of the problem or situation is not clear (Sondalini).

Pareto Analysis

The Pareto methodology is also known as the 80/20 rule. The method is used to extract the main file proportions from a range of phenomena. This is closely related to the reasoning that 20% of the causes is responsible for 80% of the consequences.

Six Sigma not only relies on technical tools and data-analysis; the other important aspect of Six Sigma considers people involvement. Training of employees to use the technical tools and identify and solve the root causes to improve process quality is essential in Six Sigma; Black Belts and Green Belts are examples of employees trained to apply the Six Sigma methodology (Reid & Sanders, 2010).

3.3.3 Lean Six Sigma

In 2002 George introduced the combination of the Lean and Six Sigma theories (George, 2002). Lean Six Sigma aims to maximize performance by improving customer satisfaction, quality, cost, flexibility and process speed (Jong & Beelaerts van Blokland, 2016). Because Lean cannot effectively bring a process under control or can it define a sustaining infrastructure for implementation (Ayeni, Baines, Lightfoot, & Ball, 2011), the combination of Lean and Six Sigma is introduced. And this combination can solve this issue. Smith and Hawkins (2004) state that Lean Six Sigma provides the tool to create continuous business improvement, where Lean "*brings action and intuition to pick low-hanging fruit",* while Six Sigma "*uses statistical tools to uncover root causes and to provide metrics as mile markers*".

3.3.4 Theory of Constraints

The theory of constraints (TOC) is a management philosophy developed by Goldratt in (1984). TOC is a method that focusses on achieving the goal by finding the main constraint that is preventing an organization of achieving its goals. Once that constraint is found, Goldratt's (1984) method also focusses on solving the bottleneck. The method does not only focusses on solving problems that achieve local optimums, but it focusses on improving the output of the whole supply chain. What constrains in the customer process chain affects the TAT performance and how can these constraint be eliminated, because in the end the chain is as weak as the weakest link.

Five steps of TOC

In order to eliminate the root cause of the constraint, Goldratt (1984) introduced a method called the five focusing steps for addressing process problems on a continuous improvement basis (Mabin, 1990);

1. Identify the constraint: Identify the operation that is limiting the productivity of the process. This may be physical or policy constraint.

2. Exploit the constraint: Achieve the best possible output from the constraint. Remove limitations that constrain the flow, and reduce non-productive time, so that the constraint is used in the most effective way possible

3. Subordinate other activities to the constraint: Link the output of other operations to suit the constraint. Smooth work flow and avoid work-in-process building up inventory. Avoid making the constraint wait for work

4. Elevate the constraint: In situations where the process constraint still does not have sufficient output invest in new equipment or increase staff numbers to increase output

5. If anything has changed, go back to step one: Asses to see if another operation or policy has become the process constraint. Goldratt (1984) states that this step is consistent with a process of ongoing improvement.

3.3.5 Summary process improvement theories

In this section, a summary is given of the described process improvement theories. In order to improve the whole supply chain it is necessary to find the main constraints that are preventing the company of achieving its goal. TOC and the Toyota Kata theories are helping with finding the main constraints and bottlenecks. After finding the constraint, Six Sigma and Lean can be used to analyse the process and find the root causes of the constraint. The root causes mainly related to the presence of waste, identified by Lean as TIMWOOD and the 4Ms. After knowing the root causes, TOC is a good tool to eliminate these root causes with the five steps.

Table 6. Summary of process improvement theories

Process improvement theories	***Description***	***Tools***
Lean Manufacturing	Lean aims for perfect customer value while minimizing waste (Womack, Jones, & Roos, 1990)	VSM, TIMWOOD(S), 4M, Flow, Pull, 5S, Kanban, Just-in-Time
Six Sigma	Six Sigma aims to maximize the probability that the output of the system complies with the expectations of the customer (Linderman, 2003)	Probability plot, Root Cause Analysis, Pareto analysis, Cause-Effect diagram
Theories of Constraints	The Theory of Constraints is a methodology for identifying the most important limiting factor (i.e. constraint) that stands in the way of achieving a goal and then systematically improving that constraint until it is no longer the limiting factor (Goldratt, 1984)	5 steps: Identify constraint Exploit constraint Subordinate everything else to constraint Elevate constraint Prevent inertia from becoming constraint

3.4 Conclusion literature review

The literature review has answered three sub questions. For sub question number ii; *"What planning and control levels are known from literature?"* four levels of planning and control have been found. These levels can be used to plan and control a company. The highest level is for long term decisions (2 – 10 years) and the lowest level, (daily) decisions on the shop floor are made. For every different company in a different type of environment, different decisions should be made to let the company perform at its best.

To know, how a company that provides engine MRO can perform at its best, it should be known in what type of environment the company is operating. In section 3.1.8, the third sub question is answered; *"Regarding planning and control, as what can the engine MRO environment be defined?"*. The engine MRO environment is a unique environment. It has a lot of characteristics of a remanufacturing environment, because the process consists of a disassembly stage as well. But the product that is delivered at the engine MRO company will always stay property of the client that delivered the product. Subsequent, the serial number specific parts causes that the majority of the parts that are disassembled of an engine, needs to get back onto the same engine. These characteristics are the reason why this environment is so unique.

There are three main findings of why it is important to know what kind of environment the engine MRO process has. The first is the least slack policy, this dispatching rule should be used on the shop floor in the engine MRO environment. Because the first-in first-out rule that is used at the moment, is ineffective. The least slack policy takes the due date and the remaining processing time into account, and ranks the parts that need to be processed much better.

The second finding is that the performance of the repair stage need to be measured on set level of the assy. This means that the availability of that whole assy is taken into account and not only the parts. The benefit of this is that it makes clear when that assy is available to assemble and not that only nine of the ten parts are available.

The third finding is that when the integral engine MRO process performance needs to be improved, there has to be looked to which assy is constraining the process of performing better instead of which process step. Because the engine cannot be built when only 20 of the 21 assy's are available. So there should be looked to improve which process step of that constraining assy should be improved.

The answer on the fourth sub question is found in section 3.2; *"What are the performance measures for engine MRO?"* One of the four KPIs that used by KLM E&M ES is also found in literature, only the Turnaround Time. The other KPIs that are found are; the average TAT, the standard deviation, the on-time performance, the on-time start, the on-time delivery, the waiting time and the process time. Three of these KPIs are relevant for the performance measurement of the engine MRO chain: the average TAT, the standard deviation and on-time performance. The average TAT is important because that is the lead time of how much time the process takes. The on-time performance is of relevance because the client needs to be satisfied by delivering the engine back on time. The standard deviation is important because the more stable the process is, the better the process can be controlled and predicted.

From literature there are found several theories to improve the performance of processes. Three of these theories are relevant to use in this thesis. Lean manufacturing is used to identify and eliminate waste in processes, which will lower the standard deviation and the average TAT. Six sigma is used because it identifies the root cause of defects and wastes to improve the quality of the process. The theory of constraints is important because this theory focusses on the constraint that is present in the process and has the goal to solve it.

4 Design of the framework

In this section, the framework, that results from the literature review, to improve the TAT of an engine MRO process will be proposed. The fifth sub question is the main focus of this chapter; *"What framework can be proposed to improve the integral engine MRO chain?"* For the design of a framework to improve the integral engine MRO process, various elements that are found in literature will be combined. To start, the five steps of the theory of constraints will be used as a backbone for the framework. These steps are adjusted to be suitable for an engine MRO environment. The framework will result in solutions that need to be implemented to improve the engine MRO chain. The solutions are related to management decisions in the various levels of planning and control. To solve a root cause, a decision at various levels of planning and control could be taken. What the several management decisions are at every level of planning and control is described in section 4.1. In section 4.2 the continuous improvement framework is designed and section 4.3 will give a conclusion chapter 4. See Figure 17 for the overview of chapter 4.

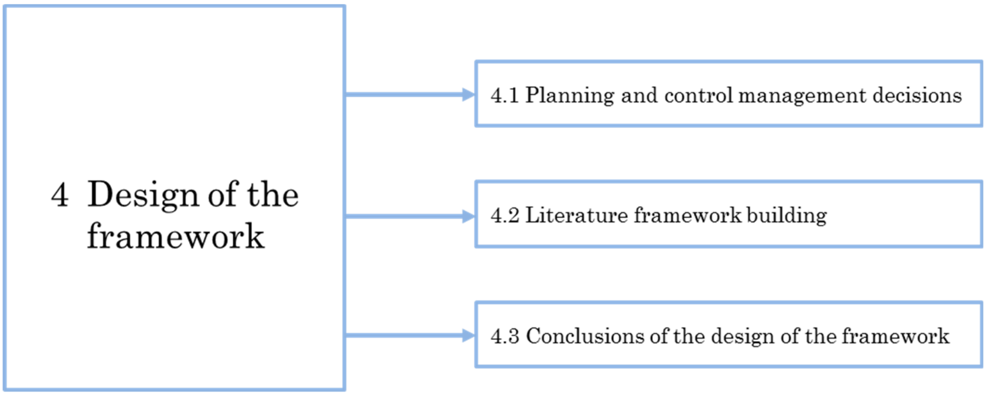

Figure 17. Schematic overview of chapter 4

4.1 Planning and control management decisions in an engine MRO environment

As explained in section 3.1.2, there are four levels of planning and control: long term+, long term, medium term and short term. At all these four levels different management decisions can be taken regarding material- or resource capacity planning and control. The levels of planning and control are necessary to decide which solution is more efficient than another. Because a decision that needs to be taken at level 1 is harder to implement than at level 4. In the paragraphs below the management decisions that must be made at the various levels of planning and control for engine MRO companies are elaborated.

4.1.1 Long term+ (level 1)

The highest level of planning and control is the strategic level. It all depends on the strategic decisions that are made by the board of directors of the company. What kind of product or service does the company offer and what kind of capacity is needed to accomplish the goal of the company. Regarding vendors, the decision is made about what kind of parts or raw material does the company order from which vendor and at which vendor does the company outsource material for repair. At this level, the engine MRO company and the vendor deal with the content of the contract they agree to. What TAT or lead-time is agreed for the repair of parts or the procured material, are there any penalties involved if the vendor does not deliver on-time?

At the highest level, long term+, management decisions that should be made regarding the material planning and control are;

- The types of engines that the company offers MRO services for.
- If the company make use of swapping material (rotables, assy's or even modules).
- Which parts the company repairs in-house and which parts the company outsources.
- The kind of contract that the company has with the vendor.

And at the same level, regarding the resource capacity planning and control the following management decisions can be made;

- The kind of skills the mechanics need at the shop floor.
- The kind of equipment that is needed.

4.1.2 Long term (level 2)

The long term level is a predictive level, on basis of the forecasted demand, capacity must be matched. That means for engine MRO companies that the capacity depends on the forecasted number of engines in a year that need a shop visit. At the long term level, management decisions for more or less the coming year are made. The decisions that should be made at this level regarding vendors, are mostly depending on what the engine MRO company can handle itself and what is better to outsource to a vendor.

The management decision that can be taken at the material planning and control are;

- The number of engines that will be serviced the coming year.
- The stock level of spare parts.
- The number of material that will be outsourced?

And the management decisions that can be taken at the resource capacity planning and control are;

- The number of mechanics that are needed for the coming year.
- The ratio of multi-skilled mechanics.
- The range of the capacity of mechanics (In other words, what is the minimum number of mechanics that are needed in a certain period and what are the maximum number of mechanics needed).
- The number of every kind of equipment that is needed to handle the total number of engines in a year.

4.1.3 Medium term (level 3)

On the medium term, management decisions for the coming month will be taken. For engine MRO companies this level of planning and control is a bit less complicated because the procurement of material is not such a big ratio compared to normal manufacturing companies. At this level engine MRO companies plan the route and time span of the different stages of the serviced engines and more detailed planning is necessary. On basis of the predicted demand, the distribution of amount of work need to be planned, stock level needs to be determined and material need to be procured. Also, the more detailed and planned information will be shared with the vendor. The exact due date that material is needed or the dates that a shipping will arrive or needs to leave at the vendor needs to be shared. For engine MRO companies the repair stage is a very important and critical process, that is why the communication and the agreed terms with the vendor must be very clear.

The main management decisions that can be taken at the material planning and control are;

- The distribution of the engines over the months.
- the material that should be procured on basis of replaced parts on engines, to keep the amount of stock at the right level.
- The shipping dates to and from the vendor, to keep control over the outsourced repairs.

The management decisions that can be taken at this level for the resource capacity planning and control are;

- The distribution of the mechanics that needs to be matched with the distribution of engines.
- The number of equipment must be matched with the distribution of the engines.

4.1.4 Short term (level 4)

For engine MRO companies this level is the shop floor control. All activities should be monitored and controlled to maintain flow in the process. The planning and control is the daily planning and control on the shop floor. A daily plan is made of what is needed to be done and who will be responsible for that task. Dependent for the scheduling of mechanics is the requirement for certain skills. A lot of mechanics have more than one skill, so these mechanics can be used at different work centres. On the short term time horizon, decisions for daily activities are made. At the lowest level of vendor planning and control, it should be controlled that the vendor is actually delivering the products on time and with the right quality. At engine MRO companies, additional to only receiving parts from vendors, the companies send parts to get repaired at the vendor as well. The part that the engine MRO company ships the parts to the vendor, that part should be controlled also, because the vendor could only repair the parts once the parts are at the vendor. For the material planning and control, the main management decisions that can be made on this level are;

- The priority dispatching rules that are used.
- The communications that the company has with the vendor.
- The method to control that parts are shipped on-time to the vendor.
- The method to control that parts are shipped back from the vendor on-time.

And at the resource capacity planning and control, on the short term level the following main management decision can be made;

- The method to determine at which work centre is manpower capacity/capability is needed (scheduling of manpower)?
- The rule that determines if the mechanics need to work over time to complete the activities of that day.

4.1.5 Conclusion of levels of planning and control at engine MRO companies

To summarize the levels of planning and control, the levels of planning and control are divided into two parts. The first part is the material planning and control and the second part is the resource capacity planning and control. Vendor management, as discussed above, is only related to material, because the product is the cause of setting up a relationship with a vendor. That is why the management decisions of vendor management will belong to the material management part. See Figure 18 for the summary of the levels of planning and control for engine MRO companies.

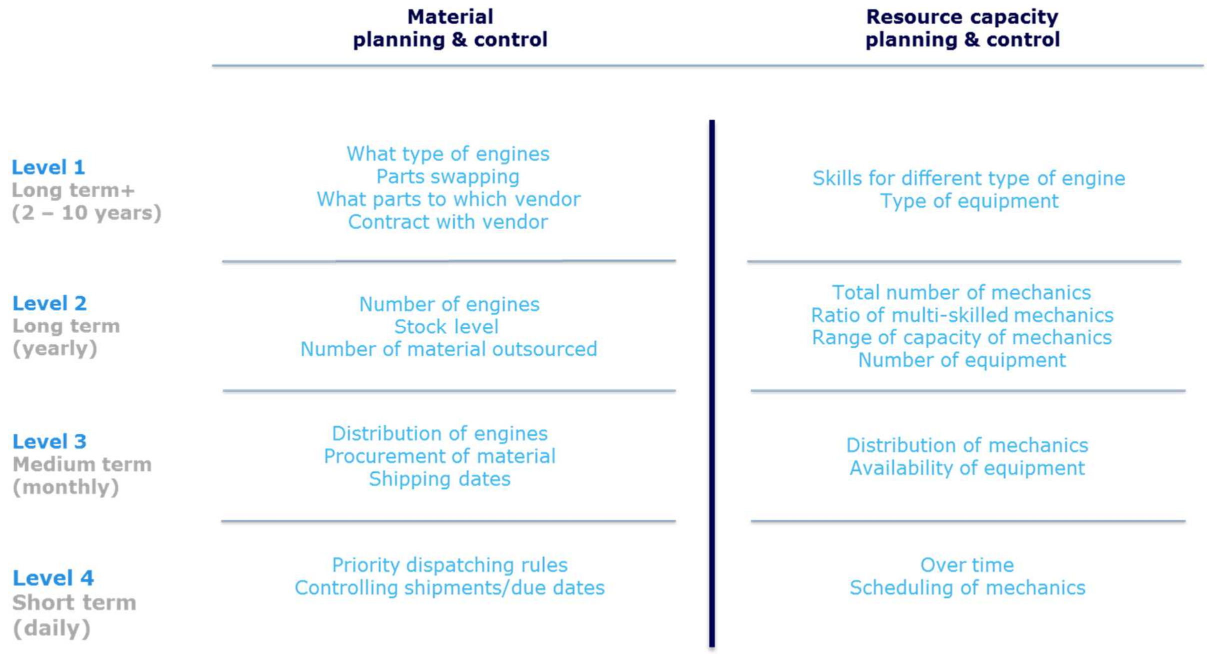

Figure 18. Levels of planning and control at engine MRO companies

4.2 Continuous improvement framework to improve the performance of the engine MRO chain

In this section a framework will be designed that can be used to continuously improve an engine MRO chain. This framework is built with knowledge from literature and the goal of companies. For the majority of the companies, the main goal is to make profit. For engine MRO companies, making profit can be stimulated by realising operational excellence. Operational excellence is operating with the main focus on the customer. So, the focus is on delivering the product back on-time. To increase the on-time performance, the average TAT of the integral engine MRO chain must be decreased. This could be realised by using the continuous improvement framework that is designed.

The continuous improvement framework consists of four steps, see Figure 19;

1. Identify the constraint of the integral engine MRO chain
2. Exploit and elevate every process step of the constraint
3. Compare the solutions and choose the most efficient
4. Implement the solution, if anything changes in the performance go back to step 1

In the first step, the constraint that is obstructing the integral engine MRO chain needs to be identified. This can be done with the performance measurement model, which will be described in section 5.3. Because of the unique environment of the engine MRO process, the constraint is always one or multiple assy's. Not like a normal production environment, where a process step is always the constraint. When the constraint is known, it is determined in step 2 how this constraint could be solved.

In step 2, all the process steps are exploited and elevated. To exploit a process step means, bring the performance back to the agreed norm performance. To elevate a process step means, to further improve the performance than the agreed norm performance. How the process steps can be exploited or elevated must be analysed with a root cause analysis. To solve the root causes, solutions must be designed. These solutions all belong to several management decisions that can be taken at the various levels of planning and control. When the solutions to solve the constraint of obstructing the integral engine MRO chain are designed, in step 3 it will be determined which solution will be implemented.

In step 3, all the solutions will be compared and the most efficient solution will be implemented. A solution is more efficient than another when the ratio of reduction in TAT and the level of planning and control better.

For example, two solutions change a decision on the same level of planning and control, and one solution has a bigger influence in reducing the TAT, that one is the more efficient solution. The level of planning and control is important, because it reflects the difficulty to change the decision and implement the solution. To change a decision on level 1 is more difficult to implement than changing a decision on level 4. This has to do with the time of implementation. A change of decision on level 1 takes a lot more time than a change in level 4. Because a change in level 1 is commonly a change in strategy of the company, which must be made by the board of the company and takes a lot of time to get approved. While a change in level 4 could be implemented the day after, because it is a change that mechanics should make on the shop floor.

In step 4, the solution will be implemented and the impact of the solution will be controlled. When the performance of the integral engine MRO chain changes, and the constraint has been solved, there should be gone back to step 1 and identify the new constraint.

Using this continuous improvement framework is an on-going process. There is always a constraint present in the process that is obstructing the integral process of performing better. In time, the impact that changes will have will get smaller and smaller when the framework is successfully used.

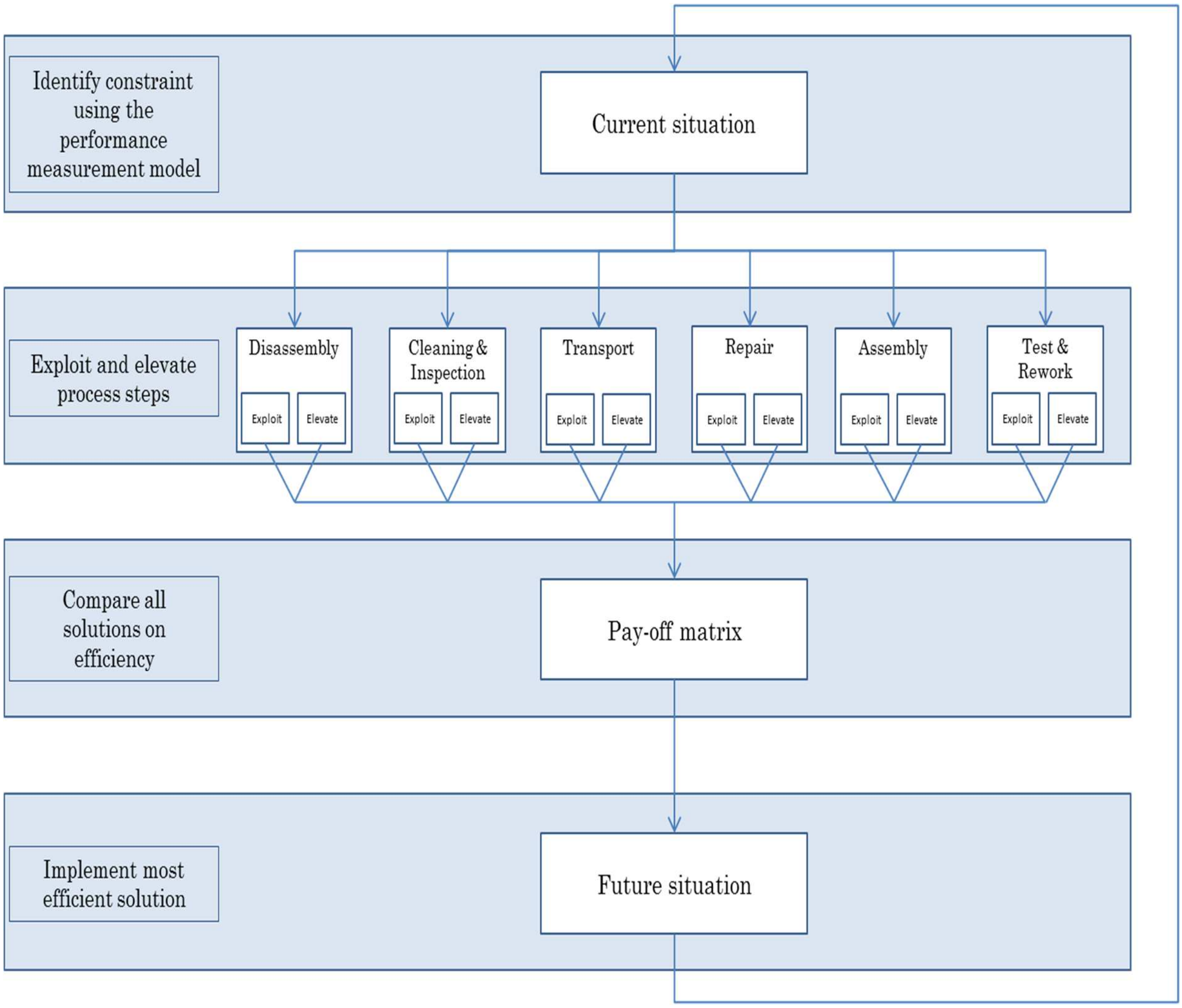

Figure 19. Continuous improvement framework

4.3 Conclusions of the design of the framework

Chapter 4 has answered the sub question *"What framework can be proposed to improve the performance of the integral engine MRO chain?"* The answer to this question is a continuous improvement framework that has been designed for the engine MRO environment. The framework is shown in Figure 19, and consists of four steps. The framework aims to realize operational excellence by continuously improving the process, that is why there is a loop in the framework. Once the current constraint has been solved and the engine MRO process has been improved, the loop will bring the process owner back to step 1. At step 1, the new constraint that has appeared, with the new performance of the process, will be identified.

The framework must be used in combination with the levels of planning and control for the engine MRO environment. The proposed solutions are based on management decisions that have to be taken to solve the root causes of the individual process steps. The level of planning and control in combination with the reduction in TAT caused by the solution, will determine the efficiency of the various solutions.

5 Current state performance at KLM E&M ES

The literature review in section 3.2 proposes to use five KPIs to measure the current state of the system; Average TAT, Standard Deviation, On-time Performance, Waiting Time, Process Time. Next to these KPIs, a distribution plot will be made, to make it clear how the outcomes are distributed. To answer sub question number six is the main goal of this chapter; *"What is the current performance of the individual process steps and how do these form the current performance of the integral engine MRO chain at KLM E&M ES?"* Measuring the engine MRO chain on these KPIs is necessary to find the constraint of the integral chain by analysing the current state. In section 5.1 the necessary data and data quality are explained. The measured results of the different process steps are shown in section 5.2. Section 5.3 will combine the measurement phase with an overview of the integral engine MRO supply chain at KLM E&M ES. A conclusion of the measurement analysis will be given in section 5.4.

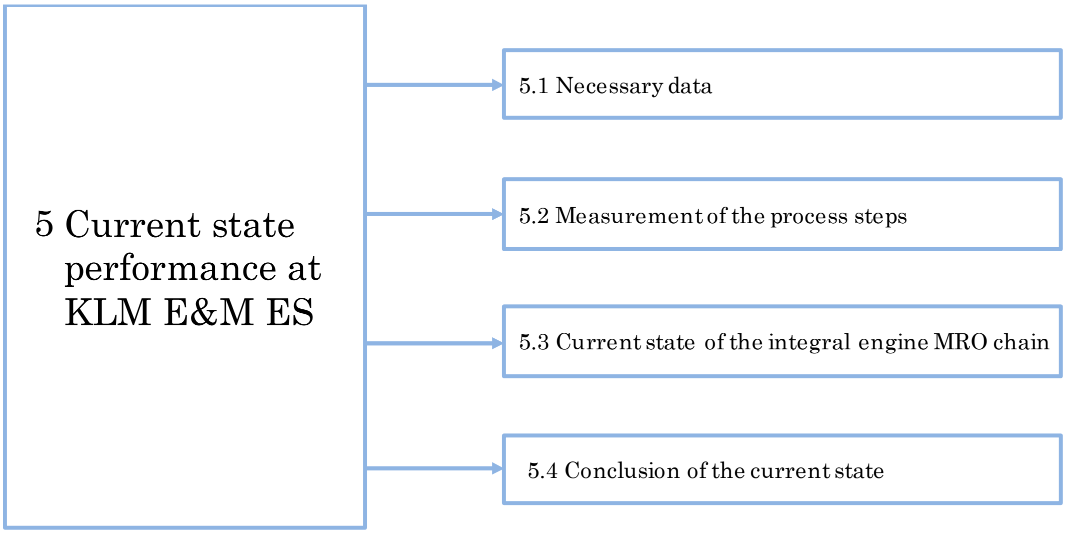

Figure 20. Schematic overview of chapter 5

5.1 Necessary data

The data that is needed to design the current state of the engine MRO chain at KLM E&M ES is based on the KPIs that are found in literature. The current situation at KLM E&M ES is measured by means of several data sets delivered by various employees. The KPIs could not be applied in real life due to organizational issues. That is why the current situation is measured by using a historical data set. The period of the historical data set is from January 2016 to December 2016.

5.1.1 Data quality

The quality of the data is very important to have reliable measurements, which is why the data should be reviewed. For every single data set the data is reviewed in a different way. But in general, all the negative numbers are removed from the data set, all data with empty cells are removed, all data that had out of proportion high numbers and other outliers were removed. See appendix H for a table with the data of specific engines that are reviewed and improved or removed.

5.2 Measurement of the process steps

To get an integral view of the performance of the engine MRO at KLM E&M ES, the different process steps are measured on the KPIs as defined in section 3.2.1; average TAT, standard deviation, on time performance, waiting time and process time. Next to these KPIs a distribution plot is shown to have an impression of how the process step is distributed. It is known from the Lean Six Sigma theory that if a process is not normally distributed, waste occurs in the process. Waste in a process makes it unstable. The various process steps are measured on different levels of detail on engine level as described in section 2.2.1. The disassembly at assy level, the cleaning and inspection on part level, the repair and transport on part level, the assembly on assy level, the test and rework on engine level. Only the results of the disassembly step are shown in figures, the figures with the results of the other five process steps can be found in Appendix C.

5.2.1 Disassembly

As described in section 2.2.1, there is a predetermined disassembly sequence. That means that some modules have to wait to get disassembled, because mechanics first need to disassemble the previous modules. When the modules are disassembled from the engine, the disassembly of the modules continues at designated work centres. In the work centres the modules are first disassembled into assy's and the assy's are disassembled in all the individual parts.

The KPIs on which the performance of the disassembly is measured are; ATAT, standard deviation, Waiting time, processing time and on-time performance. Figure 21 shows the performance of the disassembly step on assy level. The red stripes are the agreed norm times for the disassembly of assy's.

