Aircraft Engine Combustor Maintenance

A model to measure MRO turnaround time

W. A. Mogendorff

Technische Universiteit Delft

TU Delft

KLM

Aircraft Engine Combustor Maintenance

A model to measure MRO turnaround time

by W.A. Mogendorff

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Monday March 21, 2016.

Student number:	1368672	
Report:	2016.TIL.8011	
Thesis committee:	Prof. dr. ir. G. Lodewijks,	TU Delft
	Dr. W. W. A. Beelaerts van Blokland,	TU Delft
	Dr. J. H. R. van Duin,	TU Delft
	G. Philips van Buren	KLM Engineering & Maintenance
	A. Gortenmulder	KLM Engineering & Maintenance

TU Delft Delft University of Technology

Preface

This document is the final step towards the degree of Master of Science in Transport, Infrastructure & Logistics. For my graduation thesis, I was commissioned by KLM E&M to find a way to improve the turnaround time of their combustor maintenance process. After doing an internship at KLM E&M which was spent collecting data and gaining a general understanding of aircraft maintenance and combustor maintenance in particular, a thorough analysis was made of the current state performance. This made it possible to generate a simulation model that simulates the combustor maintenance process and allows changes and influences to value drivers to be tested.

Many thanks go out to my TU Delft committee: Gabriël Lodewijks,Wouter Beelaerts van Blokland and Ron van Duin, for their time and input during the project, and their guidance regarding the scope of this thesis. I would especially like to thank Mr. Beelaerts for his positivity and encouragement during the moments I was not so sure of where I was going.

I would also like to thank my supervisors at KLM: Guus Philips van Buren and Alex Gortenmulder. It has been a great experience to see what goes on 'behind the scenes' of aviation. I've had a great time walking around on the shop floor and learning things about maintenance, but also learning about how a large company such as KLM is managed and run on a daily basis. The people at KLM have been very welcoming and helpful, and I was always able to find somebody who was willing to take the time to answer my questions and guide me in the right direction.

Last but not least I would like to thank my friends and family for supporting me through this (seemingly endless) process of graduating and also for taking the time to read and comment on drafts of my report.

W. A. Mogendorff
Delft, March 2016

Abstract

This thesis involves a case-study of aircraft engine combustor maintenance at KLM E&M, which has been used as a basis to develop a discrete event simulation model that allows TAT to be measured, and the effects of changes to the main value drivers to be successfully tested. The main research question this research sought to answer is: **What are the value drivers that determine the turnaround time of the aircraft engine combustor maintenance repair and overhaul process from a Lean Six Sigma perspective?**

From literature and preliminary research it was possible to identify TAT value drivers and define performance criteria. The main value drivers have been found to be capacity, capabilities and components. Planning and routing have been defined as influential factors that aid in steering the process. In order to come to this answer the current state of combustor maintenance at KLM E&M has been analysed, using the Six Sigma Define, Measure, Analyse, Improve, Control (DMAIC) framework.

A conceptual framework including the value drivers was developed. Using this framework and Lean Six Sigma tools the combustor maintenance process has been analysed in order to define the main relationships between value drivers, as well as the current state performance at KLM. In order to simulate the process and test the effects of changes to the value drivers the current state process was modelled in Simio. Using this model it has been possible to define TAT and to test the influence of the value drivers. This has lead to recommendations regarding how TAT can be reduced.

The current maintenance TAT at the KLM combustor department is too high and is not distributed normally, indicating waste. This research has shown that the process is unpredictable, and the current planning method is not sufficient. In total 90% of TAT has been identified as waiting time. The largest share of waiting time can be found within three time-trap capabilities: Q034 (inspections), Q683 (welding) and Q702 (benchwork).

The capacity of the combustor department is determined by the available mechanics. The available capacity is highly variable. On average 50% of the available capacity is utilised. This is largely caused by a mismatch between the supply and demand of capabilities. The inspections are considered the main bottleneck, as very few people are capable of performing this task.

The simulation model allows the current state to be reproduced, and changes to the system to be tested. A sensitivity analysis regarding the value drivers has been performed to investigate their influence on TAT. It has been found that changes to capacity, capabilities and routing have a direct influence on TAT. Capacity has the largest influence, followed by capabilities. It has been found that mainly a lack of available bottleneck capabilities has a large negative effect on TAT. Finally, reducing the number of inspections in the combustor repair routes also allows TAT to be reduced.

Combining the sensitivity analysis results has allowed for a few future state scenarios to be designed, showing how TAT can be improved. It has been found that a capacity of 6 multi-skilled mechanics will allow the future state to have 100% on-time performance for a TAT of 36 days. However, it is not possible to realise 100% on-time performance for a TAT of 24 days with multi-skilled mechanics alone. On-time performance can be increased by 36-43% by optimising the mechanic capability set and reducing the inspections. Therefore it is possible that a capacity of 7 or 8 mechanics will allow 100% on-time performance for TAT 24.

It is recommended that further research is done regarding the model applicability in other areas of aircraft maintenance, as well as further expanding the model to incorporate the complete engine maintenance process.

List of Definitions

A	
AFI	Air France Industries
AFI-KLM E&M	Air France Industries KLM Engineering & Maintenance
Aprep	Assembly Preparation
C	
CBBSC	Connected Business Balanced Scorecard
D	
DES	Discrete Event Simulation
Department 2400	Combustor Department
Department 2700	Grote Machinale (large machinery)
DMAIC	Define, Measure, Analyse, Improve, Control
DMADV	Define, Measure, Analyse, Design, Verify
DFSS	Design for Six Sigma
E	
E&M	Engineering & Maintenance
ERP	Enterprise Resource Planning
EASA	European Aviation Safety Agency
EGT	Exhaust Gas Temperature
F	
FAA	Federal Aviation Administration
FIFO	First In First Out
G	
GE	General Electric
H	
HS	Handshake
J	
JIT	Just-in-Time
K	
KPI	Key Performance Indicators
L	
LSS	Lean Six Sigma
M	
MRB	Maintenance Review Board
MRO	Maintenance Repair and Overhaul
N	
NVA	Non-Value Add
O	
OAT	One factor At a Time
OEM	Original Equipment Manufacturer
P	
PCG	Planning and control group
PV	Product Verstoring (Disruption)

Q
Q033 Inspection/Repair ACC
Q034 Inspection
Q114 PVM101 Code 7
Q116 PVM101Code10
Q224 Steamcleaning
Q249 UHPW stripping
Q428 Carrouselathe turning
Q434 Drilling/Milling
Q502 Preparation Plasmaspray
Q512 Drygrit Plasma & Galvano
Q516 Plasma Spray Robot
Q518 Plasmaspray
Q683 Nickel/Cobalt alloy welding
Q685 Brazing
Q702 Benchwork
Q717 717PVM
Q800 Vacuum Oven Brazing
Q801 Vacuum Oven Solution HT
Q802 Vacuum Oven Aging Treatment
S
SB Service Bulletin
SPC Statistical process control
T
TAT Turnaround time
TOC Theory of Constraints
TPS Toyota Production System
TQM total quality management
V
VSM Value Stream Map
VA Value Add
W
WVL Werkvoorraad Lijst (work inventory list)
0
7B CFM56-7B
80C GE CF6-80C2
80E GE CF6-80E1A4

Contents

Abstract v

List of Definitions vii

1 Introduction 1

1.1 Research Context 1
1.1.1 Air-France KLM 1
1.1.2 KLM E&M 2
1.2 Field of Research 3
1.2.1 Aircraft Maintenance 3
1.2.2 Engine Maintenance 5
1.2.3 Engine Maintenance at KLM E&M Engine Services 5
1.3 Object of Research 6
1.3.1 Combustor Maintenance Process 6
1.4 Problem Statement 9
1.5 Objective 9
1.6 Scope 10
1.7 Research Question 10
1.8 Significance 10
1.9 Research Framework 11

2 Research Design 13

2.1 Literature Research 14
2.1.1 Lean 14
2.1.2 Six Sigma 16
2.1.3 Theory of Constraints 18
2.1.4 Lean Six Sigma 19
2.1.5 Simulation 22
2.1.6 Literature Research Conclusion 22
2.2 Practice Research 23
2.2.1 Process Flow and Value 25
2.2.2 Observations 29
2.2.3 Practice Research Conclusion 36
2.3 Criteria & Variables Found 37
2.4 Conceptual Framework 37

3 Problem Analysis 39

3.1 Maintenance Process 39
3.1.1 Input 40
3.1.2 Combustor Maintenance 41
3.2 Current State 46
3.3 Value Drivers 48
3.3.1 Routing 48
3.3.2 Components 54
3.3.3 Capacity 54
3.3.4 Capabilities 61
3.3.5 Planning 66
3.3.6 Main Issues Regarding Value Drivers 67
3.4 Conclusion 68

4 Modeling and Simulating a Future State **71**
4.1 Simulation . . . 71
4.1.1 Simio . . . 72
4.1.2 Model . . . 72
4.1.3 Sensitivity Analysis . . . 75
4.2 Future State . . . 77
4.3 Conclusion . . . 81

5 Conclusions & Recommendations **83**
5.1 Conclusions . . . 83
5.1.1 Main Research Question . . . 83
5.1.2 Sub-Question 1 . . . 83
5.1.3 Sub-Question 2 . . . 84
5.1.4 Sub-Question 3 . . . 84
5.1.5 Sub-Question 4 . . . 85
5.1.6 Sub-Question 5 . . . 85
5.1.7 Sub-Question 6 . . . 85
5.2 Recommendations . . . 86
5.2.1 Recommendations for Further Research . . . 86
5.2.2 Recommendations for KLM E&M . . . 87
5.3 Personal Reflection . . . 87

Bibliography **89**

A Combustor Department Observations **93**
A.1 Observations 25-03-2015 . . . 93
A.1.1 Capacity . . . 93
A.1.2 Preparation . . . 93
A.1.3 Workscope . . . 94
A.1.4 Progress tracking . . . 94
A.1.5 Skills . . . 94
A.1.6 Staff . . . 95
A.1.7 Issues concerning identification and information . . . 95
A.2 Observations 01-04-2015 . . . 96
A.2.1 Meeting Skillmanagers . . . 96

B Combustor Department Value Stream Mapping Sessions **99**

C Meeting Bart de Bakker 01-04-2015 **101**

D Simulation Input Data **103**
D.1 Scenario Information . . . 103
D.1.1 Mechanic Capabilities . . . 106
D.2 Combustor Input . . . 108

E Combustor Repair Data **111**
E.1 Data Collection . . . 111
E.2 7B Combustor Repair Data . . . 112
E.2.1 Maintenance Phases . . . 113
E.2.2 Available Mechanics . . . 116

F Process Analysis **117**
F.1 Input . . . 117
F.2 Repairs . . . 117
F.2.1 Regular In-house Repairs . . . 117
F.2.2 Exceptional In-house Repairs . . . 121
F.2.3 Outsourced Repairs . . . 124

F.3 Value Drivers 127
F.3.1 Maintenance Phases 127
F.3.2 Tasks Following Q034 127
F.3.3 Available Capbilities 129

G 7B Combustor Repair Data 131

H Capabilities 141

I Model Validation & Verification 143
I.1 Model Requirements 143
I.1.1 Required Outputs 143
I.1.2 Scope 143
I.1.3 Input 144
I.2 Design 144
I.2.1 Run Length & Replications 146
I.3 Verification 147
I.4 Validation 147
I.4.1 TAT 148
I.4.2 Mechanic Utilisation 150
I.4.3 Server Utilisation 151
I.5 Sensitivity Analysis 152
I.5.1 Capacity 153
I.5.2 Capabilities 154
I.5.3 Routing 156
I.5.4 Combined Effects 156
I.6 Conclusion 157

J Model Validation Graphs 159

K Sensitivity Analysis Output 163

L Future State Analysis 173
L.0.1 Constant Capacity of 4 Multiskilled Mechanics 173
L.0.2 Constant Capacity of 5 Multiskilled Mechanics 175
L.0.3 Constant Capacity of 6 Multiskilled Mechanics 177
L.0.4 Constant Capacity of 7 Multiskilled Mechanics 179
L.0.5 Constant Capacity of 4 Mechanics with limited capabilities 181

M Simulation Results Future State 183

N Simio Model Properties 187

1 Introduction

This chapter will serve as an introduction to the research performed in this thesis. It will first provide the context in which the research takes place, after which the field of research will be discussed, followed by a discussion of the object of research. This information allows the problem that is to be investigated and the scope of the research to be determined. This will lead to the research questions and the significance of this research. Finally, this chapter will conclude with a description of the research process.

1.1. Research Context

This thesis will focus on aircraft maintenance processes at the Engine Services (ES) department of KLM Engineering & Maintenance (KLM E&M). This section will discuss Air France-KLM, the current situation at Air France-KLM, and KLM E&M in order to place this research in context.

Air France-KLM has reported a negative income for the past several years [KLM, 2015], and is currently losing market share to both budget airlines and more luxurious Gulf state carriers. Hence, Air France-KLM is looking for ways to reduce costs and increase market share. In order to reduce costs, processes are being reevaluated to see where cuts can be made. In the case of KLM E&M Engine Services, market share can only be increased when performance is improved to meet or even exceed performance of other maintenance, repair and overhaul (MRO) companies.