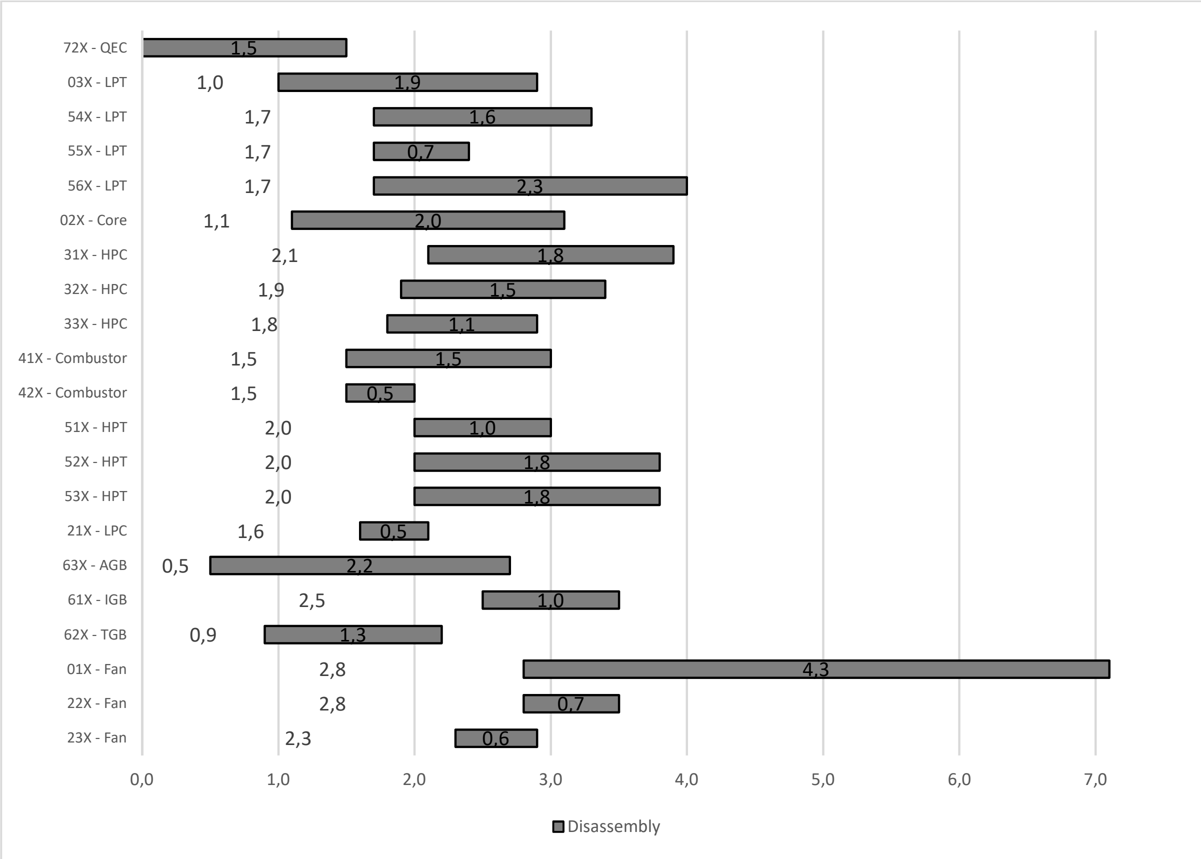

Figure 21. Waiting and process times of disassembly

As can be seen in Figure 21, there is on average zero waiting time for assy 72X – QEC, this will always be zero because; “*the clock starts ticking after the first screw is twisted with a tool”* and the first screw will always be from the QEC. From figure X the waiting time, process time and average TAT of all assy’s can be derived. The distribution plot and the remaining KPIs; the standard deviation and the OTP, are shown in Figure 22, Figure 23 and Figure 24.

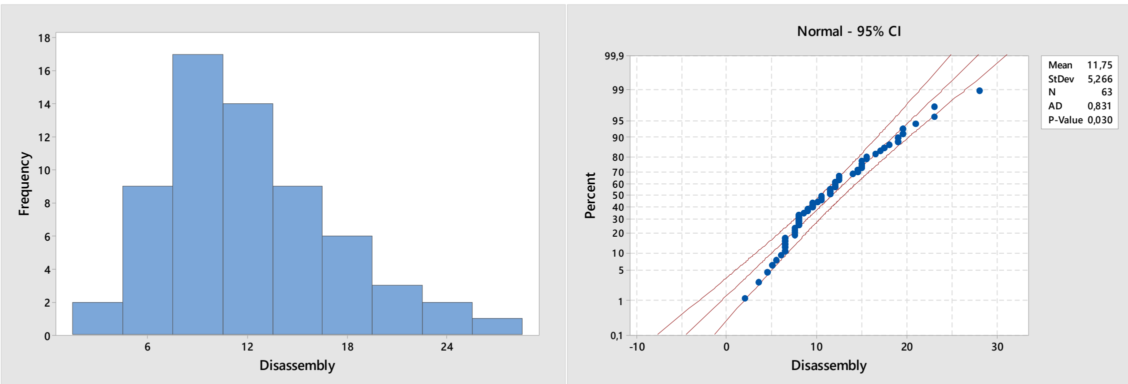

Figure 22 and Figure 23. Distribution and probability plot of the disassembly process step on engine level

The distribution plot and probability plot show that the disassembly process is not normally distributed, this means that waste occurs in the process which makes the process instable.

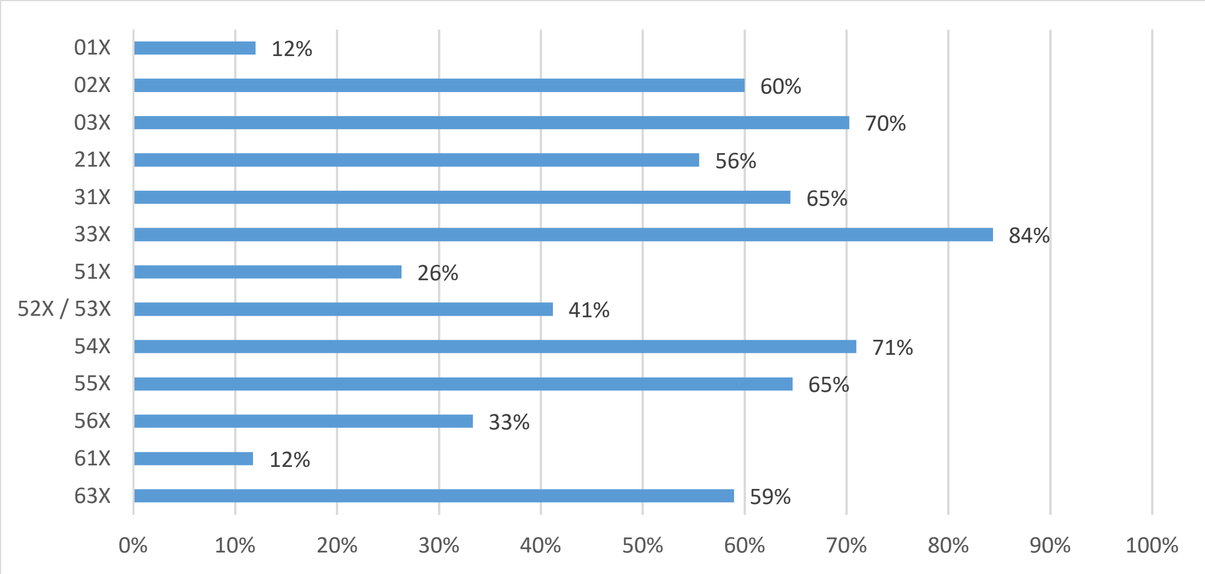

Figure 24. On time performance of disassembly per assy

As can be seen in Figure 24, the on time performance of the disassembly per assy is not very high. Besides that, not all assy's are shown due to the lack of data.

5.2.2 Cleaning and inspection

The individual parts that are repaired in-house are transported to the cleaning area where the parts will be cleaned. The parts of which the repair is outsourced will be sent 'dirty' to logistics to get transported to the vendor. After the cleaning of the parts, all the parts are inspected on damages. The damaged parts will be sent to the repair stage and the undamaged parts will be given to Aprep with the mark 'serviceable'.

The results of the measurement of the cleaning and inspection show that a lot of waiting times before this process step is present. Also the performance of the process time is very poor, none of the assy's are on average processed within the agreed norm time of five days. The distribution plot and probability plot show that the disassembly process is not normally distributed, this means that waste occurs in the process which makes the process instable. As expected, the on-time performance of the cleaning and inspection is very low. The average OTP of this process step is 46%.

5.2.3 Repair

The repair stage can be distinguished in two sides; the in-house repairs and the outsourced repairs. For both, the agreed norm time that all the parts of the assy's need to be repaired is 28 days.

In-house repairs

The in-house repairs are repaired on site at KLM E&M. After receiving the cleaned and inspected parts from the disassembly stage a work order is created for the damages that are present on that part. After the repair the parts are checked if the repair is done successfully and if so it is sent serviceable to Aprep.

Outsourced repairs

Most of the outsourced repairs are shipped 'dirty' towards the vendor. When the parts arrive at logistics, a work order is created and the parts are transported to the vendors. KLM E&M collaborates with vendors all around the world. When the parts return to KLM E&M, first an incoming inspection is done to be sure the repairs are done successfully by the vendor. If everything is repaired the parts are send, marked as serviceable, to Aprep.

For the assembly of the engine, the availability of parts is the most important criteria. Because when one part of an assy is not available, that particular assy cannot be assembled and thus the module of which that assy is part of cannot be assembled and thus the engine as a whole cannot be assembled.

The results show that the TAT performance of the outsourced repair process step on assy level is not very satisfying. It shows that half of the outsourced repairs is on average not within the agreed norm time repaired. And for the in-house repairs only the combustor – 42X – is on average not repaired within the agreed norm times. So, on average the in-house repairs have not a bad TAT performance. On average all the assy's have a very high standard deviation and the p-value is below 0,05 for all assy's, as is derived from the measurement results. This means that the repair process of the assy's are very unstable and a lot of waste occurs. The on-time performance gives on average, as expected, very low on-time performances. The assy's that score a high on-time performance are all in-house repairs and the average TAT of the repair process of these assy's are significant lower than the others.

5.2.4 Transport

The transport process step only belongs to the parts of which the repair is outsourced. After parts are disassembled and KLM E&M ES cannot repair the parts in-house, the parts will be outsourced. These parts are transported to the logistics area from where the parts will go on transport to the vendor. In this process the parts will get details attached of what the vendor needs to repair. This process step is the outbound transport. After the parts are repaired by the vendor, the parts get transported back to KLM E&M ES. The parts will arrive at the logistics area, where the parts first will be inspected on the repairs that have been made and if the part is serviceable now. This inspection is called the Insepction Incoming Goods (IIG). When the part is declared serviceable it will be transported to Aprep. This process is called the inbound transport process step.

The majority of the assy's are performing above the agreed norm time for the transport process steps. The outbound process steps have besides the process time a lot of waiting time as well. The distribution and probability plots of the inbound and outbound transport processes show that both processes have a distribution that is not normal distributed and a p-value below 0,05. This indicates that there occurs waste in the process and that the process is unstable. As expected, the on-time performance of the both transport processes is very poor. Especially of the inbound transport process. The transport of only two assy's is on average decent.

5.2.5 Assembly

When all parts are repaired and declared serviceable again, the parts are brought all together to the assembly area. At the different work centres, the parts are first assembled to assy's and the assy's are assembled to modules. Then the modules will be built together to complete the engine as a whole, this will be done in a separate work area.

The measurement results show that the average TAT of the majority of the assy's is on average higher than the agreed norm time. With the result that the total assembly stage has an average TAT of 16 days instead of 11 days. The distribution and probability plot show that the total assembly process is not normally distributed. The p-value of below 0,05 confirms that. This indicates that the process is unstable and that there is waste in the process. The on-time performance of all the assy's in the assembly process is dramatically poor. The best performance is of the 21X with also a lousy 37%.

5.2.6 Test & Rework

When the assembly is completed, the engine needs to be tested. This is done in the test cell in another building on the site. After the test is performed and the results are known, the engine goes back to the building of ES to execute any necessary rework if needed.

The test and rework process step both are performing on average worse that the agreed norm times of one day. The distribution and probability plot of the processes show that the process steps are not normally distributed. This indicates that the processes are unstable and that waste occurs inside the process steps. As could be expected from the other KPIs, the on-time performance of this process steps are low. The test process steps, with an OTP of 70%, is not very bad, but the rework process step is terrible, with an OTP of only 10%.

5.3 Current state of the integral engine MRO chain at KLM E&M ES

The previous measured stages are consecutive, but in the current state is it seen that the next process step not always directly starts after the previous process step has ended. That means that waiting times occur between the different process steps. For example, between the repair stage and the assembly stage, some assy's have a lot of waiting time. Or the other way around, in some cases the repair process step did already start while not all parts of an assy are disassembled from the engine yet. Figure 25 shows the current state of the integral engine MRO chain. This overview is shown in the self-made performance measurement model.

The average TAT of the whole MRO chain in the year 2016 was 71 days. The average TAT of the agreed contracts with the client is 60 days. That means that on average the engines are delivered 11 days too late. In the year 2016 only 19 of the 62 engines were delivered back on time to the client. That is an on-time performance of 31%. The standard deviation of the integral engine MRO process at KLM E&M ES is 30 days and the p-value is below 0,05. That means that the whole process is unstable and that there occurs waste in the process.

5.3.1 Model validation and verification

In section 7.2, the performance measurement model will be used to simulate future states after applying the continuous improvement framework. To be sure that the model works as it should work, the model is validated. The model validation is done with a sensitivity analysis and extreme condition test (Sargent, 2011). The sensitivity analysis is an analysis to test if the model shows realistic outcomes when parameters are varied (Sargent, 2011). The extreme condition test, tests the model with extreme and unlikely parameters (Sargent, 2011). After performing both tests, it can be stated that the performance measurement model, shown in Figure 25, is valid. The performed sensitivity analysis and extreme condition test can be found in Appendix D.

The verification of the model is done on basis of the historical data of 2016. The model gives an output TAT of 70,7 days for the average performance of the integral engine MRO chain at KLM E&M ES. The historical data, a data file where only the start and end time of the engine are stored, gives an average TAT of 71,3 days. The deviation is just 0,6 days, which is less than 1% deviation, so it can be assumed that the model shows realistic results.

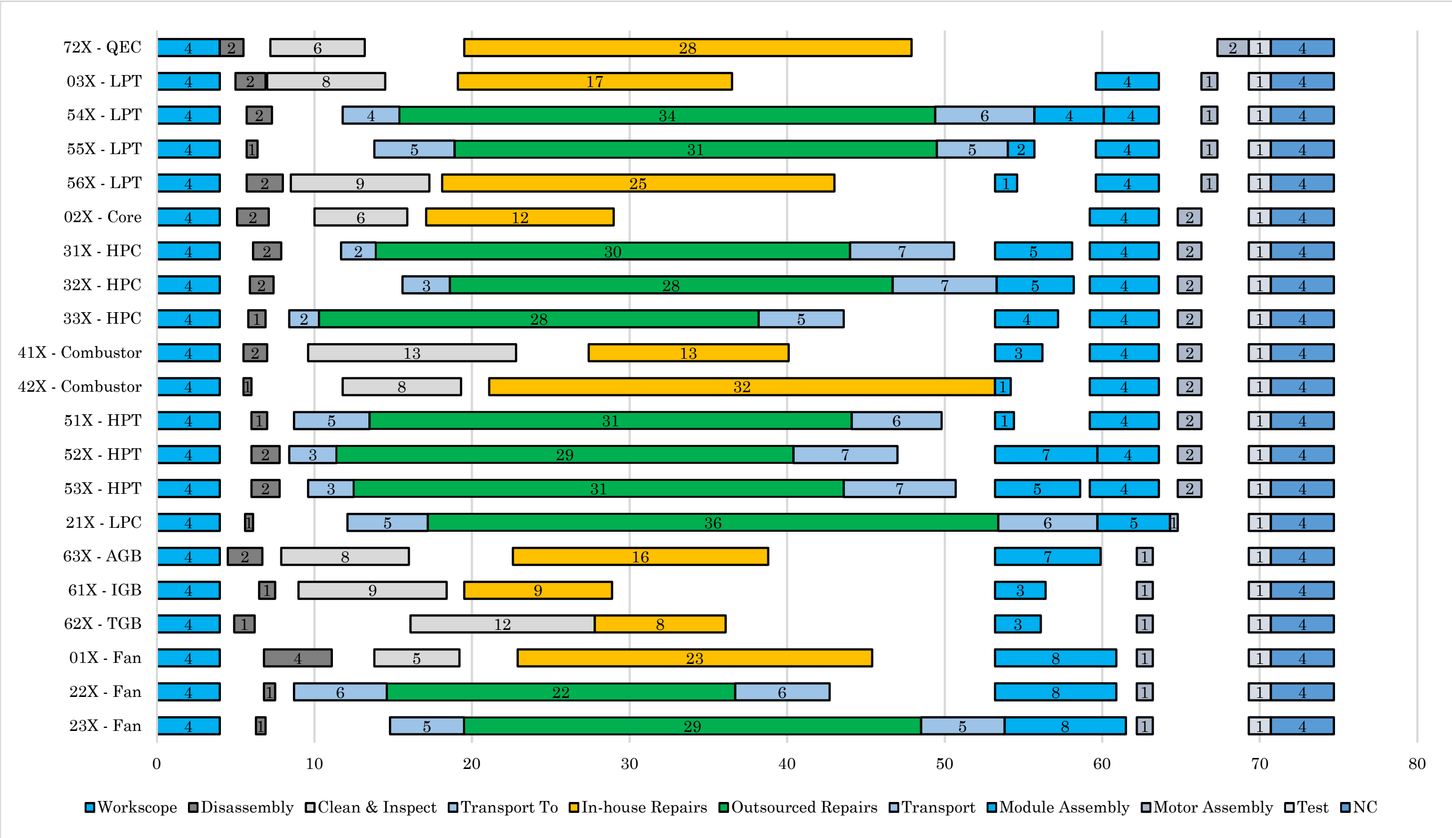

Figure 25. Overview of the current state of the integral engine MRO chain at KLM E&M ES

5.4 Conclusion of the current state of the integral engine MRO chain at KLM E&M ES

This chapter was focused on measuring the current state of the individual process steps and of the integral engine MRO chain at KLM E&M ES. In section 5.2 the first part of the sixth sub question is answered; *"What is the current performance of the individual process steps … at KLM E&M ES?"* The majority of all the process steps is performing really badly. The results in this chapter show the performances of all the process steps measured on the KPIs that are found in literature. The performance of all process steps is on average really bad. The TAT gives an indication of how many assy's are on average within the agreed norm time. From the process steps that normally are measured on assy level, the averages are taken for the waiting time, the OTP and the standard deviation.

The second part of the sixth sub question is answered in section 5.3; *"… and how does this form the current performance of the integral engine MRO chain at KLM E&M ES?"* It is measured that the TAT of the current performance of the integral engine MRO chain at KLM E&M ES is way below the desired TAT of KLM E&M ES. At the moment the TAT is 71 days on average, while the desired norm TAT is 60 days. And the ambition of KLM E&M ES is to have an average TAT of 45 days. The standard deviation is 31 days, which means that 70% of all engines are processed within the window of 41 days to 101 days. The other 30% of the processed engines are even more far away from the average TAT. Also the OTP of all the engines is just a lousy 31%. Of the 62 engines that have been handled in 2016, only 19 where returned back to the client on-time.

6 Analyse the Current State

The measurement performance model, from section 5.3, of the integral engine MRO chain gives insight in the current performance of the engine MRO process from an integral perspective. This performance model can be used to improve badly performing processes. However, it is not necessary to improve all the processes from the beginning. This chapter focusses on sub question number seven; *"What constraints become visible by analysing the performance of the engine MRO chain at KLM E&M ES and what are the root causes of these constraints?"* From literature, it is important to focus only on the performance of the processes that are currently withholding the integral chain to perform better, those processes are the constraints. With help of the KPIs and the Theory of Constraints the main constraints can be identified, this is done in section 6.1. Subsequently, the root causes of these main constraints are determined with the help of the Root Cause Analysis theory and the 4M method of lean manufacturing, which is done in section 6.2. Section 6.3 summarizes all the root causes of potential constraints. Figure 26 shows the overview of chapter 6.

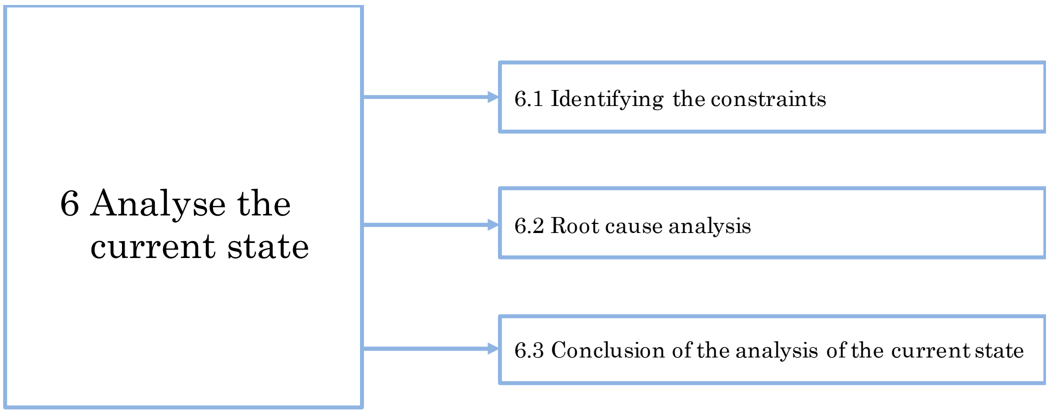

Figure 26. Schematic overview of chapter 6

6.1 Identifying the constraints

To find the main constraints of the engine MRO supply chain process at KLM E&M ES, the performance model, which is introduced in section 5.3, will be analysed. The performance model contains the waiting and process times of the current state, and because the performance model is shown as a value stream, the constraints that are withholding the integral chain of performing better are visualised. By combining all five KPIs, the order of importance of the constraints will be prioritized. Because it depends on the kind of root cause of how difficult it is to improve the constraint.

Because the environment of an engine MRO process is unique, it has also unique characteristics. One of these characteristics ensures that a slightly different is given to find the constraints of the process. Where in other processes, the process steps are the constraints that pop up, is in the engine MRO the assy that will be seen as a constraint. Because if there are parts missing of a certain assy, the assy cannot be build, and if the assy cannot be build, the engine cannot be reassembled.

By analysing the performance model of the integral MRO supply chain at KLM E&M ES, the conclusion can be made that at all process steps improvements can be made to lower the TAT of the integral chain. Because every time another assy could pop up as constraint, and that can be solved by improving a process step. It could happen that a process step is in the current situation not a constraint, but when that current constraint is solved, it becomes a constraint. That is why the root causes for the poor performances of all process steps will be identified.

6.2 Root cause analysis

Root cause analysis is done on basis of the planning and control levels and the 4M method retrieved from the lean manufacturing theory. As explained in section 3.3.1, the 4Ms stand for; method, material, machine and manpower. These four root causes lead to all the different kind of wastes as found in section 3.3.1. An explanation of how the different process steps will be analysed on basis of the 4Ms are elaborated in the next paragraphs. Note that because of the lack of detailed data in some process steps, not everything can be explained quantitative. In those cases, estimations and assumptions will be made.

Material:
When analysing the process step on the M of material, the problems that occur due to missing material will be pointed out. What kind of material and for how long is the material the obstructing factor in this process step. With the result that it will be clear of how much time could be won when the material issues would be eliminated. On the other hand, too much material can be an obstructing factor as well. The amount of engines that is injected to the shop floor could be of influence on various process steps as well. Because there could be a difference between injecting one engine in a week, or injecting six engines in a week. When six engines are injected, it could be assumed that problems may occur due to the lack of machine capacity or manpower capacity.

Machine:
With the analysis to the M of machine, the issues that occur due to a lack of available capacity on machines or tools will be pointed out. Which machines or tools and for how long is the machine or tool unavailable to use.

Method:
With analysing the M of method, there will be pointed out how much time will be wasted because of a wrong method is used to handle the process. The following activities are covered by the term method: administrative tasks, rules and guidelines etcetera.

Manpower:
With the analysis to the M of manpower, the relation between the TAT of the process step and the amount of manpower will be showed. Besides the TAT of the process step, there is a relation

between the waiting time before a process step and the manpower of that process step. Root causes for manpower will be divided in two parts, in the scheduling of manpower and in the distribution of manpower. Scheduling of manpower means that on a daily basis will be decided what activities will be done that day with the number of mechanics as provided. Distribution of manpower means that on a monthly basis the number of mechanics per day will be determined, with a fixed number of mechanics in total.

6.2.1 Disassembly

The disassembly of the engine is not performing very well in the current situation. The average on-time performance of all assy's is 50%. Analysing this process step with the planning and control levels and the 4Ms will explain the root causes of the poor performance of the disassembly process step.

Material

Material issues is not the root cause of the poor performance, because all the material is still on the engine and is thus available. When more engines are injected than normally, the process time of the disassembly will not increase, only the waiting time before the process step will be larger.

Machine

Machine could be a root cause of the poor performance of the disassembly step. When a mechanic enters the shop floor and wants to start working on the disassembly of the engine, module or assy, it could occur that there are some tools missing to disassembly particular modules or parts of the engine. The waiting for the missing tools at such a moment will on average not be longer than a couple of hours, as is told by various mechanics on the shop floor. At the disassembly phase waiting on tools for a couple of hours could result in missing the agreed TAT for disassembly of that assy.

Method

The method could be a root cause of the poor performance of the disassembly phase. At KLM E&M ES, the mechanics follow a predetermined disassembly sequence. With this sequence, it could happen that a critical part will be disassembled as last. For example, the fan module contains a part that should be repaired and the lead-time of that part is very long. This part will be disassembled as one of the last, because of this predetermined disassembly sequence. Besides the predetermined disassembly sequence, administrative issues could form the root cause as well. As long as the administrative work is not done, it is not known exactly how the engine should be disassembled. No research has been done in research to this root cause, so it cannot be defined in numbers.

Manpower

Manpower is certainly a root cause of why the disassembly phase is not performing better than it does at the moment. From interviews and observations, information is gathered that it does occur regularly that there is not enough manpower capacity for the work demand of disassembling engines. It can be stated that there is potential to improve the TAT of the disassembly process step.

6.2.2 Cleaning and inspection

The cleaning and inspection phase has a really poor performance, as can be concluded from the performance measurements of section 5.2.2. The average on-time performance of the cleaning and inspection process steps is 46%. The root causes will be determined on basis of an analysis to the 4Ms.

Material

Missing material is certainly not the root cause of the poor performance of this process step. But too much material is a root cause of the poor performance of the cleaning and inspection process step. That has been determined from observations and interviews. The material explosions caused by disassembling engines, could be too much to handle when in a short period more engines than normal are disassembled and when the resource capacity remains the same.

Machine
Machine is not a root cause of the poor performance of the cleaning and inspection process step. Because the machine capacity is big enough to handle more or less all parts of six engines per day. And that is certainly not the demand that is asked from the cleaning machines at any time.

Method
Method could be a root cause of the poor performance of these process steps. Two causes stand out when analysing the cleaning and inspection process and after taking interviews with employees. The first cause is that there is a lot of batching done at the cleaning process. Which means that a lot of parts are waiting for more parts to come until they can get processed. The second cause is the order that is chosen to process the parts. At the moment, the first-in first-out rule is used at the cleaning and inspection processes, which means that parts can be processed that are far less critical than others. But because these parts were earlier at the cleaning area, they get priority above the more critical ones.

Manpower
Manpower is also a root cause of the poor performance at the cleaning and inspection process step. Employees say that there are at some moments not enough manpower capacity to handle the demand of parts that need to be cleaned and inspect. But on other moments there is too much manpower capacity and there is not enough material to process. These situations indicate that the matching between material (demand) and manpower (supply) is not good enough.

6.2.3 Repair
As can be concluded from the measurements of the repair phase, the repair phase is performing really bad. The on-time performance is on average 46%, but the assy's with the longest lead-times even have on average the worst on-time performance. The repair process step will be analysed with the 4M method below.

Material
Missing material is not a root cause at the repair process step. Having too much material to process could be a root cause, but from interviews and the researches of Meijs (2016) and Mogendorff (2016), this is assumed not to be a root cause.

Machine
Machine is a root cause of the poor performance of the in-house repair stage. Research of Meijs (2016) shows that the unavailability of machines is one of the root causes for the high TAT of the repair of the fan blades. The research indicates that the root cause is not only the capacity of the machine, but also a lack of manpower capacity to operate the machine.

At the outsourced repair process there are no machines involved that are in hands of KLM E&M ES.

Method
The general decision that needs to be made is whether to outsource the repair of the part, or to repair the part in-house. In-house repairs have in general a lower TAT, but it is not always possible to repair the part in-house and thus the part is forced to be repaired at another vendor. So in one way, it can be said that method is a root cause of the low performance, but in the other way the capability to repair the part in-house is the root cause.

The vendor exceeds the contract TAT 34% of all the repairs of the parts that are outsourced. And there is not much that KLM E&M does about it. So there must be a problem with the vendor management, this could be seen as a root cause for the low performance of the outsourced repairs. Rozenberg (2016) states this root cause also in her research.

For the in-house repairs, the method of the repair stage depends on the type of part. Some parts are being batched for repairs and others not. The research of Mogendorff (2016) mentions the method as a root cause for the in-house repair of the combustor, because too many inspections are done. And the research of Meijs (2016) does mention the method, batching, as one of the root causes of the poor performance of the in-house repair of the fan blades. There has not been done research to the other in-house repairs assy's. But it can be assumed that also at the repair process of the other assy's, a lot of waiting time due to a wrong method exists.

Manpower:
KLM E&M cannot control the manpower capacity for the outsourced repairs, so that will not be a root cause.

The manpower capacity for the in-house repairs is a root cause for the low performance of the in-house repairs. Research of Meijs (2016) indicates that the lack of manpower capacity is one of the root causes for the high TAT of the repair of the fan blades. The bottleneck machines are not being operated all the time. The research of Mogendorff (2016) found manpower also as a root cause. The amount of manpower capacity and manpower capability is identified as a root cause. Since both researches prove that manpower is a root cause for these two in-house repairs, it can be assumed that for the other assy's the same problems exist.

6.2.4 Transport
The performance measurement of the transport step shows a poor performance. With an average OTP of 58%, there is potential for an improvement of the waiting and process time of the transport step. On basis of analyses and the 4Ms, the root causes of this poor performance will be determined. Rozenberg (2016) did detailed research to the transport process step at KLM E&M ES.

Material
Research of Rozenberg (2016) does not state that material is root cause for the poor performance of the outbound and inbound transport process step.

Machine
Also machine has not been determined by Rozenberg (2016) as a root cause for the poor performance of the outbound and inbound transport process step.

Method
Rozenberg (2016) did state that a lack of priority is a root cause of the poor performance of the outbound and inbound transport step. At outbound transport process step, at the moment, the flight cut-off times are not taken into account when picking parts to process. And at the inbound transport step, the first-in first-out priority rule is used. This rule does not take due date into account.

Manpower
Manpower is a root cause for the poor performance of the transport process step. Rozenberg (2016) concluded that the lack of manpower capacity and multi-skilled mechanics is a root cause for the poor performance of the inbound transport process steps. For the outbound transport process step, manpower is not a root cause.

6.2.5 Assembly
At the assembly process, all the individual parts come back together serviceable. The performance measurement of the assembly step shows an average OTP of just 23%. To identify the root causes of this poor performance, three engines has been followed real-time at KLM E&M ES and all activities that are done regarding the assembly of those three engines have been tracked.

Figure 27 shows all the activities that are executed on one of the tracked engines. The assy's are at the vertical axis, every colour distinguishes another module. The timeline is on the horizontal axis. The coloured boxes, with a number inside, are shifts where mechanics have worked on that assy, the number equals the number of mechanics that worked. The grey boxes, except for the row at the bottom, are shift where there has not been worked on that assy. The box is darker grey if the reason that there has not been worked on that assy is that there was no mechanic available. The box is light grey if the reason that there has not been worked on that assy is that there are parts missing to assemble that assy.

Analyses of these tracked engines, combined with the 4Ms, will determine the root causes of the poor performance of the assembly process step in the following paragraphs.

ENG NO.	891122	891122															
Datum		11-jan	11-jan	12-jan	12-jan	13-jan	13-jan	14-jan	14-jan	15-jan	15-jan	16-jan	16-jan	17-jan	17-jan	18-jan	18-jan
Ploeg		A	C	B	C	B	A	B	A	B	A	C	A	C	B	C	B
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
LPT rear frame	56X											2	Rep afd.				
LPT shaft	55X																
LPT rotor	54X																
LPT stator	54X																
LPT	03X													1			
HPC rotor	31X	Man	2	1	Manx	1	Man	1	Man	Slijpen	Man	Manx	Man	2			
HPC stator	32X	1	WO	WOx	WO	WOx	2	Manx	2	WOx	WOx	WO	WOx	WO	1	Slijpen	1
HPC stator	33X	1	WO	WOx	WO	WOx	WOx	WOx	WOx	WOx	WOx	WO	WOx	WO	1	Slijpen	1
HPT Stator	53X	Man	WOx	WOx	WOx	WOx	WO	WOx	WO	WOx	WO	2	Man	1	Slijpen	Slijpen	2
HPT rotor	52X	Man	1	Manx	1	1	Slijpen	Slijpen	Man	1							
HD	51X	Man	1	1													
Combustor case	41X	Manx	1	Man	2	WO	WOx	WO	WOx	WO	WOx	1	2	1			
HPC comp	02X															2	WO
AGB	63X	2	2	2	WOx	1	WO	WOx	WO	WOx	WO	WOx	WO	WOx	1		
TGB	62X	Man	Man	1	1	1											
IGB	61X	Man	Man	1													
Booster	21X	2	Man	Man	Man	Man	1	Man	1	Man	1						
Bearing support	22X	Man	Man	1	Mon HK												
Fan module	01X/23X	Man	2	2	3	3	Man	4	Man	4	Man	3		1			
												Fan		Gearbox			
Engine	72X												2	WO	2	WO	WO

ENG NO.																	
Datum		19-jan	19-jan	20-jan	20-jan	21-jan	21-jan	22-jan	22-jan	23-jan	23-jan	24-jan	24-jan	25-jan	25-jan	26-jan	26-jan
Ploeg		A	B	A	C	A	C	A	C	B	C	B	A	B			B
		17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
LPT rear frame	56X																
LPT shaft	55X															Man	Man
LPT rotor	54X															WO	Material
LPT stator	54X																
LPT	03X																
HPC rotor	31X																
HPC stator	32X																
HPC stator	33X																
HPT Stator	53X																
HPT rotor	52X																
HD	51X																
Combustor case	41X																
HPC comp	02X	4	2														
AGB	63X																
TGB	62X																
IGB	61X																
Booster	21X																
Bearing support	22X																
Fan module	01X/23X																
		Prep	Core	Core	LPT	QEC	QEC	QEC	QEC								
Engine	72X	1	2	2	2	2	2	2	2	testcel	testcel	testcel	NC-2	NC-2	NC-2	Man	NC-2

Figure 27. Work activities of one of the tracked engines

Material

Material is certainly a root cause of the poor performance of the assembly process step. All three engines are delayed because of material that was missing to assemble the engines. Figure 27 shows the overview of the activities that have been done at one of the tracked engines. As can be seen, there are 40 shifts, divided over the assy's, that cause delays because of a lack of material. That does not mean straight away that in total 40 shifts will be won directly, because it also depends on the fact of those shift lay on the critical path. The root cause for the lack of material will not be found in the assembly process itself. It will always be in one of the previous processes due to exceeding the agreed handshake.

Machine

Only one shift of all the shifts from the three engines that have been analysed was delayed because of the lack of machine capacity. Mechanics say that the lack of tools do delay their work sometimes, but the time of delay is in general not more than a couple of hours. Thus, it can be concluded that machine is not a root cause of the poor performance of the assembly process step.

Method
In the current situation, the rule is that all the parts are put on the shop floor for assembling when 100% of the parts of that engine are serviceable back at Aprep. In practice, Aprep deviates from this guideline and puts the parts on the shop floor when the majority of them are back serviceable. But this rule can cause that a lot of 'full' assy's are waiting to get assembled because parts of other engines are not serviceable yet.
Manpower
The influence of manpower on the performance of the assembly step can be determined in two ways. On the distribution of the manpower capacity and on the scheduling of the manpower capacity. But the TAT of the assembly process step is also very dependent on the material that is available, because the engine could be build faster with more manpower capacity but if there is some material missing, the whole engine still has to wait.

6.2.6 Test & Rework

When the engine is reassembled, it needs to be tested if the quality is good, this will be done in the test cell. After the test cell, depending on the results, some rework can be done before declaring the engine serviceable again. Information about the test and rework process steps have been gathered by interviews with mechanics and employees.

Material
Two of the main root causes of the poor performance of the test and rework process steps are the lack of material and the wrong configured material. First, when an engine is almost completely assembled and it misses a few parts, most of the times QEC parts, only for testing the engine the missing parts will be borrowed from another engine. So after the testing, these borrowed parts should be replaced for the original parts of that engine. Secondly, if the material is configured wrong, the engine test will be negative and rework needs to be done to pass the test cell positively, which will increase the TAT.

Machine
The test cell where the engines are tested can handle only one engine at a time. This could be a root cause of the moderate performance of the test process step. At the rework process step, machine is not a main root cause.

Method
The method is in the rework process step a root cause, because of the 3,4 days of process time, one shift is waiting to be transported after the engine is serviceable again. If the communication would be better, the serviceable engine would not have to wait a whole shift to get transported to the area where it will wait for transportation back to the client.

Manpower
Manpower is not a root cause of the moderate performance of the test process step, because there are just a few mechanics needed for this process. But for the rework manpower is a root cause for the poor performance of this process. The same reasons as at the assembly step count for the rework process. Because the rework of the engine is the same as the assembly, but then only for completing the last parts on the engine.

6.3 Conclusions of the analysis of the current state

In section 6.1 it is described that the constraint is not a process step in the first place. The combined processes in which assy's are handled can form the constraint. Just as what happens in the current state, the assy 21X is the constraint that is withholding the integral engine MRO chain of performing better. This constraint can be solved by improving a process step in which the 21X is handled. To improve this process step, the root cause of the poor performance of the process step needs to be clear. From section 6.2, it can be concluded that there are a lot of root causes that cause the poor performance of the individual process steps.

In Table 7 a summary is shown of all the individual process steps with its root causes and the relation of the root causes on the process and waiting time. This tables can give answer to the sub question that this chapter was focussed on; *"What constraints become visible by analysing the performance of the engine MRO chain at KLM E&M ES and what are the root causes of these constraints?"*

Table 7. Summary of Root Cause Analysis

Process step	*4M*	*Root cause*
Disassembly	Manpower	Distribution of mechanics
	"	Scheduling of mechanics
Cleaning & Inspection	Method	Wrong priority dispatching rule
	"	Batching
	Material	Distribution of injections
	Manpower	Distribution of mechanics
Repair	Method	No vendor management
	"	Batching
	Manpower	Distribution of mechanics
	Machine	Machine availability
Transport	Method	Priority dispatching rule
	Manpower	Distribution of mechanics
	"	Lack of multi-skilled mechanics
Assembly	Material	Missing material
	Manpower	Distribution of mechanics
	"	Scheduling of mechanics
Test & Rework	Material	Borrowed material
	"	Negative result test cell
	Method	Bad communication after completion
	Machine	Test cell capacity is one
	Manpower	Distribution of mechanics
		Scheduling of mechanics

7 Design improvement solutions

From the performed analyses in chapter 6, it is known which constraint needs to be improved to improve the integral engine MRO chain at KLM E&M ES. It is also known what the root cause is of the poor performance of that process step. To improve the integral engine MRO chain at KLM E&M ES, several process steps need to be improved to solve the constraints that are obstructing the integral MRO chain of performing better. After every improvement another constraint appears, this is an on-going process, because there is always an activity that is obstructing the integral process of performing better. The main goal of this chapter is answering sub questions number nine; *"Which solutions can be used to solve the root causes?"* and number ten; *What would be the impact of applying the continuous improvement framework on the integral engine MRO chain at KLM E&M ES?"* In section 7.1 the solutions that could be made to improve the individual process steps of the integral engine MRO chain at KLM E&M ES are designed. These solutions will be used in the continuous improvement framework that will be applied to the current situation of the performance of the integral engine MRO chain at KLM E&M ES in section 7.2. In section 7.3 the conclusions of the results after applying the continuous improvement framework are shown. An overview of chapter 7 will be given in Figure 28.

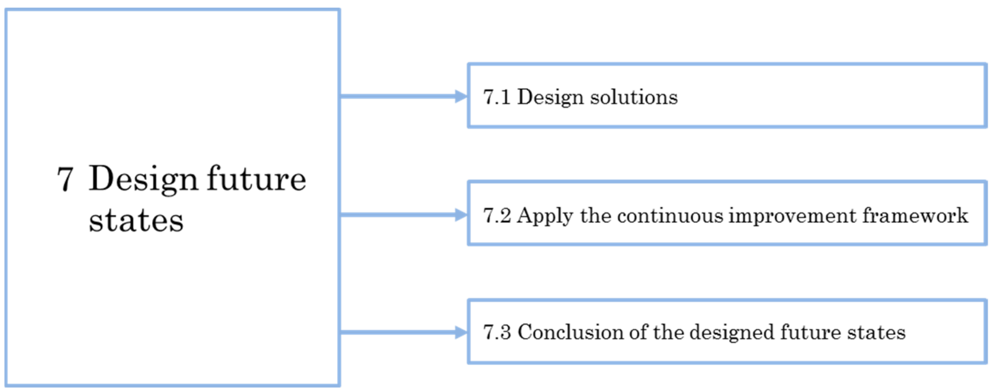

Figure 28. Schematic overview of chapter 7

7.1 Design solutions

All the process steps have at least one root cause that is obstructing the process step to perform better. To determine how the integral engine MRO chain should be improved, the continuous improvement framework, from section 4.2, will be used. The aim of the continuous improvement framework is to design two solutions per process step; the exploit solution and the elevate solution.

The exploit step will bring the process step back to its norm time, the elevate step will improve the process step even better than the norm time. Depending on the process step, it could be possible that various solutions are possible to reach the goal. Some solutions will have a high impact on the TAT and others are having less impact on the TAT, some come from a high level of planning and control and some come from a lower level of planning and control. Depending on the relation between the reduction in TAT and the level of planning and control, the solution will be more likely to be implemented or not. For example, a solution with a high reduction in TAT and a low level of planning and control will be more likely to be implemented than a solution with the same reduction in TAT but on a higher level of planning and control. The next paragraphs will give the solutions per process step at KLM E&M ES.

7.1.1 Disassembly

It is known from interviews and observations that manpower is the only main root cause for the moderate performance of the disassembly process step. But there has not been a detailed analysis to this process step, therefore no solutions can be given for the disassembly process step.

7.1.2 Cleaning & Inspection

The same counts for the process time of the cleaning and inspection process step. The root cause has been determined by means of interviews, but no detailed analysis has been performed. On the other hand, the waiting time of the outbound transport has been analysed in more detail.

Exploit – waiting time

The waiting time of the cleaning and inspection process step on the other hand, have been analysed and it is seen that the performance of the integral engine MRO process can be improved if the dispatching rule will be changed. There are several dispatching rules, as explained in section 3.1.6, that determine the priority of the different parts that need to be processed. From literature, it has been found that the best dispatching rule for an engine MRO environment would be the least slack policy. The TAT of the current performance of the integral engine MRO chain will be reduced with 6,6 days when implementing the least slack policy at the cleaning and inspection process step. The level of planning and control where this dispatching rule must be changed is level 4 of material planning and control. The management decision that must be taken is to use the least slack policy.

7.1.3 Repair

At the repair process step, two kind of repairs are distinguished; the in-house repairs and the outsourced repairs. The outsourced repairs are analysed with observations, interviews and Rozenberg (2016) did research to the outsourced repairs as well. Mogendorff (2016) and Meijs (2016) did detailed research to certain parts that are repaired in-house. These researches are of help for the determination of the improvement steps of the in-house repairs. For the combustor, there are no exploit solutions available, because these have not been examined. And since the other in-house repairs perform on average already better than the norm times, the exploit step will be passed and directly elevate solutions will be presented.

Exploit – outsourced repairs

As stated in section 6.2.3, the root cause of the poor performance of the outsourced repairs was a lack of vendor management. Interviews and the research of Rozenberg (2016) confirm that with better vendor management the outsourced repairs can be perform on the agreed norm times. Better vendor management means; proactive control on the repairs and penalizing vendors that exceed the agreed TAT. This change in method can be done on level 4 of material planning and control. The management decision that must be taken is to apply proactive vendor management.

Elevate – in-house repairs
As has been found in the researches of Mogendorff (2016) and Meijs (2016), several constraints and root causes have been of why the combustor and the fan blades in-house repair processes do not perform better than the current performance. In the exploit step only the combustor process should have been improved, because of all the other in-house repairs the average TAT is already lower than the agreed handshake, as can be found in the measurement results in section 5.2.3. But Mogendorff's results for improvements of the process of the combustor, do not include a solution to get the process on the norm time. Thus, only solutions to elevate the in-house repairs are given.

For the combustor, a solution with 4 mechanics with an extra capability (skill P) will improve the process TAT to an average of 20 days and an OTP of 96%. For the fan blades, also more than 80% of the process time is waiting time. Meijs (2016) has shown that advanced operator planning results in 16,5% less waiting time. For the other in-house repairs that need to be improved if they might become a constraint of the integral process, it can be assumed that with better scheduling of capacity or distributing the mechanics better over a period of time, the TAT performance can be reduced to a maximum of 20 days.

The solution for the combustor can be made on level 2 of resource planning and control and the solutions for the other in-house repairs can be made at level 3 and 4 of resource planning and control. The management decisions that must be taken is using less batching, to have a higher ratio of multi-skilled mechanics and to schedule and distribute manpower better.

Elevate – outsourced repairs
Rozenberg (2016) assumes that KLM has a sufficient market position to renegotiate and lower the contract TAT with the vendors. In this thesis the elevate step to a contract TAT of 21 days will be used. This new contract agreements are made at level 1 of material planning and control. The management decision that must be taken is to renew the contracts with the vendors to TAT 21 days.

7.1.4 Transport
The transport distinguishes three parts where solutions can be applied; the waiting time at the outbound transport, the process time of the outbound transport and the process time of the inbound transport. Rozenberg (2016) did detailed research to this process step and in her research, she only designed exploit solutions and solutions to get to the ideal world of the outbound and inbound transport process steps.

Exploit – waiting time of the outbound transport
The solution for exploiting the waiting time of the outbound transport is the same as is proposed for the waiting time of the cleaning and inspection. Using the least slack policy instead of the first-in first-out rule will reduce the TAT of the current performance of the integral engine MRO chain with 5,9 days. This least slack policy method is on level 4 of material planning and control. The management decision that must be taken is to use the least slack policy.

Exploit – outbound transport process time
As stated in the research of Rozenberg (2016), the root cause for the poor performance of the outbound transport process step is the method. The parts are not prioritized on the cut-off times of the outgoing flights. This could be changed with a dispatching rule that prioritizes the parts on their cut-off times. This should be done on level 4 of material planning and control. When this dispatching rule is implemented, the outbound process time will be at its norm time of three days. The management decision that must be taken is to use the prioritizing of parts based on the flight cut-off times.

Exploit – inbound transport process time
Rozenberg (2016) found in her research that the main constraint for the inbound process step, is the IIG. The IIG is not performing good enough because of a lack of manpower capacity, a lack of manpower capability and the use of the wrong method. The research of Rozenberg (2016) stated

that the inbound transport process time can be exploited to four days when; the DGO inspection and the IIG are combined, when the working shifts change from 5x2 to 7x2 (work in the weekends) and when a priority lane is added to the process. The combining of the DGO inspection and the IIG can be changed on level 3 of material planning and control, the shift change from 5x2 to 7x2 can be changed on level 3 of resource planning and control and the priority lane can be changed on level 4 of material planning and control. The management decisions that must be taken are to combine the DGO and IIG manpower capacity, change the amount of shifts from 5x2 to 7x2 and make use of a priority lane.

Elevate – outbound and inbound transport process time
The minimum transport process time for the outbound transport is 12 hours (0,5 days) and for the inbound 14 hours (0,6 days), as stated in the research of Rozenberg (2016). This 'ideal world' can be realised with Just-in-Time delivery, delivery directly to and from airside and a smooth flow in the process. To realise this ideal world, a whole new network needs to be designed. This decision needs to be made on both the level 1's of planning and control. The management decisions that must be taken are to implement JIT delivery, deliver directly to and from airside and accomplish a smooth flow in the process.

7.1.5 Assembly

When all the parts are serviceable back at KLM E&M ES, the engine will be reassembled. First the individual parts will be assembled into assy's, the assy's are assembled to modules and the seven modules will be reassembled to complete the engine. Analysis to this process step has been done and there have been identified two main root causes in the assembly process step; missing material and a lack of manpower.

Exploit – assembly
There is only one root cause that can be solved by changing a method at the process step itself, the lack of manpower. Because the missing material can only be influenced by all the process steps before the assembly. The missing material has so much influence on the assembly process step, that it is not even possible to exploit the assembly process with only solving the lack of manpower root cause. But on the other hand, if the missing material root cause is solved by improving the previous process steps, the assembly process does not have to change anything to perform on the norm time. Because that will be the result automatically when there is no missing material anymore in the assembly process step.

Elevate – assembly
Since the root cause of the missing material is solved by the previous process steps, to elevate the assembly process step the lack of manpower needs to be solved. This can be done at three levels of planning and control; the total amount of mechanics, the distribution of the mechanics and the scheduling of the mechanics. It has been analysed that with only another method of scheduling the mechanics, the process step will not be improved significantly. But with distributing the mechanics in another way, a significant improvement of TAT performance can be achieved. With a new method of distributing the mechanics better over the demand that is asked, the total assembly time can be reduced to eight days. The assembly process time can even be more decreased if more mechanics would be employed by KLM E&M ES. See Appendix E for the full analyses and calculations of the assembly process step. The management decision that must be taken is to schedule and distribute the manpower capacity better.

7.1.6 Test & rework

The test and rework process steps are the last ones in the integral engine MRO chain. As stated in section 6.2.6, various root causes exist that obstruct these process steps of performing better. Also for the rework process step, previous process steps have influence on its performance. For example, the root cause where parts have to be borrowed from other engine to perform the engine test. If the missing parts root cause in the assembly step is solved, this root cause will be automatically solved as well in the rework process step. The same counts for the lack of manpower when the rework has to be done, if this is improved in the assembly process, it will automatically be improved at the rework step as well. Also the waiting time before the test cell will be improved when the previous process steps will improve, because then it will not occur that two engine need to be tested at the same moment. The elevate step has not been analysed in detail, so that will be left out of scope.

Exploit – Test & rework
The only root cause that can be solved in order to perform at the norm time is the communication between the department after declaring the engine serviceable again. All the other solutions at the other process steps, will have a positive influence on the test & rework process step. The communication should be improved and that can be done at level 4 of material planning and control. The management decisions that must be taken is to change the method of communication between the two departments.

7.1.7 Relations between process steps

As has been described in some of the previous paragraphs, there process steps that could influence the performance of other process steps. Figure 29 shows a schematic overview of the relations that exist between the various process steps.

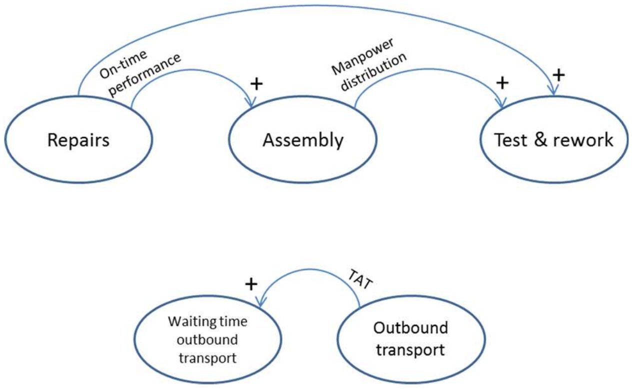

Figure 29. Relations between process steps

It is seen in Figure 29, that when the on-time performance of the repairs increases, the assembly performance and the test and rework performance increases. And also, when the manpower distribution is better, the test and rework performance will increase. The last, when the TAT of the outbound transport decreases, the waiting time before the outbound transport process decreases. There are no other process steps that have direct influence on other process steps.

7.2 Apply the continuous improvement framework

With all information from the previous chapters, future states can be designed and simulated to get a clear view of how the integral engine MRO chain can be improved at KLM E&M ES. These future states will be designed following the continuous improvement framework steps as described in section 4.2. Which means that first the assy or multiple assy's that are constraining the integral MRO chain of performing better must be identified. Then, of all process steps, the most efficient improvement solution must be chosen to implement. If anything changes after the implementation, there will be returned to the first step of identifying the constraint. This is a continuous improvement process, which in theory never stops, but in practice it could stop when there is lacking necessary information.

After it is clear which solution is most efficient to implement, a simulation will be done to see what the impact is on the TAT of the integral engine MRO chain at KLM E&M ES. With these simulated results and the edited data, the other KPIs are calculated as well. The calculations of the OTP and standard deviations can be found in Appendix F.

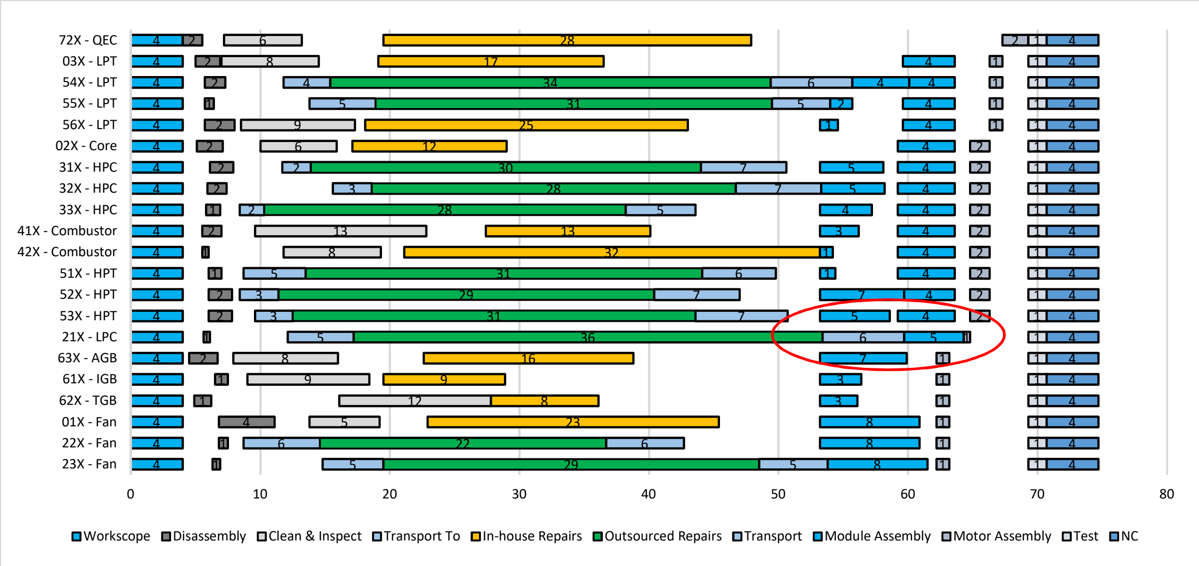

Figure 30. Current situation of the engine MRO chain at KLM E&M ES with constraining factor

As can be seen in Figure 30, the current situation, the assy that is constraining the integral MRO chain of performing better is the 21X. In section 7.1, the exploit and elevate solutions per process step are designed. All the solutions of the different process steps will be compared and the solution that is the most efficient, will be implemented.. The efficiency of a solution will be determined on basis of the influence on the TAT of the integral engine MRO chain and the level of planning and control of which the solution is based on. The levels of planning and control are used as variable, because it indicates the difficulty of implementing the solution. A solution on level 4 of planning and control is normally easier to implement than a solution on level 1 of planning and control. The solutions can vary in height inside the box of a planning and control level, because a solution could be a combination of multiple management decisions on different levels. In this research, only the reduction in TAT and the level of planning and control are taken into account to determine which solution is 'best' to implement in a certain state. There are more criteria to test the solutions, but these have not been taken into account and it is assumed that it would not have been of influence on the outcome of the research.

When a solution is implemented and a simulation is made with the performance measurement model, a future state is designed. For this future state, the solutions have a different impact on the performance of the integral engine MRO chain. So, the matrix with the efficiency of the solutions is dynamic. The efficiency of the solutions that have influence on the performance of the current situation of the integral engine MRO chain at KLM E&M ES is shown in Figure 31

Iteration 1 – Least Slack Policy

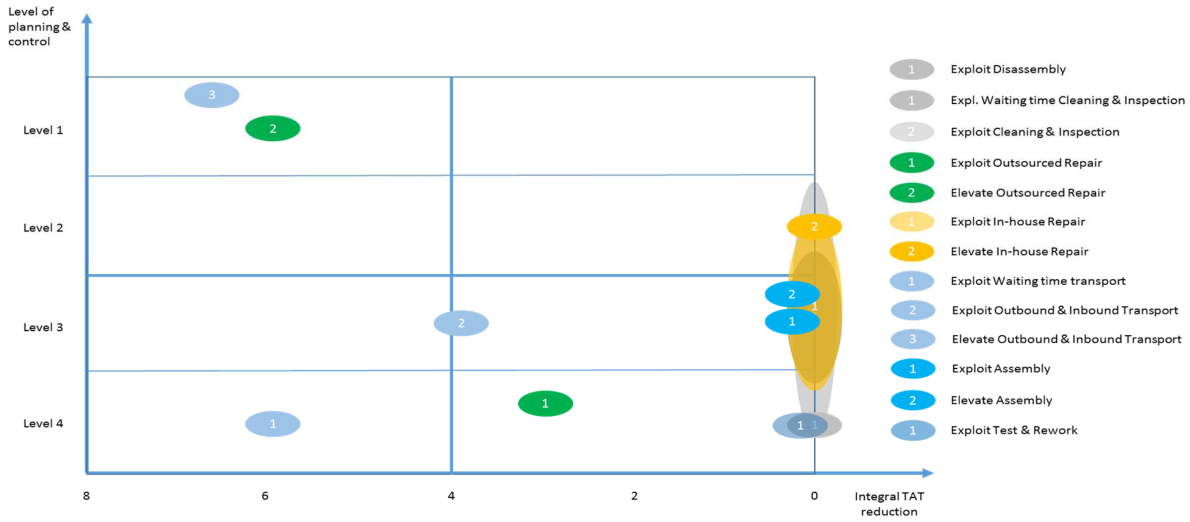

Figure 31. Efficiency of solutions for iteration 1

The solution that is the most efficient to improve the 21X in such a way that it is not the constraint anymore, is the implementation of the least slack policy in the transport process step. This can be seen in Figure 31. This solution is the one that is the closest to the down left corner, which indicates that it is the most efficient.