According to Ayeni et al. [2011] the MRO market requires that companies 'increase the margin between stock and value by considering every possible resource to maximize operational efficiency and to minimize effort, i.e. to optimize and streamline business operations'. Meaning the aviation MRO industry has to minimise overall maintenance costs and reduce turnaround times.

1.1.1. Air-France KLM

Air France and KLM Royal Dutch Airlines have joined forces since 2004 and form Europe's leading aviation group: Air France-KLM (AF-KL). Currently AF-KL is not performing as it should. This is mainly due to rapid changes in the aviation industry that AF-KL can not easily keep up with. The biggest threats for AF-KL are the quick growth of Gulf and Low Cost Carriers, and regular competitors that are generating more profit, such as British Airways, Lufthansa and Delta Airlines.

In general AF-KL's competitors can be said to be quicker, better and cheaper, whereas AF-KL is currently expensive, complex and slow. Furthermore, AF-KL's incomes are decreasing while their costs are not decreasing accordingly. This leaves little or no money for the investments needed to adapt to the changing environment. However, AF-KL wants to keep client products at a high level while investing in company processes in order to become more efficient, and generate higher returns. The KLM E&M division currently does generate profits, but changes are required in order to allow AF-KL to adapt to the current state of the aviation industry.

KLM is known as "the reliable airline" and provides high-level service to customers. According to Kearney [1994] high-level service 'is not enough in itself to gain or sustain competitive advantage. To be a major player in the global market, a company must be at least as productive as any other in its industry. Productivity leaders can use their edge to finance discounts, promotions, research and development and individualized service'. Taking this and the market developments into account, KLM needs to increase productivity.

Both Air France and KLM are looking for ways to reduce costs and increase market share. In September 2014 AF-KL introduced their new strategic plan "Perform 2020", which promotes the vision of KLM as a client focused, innovative and efficient leading carrier. This will be done by investing in the future of their fleet and quality, and by reducing costs. KLM's overall costs are to be reduced by €700 million, and the company should be flattened, continue with less people, and generate an annual 4% productivity increase.

As can bee seen in Figure 1.1, AF-KL has three main businesses: Passenger Business, Cargo, and Engineering & Maintenance (E&M). This thesis will focus on the KLM Engineering & Maintenance department, which provides MRO services for AF-KL and several other airlines.

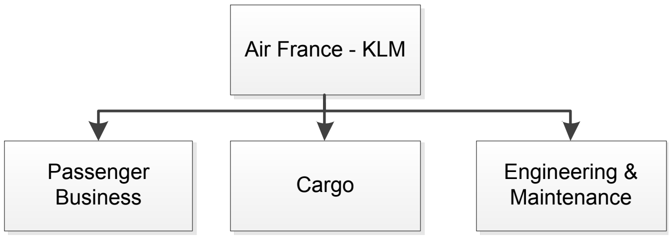


Figure 1.1: Air France-KLM Organisation Chart

1.1.2. KLM E&M

As shown in Figure 1.2, KLM Engineering & Maintenance is made up of five maintenance units: Base Maintenance, Line Maintenance NL, Line Maintenance International, Component Services and Engine services (ES). Together these units provide scheduled and unscheduled MRO for the KLM fleet and various clients such as Transavia, Finnair and Air Kenya. A Lean Six Sigma office within KLM E&M exists to enable and enforce the use of Lean and Six Sigma within the MRO process.

E&M clients can choose to make use of a pool of exchangeable and spare engines and/or components. This allows components to be maintained whilst an item from the pool is used to replace this component, allowing for a shorter aircraft turnaround time, ensuring aircraft availability and quality within a limited time span (generally 60 days).

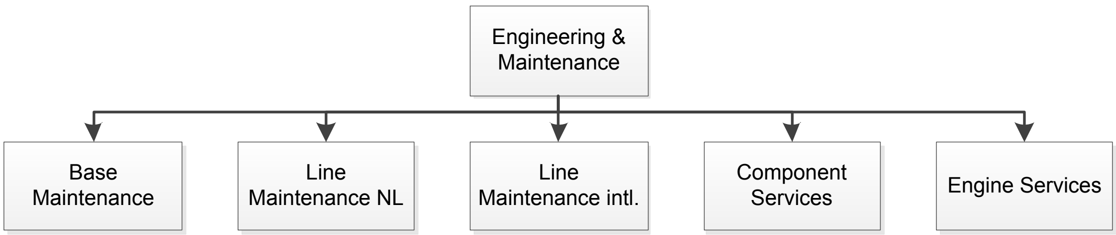


Figure 1.2: E&M Maintenance Units

Aircraft come in at E&M for both scheduled and unscheduled MRO. The majority of the work, including labour, necessary equipment and components, can be planned ahead. However, upon inspection there is always a possibility of unexpected damages creating unforeseen work. Hence, there is always some unknown demand for work.

At E&M labour costs, productivity, on-time performance and the ageing fleet are issues that need to reconsidered, as these are things competitors are currently doing better. In order to start addressing these issues E&M has decided that it should introduce process management throughout the business unit. For E&M process management can be defined as guiding and steering on a process level rather than managing based on just performance outputs.

The main focus of this thesis will be on the Engine Services department, which is responsible for efficient, on-time and qualitative MRO of engines within KLM and their clients' fleets. Engine Services, as the name suggests, is responsible for engine maintenance and servicing. Its main activities are to organise engine availability, provide engine MRO, and provide parts repair and engine accessories MRO.

As mentioned earlier, processes are being reevaluated to see where costs can be reduced. Performance needs to be up to par with that of other MRO companies. Currently, the turnaround times (TAT) and prices for engine maintenance are too high compared to competitors and need to be reduced.

1.2. Field of Research

This thesis will focus on the maintenance of an aircraft engine component. This section will discuss what maintenance is in general, what literature might say on maintenance, what aircraft maintenance is and finally what engine maintenance and a combustor are, along with a general description of engine maintenance at KLM E&M Engine Services.

Maintenance is the 'combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function' [CEN, 2010]. Maintenance can be preventive or corrective. Preventive maintenance is carried out in order to prevent breakdown or damage, and the corrective maintenance is carried out after damage has occurred.

Pham and Wang [1996] believe that optimal maintenance policies aim to provide optimum reliability and safety performance at low cost. In practice most maintenance will be imperfect repair, in which a system will not become as good as new but will be of sufficient quality to continue its regular function without causing safety issues. Maintenance provides a service that can help its "clients" to achieve their objectives. The purpose of maintenance is to effectively keep systems in the right condition to, in the case of aviation, safely perform their intended functions [Ben-Daya et al., 2009].

1.2.1. Aircraft Maintenance

The objective of aircraft maintenance is to deliver the aircraft on-time (according to schedule), airworthy and cost-effectively. The aviation industry is highly regulated in order to ensure safety. According to Sahay [2012] 'regulatory compliance is at the heart of aircraft maintenance'. Hence, the maintenance process must be highly standardised, and preventive. Aircraft maintenance continually faces a dilemma; following prescribed procedures, and reducing time and costs.

A Maintenance Review Board (MRB) consisting of original equipment manufacturers (OEMs) and regulatory authorities such as the European Aviation Safety Agency(EASA) defines the rules and regulations of aircraft maintenance. This results in a maintenance plan that is recommended to MRO companies who in turn create their own maintenance plan [Sahay, 2012].

The maintenance plan consists of prescribed, predefined tasks, which are defined in the repair manual (see Figure 1.5). Before it can be used, the repair manual needs OEM approval. Depending on what is necessary different tasks are combined and executed. Ideally, all maintenance is carried out according to schedule, and all tasks are known well in advance. In reality this is not the case, as aircraft components wear and tear depending on different and unforeseen circumstances.This is shown in figure 1.3.

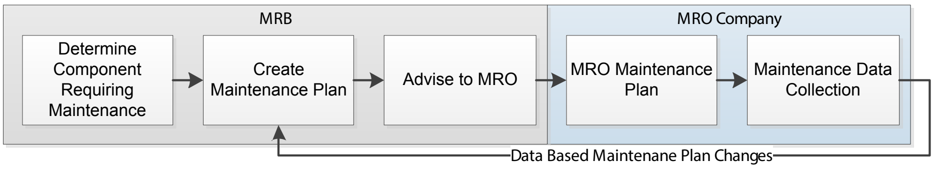


Figure 1.3: Maintenance plan development flowchart

There are four grounds for aircraft maintenance, as shown in Figure 1.4. Scheduled maintenance is part of the maintenance plan and occurs according to schedule. Modification requirements can arise due to experience with or research developments of a certain part. These lead to mandatory or advisory Service Bulletins (SBs), the latter of which are carried out depending on the aircraft owner's wishes. The deferred defects can be handled during the next scheduled maintenance visit and thus do not need immediate attention. Non-routine tasks consist of defects that have been found during a check and require immediate attention.

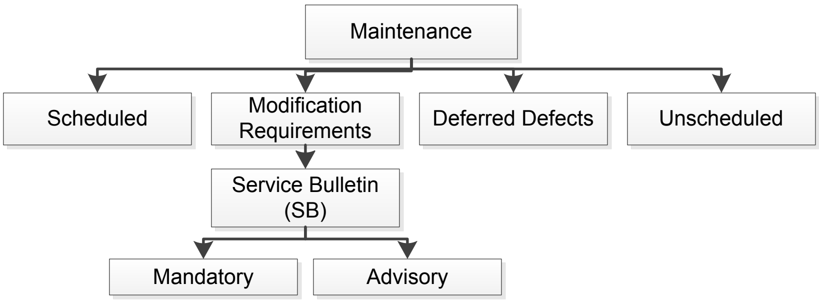


Figure 1.4: Maintenance Type Overview

Maintenance is carried out according to task cards. These are built for each maintenance instance according to scheduled maintenance, modification requirements and deferred defects. All tasks on the task card should come from the OEM repair manual, as shown in Figure 1.5. The task cards can be adapted in order to incorporate unscheduled and non-routine tasks. These changes can only be made after consulting the maintenance plan and approval of engineers. After each task is completed the task is signed-off, which allows the task card to be used for the aircraft airworthiness certification once maintenance is completed. After maintenance the aircraft and components are tested for airworthiness. If the required repairs have been performed as prescribed, and the aircraft and its components perform according to requirements the aircraft can be declared airworthy.

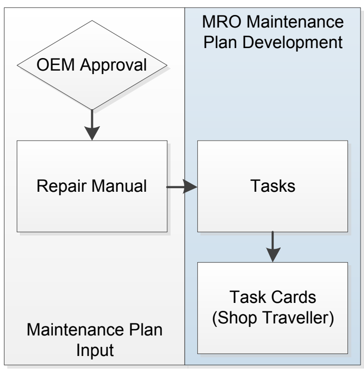


Figure 1.5: Maintenance Plan Overview

Predictability is an issue in maintenance in general; it is hard to know which issues will arise during use and when these issues will arise. It is especially an issue in aircraft MRO, as TAT agreements are made without knowing the required maintenance and time needed to execute this. Issues arise when a part is in bad condition and the time required for maintenance might exceed TAT.

1.2.2. Engine Maintenance

When an engine requires maintenance it is removed from the aircraft and taken to an Engine shop. Here the required paperwork is done ensuring the engine serial-numbers are correct and the current engine information (including maintenance requirements) is available. The information is updated according to the first inspections performed on the complete engine, and task cards are generated based on this information. Once this is done engine disassembly can commence.

The engine is disassembled into modules and components. Each module and component is recorded in order to assure proper reassembly. As soon as an engine part is removed from the engine, the engine becomes unserviceable and can only become serviceable through certification.

Once the engine has been disassembled, certain parts of the engine need cleaning and testing. The engine maintenance manual dictates which components of the disassembled engine need testing, and how these components should be tested. Furthermore, the performance requirements are defined in the engine maintenance manual, and additional performance requirements from customers may also be tested.

When the components have been tested and do not perform according to requirements they need repair, and are sent to the MRO's repair shop, or to a third party depending on the repair capabilities of the repair shop. After the components and modules have been cleaned, repaired and tested they are recollected and in turn reassembled. The maintenance work is certified once all requirements are met and the complete engine has been tested. The engine is rendered serviceable only if it meets all requirements.

As mentioned, predictability within aircraft maintenance is an issue. There are currently remote monitoring programmes available, that can be installed on components to provide up-to-date condition information. This information allows OEMs to know what maintenance is required before receiving the item for maintenance. 'However, this is a relatively new but growing phenomenon within the aviation industry and is particular to certain sectors (engines)' [Ayeni et al., 2011]. Due to the high cost of investment most traditional MRO organisations cannot afford these monitoring programmes. KLM ES does not make use of this information for the combustor maintenance.s

1.2.3. Engine Maintenance at KLM E&M Engine Services

Engine Services (ES) at KLM E&M is responsible for the MRO of the KLM fleet and several external clients such as Finn Air and Kenya Airways.

Once an aircraft comes to the Schiphol-Oost base for a maintenance check, the engines are removed from the aircraft and delivered to ES for inspection and necessary repair and maintenance. Meanwhile, the aircraft is equipped with another engine, usually from a so-called engine pool, in order to limit downtime. In the case of an engine owned by KLM the replacement engine comes from the KLM engine pool, which consists of engines in the air, engines in maintenance and spare engines.

The service type and tasks, quality, service time and costs of engine MRO can be defined in a contract between E&M and their customers. It depends on the customer whether or not these aspects are laid down in the contract. In general it is agreed within E&M that engine maintenance should have a turnaround time of 60 days. If the contract terms are not met, E&M incurs unnecessary costs that can not be transferred to the customer and can hence be seen as a loss.