From the previous chapters it is known, that the least slack policy is also an efficient solution to implement at the cleaning and inspection process step, see number 1 of the cleaning and inspection circle in Figure 31. Because of the fact that the 42X is also almost critical, a combination of the implementation of the least slack policy at both process steps will be done. The impact that the implementation of the least slack policy has at both process steps, is simulated in Figure 32.

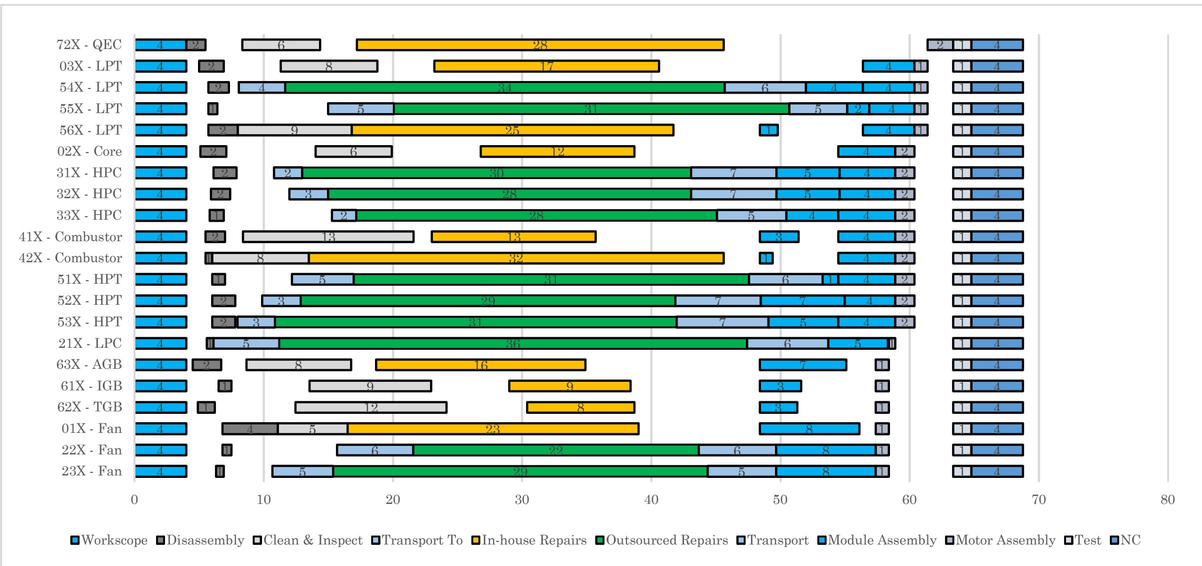

Figure 32. Measurement performance model after iteration 1

Table 8 shows the impact of iteration 1 on the performance measurement KPIs compared to the current situation.

Table 8. Impact after iteration 1 on the performance measurement KPIs

	Current situation	*Iteration 1*
Average TAT	71 days	65 days
Standard Deviation	31 days	31days
On-Time Performance	31%	36%

Iteration 2 – Exploit Outsourced repairs

After the implementation of the least slack policy, the outsourced repairs have become the constraint of the integral chain. So a solution for all the outsourced repairs must be used. The most efficient solution that could be used at this moment is to exploit the repair process step of the outsourced repairs, see number 1 of the outsourced repairs circle in Figure 33.

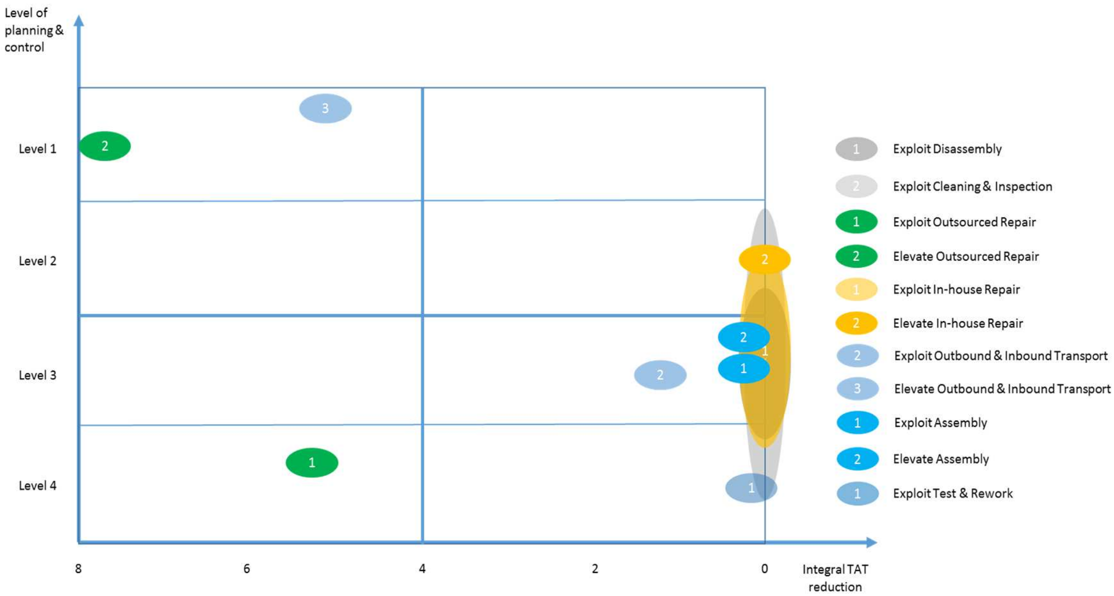

Figure 33. Efficiency of solutions for iteration 2

With this solution, all the parts will be back at KLM E&M ES within the agreed contract time. Because of this, the assembly process will profit as well, see Figure 29. The assembly process step will improve as well, because the assembly of assy's with the parts that were outsourced will not be delayed anymore due to missing parts. The test and rework process benefits as well, because borrowing outsourced repair parts from other engines will be no longer necessary. The impact of exploiting the outsourced repairs is simulated, see Figure 34

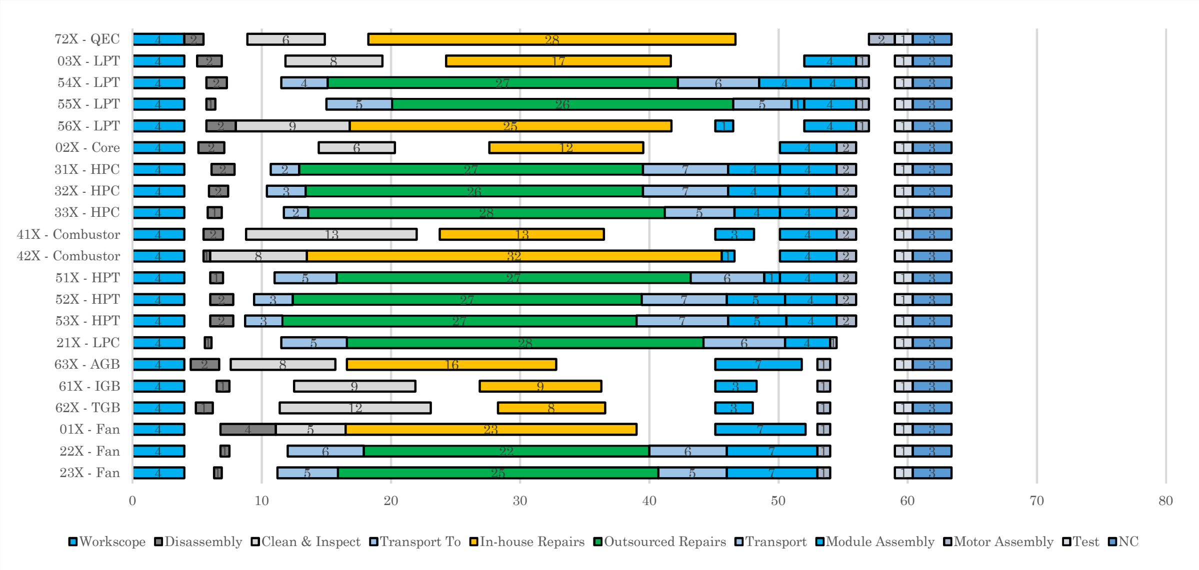

Figure 34. Measurement performance model after iteration 2

Table 9 shows the impact after iteration 2 on the performance measurement KPIs compared to the previous situations.

Table 9. Impact after iteration 2 on the performance measurement KPIs

	Current situation	*Iteration 1*	*Iteration 2*
Average TAT	71 days	65 days	59 days
Standard Deviation	31 days	31 days	20 days
On-Time Performance	31%	36%	47%

Iteration 3 – Exploit Transport

After iteration 2 where the vendor delivers the outsourced parts at least within the agreed contract TAT, the outsourced repairs remain the constraint of the integral chain. As can be seen in Figure 35, the exploit step for the transport process steps is the most efficient.

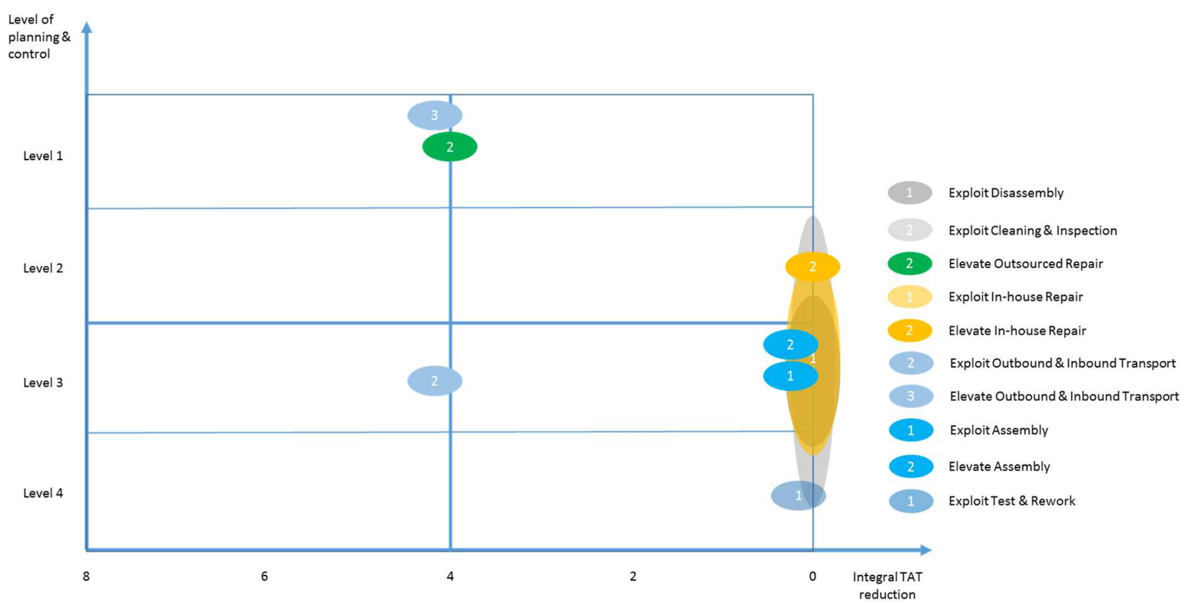

Figure 35. Efficiency of solutions for iteration 3

For the outbound transport process, this solution contains another planning and control method at the shop floor control level (prioritizing of parts). To exploit the inbound logistics a combination of the use of a multi-skilled team, more working shifts per week (7x2 instead of 5x2) and a priority lane must be made. The impact of the exploit step of the outbound and inbound transport process step is simulated in Figure 36.

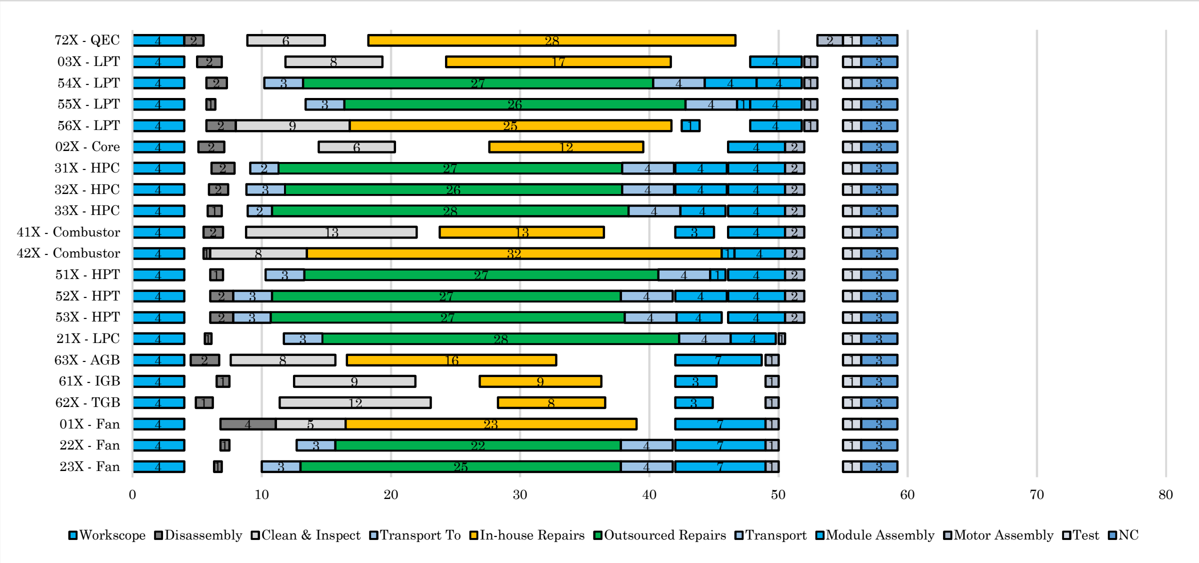

Figure 36. Measurement performance model after iteration 3

Table 10 shows the impact after iteration 3 on the performance measurement KPIs compared to the previous situations.

Table 10. Impact of Iteration 3 on the performance measurement KPIs

	Current situation	*Iteration 1*	*Iteration 2*	*Iteration 3*
Average TAT	71 days	65 days	59 days	55 days
Standard Deviation	31 days	31 days	20 days	18 days
On-Time Performance	31%	36%	47%	60%

Iteration 4 – In-house repairs

After the implementation of iteration 3, again a new constraint appears. The 42X, the combustor, is the new constraint that is obstructing the integral chain of performing better. Because the exploit step for the in-house repairs is not examined in detail, it cannot be said on which level of planning and control that solution can be made. The research of Mogendorff (2016) only showed results to improve the combustor better than the agreed handshake of 28 days. As can be seen in Figure 37, the exploit step is larger and transparent, because the exact details are not known. Due to the unknown details of the exploit step for the in-house repairs, for iteration 4, the elevate step of the in-house repairs is chosen for iteration 4.

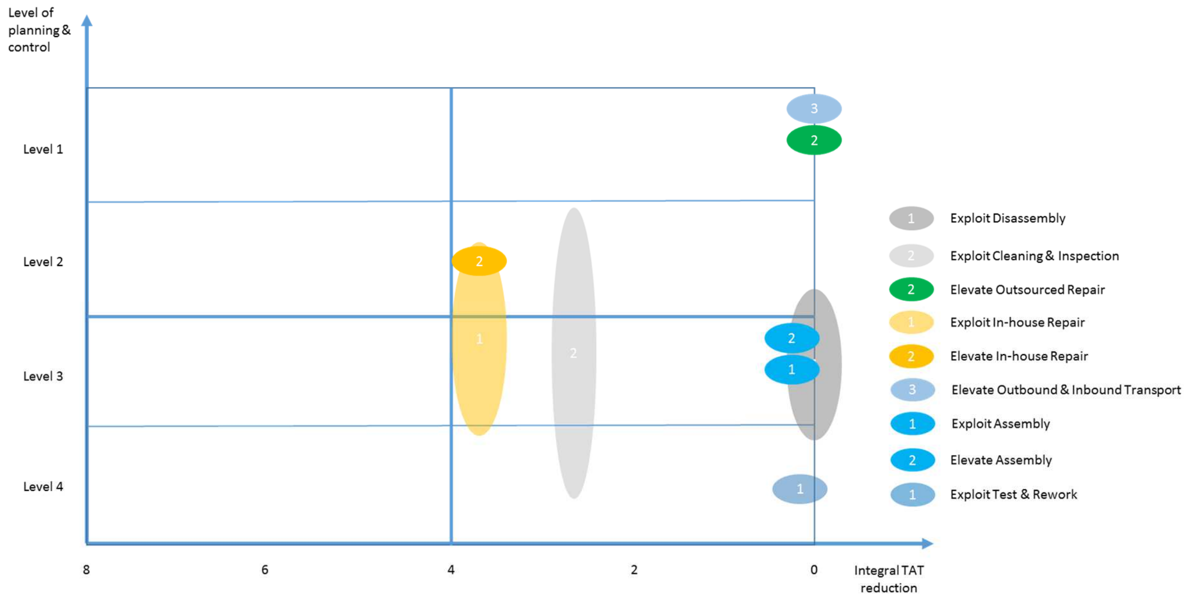

Figure 37. Efficiency of solutions for iteration 4

Implementing this solutions at the four assy's does not only realise a reduction of TAT at the repair process step, but it will also improve the assembly and rework process steps. The assembly process will be improved because, it does not have to wait anymore on parts that are still in the repair process. The rework process benefits as well, because borrowing parts from other engines will no longer be necessary. Figure 38 shows a simulations of what the impact of iteration 4 is on the performance of the integral engine MRO chain.

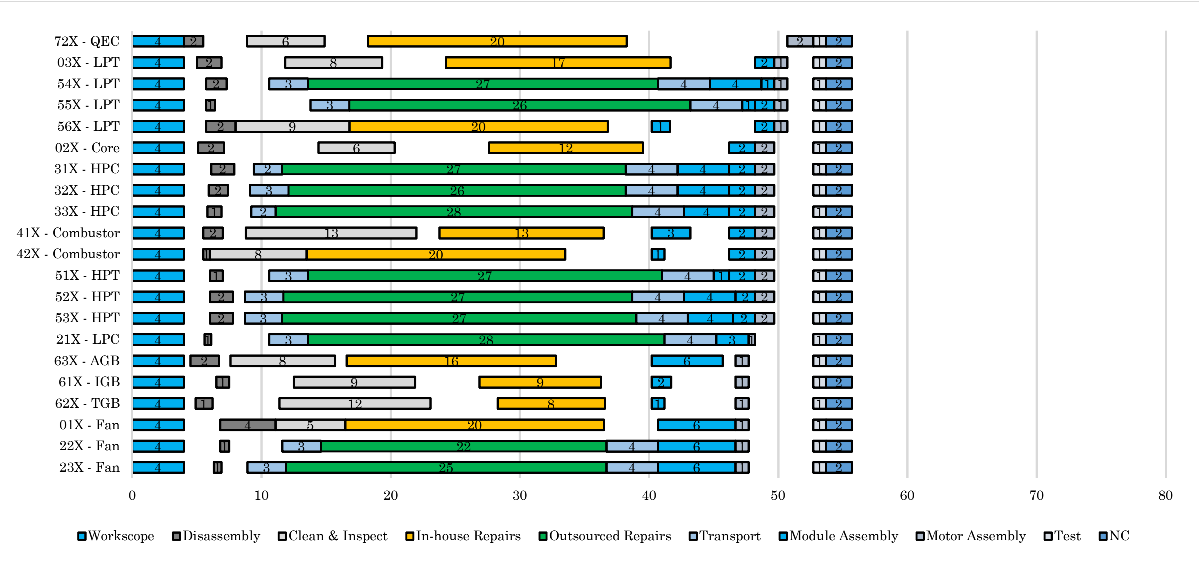

Figure 38. Measurement performance model after iteration 4

Table 11 shows the impact after iteration 4 on the performance measurement KPIs compared to the previous situations.

Table 11. Impact of Iteration 4 on the performance measurement KPIs

	Current situation	Iteration 1	Iteration 2	Iteration 3	Iteration 4
Average TAT	71 days	65 days	59 days	55 days	52 days
Standard Deviation	31 days	31 days	20 days	18 days	13 days
On-Time Performance	31%	36%	47%	60%	71%

Iteration 5 – Elevate Assembly

Due to the fact that all the parts are back on time for the assembly process, the assembly process itself has been improved as well. At this point, the average TAT of the assembly process is slightly higher than the norm time. Figure 39 shows that elevating the assembly process is for iteration 5 the most efficient.

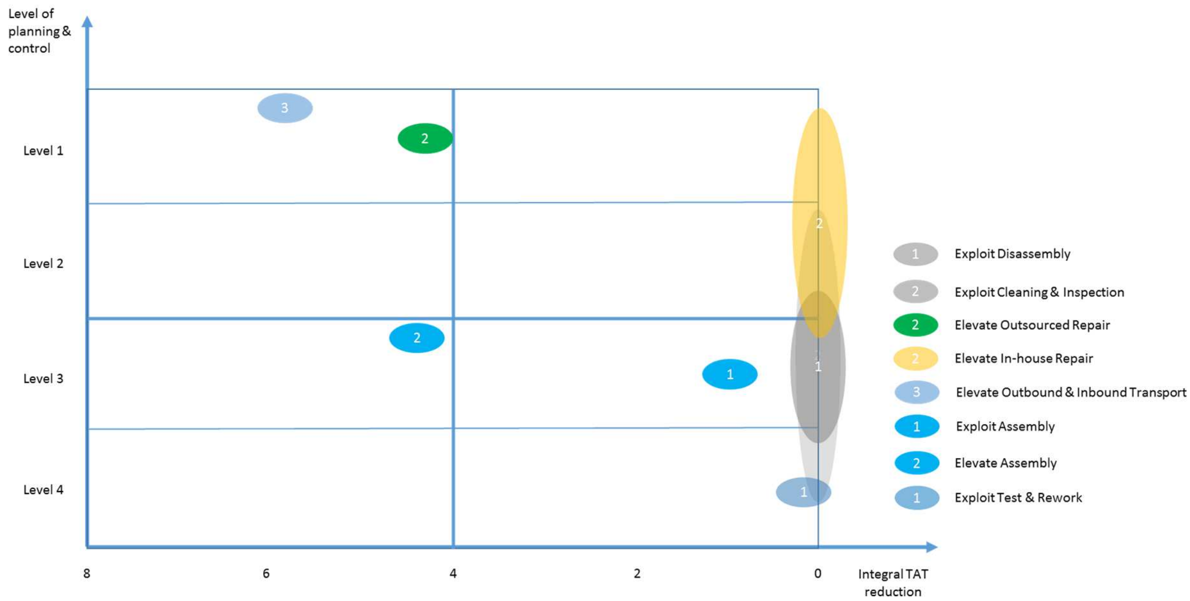

Figure 39. Efficiency of solutions for iteration 5

The elevate step consists of better scheduling and better distribution of manpower capacity at the assembly process step. The impact of this solution on the performance of the integral chain at the fifth iteration is simulated and shown in

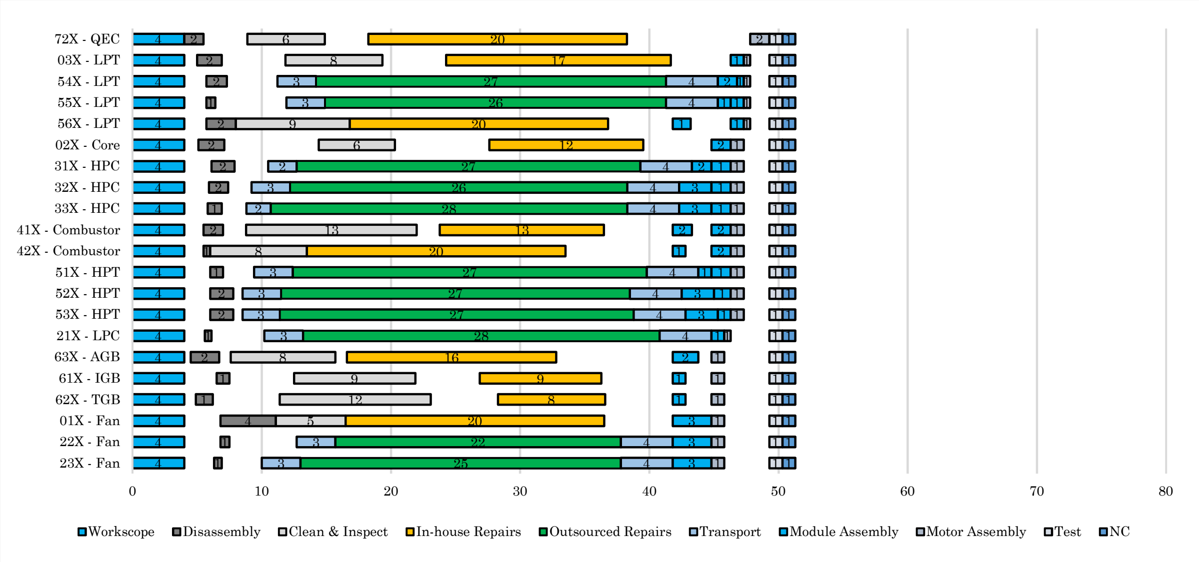

Figure 40. Measurement performance model after iteration 5

Table 12 shows the impact after iteration 5 on the performance measurement KPIs compared to the previous situations.

Table 12. Impact of Iteration 5 on the performance measurement KPIs

	Current situation	*Iteration 1*	*Iteration 2*	*Iteration 3*	*Iteration 4*	*Iteration 5*
Average TAT	71 days	65 days	59 days	55 days	52 days	47 days
Standard Deviation	31 days	31 days	20 days	18 days	13 days	11 days
On-Time Performance	31%	36%	47%	60%	71%	86%

Iteration 6 – Elevate Outsourced repairs

The constraints after iteration 5 are again the outsourced repairs. In iteration 6 a solutions will be implemented to improve the TAT of the outsourced repairs. Two examined solutions are left, both at the top of the matrix. That indicates that both are difficult to implement or will take a lot of time to implement. The elevate step of the outsourced repairs is just slightly more efficient than the elevate step of the transport processes.

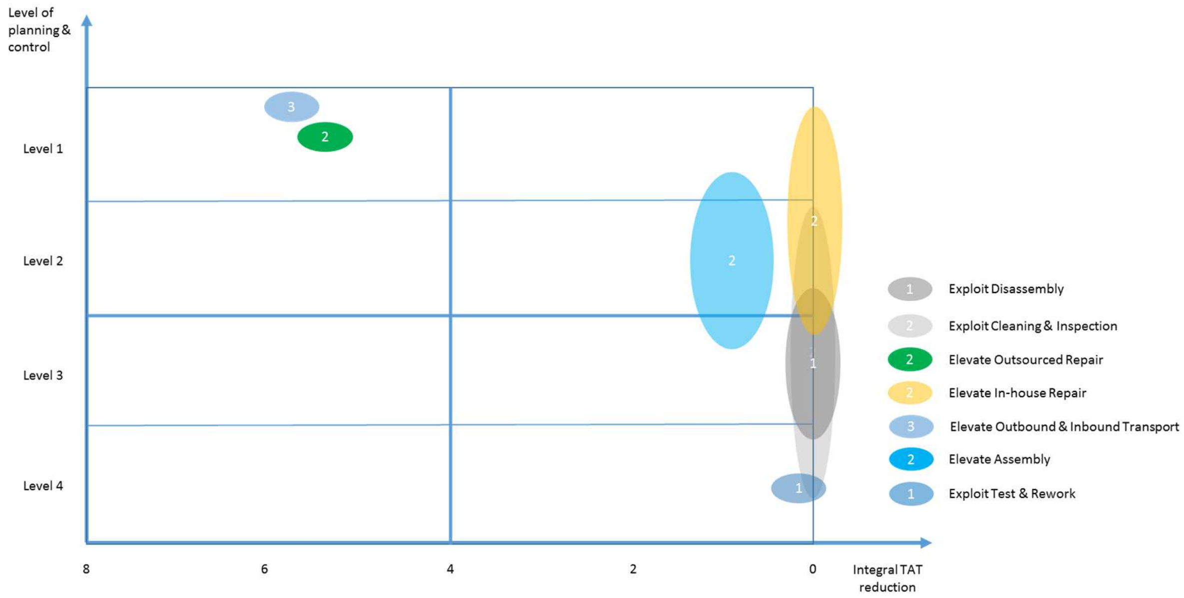

Figure 41. Efficiency of solutions for iteration 6

This solutions means that the contracts with the vendors need to be renewed. This renegotiating can take a lot of time, that is also why the solution is at the top of the matrix. A simulation of the impact of the elevation of the outsourced repairs is shown in Figure 42.

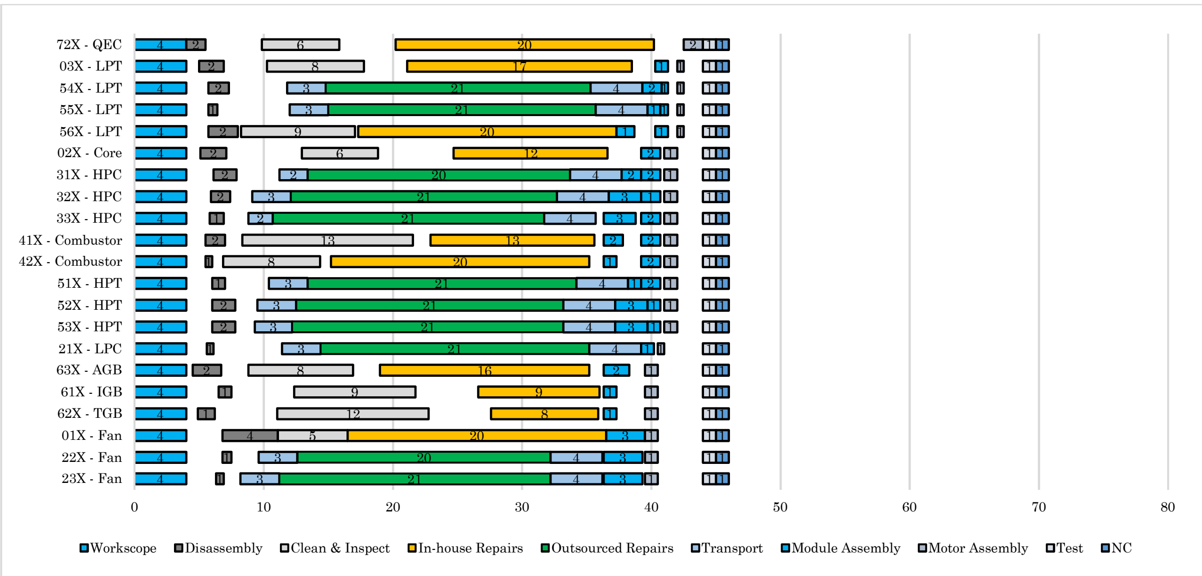

Figure 42. Measurement performance model after iteration 6

Table 13 shows the impact after iteration 6 on the performance measurement KPIs compared to the previous situations.

Table 13. Impact after iteration 6 on the performance measurement KPIs

	Current situation	*Iteration 1*	*Iteration 2*	*Iteration 3*	*Iteration 4*	*Iteration 5*	*Iteration 6*
Average TAT	71 days	65 days	59 days	55 days	54 days	47 days	42 days
Standard Deviation	31 days	31 days	20 days	18 days	13 days	11 days	11 days
On-Time Performance	31%	36%	47%	60%	71%	86%	92%

After iteration 6, there are no examined solutions left to improve the integral engine MRO chain at KLM E&M ES. Because the designed framework is continuous, in theory the amount of iteration will never stop. For example, after iteration 6 the constraint that appears is the 01X, this constraint could possibly be eliminated when the cleaning and inspection process step is improved. But because of a lack of detailed research, the continuous improvement process will stop after iteration 6.

7.3 Conclusion of the design improvement scenarios

In section 7.1, sub question viii is answered; *"Which solutions can be used to solve the root causes?"* For every process step, solutions to improve that process are designed. First, solutions are designed to improve the process step to the norm times (exploit). After that, solutions are designed to elevate the performance of that process step. All the solutions can be related to a management decisions in the levels of planning and control, as defined in section 4.1. All the solutions and associated management decisions are shown in Table 14.

Section 7.2 is focussed on sub question number ten; *"What would be the impact of applying the continuous improvement framework on the integral engine MRO chain at KLM E&M ES?"* Here the proposed continuous improvement framework, which is designed in section 4.2, is used to design future states that will improve the integral engine MRO chain at KLM E&M ES. In the current situation the assy 21X is the constraint. By following the steps of the continuous improvement framework, the 'priority dispatching rule' decision on level 4 of material planning and control could be changed in a way that the assy 21X will not be the constraint anymore and the performance of the integral engine MRO chain at KLM E&M ES will be improved. The impact on the average TAT of the integral chain when changing the 'priority dispatching rule' is a reduction of six days. The standard deviation will remain the same and the OTP will increase from 31% to 36%. This new situation is given the name 'Iteration 1'

In iteration 1, another constraint will appear. This constraint will be handled the same way as is done in the current situation. After changing another decision on different levels of planning and control, again a new situation will arise. In theory, this will be an continuous process that never ends. In this research, after iteration 6 there was not enough information available anymore to continue with improving the integral engine MRO chain at KLM E&M ES. Iteration 6 is in this research the last future state that is designed, after this iteration the average TAT of the integral engine MRO chain at KLM E&M ES is 42 days, the standard deviation is 11,5 days and the OTP is 92%. That means a reduction of average TAT of 29 day, a reduction in standard deviation of 18,5 days and an increase of OTP of 61%.

8 Control the designed future states

The designed future states of chapter 7 form the basis to improve the integral engine MRO chain at KLM E&M ES. To accomplish the ambitious performance of iteration 6, the various solutions that improve the process steps need to be implemented. The goal of this chapter is to answer sub question number eleven; *"What implementation plan can be made to translate the scenarios into practice, and how can these implementations be sustained?"* In section 8.1 the implementation plan will be described and in section 8.2 the way that the implementation plan will be sustained will be elaborated. Figure 43 will give the overview of chapter 8.

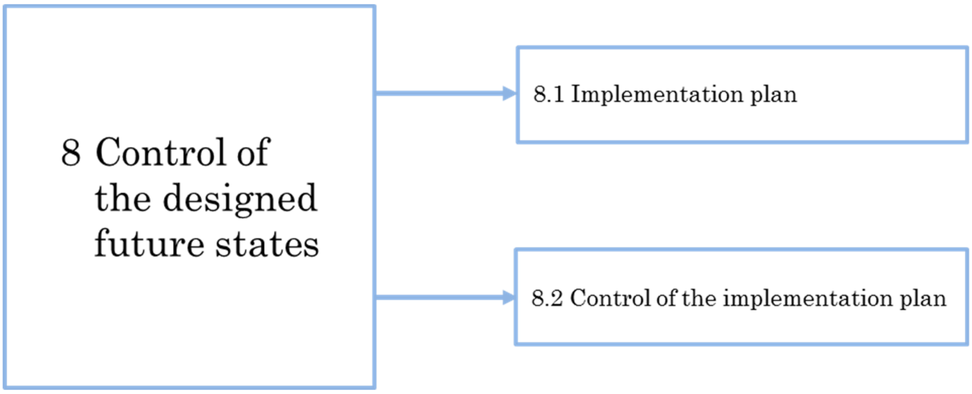

Figure 43. Schematic overview of chapter 8

8.1 Implementation plan

The six iterations from section 7.2, form the basis for the implementation plan to improve the engine MRO supply chain at KLM E&M ES. The order of the improvements are determined on the efficiency of the solutions, but that will not mean that some solutions cannot be implemented simultaneous. In the end, the goal is to improve the assy that is obstructing the integral engine MRO chain of performing better. For example, in the current situation, the 21X is the constraint and there are four process steps that can be improved to improve the 21X in a way that it will not be the constraint anymore. It does not matter if the disassembly process, the transport process, the repair process or the assembly process of the 21X will be improved. But it is recommended, on basis of the analyses that are done, to start with the waiting time before the transport process. Because in front of the transport process, a high TAT reduction with a medium complex solution can be implemented to improve the 21X TAT in such a way that it will not be the constraint anymore. But as shown with continuous improvement framework, from most of the process steps it is known how it can be improved. In the end, it is necessary to improve all of them to achieve operational excellence. Knowing that, combined with knowing that some solutions will take more time to implement, there can be started with implementing several solutions simultaneously.

But besides the solutions of the iterations, it is very important to have high quality data. In this research the data was not always very reliable and accurate. This research was conducted with the best possible data. This means, that there needs to be one other project; a project that is focussed on getting reliable and accurate data. This projects consists of better measurement of process steps and better processing of the measurements into digital data. This project should start right away and should run simultaneously along the other projects.

As has been described in section 2.2.2, three managers are responsible for the several process steps. This means that each of the three managers will be responsible for various projects to reach the goal of the company. The majority of the projects can start at the same time. Because of the complexity and implementation time of some projects, it is necessary to start them at the same time as others. With the result that when the first projects will solve the current constraint, the next project is already ready to get implemented and deliver the desired result. This is for example with the in-house repair process. The improvement of these processes will not reduce the integral TAT when implemented at first, but the implementation could take a longer time because of its complexity. And when the in-house repair(s) are the constraint, it will take less time to solve this next constraint.

8.2 Control of the implementation plan

Implementing solutions is one thing, but to have these implementations sustained is another problem. People are used to fall back into their old habits. So, it is very important to keep control over the implemented solutions. This can be done by keeping track on the performance of the integral engine MRO chain continuously. That could be done by updating the measurement performance model. For this thesis, all the necessary data for the measurement performance model was gathered from different departments and took a very long time. It would be faster if the various departments upload their performance data regularly on the network drive where an employee can easily download all the data and update the model.

On basis of change of the performance of the integral engine MRO chain, it can be seen how much impact the solutions have had until that moment. The measurement performance model should be updated regularly, to keep track of the impact that the solutions have on the integral engine MRO chain. After a certain moment, the improvement plan can be evaluated and a decision should be made if the improvement plan will be continued, or that a change must be made to reach the goal of KLM E&M ES.

9 Conclusions

Chapter 9 presents the conclusions and recommendations of this thesis. First, the answers to the main research question and all the sub questions will be given, see section 9.1. In section 9.2 the achievement of the research objectives and deliverables are shown. The contribution that this thesis has to literature and its practical value will be given in section 9.3. The limitations that this thesis had to cope with are given in section 9.4. And as last, recommendations and suggestions for further research will be given in section 9.5. Figure 44 gives a schematic overview of chapter 9.

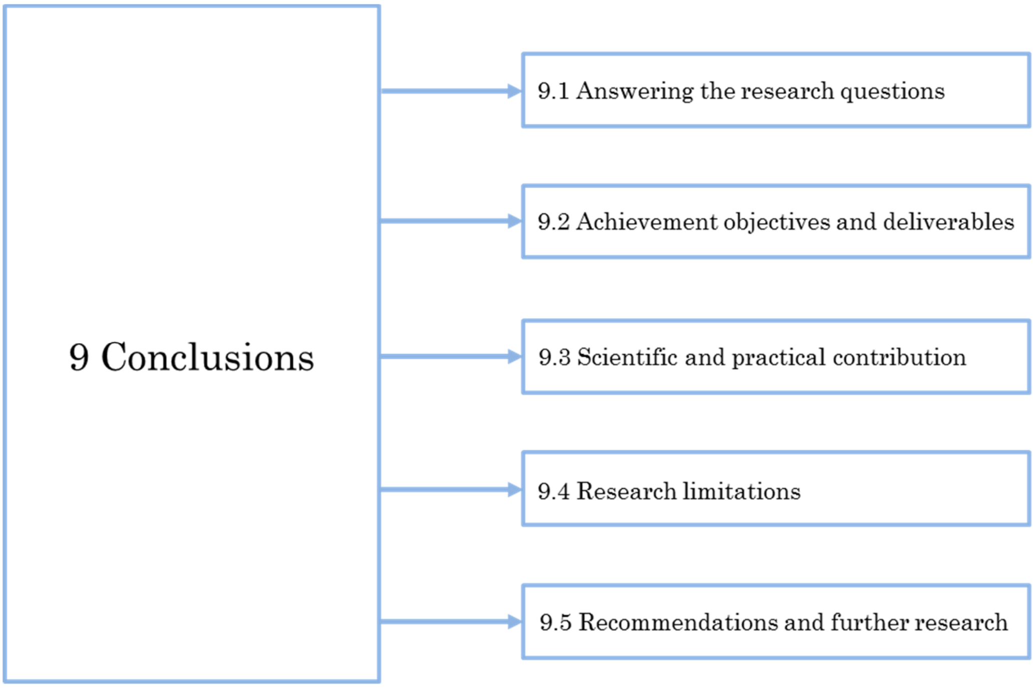

Figure 44. Schematic overview of chapter 9

9.1 Answering the research questions

Finally, the main research question *"Which management decisions need to be changed to improve the performance of the integral engine MRO chain at KLM E&M Engine Services?"*, can be answered. KLM E&M has a goal to lower and improve the TAT of the integral engine MRO chain to a maximum of 45 days. It has been found in literature that to improve the engine MRO chain does not only mean, lowering the TAT, but also means lowering the standard deviation and increasing the OTP. The answer to the main research question is that there are a lot of management decisions that need to be changed in order to reach the goal of KLM E&M ES. At every process step there are several decisions that should be changed. But it is depended on the current performance of the integral engine MRO chain. It always depends on which assy is constraining the integral engine MRO chain of performing better than it does at that moment. A summary of the planning and control decisions that need to be changed, to reach the goal of KLM E&M ES can be found in Table 14. The management decisions are ranked on recommended order of implementation.

Table 14. Decisions that need to be changed in order to reach the goal of KLM E&M ES

Management decision	*How*	*Process step*
Priority dispatching rule	Least Slack Policy	Transport Cleaning
Contract agreements	Proactive vendor control	Outsourced repairs
Priority dispatching rule *Distribution of manpower*	Priority on cut-off time of flights Priority lane Combine DGO and IIG manpower	Outbound and inbound transport
Ratio multi-skilled *Scheduling of manpower* *Distribution of manpower* *Method (Batching)*	At constraint of the combustor, more multi-skilled mechanics Better planning/matching of manpower Less batching	In-house repairs (42X, 01X, 56X, 72X)
Scheduling of manpower *Distribution of manpower*	Plan on what work needs to be done, instead of which mechanics are available	Assembly
Contract agreements	Lower TAT to 21 days in contract	Outsourced repairs

"How is the current engine MRO supply chain organized at KLM E&M ES?"

The MRO chain consists of four main stages, the work scope determination (which is left out of scope in this thesis), the disassembly stage, the repair stage and the assembly stage. All the stages contain several other process steps. The disassembly stage consists of the disassembly and the cleaning and inspection. The outsourced repairs have the repair process also a transport process to and from the vendor. The assembly stage consists of the assembly, testing of the engine and rework that needs to be done.

The engine passes the process steps on different levels of detail and for every process step agreements have been made of how long a process step may take for a part of the engine. The six agreements that are made for the process steps are; six days for the disassembly, five days for cleaning and inspection, three days for the outbound transport, four days for the inbound transport, 28 days for the repair, eleven days for the assembly and two days for test and rework.

"What planning and control levels are known from literature?"

In literature four levels of detail have been found for planning and control. The highest level, the Strategic Business Plan, contains mostly strategic decisions that have to be made for a time horizon between two and ten years. The broad direction and the kind of business the firm wants to be is determined on this level. Level 2, the Production Plan, contain decision that have a time horizon for a year. At this level, decisions about the quantities of the products and resources are made. The first part of level 3 is the Master Production Schedule, it links the firm's strategy to more specific tactical plan that will balance the demand with the supply of products. The second part of level 3 is the Material Requirements Planning, it offers management the capability to identify the products that are actually going to be produced. The time horizon is for the coming three to18 months, depending on the business. Level 4, the Production Activity Control, governs the very short-term detailed planning, execution and monitoring activities required to control the flow of an order from the time when the order is released until the time when the order is filled.

"Regarding planning and control, as what can the engine MRO environment be defined?"
The engine MRO process is not a typical production process, because in a production process (raw) materials or parts are procured to produce a new product. At the engine MRO process, the client delivers its engine at the MRO provider, the engine get disassembled, repaired and then reassembled. This gives a whole different dynamic to the environment. The MRO process, has a lot of characteristics of a remanufacturing process. Only a remanufacturing process disassembles various used products to combine different parts to produce a new product. So, the engine MRO environment is very close to the remanufacturing environment. Except that at the engine MRO environment, the delivered product will belong during the whole process to the client. The majority of the parts that are disassembled from the engine, needs to be returned on that same engine. This will give an extra dimension to the engine MRO process, which makes it even more complex. There are three main findings of why it is important to know what kind of environment the engine MRO process has.

The first is the least slack policy, this dispatching rule should be used on the shop floor in the engine MRO environment. The least slack policy takes the due date and the remaining processing time into account, which ranks the parts that need to be processed on a much better way.

The second finding is that the performance of the repair stage need to be measured on set level of the assy. This means that the availability of that whole assy is taken into account and not only the parts. The benefit of this is that it makes clear when that assy is available to assemble and not that only nine of the ten parts are available.

The third finding is that when the integral engine MRO process performance needs to be improved, there has to be looked to which assy is constraining the process of performing better instead of which process step. Because the engine cannot be built when only 20 of the 21 assy's are available. So there should be looked to improve which process step of that constraining assy should be improved.

"What are the performance measures for engine MRO?"
The performance measures that should be used in an engine MRO process are:

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

"What framework can be proposed to improve the performance of the integral engine MRO chain?"
The answer to this question is a continuous improvement framework that has been designed for the engine MRO environment. The framework consists of four steps;

1. Identify the constraint of the integral engine MRO chain

2. Exploit and elevate every process step of the constraint
3. Compare the solutions and choose the most efficient
4. Implement the solution, if anything changes in the performance go back to step 1

The framework aims to realize operational excellence by continuously improving the process, that is why there is a loop in the framework. Once the current constraint has been solved and the engine MRO process has been improved, the loop will bring the process owner back to step 1. At step 1, the new constraint that has appeared, with the new performance of the process, will be identified.

"What is the current performance of the integral engine MRO supply chain at KLM E&M ES and what are the performances of the sub-processes?"
This sub question can be best answered with the performance measurement model. This model shows at once the measurements of the process steps and the integral engine MRO chain on most of the KPIs, see Figure 45.

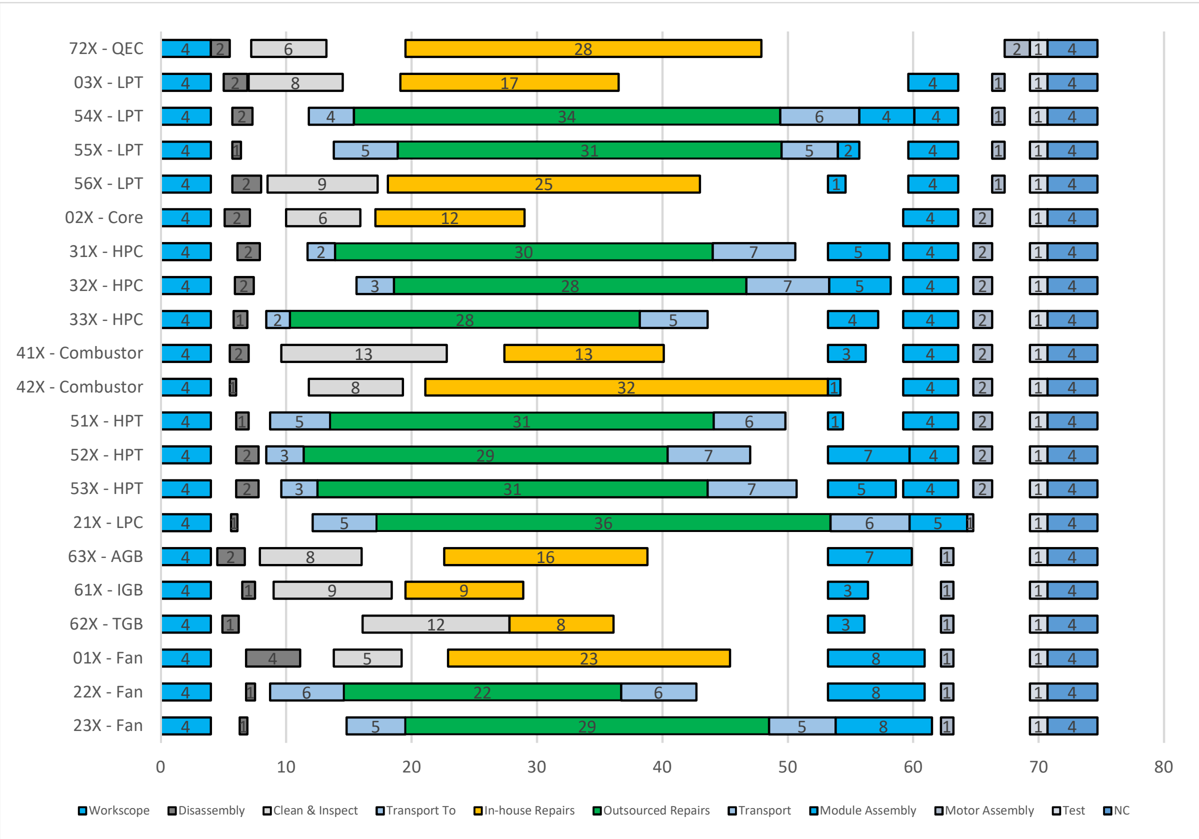

Figure 45. Performance of the integral engine MRO chain and of the individual process steps

With a performance of an average of 71 days of TAT of the integral engine MRO chain, a standard deviation of 30 and an OTP of 31%, the engine MRO chain at KLM E&M ES is not performing very well.

"What constraints become visible by analysing the performance of the engine MRO supply chain at KLM E&M ES and what are the root causes of these constraints?"
The main constraint will always be an assy of the engine, in the current situation this assy is the 21X. The performance of all the process steps that the 21X is passing are responsible for the fact that the 21X is the constraint. So, every process could be improved to ensure that the 21X is no longer the constraint. For all the process steps the root causes have been determined of why that process step is not performing better than it does at the moment.

The root causes for the disassembly process step are: the distribution and scheduling of mechanics. For the cleaning and inspection: the priority dispatching rule, batching, the distribution of engine injections and the distribution of mechanics.
For the repair: no vendor management, batching, distribution of mechanics and machine availability.
For the transport: priority dispatching rule, distribution of mechanics and a lack of multi-skilled mechanics.
For the assembly: missing material, distribution of mechanics and scheduling of mechanics
For the test and rework: Borrowed material, negative test result, bad communication after completion, test cell capacity, distribution of mechanics and scheduling of mechanics.

"Which solutions can be used to solve the root causes?"
In total 13 solutions are designed. All of them are created to solve the root causes identified in chapter 6. The solutions are based on planning and control decisions that can be changed in the system. All 13 solutions are given in Table 14, the solutions are either to exploit or otherwise to elevate a process step. Of all the solutions the influence on the TAT of the integral engine MRO chain and level of planning and control, on which the solution needs to be implemented, is determined. These solutions can be used to improve a process step of the assy that is constraining the integral engine MRO chain of performing better.

"What would be the impact of applying the continuous improvement framework on the integral engine MRO chain at KLM E&M ES?"
To improve the integral engine MRO chain at KLM E&M ES the continuous improvement framework is applied. The solutions that are proposed in every iteration are based on the efficiency of the solution that could be taken to improve the process. A choice will be made on basis of the reduction in TAT and the level of planning and control. For every iteration there is another constraint that should be solved, and for every iteration there are other solutions that can be used to solve that constraint. Below the different iterations with a brief indication of the solution that is used is shown.

Iteration 1 – Least Slack Policy at outbound transport and cleaning
Iteration 2 – Exploit Contract outsourced repairs
Iteration 3 – Exploit Transport
Iteration 4 – Elevate In-house repairs
Iteration 5 – Elevate Assembly
Iteration 6 – Elevate Outsourced repairs

The impact that the various iterations have on the performance of the integral engine MRO chain at KLM E&M ES is shown in Table 15.

Table 15. Impact of the iterations on the performance of the integral engine MRO chain at KLM E&M ES

	Current situation	*Iteration 1*	*Iteration 2*	*Iteration 3*	*Iteration 4*	*Iteration 5*	*Iteration 6*
Average TAT	71 days	65 days	59 days	55 days	54 days	47 days	42 days
Standard Deviation	31 days	31 days	20 days	18 days	13 days	11 days	11 days
On-Time Performance	31%	36%	47%	60%	71%	86%	92%

"What implementation plan can be made to translate the scenarios into practice, and how can these implementations be sustained?"
All the changes to the planning and control decisions that have to be made are given to the manager of that process step. This manager will make various projects for the changes to the decision variables. Not all projects need to be started right away, because it depends under which scenario that project falls. There is one coordinator of the integral engine MRO chain that manages the total project and updates the measurement performance model regularly to see how the implementation of the various projects is working. On basis of the measurement performance model the implementation plan will be controlled.

9.2 Achieving the research objectives and deliverables

The objective of this research is to *"Improve the integral aircraft engine MRO chain at KLM E&M Engine Services to contribute to the aim of shortening the current TAT to 45 days".* This research objective contains three parts. First, a framework must be designed to improve the process. Secondly, the levels of planning and control for an engine environment must be determined, because that is a tool of the framework. As last, a performance measurement model must be designed to simulate the impact of proposed scenarios to improve the integral engine MRO chain. As a result of this objective this thesis consists of three deliverables:

- The levels of planning and control for an engine MRO environment
- A literature framework to improve the performance of the integral aircraft engine MRO chain
- A performance measurement model to show the current performance and to simulate the impact of proposed improvements on the performance of the an aircraft engine MRO chain

Below it is discussed whether the research objectives and the related deliverables are achieved.

The levels of planning and control for an engine MRO environment
The levels of planning and control for an engine environment are determined by means of a combination between findings in literature, observations at KLM E&M ES and interviews with employees of KLM. The levels of planning and control for an engine environment give a very realistic view of how an engine MRO environment can be controlled.

A framework to improve the performance of the integral aircraft engine MRO chain
The framework has been built by means of various theories found in literature in combination with the designed levels of planning and control for engine MRO environments. The framework has been successfully applied in practice by means of a case study at KLM E&M ES.

For the first step, the identification of the constraint, the current state of the engine MRO chain at KLM E&M ES had to be measured. This is done in a self-made performance measurement model. This model is very suitable of identifying the constraint at a glance. So, identifying the constraint is rather easy following this literature framework.

In the second step, the exploit and elevate solutions were made for all the different process steps. Because of the fact that not every process step has been analysed in detail, not for all process steps a detailed and accurate exploit and elevate solution could be designed.

In the third step where the solutions are compared on efficiency, the height of the levels of planning and control are made with some assumptions. Because, it is known on which level the decision must be changed, but inside that level, there could be some variances between solutions. Because it will not be exactly known how the difficulty of implementing this solutions will be translated in practice.

And as last, to implement the most efficient solution a project plan is necessary. After implementation, the impact must be tracked and when the performance of the integral engine MRO chain changes and the constraint is solved, there should be gone back to step 1.

Overall, the framework was very effective in designing solutions to improve the performance of the engine MRO chain from an integral perspective. The framework was very easy to use. The only downside is that assumptions on the impact on the performance have to be made when the gathered data is not very detailed. But the results will not be influenced significantly due to the lack of detailed data.

To make the framework more robust, it would be necessary to do another case study with this framework. That could be in another engine MRO environment, or otherwise in an environment that is very similar to that of engine MRO. The main condition should be that the disassembled parts need to return to the same product.

A performance measurement model to show the current performance and to simulate the impact of proposed improvements on the performance of the an aircraft engine MRO chain
The performance measurement model that is built during this research has been of great value for the outcomes of this research. With this model, the performance of the engine MRO chain was very easy to determine and constraints where very easy to identify. With the model is was very easy to simulate different scenarios and to see the impact of changes of the performance of individual process steps on the integral engine MRO chain. Updating the model is not that easy, and certainly not for people who have not worked with it yet.

9.3 Contribution to literature and practice

In this section, a reflection is given to which extend this research could have a scientific contribution and in which extend it could have a practical contribution.

9.3.1 Scientific relevance

This research aims to contribute to science in four ways. First, the environment of the engine MRO process has been determined, since this was not yet written in literature. This is very useful for the board of engine MRO companies or divisions of companies. Because a different environment, means different characteristics of the process. Different characteristics mean that different ways of planning and control should be applied to control the supply chain. With the determination of the environment of the engine MRO process, all kinds of decision are made easier because it is known in what kind of environment the company is operating.

The second contribution is a continuation on the first. Since it is known in what kind of environment engine MRO providers are operating, the levels of planning and control can be determined. In this research these levels are determined by means of findings in literature and interviews with employees of the engine MRO provider. With the levels of planning and control for the engine MRO process, it is now determined what kind of decision variables are useable to change in order to change the engine MRO process.