1.3. Object of Research

The object of this research is the aircraft engine combustor maintenance process. This section will give a general description of how combustor maintenance is performed within ES, and will focus mainly on the combustor within a turbofan engine, which is primarily used in airline operations. As can be seen in Figure 1.6 and 1.7, the combustor, also known as a combustion chamber is a central section of the engine. In the combustion chamber fuel is injected to the air that has come in from the compressor and is burned. The air flowing through the combustor expands due to the heat and continues to the turbine.

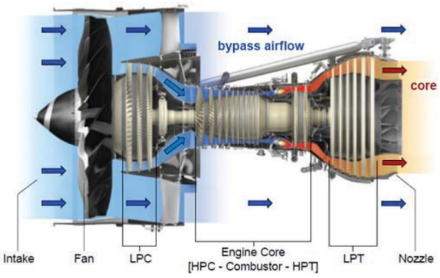


Figure 1.6: Turbofan Engine, [Ackert, 2010]

Figure 1.7: Incoming Combustor

The primary function of the combustion chamber is to burn the fuel/air mixture, thereby adding heat energy to the air that flows through it. To do this efficiently, the combustion chamber must assure good combustion by allowing fuel and air to mix sufficiently, burning the mixture efficiently and delivering the hot gases to the turbine. During regular combustion, the mixture burns in a very controlled and predictable manner. This type of combustion causes a smooth build-up of temperature (which can reach 1700°C in a CFM56-7B combustor) and pressure, and ensures that the expanding gases deliver the maximum force to the piston at exactly the right time in the power stroke [Administration, 2008].

1.3.1. Combustor Maintenance Process

This section will discuss the combustor maintenance process. First, enablers will be discussed, which are the tools and systems that enable maintenance to be carried out according to regulations and specifications. Second, the different phases of the maintenance process will be discussed, including what each phase entails. Finally, a SIPOC diagram will be created, in which the main parties and factors that influence the process are shown.

The combustor department provides maintenance for three types of combustors; the combustor from the CFM56-7B (7B), GE CF6-80C2 (80C), and GE CF6-80E1A4 (80E) engines. The maintenance for each combustor type varies. Not only do the repairs vary, the skills required and the experience with certain repairs differs as well. This means it is possible that quality, turn-around time and costs vary between combustor types.

The 7B engine is used on Boeing 737 aircraft and AFI KLM E&M has one of the most experienced CFM56-7 shops in the world. This means that the combustor department has a lot of maintenance experience for this combustor and is proficient at carrying out maintenance on 7B combustors. The 80C combustors are “oldest”, which means that the combustor shop has a lot of experience with its maintenance tasks. 80C engines are mainly used on Boeing 747’s and the McDonnell Douglas MD-11. The 80E engine is one of the most recent engines, and is mainly used on the Airbus A300. Hence ES is least proficient at performing repairs on this combustor type.

The AFI engine shop in Paris is currently “full capable” to carry out maintenance on the 7B combustors. As the combustor shop at E&M is not performing to satisfaction AFI KLM E&M is considering shifting maintenance of the 7B combustor from Schiphol to Paris if performance does not improve. This is why the analysis of current performance will focus on the 7B combustor.

Enablers

Maintenance is strictly regulated and needs to be carried out according to a maintenance plan. In order to carry out maintenance according to this plan ES has systems and tools that facilitate this, such as an enterprise resource planning (ERP) system, maintenance manuals, task cards and scanners.

ES makes use of SAP, an ERP system which contains the standard maintenance routine and all the possible tasks that can be performed on an engine. Each engine, and each of its modules and parts has a serial number. SAP stores the information linked to this serial number, so that for each engine it is known which modules and parts it contains, how old these parts are, and when they have last been checked, inspected or repaired.

When a combustor arrives at the combustor shop it is accompanied by a task card. A task card contains information and tasks that need to be performed on the module. The complete maintenance process is carried out according to task cards. Each of the tasks is described in the maintenance manual, which notes how tasks should be carried out and what the results of the task should be. The manual also specifies things such as size range and shape of the part, and materials that should be used to carry out a task. Each task on the task card can only be carried out after the previous task has been completed and marked as completed in SAP. This is done by scanning the bar-code that accompanies the task and putting a personal stamp below this bar-code.

On the task card each task is defined by a line which shows information that is needed to perform the task, see Figure 1.8. The operation number marked by Op, is the sequence of the tasks. The Workcentre Description, shows the workcentre by which the task should be performed and a description of the task; it shows the pages of the manual on which the task is described and the part of the task that should be performed. The RP shows at which workshop within the workcentre the task is performed. IA Un, in this line a task is marked I if the task only needs to be performed if it is applicable, the number in this column is the number of the manual that should be used. Barcode Processed by shows the barcode that needs to be scanned and the stamp of the person that has performed the task.

Op	Wrkctr RP Description	IA Un	Barcode Processed by
0040 1	2400 Q034 1-2 TASK.A	09	

Figure 1.8: Task description on task card

Furthermore, SAP is used to calculate the time and costs involved with the planned maintenance. Each task in SAP has a normative time and a cost so the combination of tasks and their times allows for a general time planning to be made, and an accompanying cost calculation. These are used to create an invoice. Clients only pay for work that is actually performed on their components. However SAP also tracks the actual time spent on tasks as it notes at which time a scan is made (task is finished). After a scan is made the time for the following task automatically starts.

Maintenance Phases

The combustor maintenance process is similar to the engine maintenance process. The combustor module is brought to the combustor workcentre where it is inspected, and, if necessary, disassembled, cleaned, repaired and reassembled. As the combustor is a module rather than a single part it needs to be inspected as a whole, after which it is disassembled and cleaned before it is inspected, repaired and assembled. The activities carried out in the combustor shop are part of stage 1 and 2 instead of only phase 2. Hence the TAT ES has defined for combustor maintenance is 36 days instead of 28 days.

Maintenance (stage 2 of MRO) at the combustor department is divided into six phases as can be seen in Figure 1.9. For each phase a new task card is created. Transportation to the workcentre is technically still part of stage 1 of MRO, and the only task on the task card that needs to be performed is to scan the barcode to mark the arrival of the combustor and its bill of work. However, the task does need to be executed within the combustor department and the time it takes for the combustor to be transported to the workcentre and scanned is part of the TAT for combustor maintenance.

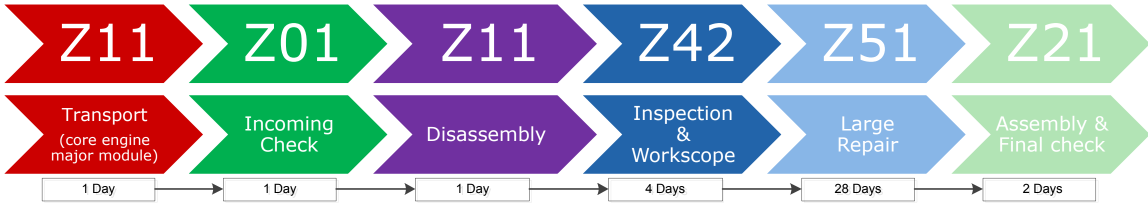


Figure 1.9: Combustor maintenance phases

After the combustor has been marked as arrived an inspector starts Z01 (the maintenance activity type) in SAP. This is the incoming check, which is performed according to the bill of work. During this phase the workscope is determined, and the condition of the combustor is determined. All the findings are recorded in SAP and a hardcopy of these findings will be delivered to the customer once maintenance is completed.

Once everything has been recorded Z11 is started, and disassembly takes place. The combustor consists of six parts, swirlers, an inner cowl, an outer cowl, an inner liner, an outer liner and a dome. Each of these parts is taken to the inspector where Z42, the preroute, is started for each of these parts. The tasks for both Z01 and Z11 are predefined and are the same for any combustor or part. Z42 is also predefined, but it differs depending on the part and combustor type. For instance Z42 is always the same for the inner liner of the 7B combustor, and it is always the same for the inner liner of the 8E combustor. However these routes are different from eachother. For the 7B combustor the part is sent to the oven during the preroute, to soften the material, after which it is sent to the ultra high pressure wash (UHPW) where the part is stripped clean so that it can be inspected for tears etc.

Based on the results of the inspections that have been done during Z42 SAP can be used to determine which repairs are necessary. Based on the state of the part it is determined if it meets quality requirements. If the part does not meet the certain quality standard specific repairs are needed. Based on the required repairs a maintenance route can be built. This route includes all the steps that are required for each repair. However, the repairs are not carried out sequentially but the tasks within the repairs are organised in such a way that the maintenance route is most efficient (according to the ES engineering department). Once the maintenance route is determined Z42 is completed and Z51 can start. The maintenance route is defined on the task card and all that needs to be done is carry out and scan each task. Once all the repairs have been made the combustor can be assembled and inspected in order to render the combustor serviceable. Once the combustor is declared serviceable it is transported to the assembly perparation department (aprep) where all engine parts are collected for engine assembly.

It should be noted that each of the phases also has a specified TAT, within KLM this TAT is known as a “handshake”. The handshake TAT per phase is only for internal purposes, but each of the tasks within the phases should be possible within the given timeframe. The TAT is 1 day per phase for 02X-Z11, Z01 and Z11, 4 days for Z42, 28 days for Z51 and 2 days for Z21. A quick calculation shows that the handshakes add up to 37 days. This is partially due to the fact that the 02X-Z11 and Z01 tasks should be completed within the same day.

Next to the six phases listed above there are additional phases that are only entered in case something exceptional has happened to the combustor or part. For instance Z03 is a group of tasks that occurs if a part or a combustor has been outsourced. In this case a visual inspection is performed to see if the combustor is in the required state. The handshake TAT for this is 3 days. Z32 is a condition inspection, which only occurs very rarely and will hence not be further discussed, the handshake is within a day.

SIPOC
A SIPOC diagram shows the suppliers, input, process, output and customers of the combustor maintenance process. It gives a high level overview of the parties and factors influencing the process. The combustor maintenance process as discussed in the previous paragraphs can be summarised in the SIPOC diagram in Figure 1.10.

The combustor maintenance process is an internal process within ES as can be seen in Figure 1.10.

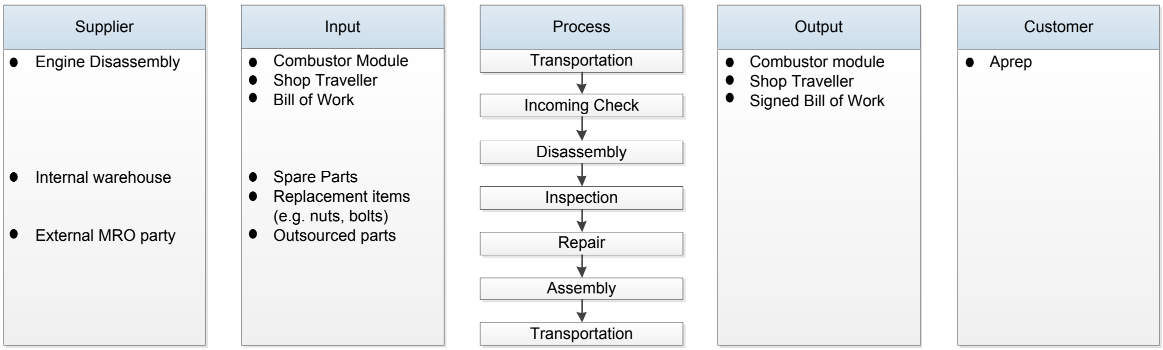


Figure 1.10: Combustor maintenance SIPOC diagram

It's supplier and customer are internal processes that precede and antecede the combustor maintenance process. Other suppliers include the warehouse and external maintenance companies. These supply replacement parts, and parts or combustors that have had external maintenance. As can be seen the process does not require many external inputs or outputs on a high level, the process as such is fairly straightforward.

1.4. Problem Statement

The current performance of the combustor repair process at KLM E&M is too slow, too expensive, and difficult to plan. Seen in the context of engine maintenance, higher management has defined the combustor as one of the bottlenecks in the engine maintenance process. The combustor repairs frequently exceed the agreed turnaround time of 36 days, thus putting pressure on the timely engine assembly. However, the combustor department feels that they are not necessarily the bottleneck, and they do not understand why their performance is so bad. They feel they are performing as they should.

Based on the context of this research and its practice oriented nature, the research will focus on problem analysis. This thesis will try to define what causes the tension between current performance and the desired performance of the combustor department. Furthermore, it should also become clear what the problem exactly entails; why the current performance is problematic and what the nature and cause of the problem is. Hence, the problem can be stated as follows:

There is a discrepancy between actual and desired performance within the KLM E&M combustor maintenance department. The cause of this discrepancy is unknown.

By clearly describing what the problem within the combustor department is, further steps can be taken to identify underlying causes and a possible course of action to improve the combustor maintenance process.

1.5. Objective

This thesis will look into how processes at KLM E&M Engine Services can be improved by use of a simulation model. This research provides an analysis of the main value drivers that influence the turnaround time of the combustor repair. The research will investigate the means of reducing TAT at KLM E&M by applying changes to the value drivers and testing these changes using simulation. These findings will not directly improve the performance of the combustor department, but the recommendations may provide guidance as to how the combustor maintenance process may be improved.

Hence, the research objective of this thesis is to make recommendations to KLM E&M regarding the necessary changes within their aircraft engine combustor maintenance process in order to improve process performance. This will be done by providing a clear overview of the current combustor repair process, and the value drivers that influence the TAT.

1.6. Scope

The recommendations that will be made to KLM E&M will be based on process management theories such as Lean, Six Sigma and the Theory of Constraints. The research will be focussed on one particular department within KLM E&M ES; the combustor maintenance department. The theories on process management and aircraft maintenance will be applied to analyse the combustor maintenance process, the process will then be modelled in order to simulate the process and test the effects of changes to the value drivers. This will allow recommendations to be made in which the theories can be applied to a possible new situation.

1.7. Research Question

In order to realise the research objective, research questions are needed to help guide the research in the right direction and to help reach the aim of the research efficiently. Once the main research question is answered this will allow the research objective to be realised. A set of sub questions is used to help find the answer to the main research question. The main research question of this thesis can be stated as follows:

What are the value drivers that determine the turnaround time of the aircraft engine combustor maintenance repair and overhaul process from a Lean Six Sigma perspective?

In order to answer this question a clear overview of the current state of the combustor maintenance process should be established, along with the current state of the art in process management. This will allow for a solid base for recommendations that can be used to improve the maintenance process. Sub-questions will be asked in order to help generate an answer to the main question.
The sub research questions can be formulated as follows:

1. *How is combustor maintenance performance measured?*
2. *How is combustor maintenance carried out?*
3. *Which value drivers are most influential to combustor maintenance?*
4. *How are the value drivers related to each other?*
5. *Can a model be created that simulates the current process in order to test changes to the value drivers?*
6. *How can TAT be improved?*

Together, the answers to these questions should allow the main question to be answered. Each answer should bring the research a step closer to achieving the aim of the report; providing recommendations for change.

1.8. Significance

The significance of this research is twofold. It is useful for KLM E&M, as it should provide the company with a basis to improve their current process and performance. The research also has scientific significance as a model will be developed to analyse and test changes to the combustor maintenance process. As such the model might be applicable to a broader field than just the combustor maintenance process at KLM E&M.

This thesis aims to generate a model that helps identify which value drivers influence the TAT of an aircraft engine combustor maintenance process, and how these factors influence each other. In doing so a conceptual framework can be created of these value drivers and their relation to each other. As of yet there is no framework in which the factors that influence TAT in aircraft engine maintenance are identified. Therefore, the defined framework creates new knowledge for approaching aircraft engine maintenance. Both the model and framework that will be generated will serve as a tool for both practice and theory.

A case-study will be performed on a combustor maintenance process in order to verify if the identified value drivers do influence TAT. In doing so, a simulation model will be created that allows the TAT to be defined, and the value drivers to be tested. If this model can be applied to the combustor maintenance process it is likely that it can be used for application in other engine maintenance processes. Furthermore, if it is established that the value drivers and their interrelationships do influence TAT within combustor maintenance, it is possible that they exist in other engine maintenance processes and can thus be used to improve TAT within these processes. Furthermore the model might be of further use in the aircraft MRO sector where people are used to carry out maintenance, rather than machines. Therefore the research done can add value to practice, by identifying which factors in a process require focus, and to theory by creating a framework that shows relationships that have not yet been identified in this context.

1.9. Research Framework

The research will be carried out according to the Six Sigma Define, Measure, Analyse, Improve, Control framework as suggested by Pyzdek and Keller [2003]. This chapter has discussed the the context, field, object and objective of the research along with the definition of the problem, scope and main research question, and can hence be seen as the Define phase. The following chapters will discuss the research performed in order to come to conclusions for both theory and practice. The remainder of the report is structured as follows.

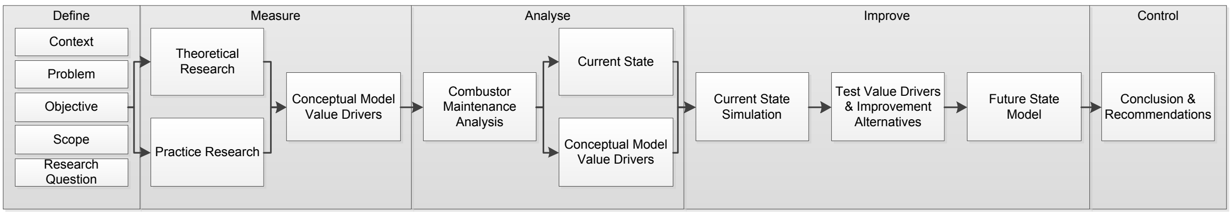


Figure 1.11: Research Framework

Chapter 2 contains the research design and will answer the first two research questions. Through research of literature and practice the sub-research questions have been generated along with performance criteria and variables that are relevant to answering the main research question. From these factors a conceptual framework can be generated that forms the basis of the analysis. This coincides with the Measure phase.

Chapter 3 discusses the analyse phase, and will answer the third and fourth sub-research question. In this chapter the current state of the combustor maintenance department will be defined, after which data is collected and the process is analysed regarding the factors that have been defined in the conceptual framework. The relationships between these factors are analysed and the chapter concludes with the validation of the framework.

Chapter 4 will verify the answers to the third and fourth sub-research question. The chapter covers the improve phase and contains alternatives for the future state design, and shows how the conceptual framework can be applied in practice. As such this chapter will also provide answers to the fifth and sixth sub-research questions.

Finally, Chapter 5 will discuss the conclusions regarding both theory and practice, and contains the recommendations for further research. Furthermore the outcomes and recommendations of this research should allow the process to be controlled, which is the final phase in the DMAIC process framework.

2

Research Design

The purpose of this chapter is to establish the context and the significance of the thesis. In this chapter the literature research will be carried out, followed by the practice research. From this research the sub research questions can be determined along with the identification of the criteria and variables that require further investigation. These factors are used to create a conceptual framework that forms the basis of the research. Through use of this framework a clear answer to the research questions can be generated.

Currently, the main performance indicator of the maintenance process at the ES combustor department is the turnaround time (TAT). If the TAT of the repair exceeds 36 days the combustor part is considered late. The TAT is the main dependent variable for which improvement is sought, and it is influenced by several value drivers. It can thus be said that the research perspective is based on a causal conceptual model.

By studying scientific literature, by interviewing experts, and by investigating the current state of the art within aircraft maintenance a conceptual model can be developed. The findings from these studies can be found within this chapter. The research objective has several underlying key concepts that can be linked to certain theories, these will form the basis of this research. The key concepts that will be studied are process management and aircraft maintenance, or maintenance in general as well as simulation. Table 2.1 shows the key concepts underlying the research objective and their accompanying theories.

Table 2.1: Key concepts and theories

Key Concept	**Theory**
(Aircraft)Maintenance	Maintenance theories
Process management	Lean Six Sigma Theory of Constraints Lean Six Sigma
Simulation	Simulation theory

This chapter will look into the theories behind the key concepts. The theories that will be looked into within process management are Lean Manufacturing, Six Sigma, the Theory of Constraints and Lean Six Sigma. Furthermore, simulation will be briefly discussed. Finally, this chapter will be concluded with how the discussed theories can be applied to the purpose of KLM E&M.

2.1. Literature Research

The general concepts of aircraft maintenance and the accompanying theories have been discussed during the introduction. This section will discuss the literature research performed on one of the key concepts of the thesis, process management, along with its relevant theories: lean, Six Sigma, Lean Six Sigma, and the Theory of Constraints. Each theory will be briefly described, after which its main methodology and possible application for maintenance processes will be discussed. Furthermore, simulation will also be briefly discussed as a model will be created that allows TAT to be measured.

2.1.1. Lean

Process management and improvement requires leaning, cleaning, and greening accoriding to Conger [2015]. Lean, or lean thinking 'provides a way to specify value, line up value-creating actions in the best sequence, conduct these activities without interruption whenever someone requests them, and perform them more and more effectively' [Womack and Jones, 2003]. According to Womack and Jones 'lean thinking provides a way to do more and more with less and less – less human effort, less equipment, less time and less space – while coming closer and closer to providing customers with exactly what they want' Womack and Jones [2003]. This aligns very well with KLM, who want to improve their practices at zero costs.

Lean thinking is summarized by Womack Womack and Jones [1996] in the following steps:

1. 'Define value precisely from the perspective of the end customer in terms of a specific product with specific capabilities offered at a specific price and time;
2. Identify the entire value stream for each product or product family and eliminate waste;
3. Make the remaining value-creating steps flow;
4. Design and provide what the customer wants only when the customer wants it; (push)
5. Pursue perfection.'

The key concept of lean is based on the premise that everything that does not add value to the customer is waste, and waste should be eliminated. Furthermore within a chain of processes the next process in line is the customer, even though the production is pulled by the final end-customer.

Womack and Jones believe Lean thinking 'must start with a conscious attempt to precisely define value in terms of specific products with specific capabilities offered at specific prices through a dialogue with specific customers' [Womack and Jones, 2003]. They continue, that it is essential to form a clear view of what is really needed. The value for the customers of KLM ES will be defined in the following chapter.

The value stream 'is the set of all the specific actions required to bring a specific product through the business' [Womack and Jones, 2003]. According to Womack and Jones the business has three critical management tasks: problem solving, information management, and physical transformation. Without these tasks it will not be possible to create value for the customer, in addition it should be clear what the customer values. Along the value stream several types of activities are undertaken. Keeping in mind that all activities should add value, we can define three types of tasks: tasks that add value, tasks that do not add value but are necessary nonetheless, and finally tasks that do not add value and should hence be eliminated.

It should be noted that lean has its limitations, and it is still developing. According to Hines [Hines et al., 2004] the main criticism on lean it a narrow operational focus on the shop floor and a lack of ability to cope with variability. The fact that lean focuses on the shop floor is useful for this research as the focus lies with a maintenance process that is carried out on the shop floor of ES. The variability is an issue, as this thesis deals with maintenance which is variable in nature. Furthermore, lean is mainly focused on the production process which is somewhat different than a maintenance process.

Lean is not a comprehensive theory, concepts that are not part of lean production are: production capacity, quality, responsiveness of the manufacturing system, demand variability, availability of production resources, and production control. However, these are all relevant factors within aircraft maintenance. This, combined with the need to increase process capability and remove bottlenecks should be addressed. According to Hines et al. the use of tools and methods from six sigma and the theory of constraints (TOC) are useful additions to lean [Hines et al., 2004], their use and interaction can be seen in Figure 2.1. ‘These additional perspectives help to create a more rounded and focused tool-set for applying lean in order to create capacity at the constraint resources’ [Hines et al., 2004].

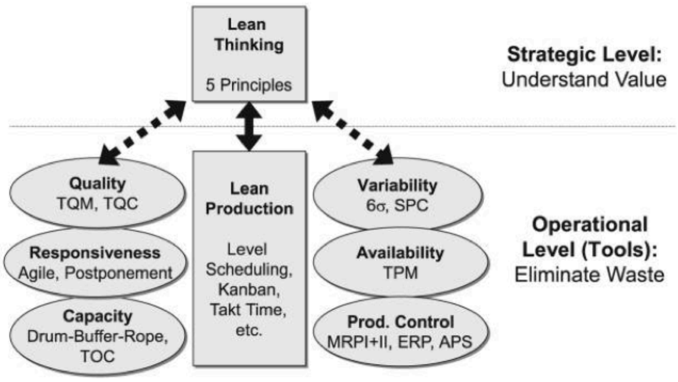


Figure 2.1: Lean Framework [Hines et al., 2004]

Womack and Jones provide an account of the introduction of lean throughout the engine production division of Pratt & Whitney. This validates the applicability of lean within aviation. Even though the account regards production, Womack and Jones do raise the question whether flow thinking can make it possible to perform a complete engine overhaul overnight [Womack and Jones, 2003]. Aside from suggesting the application of lean within maintenance, they do not give any advice regarding how to adapt the theory to maintenance. Using lean for aircraft maintenance means continuously improving the process. ‘The goal is to minimize waste in terms of non-value-added activities, such as waiting time, motion time, set-up time, etc.’[Ayeni et al., 2011].

Lean Maintenance

This section will look into how lean can be applied within maintenance. Levitt defines lean maintenance as the ‘delivery of maintenance services to customers with as little waste as possible, or producing a desirable maintenance outcome with the fewest inputs possible’[Levitt, 2008]. A lot of the literature on lean maintenance (including Levitt) focuses on the maintenance of for instance the machinery that enables a process rather than as a process itself.

Literature review, performed by Ayeni et al., on the state of the art of lean in the MRO sector, shows that in 2010 there seemed to be a strong emphasis on adopting lean techniques within maintenance operations, mainly due to the strong competition within the MRO sector. They note that there is a scarcity of literature available on the adoption of lean in the aerospace MRO sector. But, they have found that lean is considered a useful tool within aviation, that should be used in combination with other relevant tools to realise all company goals. Frequently suggested was the combination of lean and Six Sigma. According to Sunjka, ‘Globally, the implementation of lean techniques has proven to be successful in improving quality while reducing turnaround times and costs within aircraft maintenance organisations’ [Sunjka and Murphy, 2014]. This implies that lean would be suitable not only for MRO but also for the purpose of KLM and this thesis.