The third scientific contribution is the proposed continuous improvement framework. This framework can be used by engine MRO companies to improve the engine MRO process. This framework is conducted by means of findings in literature and the determination of the engine MRO environment and the levels of planning and control for engine MRO processes. This framework could be used in other industries as well, this has not been tested yet. But because of the general body it is assumed that it will work in other industries as well.

The fourth scientific contribution is the performance measurement model that is built during this research. This model can be used to measure the performance of the current situation of engine MRO companies. With the current situation, the constraint can be identified and a simulation can be made to see the impact of improvements in individual process steps on the integral engine MRO chain. This model is built for an engine MRO environment, but it can be easily adjusted for other industries as well.

9.3.2 Practical relevance

To begin, this research does have practical relevance for KLM E&M ES. Some parts of this research are already used by KLM E&M ES. The performance measurement model with the current situation of the engine MRO chain at KLM E&M ES is the basis of the project called 'TAT45'. The simulated future states, which are designed with the use of the continuous improvement framework form the basis of the improvement plan that is currently worked out at KLM E&M ES.

9.4 Research limitations

In this section, the limitations of the conducted research are discussed.

First, the data that is used for this research is not for hundred per cent complete and does not fully represent a realistic view of the real world. The data does give a realistic approximation of the real world, which is why the results are valid. The reason of this is that an engine contains more than 10,000 parts and a lot of those parts are really small and cannot be tracked properly. Besides that, the mechanics do not perform the administrative tasks how it should be to get full realistic data. The mechanics are not to blame for it, but the complex process an engine goes to is the problem.

Because of the, not hundred per cent realistic or complete, data that was available to conduct this research, all the numbers that are given are an approximation of the real world. That is why the decision and design solutions are not given with exact numbers. For example, the change of mechanics that should be made is clear, but with how many mechanics is an approximation.

The performance measurement model that is used to give an overview of the current situation, is based on averages of all the engines over an historical time period. So per engine the constraint could be different, but on average in the current situation the 21X is the constraint. On the other hand, the root causes of all the individual process steps have been given, which means that it does not matter which assy the constraint is. The way to improve the engine MRO chain will stay the same, and because in the implementation plan several projects start at the same time.

In the model, an assy is based on outsourced and in-house repairs. This determination cannot be done as black and white as is done in this research. Because the majority of the assy's has outsourced and in-house repairs. But for simplicity, one of the two is chosen based on the frequencies of appearance. Appendix G shows the ratio of in-house and outsourced repairs per assy. The same counts for the outsourced repairs and the cleaning and inspection process step. Not all outsourced are transported to the vendor without getting cleaned and inspect at KLM E&M ES. But the majority of the outsourced repairs do go dirty to the vendor. The ratio of outsourced repairs that go straight to the vendor without cleaning and inspection is shown in Appendix G.

9.5 Recommendations and further research

In section 9.5.1 the recommendations for KLM E&M ES are discussed and in section 9.5.2 recommendations for further research is discussed.

9.5.1 Recommendations for KLM E&M ES

With the outcomes of this research several recommendations for KLM E&M ES are made. First, it is strongly recommended to make use of the performance measurement model as is used in this research. This model uses a different way of measuring the repair process step than is done currently at KLM E&M ES. With this new measurement, the performance of this process step is much more realistic. Besides this, the performance measurement model that is used in this research gives a very realistic overview of the performance of the engine MRO chain. To make the model more realistic, it is recommended to measure data in a more realistic way. Next tot that, the performance must be measured on three KPIs (TAT, OTP and SD) and not on one (OTP) as in the current situation.

Secondly, to start improvement projects, the projects that will be initiated need to be a result on basis of the proposed literature framework. Because this framework has a look on the integral engine MRO chain and not only at individual processes. So it is strongly recommended to use the proposed literature framework to start projects to improve the integral MRO chain.

Further it is recommended to use the performance measurement model and the literature framework also on other engine types. In Appendix J the current performance of the CF6-80C2 is shown with the performance measurement model. This shows that it is easy to use the model also for other engine types. With this current situation of the other engine type, the constraint of that type can be identified easily and improvement scenarios can be made on basis of the proposed literature framework.

9.5.2 Further research

Further research needs to be done on the exact numbers of the distribution and scheduling of manpower capacity. The used data is an approximation of the real world and hundred per cent realistic data is lacking. It is known, and because of the approximation in this research that a huge root cause of the poor performance of several process steps is due to both distribution and scheduling of manpower capacity.

Subsequently, further research should be done to the disassembly and the cleaning and inspection process step. In fact, the cleaning and inspection are two process steps, the cleaning process and the inspection process. For the in-house repairs these steps have a big impact. The disassembly process does perform fine in the current situation, but when the integral engine MRO chain will improve further, it could be necessary that the disassembly process must be improved.

As last, more research must be done inside various process steps. For example, various in-house repair processes. There has only be done research to the combustor (42X) and the fan blades (01X), but there are more parts that need research to improve those in-house process repairs. The same counts for the assembly process on engine level, not a lot of improvements have been made on that process step.

And from a scientific point of view, more research should be done to the continuous improvement framework and the performance measurement model. Research should be done to see if the framework and the model also are suitable to be applied in other industries.

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Appendix

A. Research methodology

A.1 Plan-Do-Check-Act research methodology

Plan

To deliver results in accordance with the expected output, it is necessary that the objectives and processes are established. By establishing output expectations, the completeness and accuracy of the specification is also a part of the targeted improvement. If it is possible start on a small scale to test possible effects.

Do

Implement the plan, execute the process, and make the product. Collect data for charting and analysis in the following "Check" and "Act" steps.

Check

First, study the actual results that are measured and collected in the previous step, and compare the results against the expected results to ascertain any differences. Then, look for deviation in implementation from the initial plan and also look for the appropriateness and completeness of the plan to enable the execution. Charting data can make this much easier to see trends over several PDCA cycles and in order to convert the collected data into information. Information is what you need for the next step "Act".

Act

If the "Check" shows that the "Plan" that was implemented in "Do" is an improvement to the prior current situation, then the improvement becomes the new standard for how the organization should Act going forward. If the "Check" shows that the "Plan" that was implemented in "Do" is not an improvement, then the existing current situation will remain in place. In either case, if the "Check" showed something different than expected, then there is some more learning to be done. That will suggest potential future PDCA cycles.

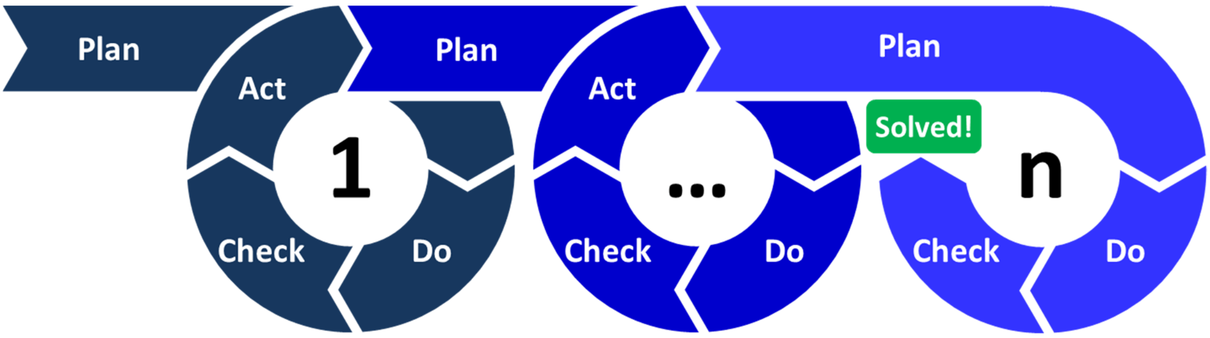


Figure 46. The iterative PDCA cycle

B. Literature review descriptions

B.1 Complexity of remanufacturing

Material recovery rate

The material recovery rate is defined by Guide Jr. *et al.* (1999) as: *"how often a part is in a suitable condition to be remanufactured."* Any parts that are not recoverable should be replaced by new parts. The recovery rate plays in important role in the material requirement planning, because it determines how many new components have to be purchased. Managers have several concerns with purchasing new components which all can lead to long lead times (Guide Jr., 2000). For example, a sole supplier for a part or component, where the particular component could be out-of-stock. Or small purchase orders, with the result of unresponsive vendors or the need to order a batch. Guide Jr. (2000) found that purchased orders caused a high percentage (~45%) of late orders.

Stochastic routings and processing times

A parts condition will not be known until a unit is disassembled, cleaned and inspected, this results in stochastic routings and processing times (Guide Jr., Jayaraman, & Srivastava, 1999). Different operating conditions, wear and age may vary the operations required for each part drastically. These highly variable process times and stochastic routings that are common in this environment cause shifting bottlenecks. That makes resource planning and estimating flowtimes very difficult and challenging (Guide Jr., 2000). That makes this characteristic the single most complicating factor for scheduling and lot sizing decisions. Due to the late determination of a part's suitability further complicates purchasing and capacity planning due to the short planning horizon.

Serial number specific parts matching

A third factor that complicates the remanufacturing system is serial number specific reassembly operations. This is applicable in situations where the customer retains ownership of the product and requires the same unit returned. This requirement may be customer-driven, e.g. a customer turns in a unit to be remanufactured and then requests that the same unit will be returned to them (Guide Jr., 2000). This characteristic will add more complexity to the materials management, shop floor control and resource planning and it requires a very good coordination between all the different remanufacturing processes. Parts must be numbered, tagged and tracked in order to provide the same unit back to the customer. This places an additional burden on the information system (Guide Jr., 2000). This characteristic can easily cause delays in the reassembly of the unit when a specific part number is delayed and will in the end delay the order. A major impact of this characteristic is on the scheduling and information systems. With the presence of any serial number specific items coordination between disassembly and reassembly becomes critical if customer due dates are to be met (Guide Jr., Jayaraman, & Srivastava, 1999).

Disassembly

The effects of the disassembly operations has impact on a large number of areas, including, shop floor control, production control, scheduling, and materials and resource planning. The disassembly and subsequent release of parts to the processing activities require a high degree of coordination with reassembly to avoid high inventory levels or poor customer service (Guide Jr., Jayaraman, & Srivastava, 1999). When the company remanufactures just a low variety of products, the average times for disassembly will have a low variance. On the opposite, if the variety of products is high, the disassembly times will have a wide range. This leads to uncertain flow times and makes it difficult to estimate and set accurate lead-times (Guide Jr., 2000). The decision of how to release parts from the disassembly area to the remanufacturing shop is one of the decision a planner is facing. Firms in the industry are using push, pull or push/pull release mechanisms. Careful coordination between disassembly and reassembly is required to provide responsive, short lead-times (Guide Jr., 2000). Uncontrolled release of parts from the disassembly area to the processing activities leads to large waves of material being pushed through the shop and may cause long queues at machine centres, which could lead to increased lead-times, increased variability of lead-time and decreasing customer service level (Guide Jr., Jayaraman, & Srivastava, 1999). Guide and

Srivastava (1998) found that after the disassembly process, serial number specific parts should be released to the shop floor as soon as possible to insure due date performance. For common parts they found that the parts should be released in a gradual fashion to the shop floor to avoid congestion.

B.2 Environment types

Complex customer order production, type 1, implies low volume, low standardization and high product variety. The products are more or less designed and engineered to customer order, i.e. an engineer-to-order type. Manufacturing batches are typically small, products are complex with deep and wide bills of material. Throughput times and delivery lead-times are long and the production process is designed for one-off production.

In the configure to order environment, type 2, the products have less complexity and are assembled in small batches. It can be characterized with an assembly-to-order or made-to-order type of operation, where many optional products can be configured and manufactured by combining standardized and stocked components and semi-finished items. The delivery lead-times are much less than the lead-times of type 1. The throughput time for the assembly or finishing operations are short and the batch sizes are typically small.

The batch production of standardized products, type 3, can mainly be characterized as manufacturing to stock. The products are mainly standardized in medium to large size order quantities.

Type 4, repetitive mass production, represents a planning environment where products are made in large volumes on a repetitive and more or less continuous basis. It concerns standardized products or optional products made or assembled from standardized components characterized by having flat and simple bills of material.

B.3 Material planning methods

Re-order point planning uses demand forecasts to decide when to order a new quantity to avoid dipping into safety stock. Re-order point planning suggests a new order for an item when the available quantity drops below the item's safety stock level plus forecast demand for the item during its replenishment lead time. The suggested order quantity is an economic order quantity that minimizes the total cost of ordering and carrying inventory. Re-order point systems are basically designed for items with independent demand, and it cannot be expected to perform very effectively in all environment type combinations. Re-order point systems can, however, be used reasonably effectively the more standardized the product components are, the longer life cycles they have and the more stable demand (Jacobs & Whybark, 1992) (Newman & Sridharan, 1995). These conditions apply the best to environment type 3.

Material Requirements Planning is a concept of creating material plans and production schedules based on the lead times of a supply chain. It brings a maximum of planning ability to accommodate dynamic natures (Newman & Sridharan, 1995). Material requirements planning can be seen as a generally applicable material planning method. In all manufacturing companies, irrespective of the specific planning environment it will work reasonably well (Newman & Sridharan, 1992). Because of its strength in planning items with dependent demand. In environments with complex standardized products, long manufacturing lead-times and items with time variations and uneven demand material requirements planning will be most effective (Plenert, 1999). Material requirements planning captures the actual assembly requirements better than re-order point systems. Environment types 2 and 3 are most likely to function good with the material requirements planning method.

The opposite of material requirements planning is the *Kanban system*. Kanban is a way to organize the chaos by making a need for prioritization and focus clear, and Kanban is also a way to uncover workflow and process problems in order to deliver more consistently to the customer. Kanban accomplishes these things by introducing constraints into the system to optimize the flow of value.

Kanban functions best in environments with a regular and steady demand and where products have a simple and flat bill of material (Gianque & Sawaya, 1992). Also, short lead-times and small order quantities suits Kanban best (Newman & Sridharan, 1992). Long lead-times, complex products, often designed to order, and lumpy and unpredictable demand are in general so far away from what Kanban can cope with effectively. However, integrated Kanban/MRP approaches can successfully cope with planning problems in high variety and low volume manufacturing environments (Stockton & Lindley, 1995). With this information, it can be said that environment type 4 suits good for the Kanban method.

Drum-buffer-rope (DBR) has close relations with the Kanban approach. The DBR method is coming from the Theory of Constraints and is based on only scheduling the constraint, thus the data that is needed will be reduced drastically (Goldratt, 1984). The drumbeat, or pace, of production is adjusted to the constraint and a rope is pulling material when the constraint is ready for it. In Guide's (1996) research the reassembly process was the drumbeat, or constraint, on which the whole process was planned. The reassembly process was the drumbeat in his research because the majority of parts where not serial number specific and it did not matter which parts were assembled together. The processing time of assembly was the longest and thus the constraint. Just as with the Kanban method, environment type 4 suits good for the DBR material planning method.

Order-based planning is the functionality that plans planned orders to cover components and end items. This functionality largely corresponds to Materials Requirement Planning and uses Bill of Materials to explode material requirements and the routings to calculate lead-time of planned production orders. To manage complex and customer order specific products is the most characteristic feature of order-based planning. Also in environments characterized by long lead-times, lumpy demand and items with dependent demand order-based planning is a relative strong material planning method (Jonsson & Mattsson, 2002a). It can be concluded, that for type 1 and 2 a good material planning method would be the order-based planning.

Order release methods

Infinite capacity scheduling basically means that orders are released to the shop floor, irrespective whether the current load is above available capacity. The method suits best in environments with reasonably even, small order quantities and a smooth demand, such as in environment type 4.

In environments with large order quantities and uneven product demand, a scheduling system capable of loading orders to *finite capacity* becomes more important. This system makes it possible to more effectively avoid overload and underload situations on the shop floor. It does not solve the under-capacity problem. However, it will determine which jobs will be dealt with, based on priorities (Melnyk, Carter, Dits, & Lyth, 1985). The use of finite capacity favours with unstable and unpredictable demand, like types 1 and 3 environments, as it allows for more frequent rescheduling and more sophisticated considerations to the entire scheduling situation.

The method that is based on the availability of capacity in the gateway work centre for the release of orders to the shop floor, is the *input/output control method* (Vollmann, Berry, & Whybark, 1997). In environments that it is important to monitor backlog and to control queues, work in process and manufacturing lead-times, this method is relatively effective (Fogarty, Blackstone, & Hoffmann, 1991). Which means that environment type 2 and 4 will function good with this method.

Capacity planning

To use the *overall factors method* for capacity planning the products should be homogeneous from a manufacturing point of view. The method also assumes that the load from manufacturing a product is in the same planning period as the delivery date (Vollmann, Berry, & Whybark, 1997). This method will be affected most when changes in product volume or the level of effort required to build a product occur (Blackstone, 1989). That means that the method only should be used in environments with short lead-times and a flat bill of material, compared to the planning period (Jonsson & Mattsson, 2002b), like environment type 4.

When using capacity bills as capacity planning method, manufacturing homogeneous products is of less importance. It employs detailed data on the time standards for each product. That is why poor time standards could become an obstacle when using this method (Fogarty, Blackstone, & Hoffmann, 1991). The lack of optimum use of capacity and resource planning was unreliable data or the absence of time standards and routing information (Burcher, 1992). For capacity planning employing resource profiles and capacity requirements planning, this effect becomes even greater. The capacity bills method does not take stock-on-hand for components into account and assumes that the load from manufacturing a product is in the same planning period as the delivery date (Vollmann, Berry, & Whybark, 1997). This means that the capacity bills method suits good for environment type 1.

The resource profiles method has advantages compared to the previously mentioned methods for planning environments with long lead-times, because it allows the lead-time off-setting of a load relative to the delivery date. Resource profiles rely on time standards and do not consider the stock-in-hand of components used in the products, as does the capacity bills method (Blackstone, 1989). The method allows for capacity planning prior to the conclusion of the detailed design and production planning phase, this is particularly relevant for engineer-to-order type of products (Jonsson & Mattsson, 2002b), like environment type 1.

The capacity requirement planning method is the most generally applicable capacity planning method. It can be used successfully in all four types of environment, but its relative strength is in environments with complex products that are custom built from standardized components or complex standard products (Jonsson & Mattsson, 2003). Capacity requirements planning has major advantages in environments where components are manufactured in batches to stock, like in the planning of stock-on-hand of components (Fogarty, Blackstone, & Hoffmann, 1991) (Vollmann, Berry, & Whybark, 1997) (Jonsson & Mattsson, 2002b). The strength of capacity requirements planning will come forward the most in environment types 2 and 3.

C. Current state measurement per process step

C.1 Cleaning & Inspection

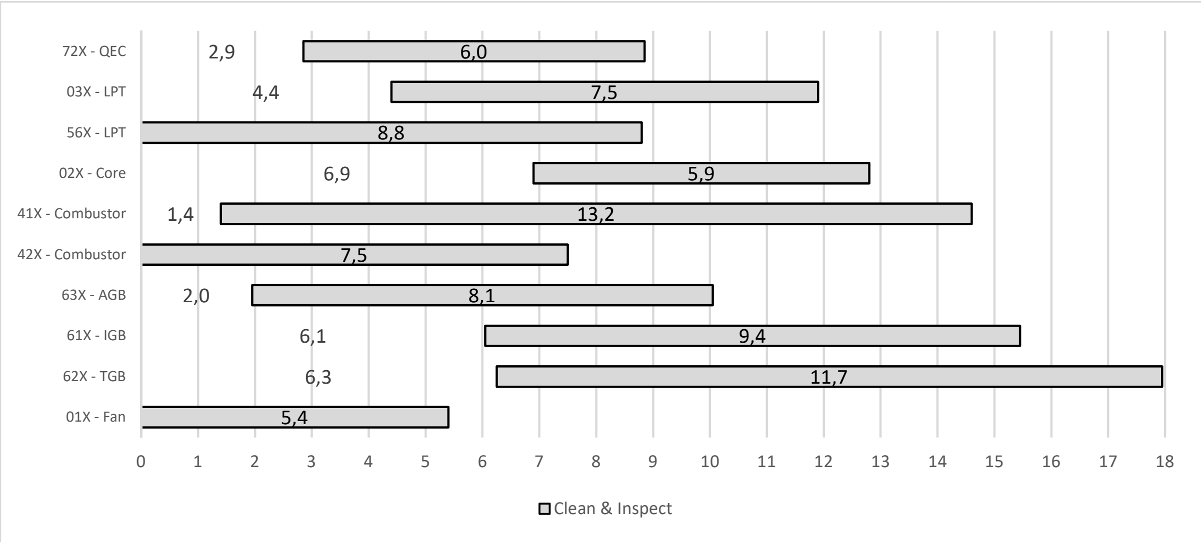
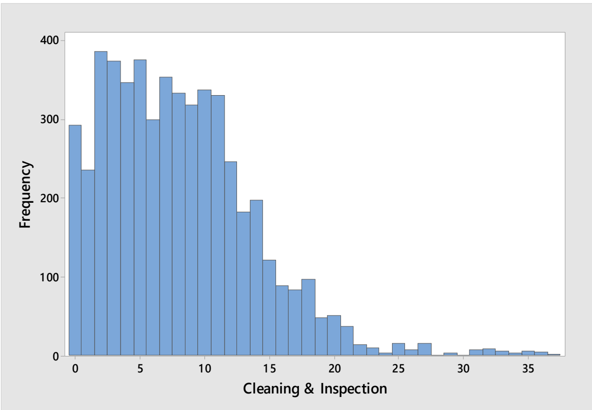


Figure 47. Processing and waiting times of cleaning and inspection



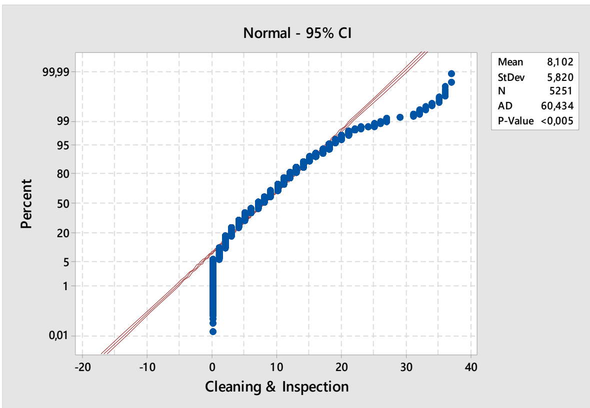


Figure 48 and Figure 49. Distribution and probability plot of the average of the cleaning and inspection process step

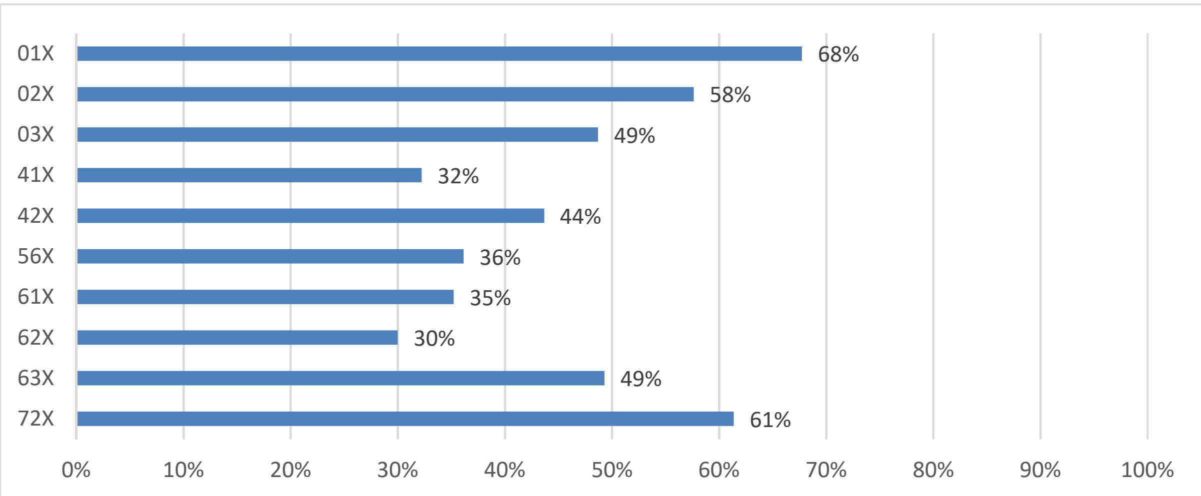


Figure 50. On-time performance of cleaning and inspection

C.2 Repair

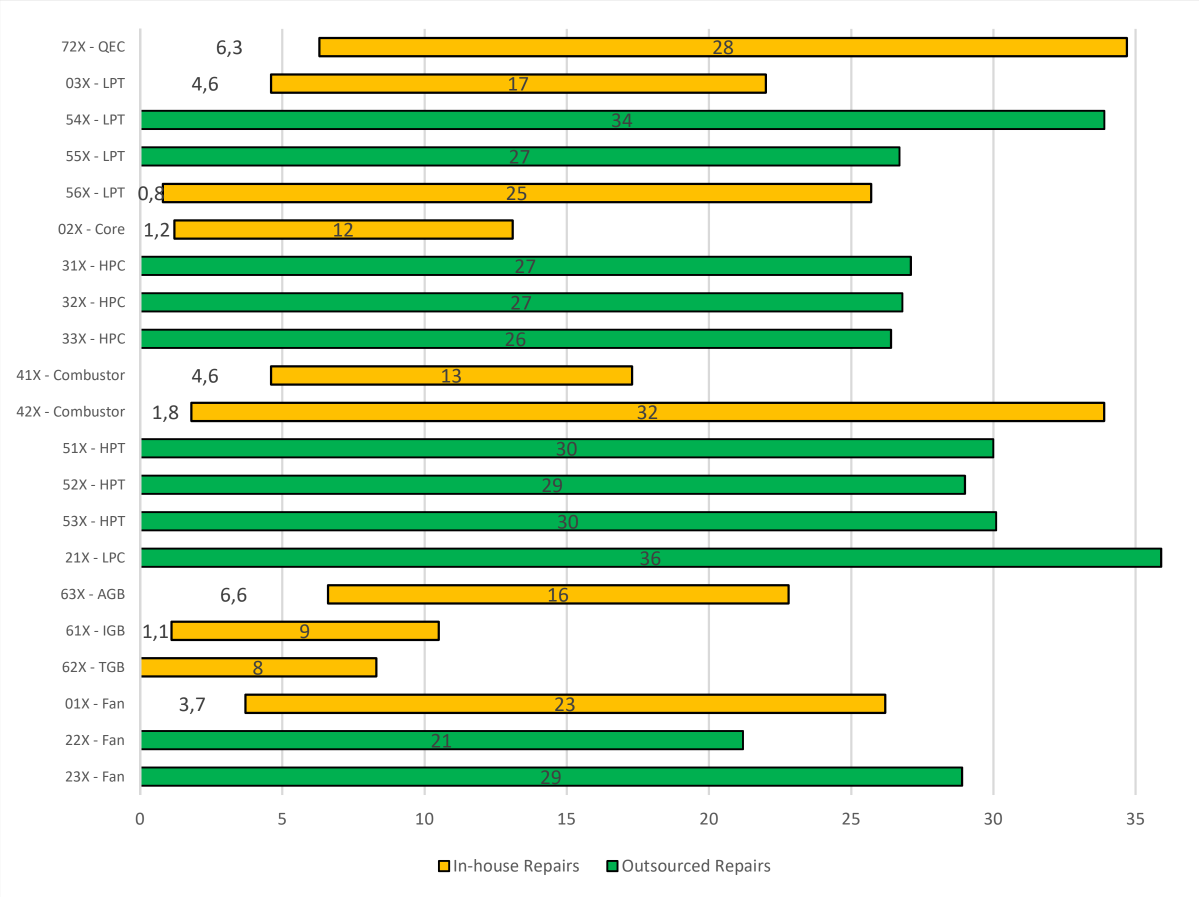


Figure 51. Processing and waiting times repair

Table 16. Standard deviation and p-value of the repairs stage on assy level

Assy	*Standard Deviation*	*P-value*	*Assy*	*Standard Deviation*	*P-value*
01X	15.5		*51X*	11.2	
02X	9.6		*52X*	9.4	
03X	14.9		*53X*	10.0	
21X	13.5		*54X*	14.5	
22X	12.5		*55X*	13.8	
23X	17.1		*56X*	11.8	
31X	11.5		*61X*	9.5	
32X	14.2		*62X*	6.1	
33X	5.9		*63X*	11.3	
41X	11.8		*72X*	16.5	
42X	6.9				