Ayeni et al. note a few issues regarding the use of lean. First of all they point out that ‘the difficulty in accurate forecasting, typically characteristic of the aerospace MRO industry, results in practices which contradict the ideals of lean, thus serving as an inhibitor to its adoption and or its advancement’[Ayeni et al., 2011]. Depending on the use of monitoring systems, better maintenance forecasts might be made. Secondly, as has been noted with the general use of lean, successful implementation depends on employee involvement and project leader’s management skills. The company culture needs to change so that everyone is involved in identifying problems and waste, and continuous improvement of the maintenance processes becomes the norm.

Lean is mostly applied in order to reduce waste, rather than to create value. As lean was fairly recently adopted in aviation MRO there was not a clear implementation strategy, nor was it clear which factors accounted for success [Ayeni et al., 2011]. Examples of how lean is implemented within MRO companies is scarce. There are however examples of the implementation of Lean Six Sigma to MRO processes, which will be discussed in section 2.1.4.

Value stream mapping is one of the lean tools that has been used in several MRO businesses, such as EPCOR [Beelaerts van Blokland et al., 2008] and JetSupport [Stander et al., 2012]. According to Parida 'in order to understand a process it should be mapped, after which possible gaps between the maintenance planning and execution can be identified' [Parida and Kumar, 2006]. Value Stream Mapping is used to identifiy the elements used to deliver products or services to market, identifying value adding activity and flow and to make visible the value stream and the value flow (lean principles) and identifying the skills, assets and technological resources of this process [Parry et al., 2010] [Stander et al., 2012].

When Value Stream Mapping is used to identify value (the first step in the lean cycle), it can provide the scope of the project as it gives a definition of the current state as well as the desired future state of the system. The future state map can then be used to develop lean improvement strategies, for example parallel working and flexibility through multi-skilling employees (requiring minimal expenditure) [Clegg et al., 2010].

Lean can be applied within aircraft maintenance. However, there are no clear guidelines on how to implement lean within aircraft MRO. The cases where lean is applied seem to make use of value stream mapping as an initial step, other steps are not clear. Several sources state that lean should be used in combination with other management theories. There are examples of successful implementation of lean in combination with six sigma and the theory of constraints. These combinations will be looked into after Six Sigma and the Theory of Constrains are discussed.

2.1.2. Six Sigma

The purpose of Six Sigma is to improve predictable quality of developed products and services through the removal of normally distributed errors. 'Six Sigma practice strives for 99.9997 % accuracy in the process' Conger [2015]. In other words Six Sigma is a target of a performance that has only 3.4 defects per million actions. If we look at KLM E&M activities from this perspective we would see that they are still a long way away from only 3.4 defects per million operations.

Six Sigma encompasses a broad array of tried methods and skills that are essential ingredients for success and growth. It is not just about performance, it is also about the people that realise the performance. According to William Truscott there are several management principles, which can be derived from the ISO 9001 system, that underpin the Six Sigma approach: customer focus, leadership, involvement of people, a process and system approach, a factual approach to decision-making, and mutually beneficial supplier relationships [Truscott and Truscott, 2003]. These principles should be incorporated in the company if Six Sigma is to be implemented.

In order to incorporate Six Sigma, training is required which involves an introduction to Six Sigma and the theory behind it, its typical use, and practical experimentation with several tools. As with all the theories discussed earlier, Six Sigma also has a predefined set of steps that should be followed in order to successfully apply Six Sigma. The steps are shortly summarised in the DMAIC framework [Pyzdek and Keller, 2003]:

Define the goals of the improvement activity

Measure the existing system

Analyse the system to identify ways to eliminate the gap between the current performance of the system or process and the desired goal

Improve the system

Control the new system

The Design for Six Sigma (DFSS) approach allows new processes to be designed that will be in line with Six Sigma with the Define, Measure, Analyse, Design, and Verify (DMADV) framework. As this thesis will focus on the current process within KLM E&M, the focus of this discussion of Six Sigma will be on the DMAIC framework.

For the define stage the company goals should be known. The most important goals are obtained from customers, and all other goals should help work towards creating customer value (customers may be internal as well as external). For the measure stage company metrics should be defined and used to give a good indication of process performance, and the progress towards a goal. In Six Sigma the outcomes of the metrics are frequently presented using a Balanced Scorecard. This Scorecard can be compared to a cockpit, as it displays the relevant information in a way that is comprehensive, and gives a good overview of the company activities and performance. Depending on the metrics and the defined goals Six Sigma projects can be defined. Usually, projects are started where the metrics show a poor performance. Once a project has been defined, the steps of the DMAIC framework can be followed.

Table 2.2: Steps during DMAIC phases [Pyzdek and Keller, 2003]

Phase	Steps	Tools
Define	What is the business case for the project? Identify customer Current state map Future state map Define scope Deliverables Due date	Process Map Flow Chart SIPOC
Measure	Define key process metrics Are the metrics reliable and valid? Is there adequate process data? Define progress measurement Define project success measurement	Pareto Analysis Statistical Tools
Analyse	Current state analysis Is the current state at an optimum? Identify who will help make the change Resource requirements Identify possible failure causes Identify possible obstacles	Brainstorming Root Cause Analysis Process Maps Simulation Benchmarking
Improve	What is the work breakdown? Identify necessary activities to meet project goals Identify how to re-integrate sub projects	Force Field Diagrams 7M Tools Project Planning and Management tools
Control	Define how to control risk, quality, cost, schedule, scope and changes to plan Define type(s) of progress report Define how to assure project goal accomplishment Define how to maintain profits	Statistical Process Control Reporting System

In each of the phases in the DMAIC framework certain steps should be taken. Table 2.2 shows the steps and questions that should be considered for each phase. There are many tools that can be used during each of these phases. Some of these tools are also shown in Table 2.2. Note that the tools do not necessarily match the steps in the table, e.g. a flow chart is not needed to identify the customer. Depending on the type of project different tools might be used, and can be found in “tool books” that list and describe all available tools. For every project a standard methodology is used as a basis, which is then tailored for the specific project. The focus of the methodology should be on making the process at hand more robust and less subject to errors. For instance, during the measure and analyse phases many statistical tools such as linear regression and scatter plots might be used. The tools that are used for this thesis will be discussed in Chapter analysis.

A point of criticism regarding Six Sigma is that processes are improved independently and that system interaction is not considered [Nave, 2002]. In this case, where a single process is to be analysed, this does not directly form an issue. However, the idea is that KLM E&M uses a management theory and system that can be applied throughout KLM E&M, and that all processes are aligned, especially since all processes at E&M eventually lead to a complete aircraft. Furthermore, Six Sigma does not clearly specify how processes should be controlled. Many sources suggest a combination of lean and Six Sigma (see section 2.1.4).

General Electric (GE), is one of the companies that has successfully implemented Six Sigma throughout all its divisions. For instance, at GE Aircreaft engines each project includes a dashboard which is used to 'collect, report, track, and improve customer satisfaction through focusing on requirements identified as vital to key customers. Dashboards are negotiated with individual customers to identify what is most important about GE products and services to the customer' [Henderson and Evans, 2000]. The financial results that GE has generated after implementing Six Sigma show how fruitful the use of Six Sigma can be. Furthermore this shows the applicability of Six Sigma within aviation and manufacture.

There are few examples in literature regarding the application of Six Sigma to maintenance processes. However, examples can be found where (preventive) maintenance is made part of the Six Sigma strategy; by maintaining machinery quality can be guaranteed and breakdowns can be prevented.

Due to the general nature of DMAIC Six Sigma is likely to be applicable to aircraft maintenance. The Six Sigma tools that are available can be used as long as there is a clear process, sufficient data available to track and analyse, and the goals are clearly defined. As with lean, tools can be chosen depending on the process and project.

2.1.3. Theory of Constraints

The Theory of Constraints (TOC) is a theory first introduced by Eliyahu Goldratt in his novel *The Goal*. According to Goldratt the goal of a company can be measured by throughput, inventory and operating expenses. The idea is that a company will always want to maximise throughput while minimising inventory and operating expenses. Furthermore, the theory sees a company as a system which exists of chains, or a network of chains, and a chain is always as strong as its weakest link. This means that no matter how much and how many links (processes or process steps) you improve, it will not have an effect unless you strengthen the weakest link in the chain. This weakest link is the system constraint. When all departments of a company work at their best productivity level it does not mean the company will perform at its best.

A constraint is defined as 'anything that limits a system from achieving higher performance versus its goal'[Goldratt, 1990]. Each company or system is believed to have one constraint, at any given time, that limits the output or productivity. By identifying this constraint, and adjusting the way of thinking, working, etc. this constraint can be eliminated so that the output is no longer constrained. The theory of constraints allows a company to focus by following the steps below:

1. Identify the system's constraints;
2. Decide how to exploit the system's constraints;
3. Subordinate everything else to the above decision;
4. Elevate the system's constraints;
5. If in the previous steps a constraint has been broken, go back to the first step, but do not allow inertia to cause a system constraint.

The constraint is usually found based on the amount of work that is waiting to undergo a certain process step. Then, the process should be improved and the constraints should be exploited in order to achieve its maximum capacity (without changing machinery or investing a lot of money). Once this has been done, all other processes are subordinated to the speed or capacity of the constraint, and should follow its pace. This means that if steps ahead of the process have a higher capacity, they should be limited in their production in order to keep pace. Then, the whole system might need improvement, and major changes to the constraint might be necessary. The system's constraints should be elevated or even eliminated. Finally, the complete cycle can be performed again in order to define and fix the next constraint.

Management should seek to find out what to change, what should be the result of this change, and how to go about causing this change. They should involve and engage people to think about how to solve the problems that require change, they should make people see their own problems and make them become problem owners in order to make them see the need for change[Nave, 2002].

According to Dettmer, the Theory of Constraints is a collection of system principles and tools for solving the problem of improving overall system performance [Dettmer, 1997]. One of these frequently used methods to approach production control is the Drum-Buffer-Rope approach. The idea is that the constraint should provide the beat or the pace at which the system should work. The drum should be enabled to function optimally, basically it should never stop, as once it stops everything stops. The buffer is a strategically placed inventory that helps prevent variable outputs caused by disruptions at non-constraint resources. The rope releases material for the first step at a pace determined by the drum. What's more, the Drum-Buffer-Rope approach makes use of time buffers, in order to remain responsive in case of disruptions. These buffers can be used as an information system to manage and improve throughput. The information is based on planned and actual performance and can be used to monitor the performance[Rahman, 1998][Watson et al., 2007].

The Delta Tech Ops Engine Maintenance Group has successfully implemented TOC by using the Drum-Buffer-Rope system in its repair and support shops, in combination with the critical chain method for engine disassembly and reassembly areas. The critical chain method allowed individual tasks to be performed within a short time-span while adding a few time-buffers within the network of tasks and an aggregate buffer at the end of the project. Parts were given a set time by which they should pass specific milestones. By organising the work as such, tasks had to be performed before a certain date, and the products with the nearest 'deadline' were given priority over parts that had a longer time to spare. By implementing these methods they reduced engine turnaround times by 15%, and increased throughput by 22 % [Bowers and Adams, 2008].

The successful application of TOC within an engine maintenance process shows that it could be useful for the maintenance process at ES. However, as can be seen in the example of Delta Tech Ops, TOC has not been used on its own. The drum-buffer-rope approach might be very useful to guide the maintenance process. TOC provides tools that help identify the constraint within a production process and assumes the constraint can be found based on a high amount of work in one place while other places in the chain have less work. However, this might not be the case for the maintenance process and additional tools for identifying constraints will be necessary.

2.1.4. Lean Six Sigma

As mentioned before, lean and Six Sigma are not comprehensive management tools. When used individually, both seem to lack certain elements that are necessary for continuous improvement and further company developments. Several sources believe lean and Six Sigma can complement each other.

Pepper and Spedding suggest that if lean and Six Sigma are to be combined a framework for Lean Six Sigma (LSS) needs to be comprehensive, strategic, and process focused. The framework should be balanced between the two philosophies to harness the recognised advantages of both. Furthermore, a balance between complexity and sustainability must be reached, and the framework should be structured around the type of problem experienced [Clegg et al., 2010].

LSS has been applied in many different sectors such as manufacturing and services. However, literature on LSS in maintenance is scarce, and even more so regarding LSS within aircraft maintenance. In the cases that literature is available the focus is usually on the factors that enable successful use rather than how LSS is used and applied. Pepper and Spedding note that there are a number of LSS models available, but that there is no logical explanation for the combination, and no theoretical underpinning or explanation for the choice of techniques [Clegg et al., 2010]. Bendell remarks that it would be desirable if a single process improvement-based approach which effectively combined the approaches was available [Mi Dahlgaard-Park and Bendell, 2006].

Snee [Snee, 2010], considers the lack of methodologies to follow within LSS to be a challenge. He counters this by mentioning that there are several methodologies that can be adapted to specific organisational needs. He also points out that Lean Six Sigma has a strong underlying theory, and the effectiveness of the LSS approach depends on several factors, such as the use of small project teams, the focus on finding critical process drivers and using the Pareto principle, improving on a project basis, using tools that generate proven results, and the use of the DMAIC framework for problem solving.

According to Franchetti, ‘Lean Six Sigma (LSS) is a comprehensive and flexible system for achieving, sustaining, and maximizing business success. It is uniquely driven by a close understanding of customer needs, disciplined use of facts, data, and statistical analysis, and diligent attention to managing, improving, and reinventing business processes’ [Franchetti, 2015]. He also defines six fundamentals of LSS [Franchetti, 2015], namely:

1. Define products or services.
2. Know the stakeholders and customers and their critical needs.
3. Identify processes, methods, and systems to meet stakeholders’ critical needs.
4. Establish a process of doing work consistently.
5. Error-proof process and eliminate waste.
6. Measure and analyse performance.