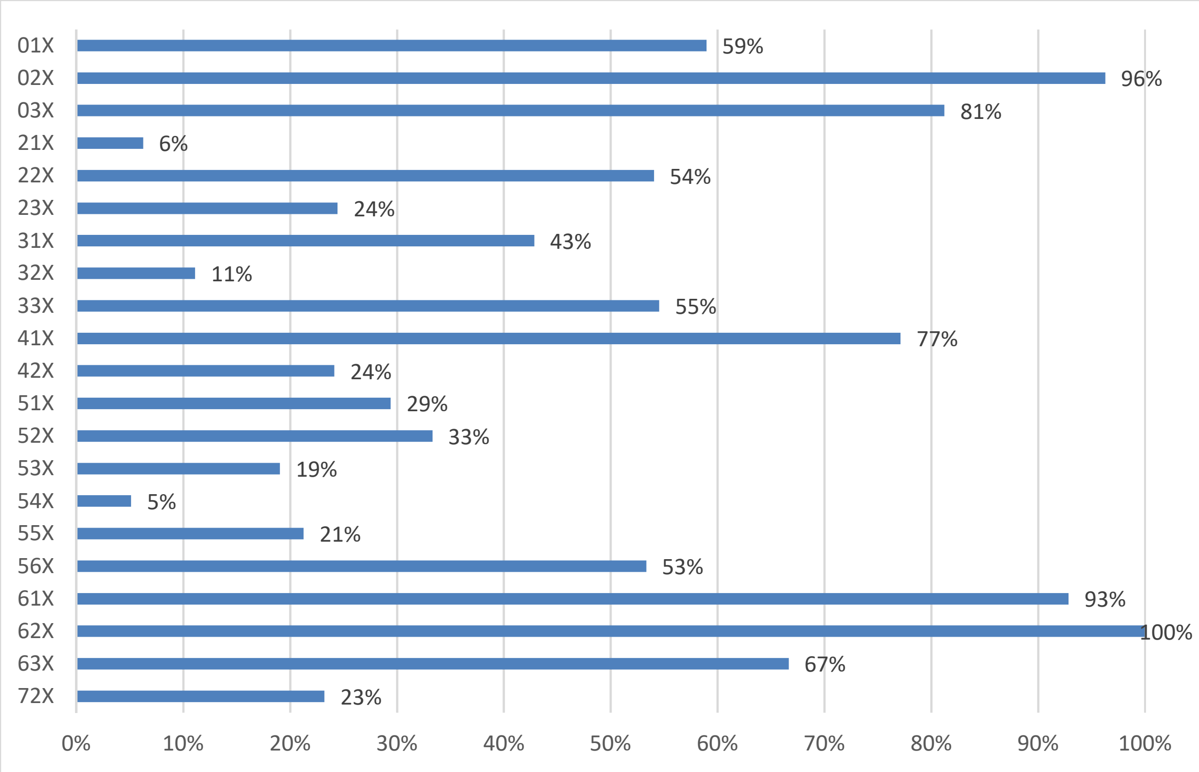


Figure 52. On-time performance of the repair process step on assy level

C.3 Outbound and inbound transport

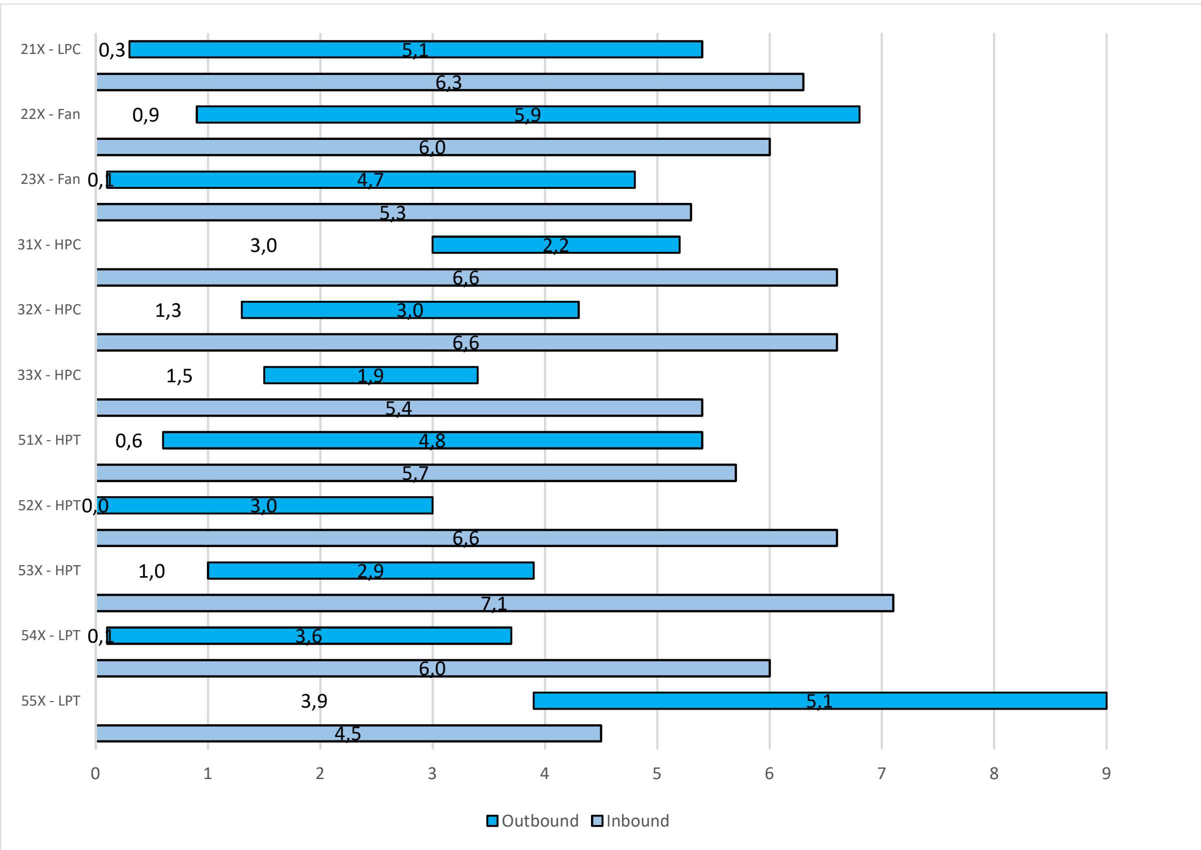
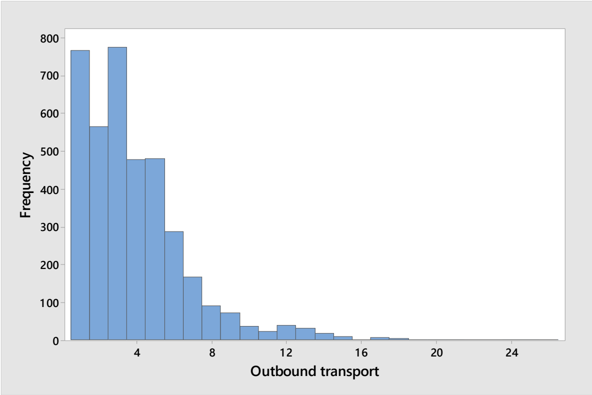


Figure 53. On-time performance of the outbound and inbound transport process step



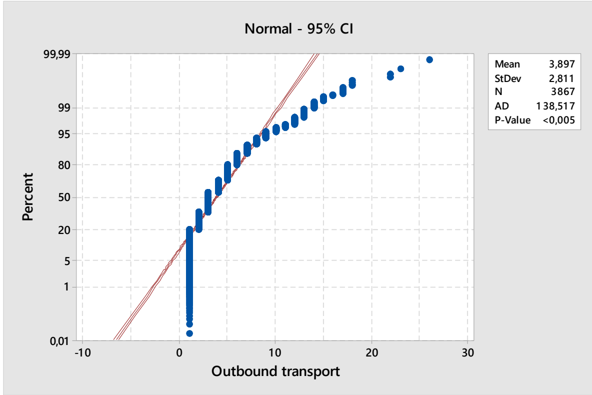
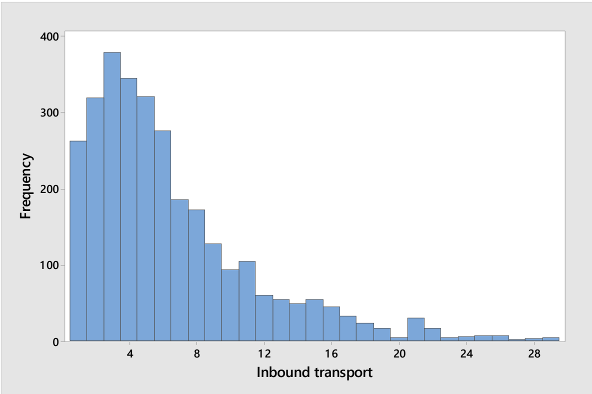


Figure 54 and Figure 55. The Distribution and the probability plot of the outbound transport on part level



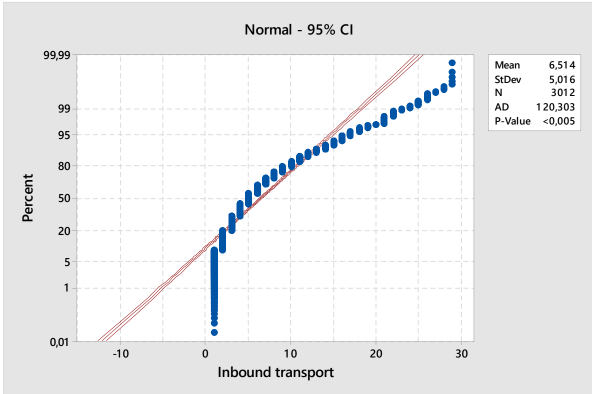


Figure 56 and Figure 57. Distribution and probability plot of the inbound transport process

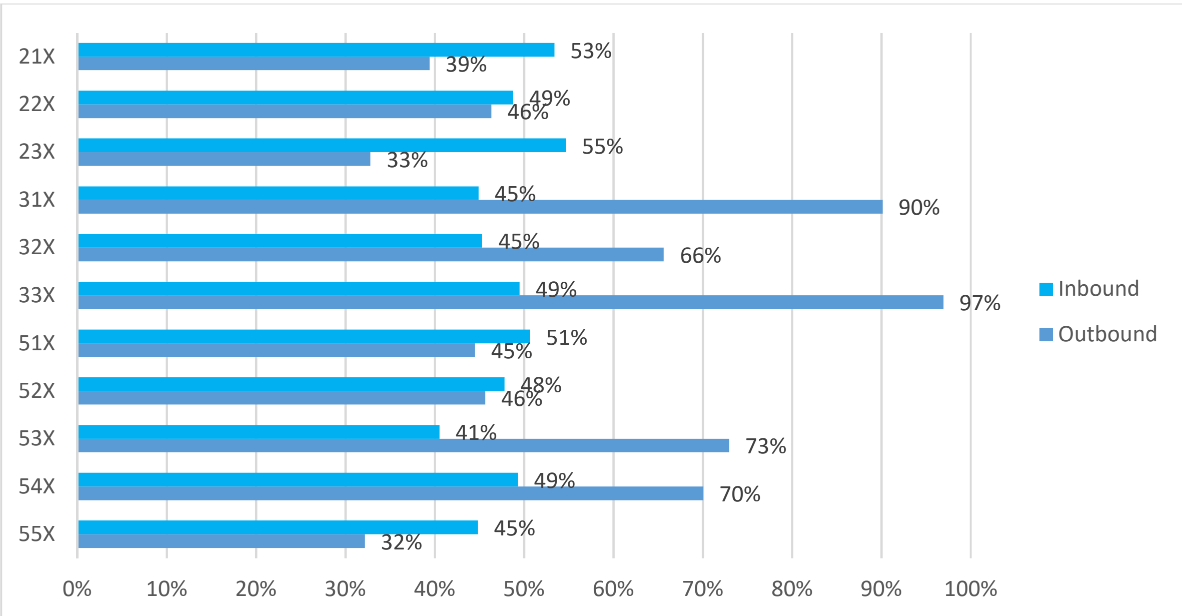
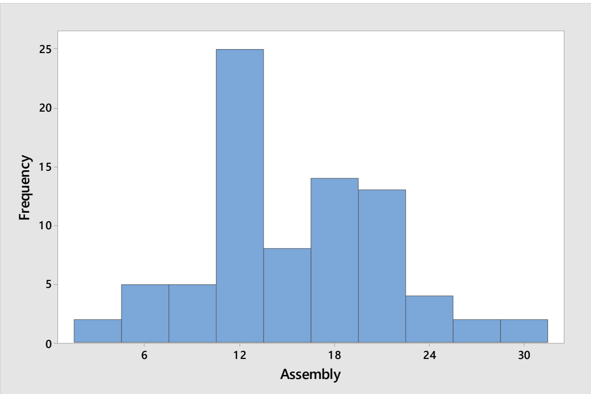


Figure 58. On-time performance of the outbound and inbound transport step

C.4 Assembly

Figure 59. TAT performance of the assy, module and engine performance of the assembly process step



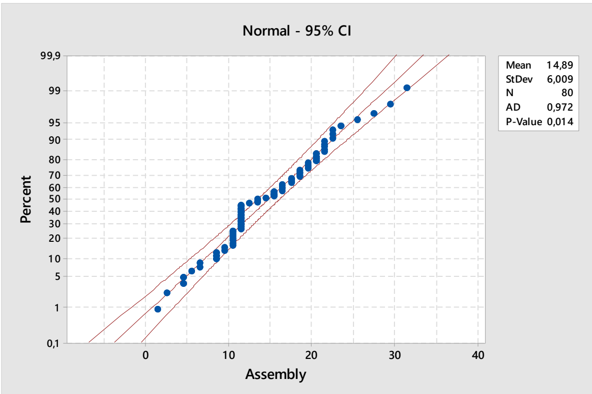


Figure 60 and Figure 61. Distribution and probability plot of the assembly process step

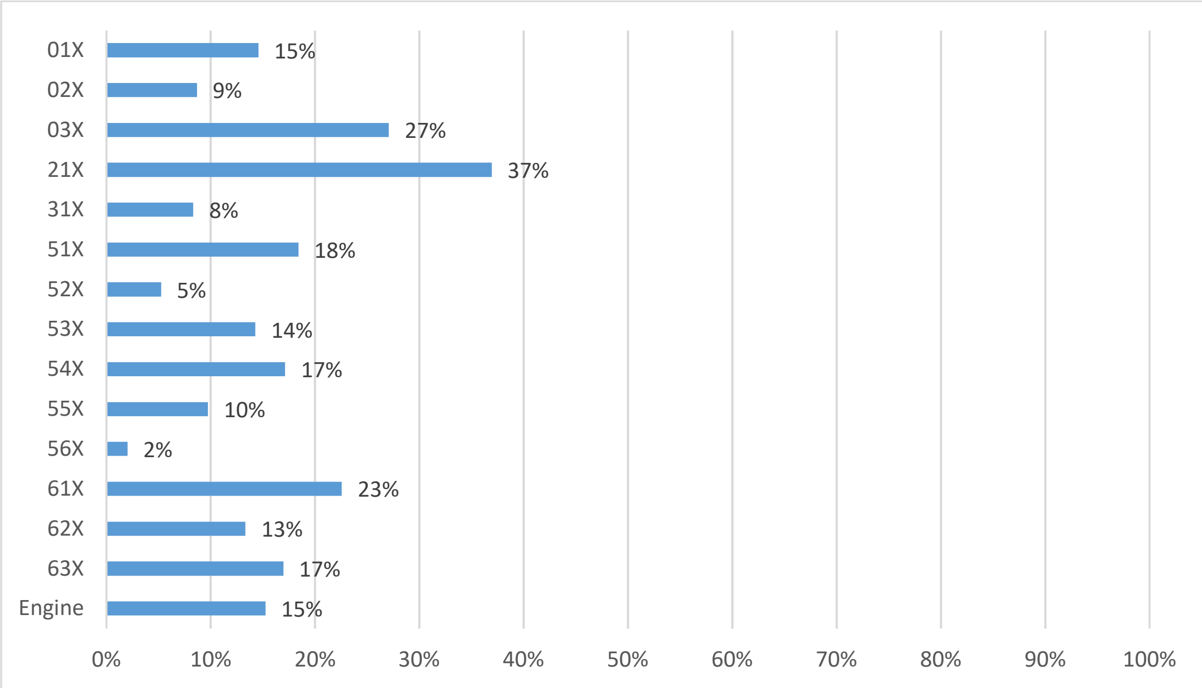
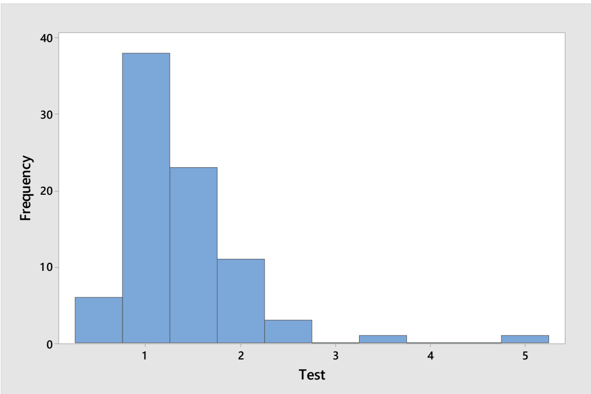


Figure 62. On-time performance of the assembly process step per assy

C.5 Test & Rework



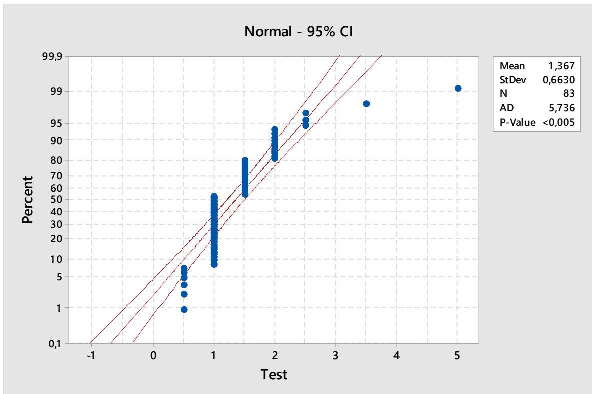
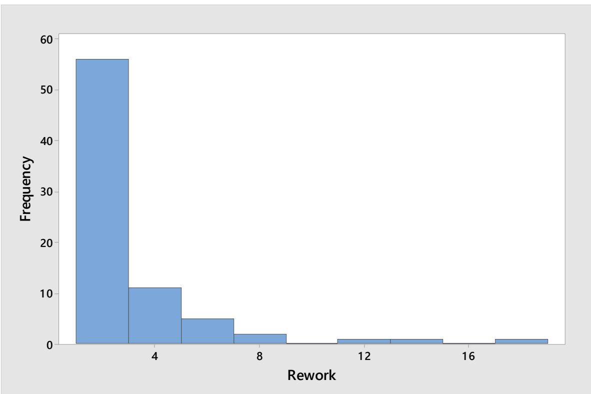


Figure 63 and Figure 64. Distribution and probability plots of the test process step



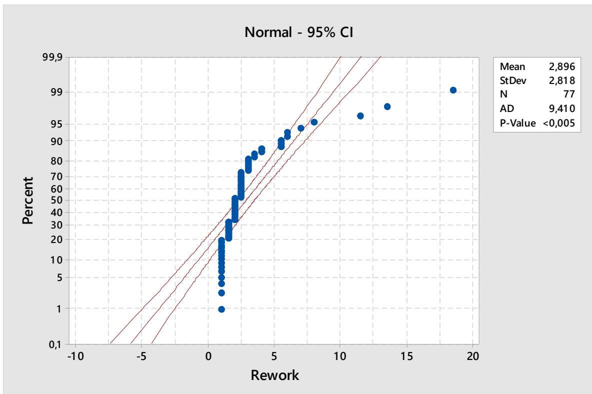


Figure 65 and Figure 66. Distribution and probability plots of the rework process step

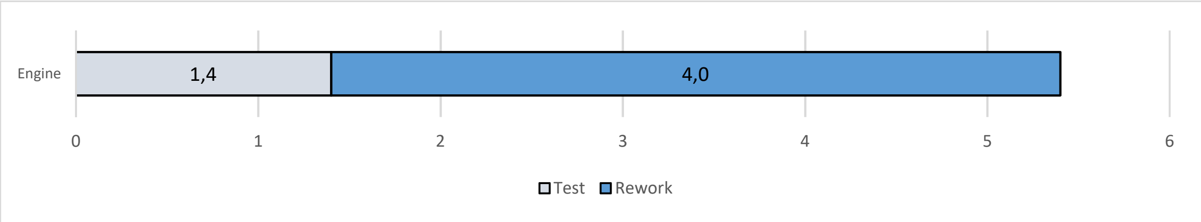


Figure 67. TAT performance of the test and rework process step on engine level

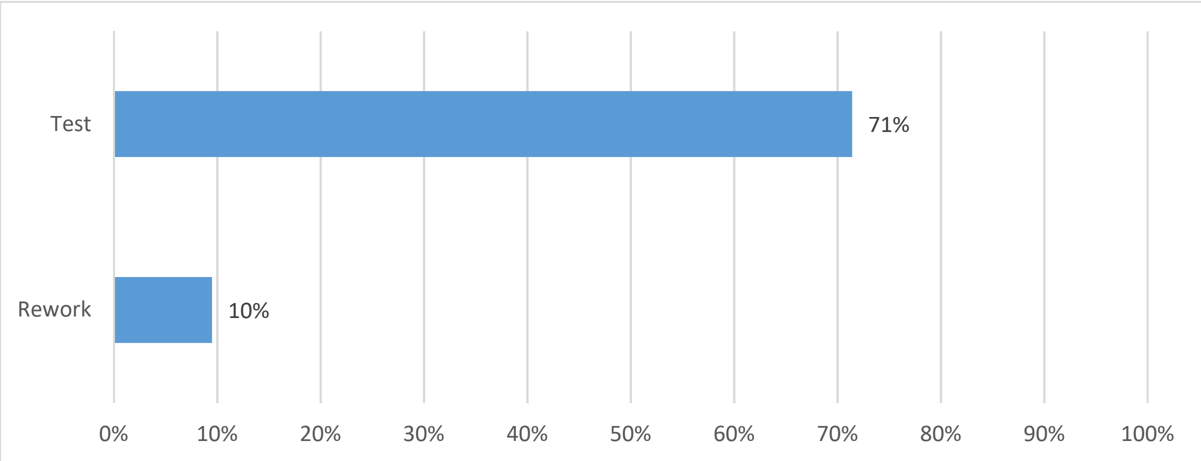


Figure 68. On-time performance of the test and rework process step

D. Model validation

To validate the performance measurement model, a sensitivity analysis and an extreme condition test are performed. For the sensitivity analysis all the values of the process steps and waiting time are divided by two and multiplied by two. The results are shown in Figure 69 and Figure 70.

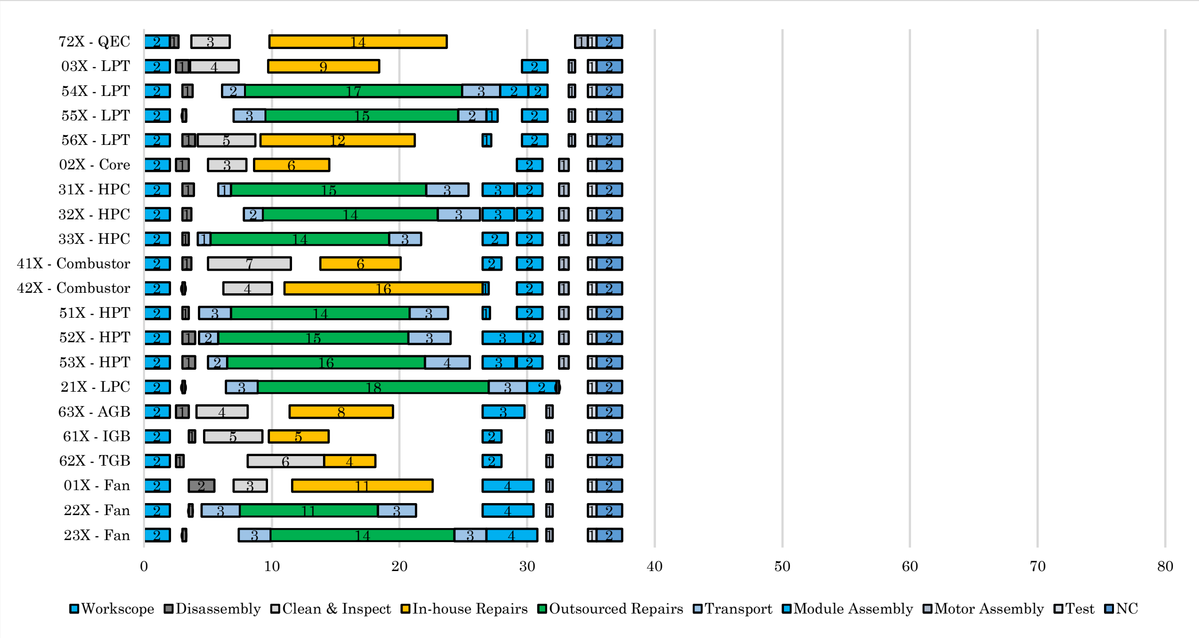


Figure 69. Sensitivity analysis with values divided by two

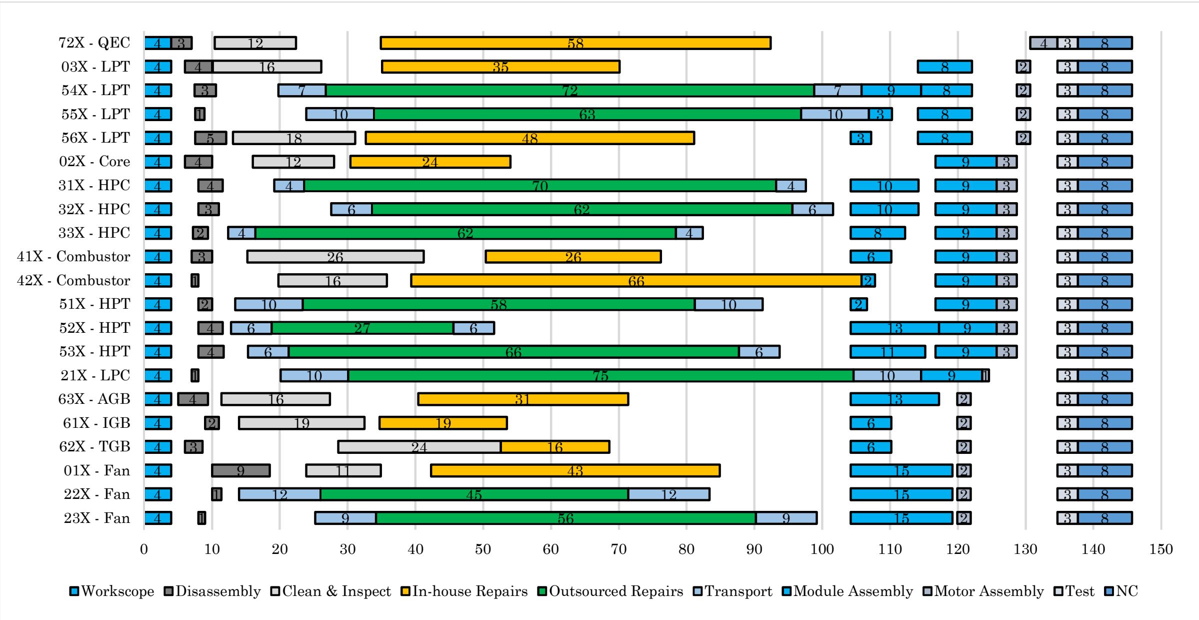


Figure 70. Sensitivity analysis with values multiplied by two

Both figures show that the does what was expected by dividing and multiplying by two. The integral TAT performance of the process is for Figure 69 35,5 days and for Figure 70 142 days. This is exactly what was expected.

For the extreme condition test, one situation with extremely low values and one situation with extremely high values will be tested. As can be seen in Figure 71 and Figure 72, also with extreme values the model performs as expected.

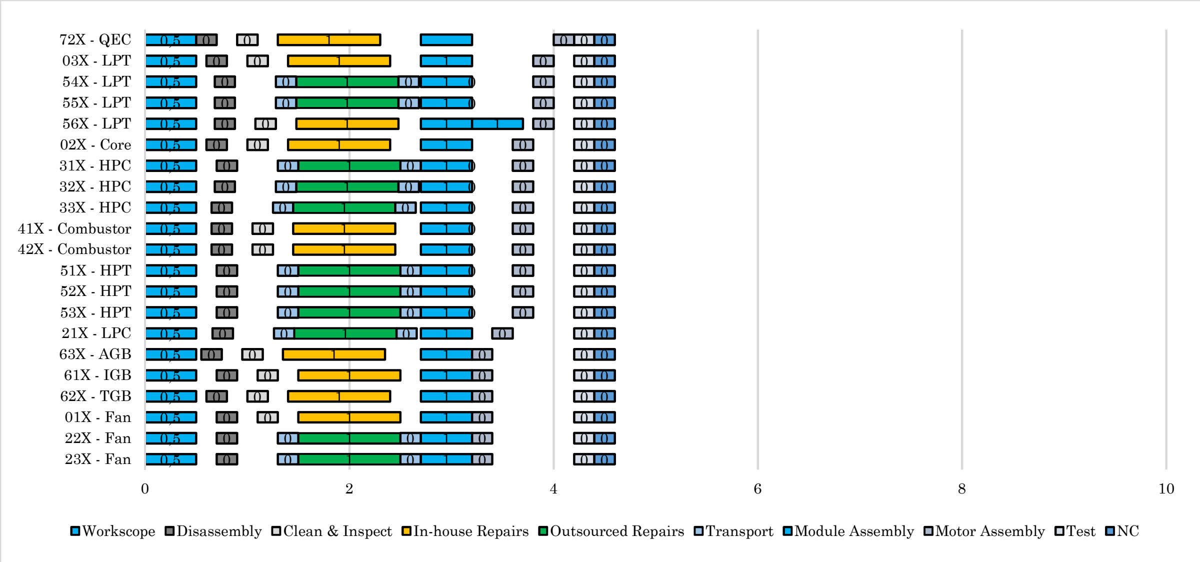


Figure 71. Extreme conditions test with extremely low values

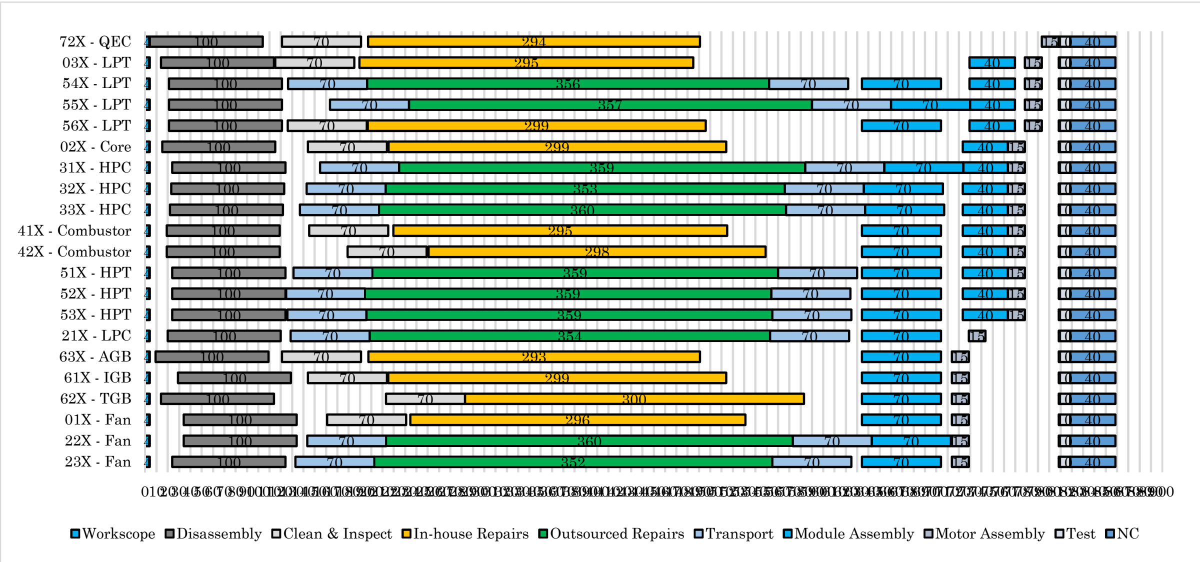


Figure 72. Extreme conditions test with extremely high values

E. Assembly analysis

As already stated in section 6.2.5, for the analysis of the assembly process step three engines have been followed closely. Every shift it has been noted how many mechanics have worked. This resulted in three overviews of the current situation of those three assembly processes, see Figure 73, Figure 74 and Figure 75. On the vertical axis the assy's are shown and on the horizontal axis the timeline. The coloured cells are cells where mechanics have worked, the number in the cell indicates the number of mechanics that have worked that shift on that assy. The light grey cells, with WO inside, indicate that there has not been worked on that assy that shift because not all material was available to build dat assy. The dark grey cells, with Man inside, indicate that there has not been worked on that assy that shift because there was no mechanic available to work on that assy. It has to be noted that the TATs of all the engine were already below the average TAT of all the average assembly processes of 2016. Engine 1 16 days, engine 2 15,5 days and engine 3 12,5 days.

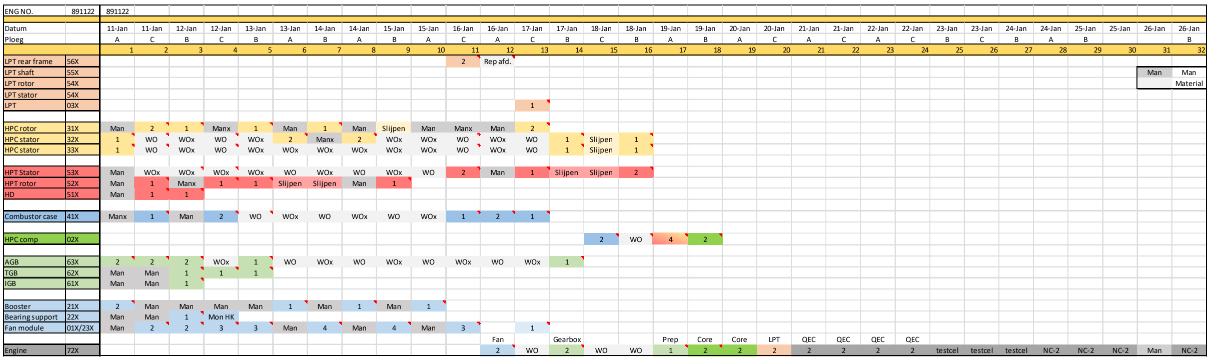


Figure 73. Assembly process step of engine 1

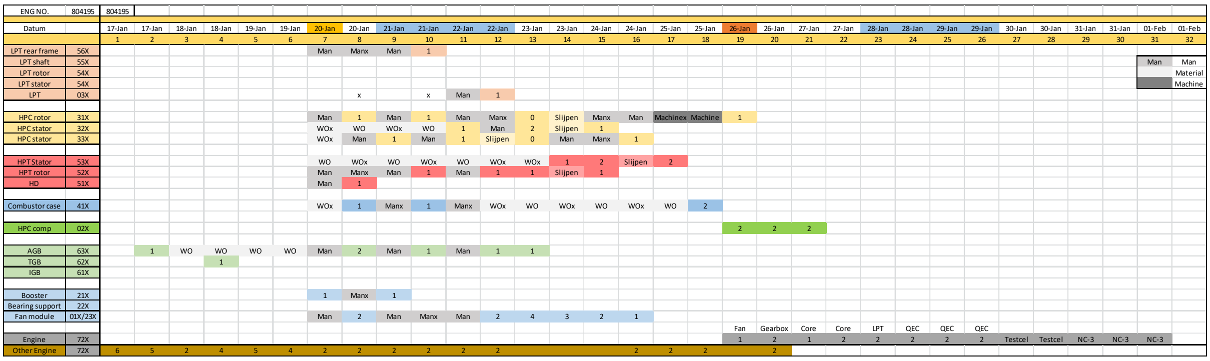


Figure 74. Assembly process step of engine 2

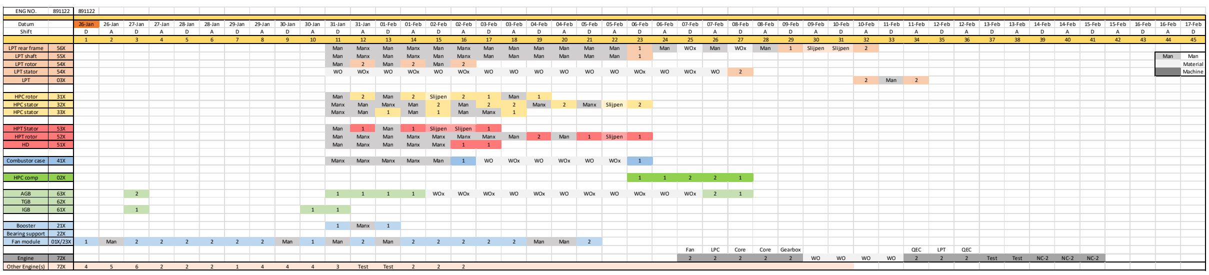


Figure 75. Assembly process step of engine 3

As can be seen in the figures above, there is a lot of wasted time present in the assembly processes of the three engines. As stated in section 7.1.5, the material issues cannot be solved at the assembly process itself, that has to be done in the repair process step before assembly. Thus, what-if situations will be made to see what happens if the material issues were all solved. The results are shown in Figure 76, Figure 77 and Figure 78.

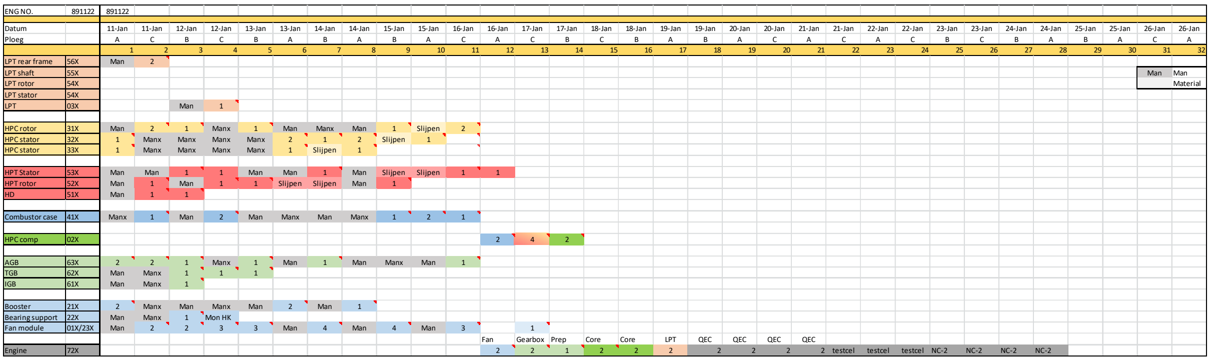


Figure 76. What-if material issues were solved for engine 1

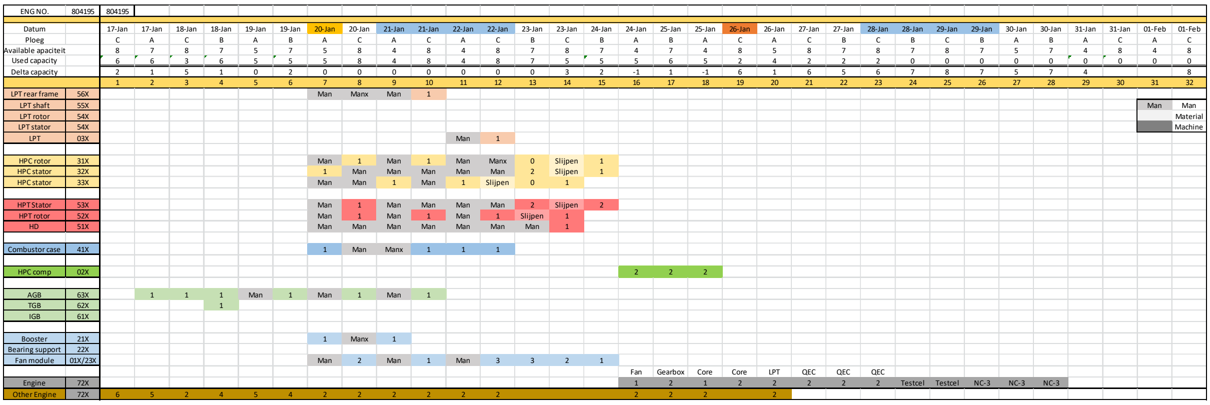


Figure 77. What-if material issues were solved for engine 2

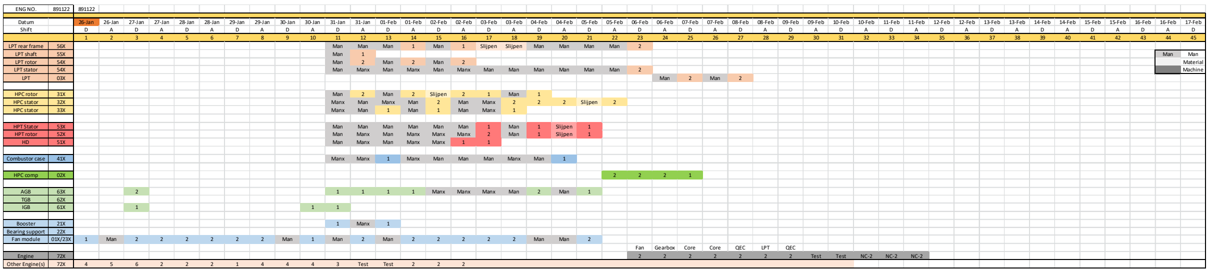


Figure 78.What-if material issues were solved for engine 3

The results are not very surprising, the TATs of all engines will reduce. The TAT of engine 1 will reduce with two days, engine 2 with 1,5 day and engine 3 with 3,5 days. While if only manpower capacity should have been solved, the results were more surprising. For two engines it would not have matter in TAT, only for engine 1 one shift would be won.

Figure 76, Figure 77 and Figure 78, show that a lot of time is wasted because there is not enough manpower capacity, in the situation if the material issues are solved. This means that, in these situations, a better manpower planning would reduce the TAT even further. Calculations have been done to the number of mechanics that are needed to fill up all the shifts that are not occupied in Figure 76, Figure 77 and Figure 78. It is calculated that on average, there is a lack of 6 mechanics per shift. That means that there are 18 more mechanics needed in one team that handles one engine. In the current situation a team consists of 21 mechanics, this would mean that a new team would consist of 39 mechanics. If this would be realized, the assembly processes would reduce a lot. See Figure 79, Figure 80 and Figure 81 for the overview of the assembly process of the three engines if the material and manpower issues would be solved.

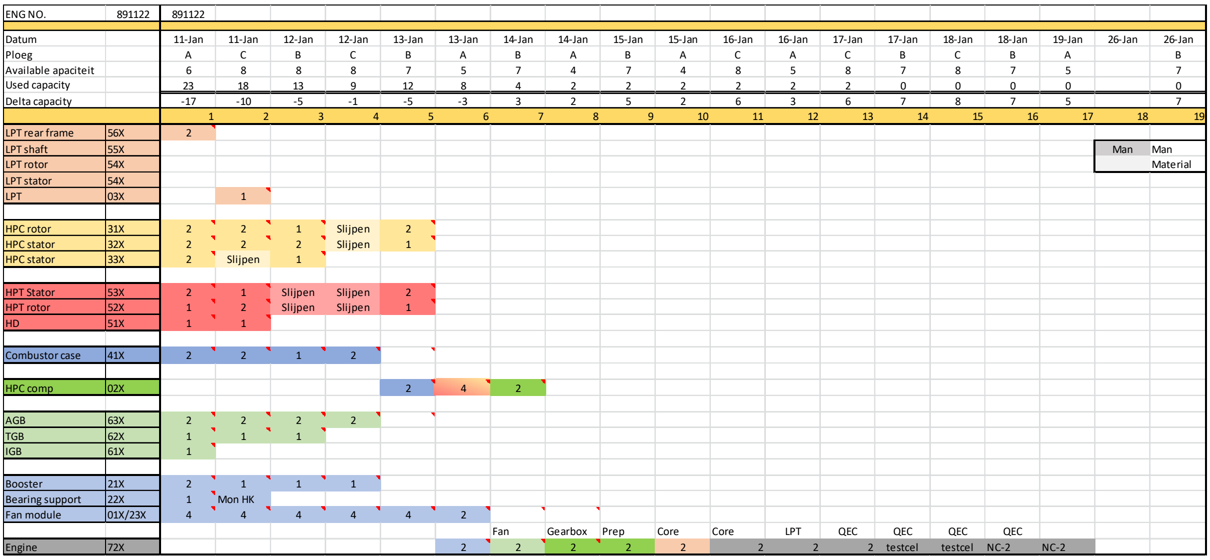


Figure 79. What-if material and manpower issues were solved for engine 1

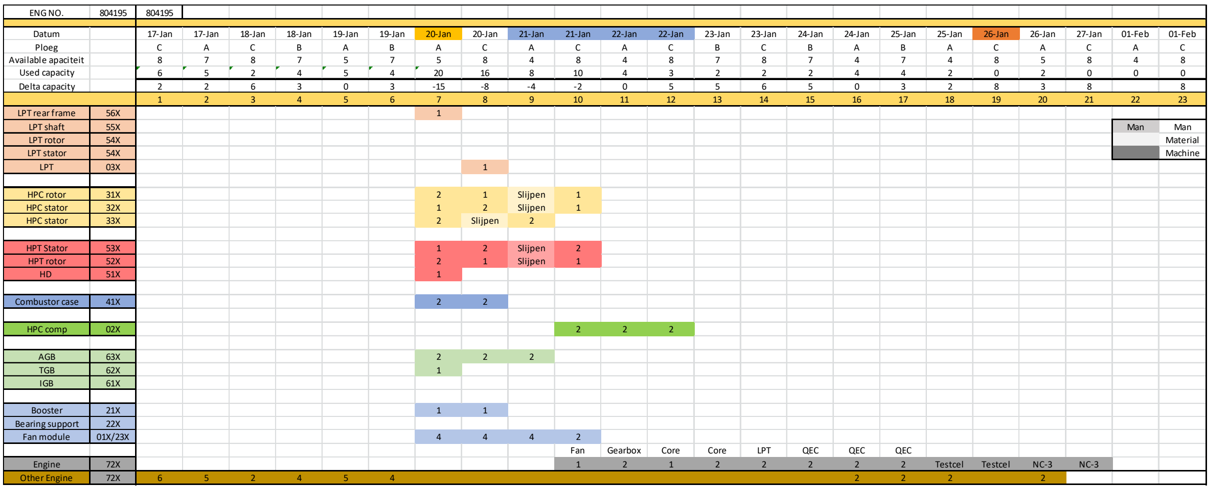


Figure 80. What-if material and manpower issues were solved for engine 2

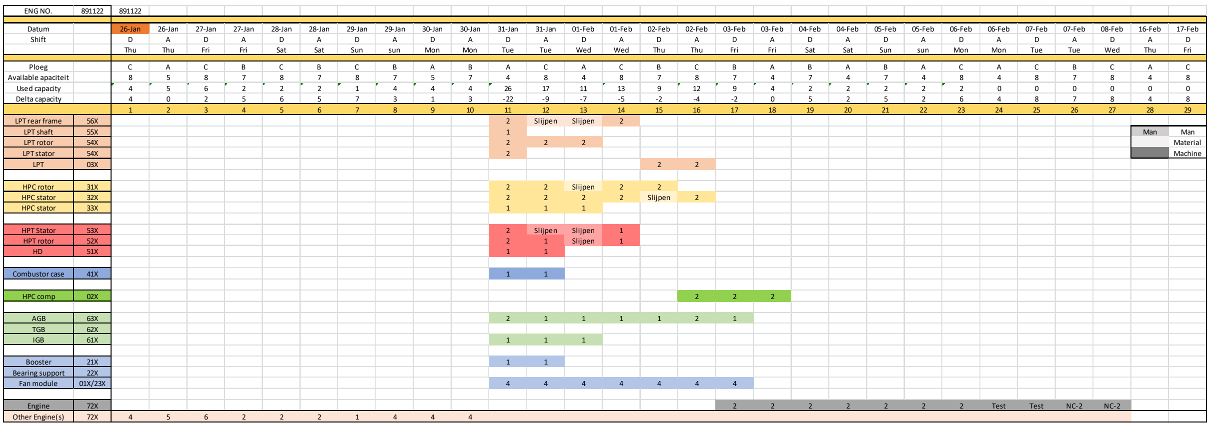


Figure 81. What-if material and manpower issues were solved for engine 3

As can be seen, the average TAT of the assembly process will be 5,5 days. That would mean that one team of 39 mechanics can handle 66 engines per year. So, for this improvement no new mechanics need to be hired.

F. Calculations of Standard Deviation and On-Time Performance

F.1 Standard Deviation

After every iteration, the standard deviation and the on-time performance of the performance of the integral engine MRO chain at KLM E&M are calculated. For the standard deviation, the calculation is based on a summation of all the standard deviations of the process steps of the constraint. Table 17 shows all the standard deviations of the individual process steps and the standard deviation of the integral chain after every iteration. In the current situation, for the disassembly and the assembly steps, half of the value is taken into account. Because the 21X is on average already disassembled from the engine halfway and for assembly the same but then it starts with assembling the 21X halfway.

Table 17. Calculations of standard deviation after the iterations

Iteration	***SD of Disassembly***	***SD of Cleaning Inspection***	***SD of Outbound transport***	***SD of Inbound transport***	***SD of Repair***	***SD of Assembly***	***SD of Test***	***SD of Rework***	***SD integral chain***
1	5.2	5.8	2.9	5.0	13.3	6.0	0.7	1.0	**30.6**
2	5.2	5.8	2.9	5.0	2.2	6.0	0.7	1.0	**19.5**
3	5.2	5.8	0.8	1.0	6.8	6.0	0.7	1.0	**17.9**
4	5.2	5.8	0.8	1.0	2.2	6.0	0.7	1.0	**13.4**
5	5.2	5.8	0.8	1.0	2.2	2.2	0.7	1.0	**11.5**
6	5.2	5.8	0.8	1.0	2.2	2.2	0.7	1.0	**11.5**

F.2 On-Time Performance

In the current situation the distribution of the integral chain is left skewed. An assumption is made that 40% of the values are left of the mean and 60% are right of the mean. The average contract TAT is 60 days, the average TAT is 71 days and the standard deviation is 31 days. These values are shown in Figure 82. With the values a calculation can be done to determine the OTP of the current situation; 60 – 40 = 20 days inside the first SD. These 20 / 31 = 65%. 65% of (40% of 68%) = 18% gives 18%+13% (the percentage left after 1 SD) = 31%

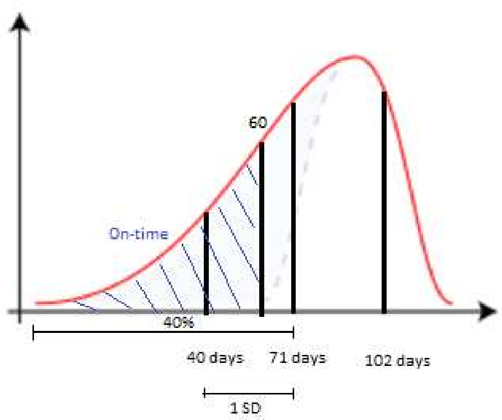


Figure 82. Calculation of OTP of current situation

For the next iterations the same calculations can be made. From the second iteration the distribution will be assumed to be normal.

G. Ratio of shipdirty and outsourced repairs

In some cases, the number of outsourced parts of an assy is lower than the number of in-house parts, but still it has been chosen to use the outsourced parts for that assy. This could be, because the repair time is significant higher for the outsourced repairs, and has more impact on the integral chain. For example, the 52X and 55X.

	Dirty/outsourced	outsourced/total
01X	75%	38%
03X	29%	29%
21X	100%	61%
22X	36%	14%
31X	99%	91%
32X	82%	77%
33X	100%	62%
41X	80%	35%
42X	41%	9%
51X	100%	79%
52X	84%	45%
53X	93%	82%
54X	98%	87%
55X	37%	25%
63X	96%	6%
72X	61%	8%

H. Outliers

Engines that had data that was not very common. The reasons for that have been identified and are shown in Table 18.

Table 18. Outliers

Projectnr.	Reden van rare data
7B/0196660	Heeft geacht op CDR OTA proces van de HK demontage is in 2 fase uitgevoerd
7B/0199834	Motor bouw heeft stil gestaan ivm booster van deze module zijn diverse zaken niet in orde geweest
7B/0204538	Heeft gewacht op LPT delen
7B/0204856	Motor heeft een beperkte workscope heeft gewacht op klant leveringen LPT stg 1 nozzles zijn afgekeurd tijdens montage heeft gewacht op nieuwe
7B/0206115	Planning is aangepast en motor is tijdelijk stil gezet
7B/0207643	Heeft stil gestaan LPT delen zijn niet optijd geleverd
7B/0207666	Containment case is in STG 3 vervangen dit had in STG 1 moeten gebeuren
7B/0210113	GMF motor losse modules die zeer gefaseerd is uitgereden als motor tellen is niet realisties
7B/0218000	Moet iets mis zijn met de sheet waarschijnlijk met de jaar doorgang
7B/0221068	deze motor heeft van 21-01 gelopen tot 18-02 totaal 56 shiften HK is terug geweest op de afdeling voor extra dem werkzaamheden 4 shiften maart
7B/0231043	Motor heeft gelopen van 08-03 tot en met 18-03 totaal 20 shiften
7B/0232559	HK heeft gewacht op een OTA voor de HK proces is in de tool niet on hold gezet
7B/0247069	Is iets mis in de sheet staat niets bijzonders in
7B/0272268	Heeft gewacht op de klant ivm change BOW 02X
7B/0279350	3e pilot motor Moet een fout in de sheet zitten tussen 6-12 en 10-3 zitten geen 765 shiften

I. Handshakes of the disassembly and assembly process steps

Table 19. Norm times for the disassembly process step per assy

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

Table 20. Norm times for the assembly process step per assy

Shift		D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D	A	D
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Fan module	01X 23X	APREP Uitrijden	fwd fan case + QEC montage	fwd fan case + QEC montage	fwd fan case + QEC montage	OGV's + Liners + VBV	IGB + fan frame leak test + #2 brg	#1 brg supp. assy + fwd sump flow chk	Montage	Montage	Installatie LRU's	Installatie LRU's	Nacontrole, administratie															
Bearing Support Assembly	22X	APREP Uitrijden	Montage	Slijpen	Montage	Montage	Administratie + releasen																					
Low pres. Compr.	21X	APREP Uitrijden	Montage Disk+Spool+ vullen	Montage Disk+Spool+ vullen	End gap + angular distribution	montage boosterblades + casings	Dynamisch Balanceren	Stg.4 vanes, assembly+guide pads	Angular distribution Fanblades	Nacontrole, administratie																		
HPC Rotor	31X	APREP Uitrijden	vullen	Stat.+ dyn. Bal	Stack	Stack	Stack / Voorballen	slijpen	Final Balanceren + administratie																			
HP-Compr. Front case	32X	APREP Uitrijden	Segmenten monteren	VSV assembly	Samenbouwen + pullcheck		inpakken voor slijpen	slijpen meten	uitpakken + cleanen	nacontrole administratie																		
HP-Compr. Rear case	33X	APREP Uitrijden	Segmenten monteren	Inpakken voor slijpen	slijpen meten	uitpakken + cleanen	nacontrole administratie																					
Combuster Case assembly	41X	APREP Uitrijden	Combuster + Fuel	Fuel	stg. 1 nozzle assembly	nacontrole administratie																						
Combuster	42X	APREP Uitrijden	Inbouw in comb assy																									
HD	51X	APREP Uitrijden	Invent. + montage	Montage+ Administratie																								
HPC (Core)	02X	APREP Uitrijden								Stack-up31x,41x (41x+42x+51x)	53X mont + bore meeting + Wax check 2x	Wax check + rear en fwd casing	Linipotmetingen +flangen 2x	VSV + riggen + QEC + Lengte meting	Nacontrole administratie 2x	Put uitklokken 1x												
HPT Support	53X	APREP Uitrijden	Montage	Montage		Slijpen	Slijpen	Uitpakken + Was & adm.	montage nozzle krans administratie																			
HPT Rotor	52X	APREP Uitrijden	Montage	Montage	Voorbalanceren	Slijpen	Final Balanceren	Administratie																				
LPT Rotor	54X	APREP Uitrijden	Vullen + Statisch ballen	Vullen + Statisch ballen	Vullen + Statisch ballen	Vullen + Statisch ballen	Stack	Stack	adminestratie																			
LPT Stator	54X	APREP Uitrijden			Montage	Montage			Administratie																			
TRF	56X	APREP Uitrijden	Montage	Montage + Administratie																								
LPT Fan shaft	55X	APREP Uitrijden			Supp+Ven.tube +Adm.	Midshaft+ Fwd.shaft+brg.	mont lagers + seals	Adm. + releasen																				
LPT Assembly	03X	APREP Uitrijden							Mont -TRF + slijp fixure	Adjust. Sleeve slijpen	Montage shaft	dynamisch balanceren	dynamisch balanceren	Mont -TRF	Montage + Administratie													
Gearbox	63X	APREP Uitrijden		Mont. Pads + gearshaft+flow test	Mont. Pads + Breakets	Mont. Seals+ druktest	Mont. Oilpump+ sensor.drukte	Mont. Drainmodule+ tubes	Fuelpump+heat-exch, servoh+ eductorvalve	MEC + Tube + clamps	CSD + Starter + 2x Hydr.pumps	Nacontrole + Administratie																
IGB	61X	APREP Uitrijden	Radial gearschaft assembly	Horizontal gearschaft assembly	Finishing gearshafts ass. + backlash	Finishing backlash & tooth pattern check	Flowcheck & administratie																					
TGB	62X	APREP Uitrijden			Flow/impinggement check and shims	Gearshaft ass. Axial play check	Backlash & tooth pattern check+	Pressure test + administratie																				
Engine Assembly														Fan + Gearbox 2X	HA 3X	Core 3X	LPT 3X	LPT +linipot 3X	QEC 3X	QEC 3X	QEC 2X	QEC 2X	Administratie 2X					
Proefbank																								Opbouw & Tunnel	Test + Afbouw + adm.			
Nacontrole																										Klachten oplossen	Klachten oplossen	

J. Current situation for the CF6-80C2