George has written *Lean Six Sigma for service*, in which the use of LSS is discussed for ‘everything except “the making of goods and articles by hand or especially by machinery”’ [George and George, 2003], and as such should be appliccable to maintenance . The framework suggested by George in *Lean Six Sigma for service* is the framework that will be discussed below.

Both Franchetti and George suggest the Six Sigma DMAIC framework should be used for LSS project implementation. They each identify different steps that should be taken during each of the phases of the DMAIC framework. However, the steps they suggest show similarities and work towards a similar result, namely an improved process that continues to be monitored and improved. Furthermore, both frameworks contain the success factors as identified by Snee. Each of the steps suggested by George and Franchetti can be seen in Table 2.3.

As can be seen the suggested steps and tools differ, as well as where in the process certain things should take place, but the main ideas are similar. The steps that both Franchetti and George describe within the DMAIC framework require the use of both lean and Six Sigma tools. The KLM E&M Lean Six Sigma Office provides so called “Green Belt Training” in which a large array of lean and Six Sigma tools are discussed along with examples and possible applications. During this training “students” are provided with a lean Six Sigma Toolbook. This toolbook contains an explanation of many of the tools that have been discussed in this section, along with a description of how to use these tools and when they might be useful to apply.

An example of LSS in practice within aircraft MRO is the introduction of LSS at EPCOR [Beelaerts van Blokland et al., 2008]. EPCOR is the European Pneumatic Component Overhaul and Repair company, and takes care of MRO for aircraft components. EPCOR wanted to reduce its maintenance lead time and variability. At the start of the project the average TAT was 28 days while 15 days was promised to the customer. The use of Lean Six Sigma principles reduced the standard deviation from 20.49 days at the start of the project to 13.13 days.

During this project the DMAIC steps were followed. Value stream mapping was used to define and

Table 2.3: Lean Six Sigma Steps

Phase	George [George and George, 2003]	Franchetti [Franchetti, 2015]
Define	Agree on problem Understand project and link to strategy Agree on project boundaries Know what metrics will be used to evaluate success	Establish team and charter
Measure	Establish baselines Observe process Collect data by participating	Review existing records and data Create process flowcharts Conduct throughput analyses Collect data
Analyse	Analyse data Create Value Stream Map	Analyse data by work unit or area to establish baseline data
Improve	Change process to eliminate defects, waste, costs etc. Change process to add customer value	Identify major cost and quality improvement opportunities Determine, evaluate and select process, equipment, and method for improvement alternatives Develop LSS deployment and execution plan.
Control	Document improved process Install automatic monitoring Develop control plan	Execute and implement the LSS plan and timeline. Validate the programme against goals Monitor and continually improve performance.

illustrate the current state for one representative component in thee measure and analyse phase. The planning system, actual timing and personal experience were used to gather data. Analysis of the current state allowed for the identification of a part of the process that needed further analysis and improvement. This part of the process was analysed into more depth and many opportunities to remove waste were identified. After this, a future state was designed keeping in mind flow in the process and reducing removing unnecessary handlings/movements and reducing/eliminating waiting times.

Furthermore, people were involved in the process, and management backed it as well. This was considered vital to the project's success. However, according to De Waard [2007], more mechanics should have been involved in the design phase in order to make them more positive towards changes.

The example of LSS at EPCOR does not make use of a very clear framework that can be followed. However, it is specifically used within aircraft MRO and hence takes into account the fact that not all parts of the maintenance process can be made lean due to certain requirements. Furthermore it simply follows the DMAIC framework and uses only a few lean and Six Sigma tools that are easy find and use. By doing this a lean project is can be understood by everyone within the maintenance process; from shop workers to higher management. It would therefore be good to keep in mind that the LSS framework does not have to be extremely elaborate or complicated in order to realise success.

LSS can be very useful for the maintenance process at KLM E&M. However, there is no single methodology for the use of Lean Six Sigma. A framework that is very frequently used for various methodologies within LSS is the DMAIC framework. The two methodologies suggested by Franchetti and George are placed within the DMAIC framework, are relatively easy to follow guidelines for the implementation of Lean Six Sigma, and are hence useful for application at KLM E&M. Depending on the amount of data and information that is available either George or Franchetti's steps can be followed during the define, measure and analyse stages. However, it would be most sensible to perform the improve and control phases according to the steps described by Franchetti, as these steps incorporate the generation and selection of alternatives. Furthermore, it is important to keep the framework and steps simple and easy to follow so that everyone involved can understand.

2.1.5. Simulation

According to Ferrin et al. [2005], simulation is a good fit for LSS and the DMAIC method. They say it is used by many of the world's "best" companies, and that it is can help to reduce variation through continuous process improvement. As such it can be a good addition to design a simulation model to measure TAT, and to test improvements Simulation will also be briefly discussed here. According to Fishman [2013]'a model can be a formal representation based on theory or a detailed account based on empirical observation' that usually combines both. Furthermore, Fishman states that 'in a discrete-event system, one or more phenomena of interest change value or state at discrete points in time, rather than continuously with time.' Manufacturing plants, inventory systems as well as many other environments can be modeled as discrete event systems, which measure their performance in terms of delay, number waiting, throughput, and resource utilisation [Fishman, 2013]. As such the combustor maintenance process could be modelled in order to perform a discrete-event simulation that allows TAT to be measured, and changes to the process to be analysed.

According to Shannon [1992] simulation can be defined as 'the process of designing a model of a real system and conducting experiments with this model for the purpose of either understanding the behavior of the system and/or evaluating various strategies for the operation of the system.' As such simulation includes both the development of the model, as well as testing the model in order to study the process or issue modeled. This is in line with the goal of the development of the maintenance model. The idea is to create a model that represents the process and the current state in order to identify the influence of the value drivers and to see how changes to the process might improve the process performance.

Shannon [1975] describes the process of simulation in 11 steps. First the system or process should be defined, and an abstract model that represents the process should be formulated (in a flow diagram). This will been done during the preliminary research and the process analysis. After defining the abstract model, the required input data should be identified and prepared for use in the simulation, the model should be built within a software environment and should be validated. Once the model has been validated an experiment that yields the required information can be designed, and the practical approach to carry out the experiment runs should be determined. After doing this the model can be used to experiment, in order to generate the required data and perform sensitivity analyses, after which the generated data can be interpreted. After this the model and results can be implemented, and the project activities and results as well as the model and its use can be documented.

2.1.6. Literature Research Conclusion

In this section various process management theories have been discussed in relation to maintenance. The common factor between all theories that have been discussed is that there should be a focus on the process. Furthermore lean, Six Sigma, LSS, and TOC all strive for a system of continuous improvement. The combustor maintenance process at ES needs improvement and needs to be managed towards a process of continuous improvement. Various elements of the systems previously discussed have been found to be useful for this purpose.

Process management will be used within this thesis in the sense that a shift towards process thinking should take place. It can be used as an underlying theory and way of thinking. Combustor maintenance should be considered as a process that begins once an order for combustor maintenance comes in and ends once the combustor has been inspected and declared serviceable, and has been delivered to where engine assembly takes place.

There are no clear guidelines on how to implement any of the theories within aircraft MRO. Lean, Six Sigma and TOC are not comprehensive management tools and have fairly generalised frameworks which can be used in different ways, shapes and forms. Table 2.4 shortly summarises the underlying concept (theory), frameworks (application guidelines), and the focus points of Lean, Six Sigma and the Theory of constraints. However, several sources have suggested a combination of the three, and especially Lean Six Sigma which combines Lean and Six Sigma is a frequently suggested tool.

Table 2.4: Lean, Six Sigma and TOC basics [Nave, 2002]

Program	Six Sigma	Lean thinking	Theory of constraints
Theory	Reduce variation	Remove waste	Manage constraints
Application guidelines	1. Define. 2. Measure. 3. Analyze. 4. Improve. 5. Control.	1. Identify value. 2. Identify value stream. 3. Flow. 4. Pull. 5. Perfection.	1. Identify constraint. 2. Exploit constraint. 3. Subordinate processes. 4. Elevate constraint. 5. Repeat cycle.
Focus	Problem focused	Flow focused	Systems constraints

From the TOC a relevant notion is seeing a system as a chain that is constrained by its weakest link. A maintenance process is not a simple chain and it might be difficult to identify a single constraint or bottleneck. However, the way Delta Tech Ops has used TOC by making a maintenance time-line, using the drum-buffer-rope system, and clearly indicating milestones whilst prioritising parts that are nearing their end date might be very helpful for the design of an improved process.

Lean Six Sigma will be used, as several sources in both lean and Six Sigma literature have suggested this as a comprehensive theory to enable business process improvement. The DMAIC framework is frequently used for this purpose. Following this framework along with the steps suggested by George and Franchetti will be part of the methodology for the combustor maintenance process improvement at KLM E&M Engine Services. Because intermediate steps are described within the different phases it makes the process easier to grasp and to follow. Due to the smaller steps it will be easier to select appropriate tools.

The tools that have been successfully used within aircraft MRO are value stream mapping and cause and effect diagrams. These tools will also be used within this thesis. It is likely that a lot of data regarding the combustor maintenance process is available. However, observations and input from people on the floor will be required in addition to this to create a value stream map. If observations and additional data collection are needed it is likely that in the case of the KLM E&M combustor department a combination of Franchetti and George's measure methods will be used during the measure and analyse phase. The improve and control phases should be executed according to the steps as described by Franchetti. However, the control phase is outside of the scope of this thesis as it would not be realistic to realise this within the given time-frame. Furthermore, the general goal of the two theories is to find critical value drivers, this can be done according to the Pareto principle where a large part of the process is influenced by a few factors.

Finally, the 11 steps for simulation as suggested by Shannon [1975] will be followed to create a simulation model during the improve phase of the DMAIC framework.

2.2. Practice Research

In Chapter 1 the engine combustor maintenance process has been briefly described. This section will give a more in depth description of the ongoing processes and performance of ES and the combustor maintenance department. In order to define the cause(s) of this issue a clear overview is needed of the combustor maintenance process. This research will help establish further research questions and criteria and variables that influence the problem and require further analysis.

Various types of aircraft, components and engines come in at E&M for both scheduled and unscheduled MRO. In 2015, for the second year in a row, AFI KLM Engineering & Maintenance has been awarded the MRO of the year award. This year, it was mainly for their support to the latest generation of aircraft and engines. One of the reasons is that they will become the first non-OEM shop to perform quick-turn shop visits for the GEnx engine. Furthermore their order book grew with 20% in 2014 [Shay, 2015]. However, simultaneously AF-KL is facing drastic financial measures due to poor performance. Hence, all the current processes need to be reevaluated in order to determine an alternative course of action.

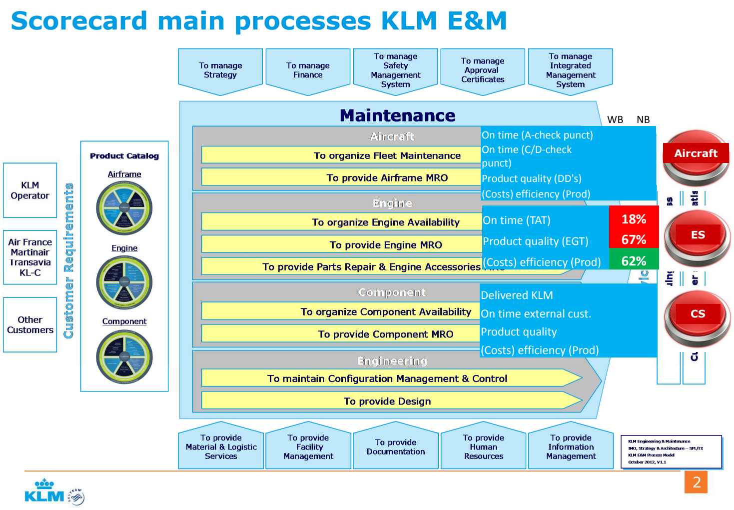


Figure 2.2: E&M CBBSC January 2015[Gortenmulder and Wiggelinkhuizen, 2015]

The CBBSC as seen in Figure 2.2 is used by KLM as a reporting tool for managers to communicate their performance to higher management during their monthly meetings. The current scorecard shows the core MRO activities and their aims, along with the key performance indicators (KPIs) that show to which extent aims are met. The core aims of ES are to organise engine availability, to provide engine MRO and to provide parts repair and engine accessories MRO. As can be seen in Figure 2.2, which focuses on the performance at ES, only 18% of engines was delivered on time in January 2015, the product quality is at 67% and the efficiency of production was only 62%.

The process of engine MRO as performed and defined by ES is shown in Figure 2.3. As can be seen engine maintenance is only a part of this process. Figure 2.4 shows how engine maintenance is carried out within ES. As can be seen, once the engine is received at ES it will go through four stages of maintenance.

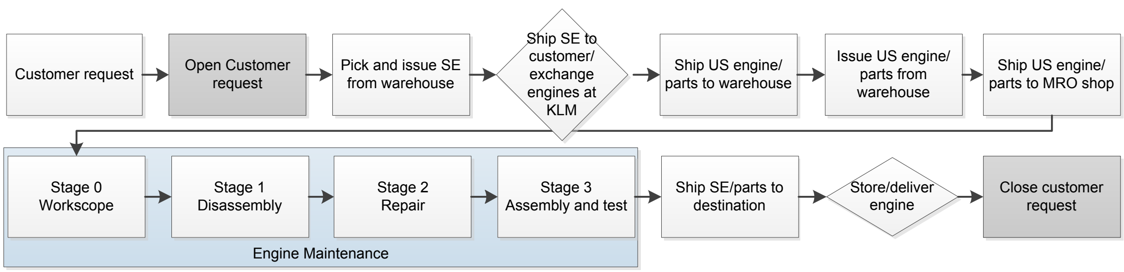


Figure 2.3: Engine Services MRO activities

Stage 0 Define workscope
Stage 1 Disassembly, cleaning, nondestructive testing and inspections
Stage 2 Repair
Stage 3 Assembly and engine test

The workscope is defined based on inspection, Service Bulletins, part history and customer requests.

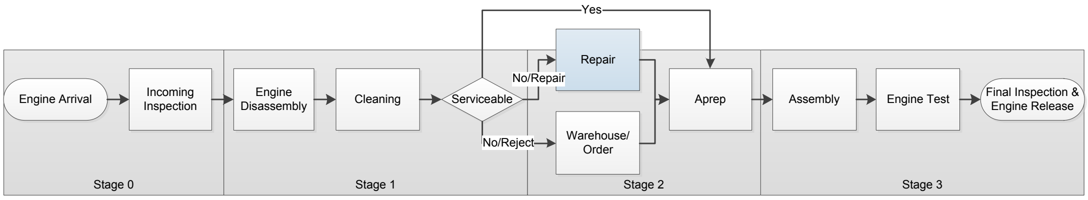


Figure 2.4: Engine Services Engine Maintenance

It is possible that once the workscope is defined it becomes clear that ES is not licensed to perform a certain repair, in this case the component or part is sent of to a third party MRO company. This part is then returned before stage 3 of maintenance is entered. In stage 1 the engine is disassembled into modules and parts. Each module and part has its own unique serial number, which allows the part to be tracked and linked to an engine. The modules are cleaned, and it is determined if the parts meet safety requirements through nondestructive testing and inspections. The module can be serviceable, need repair or be rejected. If repair is needed stage 2 is started and the module is sent off for repair at the different workcentres. After repair stage 3 start and all parts are collected for engine assembly after which the engine is tested.

When the engine has passed the engine test it is shipped to its destination. Depending on the customer's preference this destination can be either a warehouse or direct delivery to the customer. After delivery ES has fulfilled their customer request. The customer mentioned in the MRO process creates a customer pull after they supply their engine to the process. Furthermore when, and how many engines customers will send is not always clear, resulting in a fluctuating demand.

ES is divided into several workcentres where different modules of the engine are maintained. There are twelve different departments ranging from plating to electric accessories. Each of these workcentres performs stage 2 of MRO. Depending on the modules during stage 2 the modules might need disassembling into separate parts.

The turnaround time for complete engine MRO is 60 days, regardless of what maintenance needs to be performed. The turnaround time starts once the engine is received and is finished once the engine is shipped to the customer. Throughout 2014, ES has delivered less than 30 % of the engines on time, and the engine quality has been variable Gortenmulder and Wiggelinkhuizen [2015]. The internal agreement for engine maintenance (stage 2) TAT is currently 28 days. Both the internal and external TAT's are to be reduced by 25%. The TAT for MRO should become 45 days, and the TAT for engine maintenance should become 21 days. However, if we look at the performance within the different workcentres we can see that a TAT of 28 days is already difficult in some cases.

Engine Services needs to improve their process, and has decided to start the improvement and performance analysis within one workcentre. As both the fanblades and combustor departments show poorest performance, in line with TOC, improvement should be started with the "weakest link" in the chain. ES has decided to start process improvement within the combustor department. Mainly because the combustor has a lower range of flexibility; the combustor is one of the last parts to leave the engine, and one of the first parts that is needed for assembly.

2.2.1. Process Flow and Value

As discussed in the previous section one of the main focuses of lean is on creating customer value by removing waste. In order to do so, waste needs to be identified. One way to do this is to create an overview of the process, so that value-adding and non-value-adding activities can be identified. As we now know how the maintenance process looks on a higher level, it is possible to zoom in, in order to identify wastes and weaknesses in the process.

In order to know what does and does not add value it is important to know what the customer value of combustor maintenance is. First and foremost the customer requires their combustors to be returned

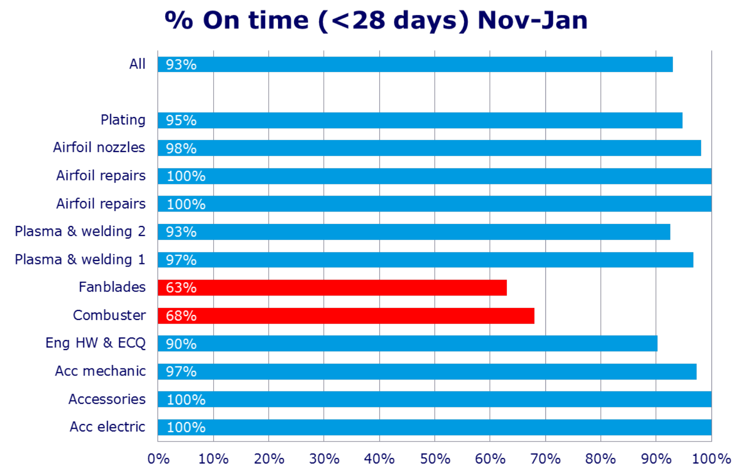


Figure 2.5: Engine Services Workcentre Performance November '14-January '15

to a serviceable state that will remain serviceable for as long as possible. Secondly, the customer prefers this to happen at a low cost. Thirdly the customer wants the maintenance to take as little time as possible, so a short TAT is preferred. All activities that do not work towards the restoration of the combustor to a servicable state do not add value.

Process Flow

One of the main concepts in lean is to create flow in the process. A process flowchart shows all activities and events that are in a process and it can be used to define which steps within the process add value, and which steps do not add value. As the process within the combustor department is divided into phases a general process flowchart has been made, in which each of the phases is marked as a sub-processes. Each of these sub-processes is then shown in an individual flowchart.

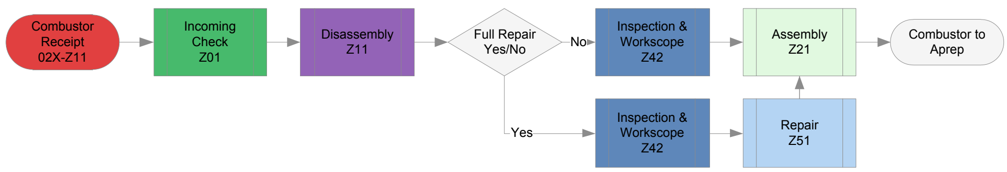


Figure 2.6: Combustor maintenance process flowchart

The flowchart for the general combustor maintenance process (Figure 2.6) starts when the combustor comes into the department and phase 02X-Z11 is signed off. Then the combustor is taken through the maintenance process and is disassembled. Each separate part goes through Z42. However, at the beginning of this phase a decision is made, aided by SAP prescriptions, whether or not a full maintenance route is needed for each part. Depending on this decision the part is inspected and has to wait for assembly, or is prepared for maintenance and enters the main maintenance route after which the combustor is assembled. When all parts are finished the combustor is sent to Aprep. It becomes clear that the combustor maintenance process does not consist of just repair. Actually the process is the same as engine maintenance as shown in figure without the steps after assembly 2.4.

Maintenance does not actually add value to the product. However, maintenance does create value for the customer as it allows the customer to continue operations without having to do a large investment to replace the parts. The part of the combustor maintenance process that adds value is the repair, so the phase that adds value is Z51. During Z42 small benchwork activities and cleaning are performed in order to restore the parts to their required state. This phase adds value, but not each step within the value adding phases actually add value.

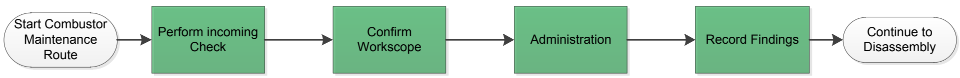


Figure 2.7: Phase Z01 process flowchart

Figure 2.7 shows the Z01 process. This is mainly a preparatory phase in which administrative tasks are performed in order to determine the state in which the combustor was received and to ensure the customer is provided with the correct information and bill etc. after maintenance. None of these tasks add value for the customer, but they are required by both the customer and the OEM. Hence, these steps are necessary non-value added parts of the process.

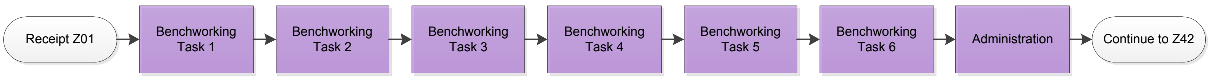


Figure 2.8: Phase Z11 process flowchart

During Z11 (Figure 2.8) several benchworking tasks are performed in order to disassemble the combustor, after which administration is performed. None of these tasks add value, but disassembly is necessary in order to perform maintenance on each part. Hence, these steps are also necessary non-value added tasks. The administration task of this phase is necessary according to the inspectors at the combustor department, but it cdoes not add any value. Hence this task is now marked as necessary non-value added.

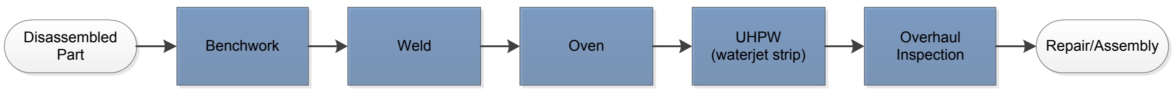


Figure 2.9: Phase Z42 process flowchart

As mentioned earlier, the Z42 process differs for each combustor part and combustor type. For instance Z42 for the cowls of the 7B combustor exists of only one inspection, whereas the for the 8E combustor there are two inspection tasks; one according to US standards and one according to GE E&M standards. Figure 2.9 shows the process steps for the Z42 route of the inner liner, which should consist of 5 steps. First a benchwork and welding task is performed on the combustor in order to prepare it for the oven, in which the part is heated in order to soften the material so that it is easier to handle. After the oven the part is taken to the Ultra High-Pressure Washer (UHPW), where it is stripped from the plasma layer that coats the material. Finally an overhaul inspection is performed in which damages are marked and recorded. None of the tasks in Z42 adds value. However, the oven and UHPW tasks are necessary in order to perform maintenance, hence these tasks are necessary non-value added tasks. The rest of the tasks are also non-value added tasks, but it is unclear if these tasks are necessary.

Phase Z51 is highly variable as the necessary repairs depend on the state of the component, and customer requirement. In general this phase is value added. However, not all tasks add value, as there are several inspections that take place during this phase, and according to mechanics possible rework is already embedded in the maintenance route.

The process shown in Figure 2.10 is a maintenance route as carried out for the 7b-174790 combustor outer liner. All Z51 activities carried out outside the combustor department are marked orange, all internal tasks are marked blue. The process as recorded by SAP consists of 79 steps, for brevity the sequential steps that require the same capabilities are pictured as one task in this flowchart.

The shown route is unique, but shows many similarities with other Z51 maintenance routes. This phase consists of many steps, with a limited variety. Many steps are repeated, which could be the rework loops mentioned by the mechanics. This is mainly the case for welding, benchwork and inspec-

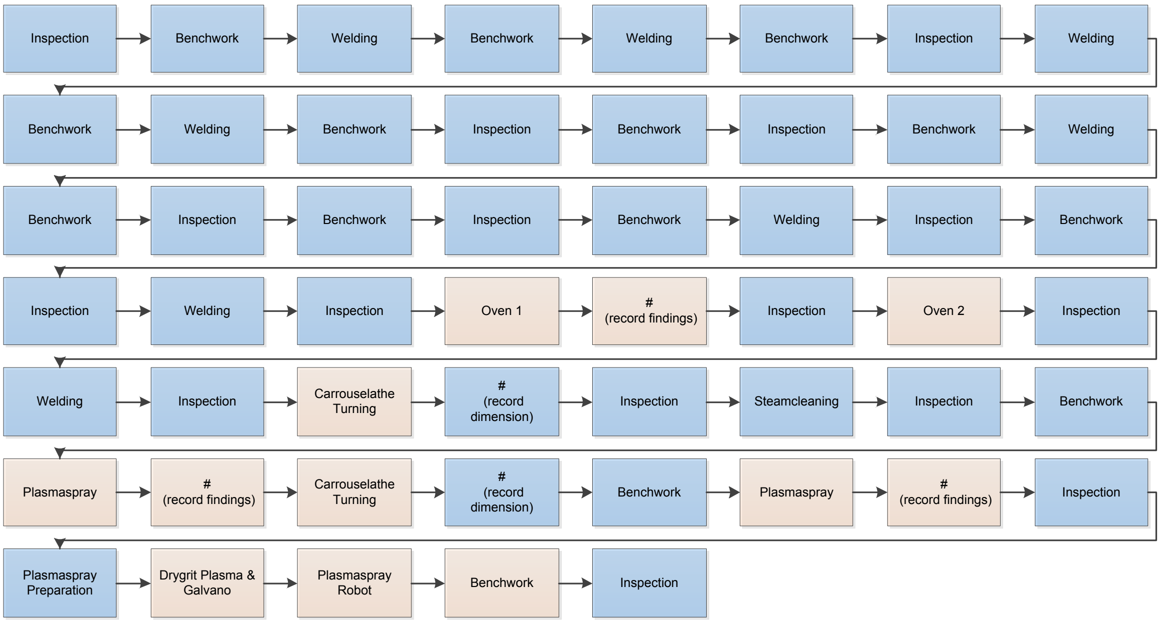


Figure 2.10: Phase Z51 process flowchart

tions. It would seem logical to have only one of each type of task, or group the tasks according to type. However this is clearly not the case. Furthermore, it is not clear which steps within the process are rework (either due to frequent poor quality which is accounted for, or due to extra damage during the process), and which steps are necessary and value added. The value added activities within the Z51 process hence need further analysis.

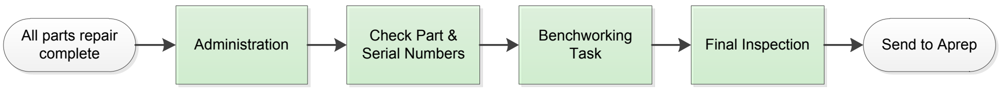


Figure 2.11: Phase Z21 process flowchart

Z21 is the last phase in combustor maintenance. As can be seen in Figure 2.11 the assembly phase consists of several administrative tasks in which the administration of the individual parts is connected to the administration of the complete combustor and engine, and the state of the combustor is validated as required by the customer. The only task that is actually necessary is the benchwork task in which all parts are actually assembled. However, this does not add value for the customer. Hence all tasks within this phase are necessary non-value added.

Value

All activities in the maintenance process that do not add value should be eliminated. As seen through the different flowcharts most of the maintenance phases do not add value. However, within aviation and maintenance it is very difficult to create a process in which all activities add value as additional safety guaranteeing activities are required. These safety guarantees do not make the combustor any more or less serviceable, they only exist as proof that activities have been carried out safely and the combustor should not fail during flight.

For instance, the many inspections that are performed throughout combustor maintenance do not add value, but they are required by GE, the OEM. An inspection shows whether or not the process has been performed to specification. The inspection itself does not improve the quality of the product nor does it improve the quality of the process. It only shows whether or not the performance is up to par. One final inspection is mandatory as this is needed to verify the repair has been performed as it should, and to demonstrate to all parties involved (GE, customers and KLM) that the quality is of the required standard. All other inspections have been added after certain steps in the process failed to meet the required quality.

According to W. Edwards Deming ‘it is important to carry out inspection at the right point for minimum total cost’ [Deming, 1986]. This notion is very relevant to the maintenance process at the combustor workplace. It is very likely that not all inspections that are currently performed are necessary or done at the point at which it is most efficient. Hence, all inspection and administration tasks are at this point considered necessary non-value adding activities. However, this should be analysed in order to determine the necessity of all of these inspections.

Aside from the many inspections throughout the process, it seems as though many of the maintenance phases do not add value, and are not necessary. Of course disassembly and assembly are necessary activities. However, the necessity of many of the administrative tasks it is debateable. In the Z42 and Z51 phases, which are considered to be the phases that actually do add value for the customer, there are many tasks for which it is not clear if they add value. In the cases where the tasks do not add value, it is also not clear if and why these tasks are necessary. Hence, these phases require a deeper analysis in order to determine value.

Tasks
The phases of combustor maintenance each consist of a certain amount of tasks. Each phase has different tasks, some tasks are always part of the maintenance process, others depend on the state of the combustor and the necessary repair. Each task is specified and described in the maintenance manual. Futhermore, there is a normative time specified for each task. The normative times are determined when a repair or task is first “designed”. Hence, the norm times are estimated based on previous performance on similar tasks. Furthermore it is generally accepted that newer repairs take longer to perform as personnel has to become proficient at executing the new tasks and getting a feel for possibly new materials. Needless to say, normative times are an estimate and need reviewing once the task or repair is frequently performed. The norm time allocated to a task includes the time that is actually needed to execute the task, this is so-called hands to metal time, time that is needed to read the manual before executing the task, time to clean and personal care.

2.2.2. Observations
Along with collecting data it is important to see what is going on within the combustor department. By visiting the department and asking questions to those involved a better overview can be made of the process and general practices. At the heart of the maintenance process there are 5 key factors identified within Lean Six Sigma. These are manpower, material, machine, method and measurement. These 5 M’s are usually used in combination with a fishbone diagram or root-cause analysis. The observations will be organised according to these factors. Below, the most relevant observations have been summarised. This section will be concluded with the fishbone diagram that summarises the found issues. A full report of the observations as done at the shop can be found in Appendix A.

Manpower
The combustor department is headed by a department manager, who is also in charge of the Engine HW&QEC department. There are two skill managers, who are in charge of the day to day management of the mechanics for both the combustor and engine HW&QEC departments.

The engine workshop is open 5 days a week from 7:10 to 00:00. Work is divided into two shifts, the early shift from 7.10 to 15.40 and the late shift from 15.30 to 00.00. During the 10 minute overlap in shifts the handover of work and information takes place between the two groups. Furthermore, mechanics are only allowed to take breaks at set times. Each team and skill manager alternates early and late shifts each week.

There are 16 mechanics that work in the department, and they form 2 teams. Each team consists of skilled mechanics, has a team-leader and at least one inspector. One team has 7 members and one inspector. The other team has 6 members and two inspectors. The mechanics are the driving force behind combustor maintenance as their so-called “hands-to-metal” time can be directly translated to maintained combustors. Hence their productivity directly influences the TAT.

It is possible that mechanics are lent to other departments, this is done if other departments are busy, based on workload calculations. One of the mechanics has been "lent" to another department because the department was understaffed. In the case it is very busy another mechanic that used to be an inspector but now works in a different department can occasionally be called upon. As inspectors are the only ones that are allowed to perform inspections and checks it is crucial that they can be used efficiently. However, if only one person is available for all the checks and several parts need to be inspected it is almost inevitable that parts will have to wait a considerable time.

According to the skill managers they do not have enough staff available to carry out the work, in general. Furthermore, there is an issue with available inspectors and skills.

Table 2.5: Combustor mechanic skill set

Mechanic	Skills
A	Q034
B	Q502, Q116, Q685, Q683, Q702
C	Q502, Q685, Q702
D	Q502, Q702
E	Q502, Q116, Q114, Q683, Q702
F	Q034
G	Q034, Q502
H	Q502, Q116, Q114, Q685, Q683, Q702
I	Q502, Q116, Q114, Q685, Q683, Q702
J	Q502, Q702
K	Q502, Q116, Q114, Q685, Q683, Q702

Table 2.5 shows a list of the mechanics within the combustor department and their skills. Each "Q-code" represents a type of skill, for instance Q034 is the inspection skill. As can be seen each mechanic has different skills. Each skill is acquired through specific training and generally certification is required in order to be able to actually apply that skill. Some skills require yearly certification and the mechanics need to spend some days to be re-certified. For example with welding (Q683), every six months a new certificate is required per weld type, as a proof of ability. If one welder can perform three types of welds 6 tests should be done per year. This means it is expensive to teach or allow everyone to weld.

As not everyone has the same set or the same level of skills some people can or will only be used for a limited number of tasks. As some people are better at a certain skill than others people prefer to hand over or leave the work to more skilled people. Mechanics choose which task to do. The result is that mechanics pick the tasks they prefer, and leave difficult tasks to others or for a later time. Another result is that if one mechanic is working on a certain chain of tasks towards the end of the day no one will continue/take over this chain of tasks during the late shift. Hence this part is left unattended until the next morning, when the mechanic can continue his work.

Furthermore, there is little trust among the mechanics according to their managers. They don't rely on each other and do not trust others to do their jobs well. There are monthly meetings in which mechanics discuss how they can improve and what they should do. Everyone feels pressure that improvement is needed, but no one takes responsibility and blames it on someone else. The line managers believe it would be very helpful to have a group activity outside of the workplace where they can all go bowling or have dinner or something like that. However, this doesn't seem to happen.

Material
There are several types of materials that are used within combustor maintenance. First of all the main materials in the process are the combustor components, their type and physical state directly influences TAT as it determines the maintenance routes that are necessary. Secondly, there is the material that

accompanies the combustor throughout the maintenance process, such as shop travellers and certificates, but also materials that are used in the maintenance process, such as sealants and extra parts. Furthermore, one of the key materials that is necessary for the process are the maintenance manuals.

A combustor part moves around the shop and is always accompanied by the shop traveller. However this traveller can not be taken into the oven for instance. When the traveller and part are temporarily separated mix-ups or issues might arise regarding the match between the traveller and the part.

Issues also arise when the part is plasma sprayed. Along with the part a small plate is sprayed. This plate is then tested in order to verify if the plasma spray was of the right quality. Once the plate has been tested a quality form is filled out that indicates the quality of the spray. This form should always accompany the combustor part, and is needed to verify that the combustor is ready for release. However, it is possible that either the plate or the form gets lost. If the plate gets lost the whole part has to be plasma sprayed again, if the form gets lost the plate needs to be retested. In both instances this causes extra time and costs to be made in order to validate the engine quality. Even if this work has been done, the engine assembly can only take place once the form is available (the form is found, the test is redone or the plasma has been reapplied).

There are certain materials that are needed to complete a repair such as nuts and bolts, and sealant for welds. These materials should be available when they are needed for maintenance. It has happened that the correct sealant ran out, and that new sealant had not been ordered. In this case no welding that required that sealant could be carried out until the sealant was ordered and delivered. Very few materials that are needed for the maintenance process are kept in stock within the department. The parts that are kept in stock are the swirlers, nuts and bolts (in the warehouse) and igniter formula. The swirlers are frequently needed and are regularly the cause of delay according to the line manager.

Necessary parts are usually ordered during phase Z42, when the maintenance route has been defined. This is a very short period of time but the warehouse where most parts are kept is within the ES building and is around the corner from the combustor department.

If something runs out or is about to run out the mechanic needs to notify the skill manager who then fills out a logistics order form in SAP that goes via Aprep to the warehouse where the material is stored. If this is not the case the material is reordered by the warehouse. There don't seem to be clear rules on when the reorder point is for the combustor department. Usually the roll-call between all the departments (which occurs every morning at 8:30) is used as a moment to notify the Aprep manager that the item is out of stock. Aprep then makes a reservation in SAP, which triggers an order at the warehouse. Meanwhile Aprep checks their internal stock and delivers the item if it is in house. However, this does not always work flawlessly, and the combustor department (dept. 2400) almost always has to wait some time before they receive their item.

Nuts and bolts in aviation are fairly expensive (e.g.€100 for one bolt), and all materials that are used for a certain combustor are billed to the customer. The customer requires both bills and certificates for each of the parts that are added. The same is true for replacement parts, such as retainers or swirlers. Because of this requirement these parts are not kept in stock within the department but they have to be ordered for every single combustor if and when they are needed so that they can be correctly billed. These parts are also ordered from the Aprep via SAP.

Parts that are not ordered internally via SAP are the main combustor parts, such as the dome. If these are to be replaced that is because the part that was originally part of the combustor has been rejected and can no longer be used, or needs more extensive maintenance. The customer is then informed and makes the decision to replace the part, after which a new part has to be ordered at the OEM. This does not happen frequently, but when it does happens it can cause large delays, depending on the point/time in the process the part is rejected.

Finally, the maintenance manuals dictate how tasks should be carried out. Each task needs to be performed according to the manual and mechanics need to read the manual every time they perform a task. The manuals are stored in a cupboard on the shopfloor and each manual is in a binder and the pages of the manual are printed on separate A4 papers that can be replaced if task descriptions are changed. The binders are then taken to wherever the mechanic needs to perform his task. This sounds fairly impractical, but this is the way it has been done for years and everyone seems fine with it.

Brazing special task, 2400 is one of the few departments that is capable of performing these tasks. All that is needed is a small machine, two pots of paste and an injection needle. A material is injected into a part and the material needs to be hardened in the oven. This has to be done within 24 hours, if this does not happen, the material needs to be removed and the task has to be repeated. Hence, the performance of a brazing task needs to be planned ahead in order to ensure that a space in the oven is available. According to the mechanics at 2400 this is only necessary for the dome.

Machine
The combustor department does not own large machinery. The machines within the department are mainly hand tools such as welders, tapemeasures and magnifying glasses. There are two welding compartments within the department where two people can work at a time. Each of these compartments is fitted with all the tools and materials that are necessary for the welding operations. Furthermore, there are two benchworking compartments where one person can work at a time. These compartments are also fitted with all the necessary tools and materials. There are two inspection tables where inspections can take place. And there are several adjusting divices in which for instance liners can be adjusted to the right shape and size. These devices are fairly large and can only be moved around the department by hoisting them.

The heavy (large) machinery that is used for combustor maintenance is in other departments within ES, namely the oven, large machining, high pressure cleaning, and plasma and welding. If any of these machines are needed, and they are needed at least once during the maintenance of each combustor part, the part is transported on a pallet with a pallet truck. The part is taken downstairs using a large lift (elevator) and wheeled to each of the machines where it enters a queue that is handled by the responsible department. Each of these departments has its own planning system, and the combustor department is fully dependent on their planning and schedule to get their combustors back in time. If speed is required the combustor line manager can ask the department line manager to handle the combustor as soon as possible, however several departments are dependent on these machines and exceptions can not be made for everyone. This frequently leads to long waiting times within the combustor maintenance process.

The attitude at other departments is that if the part is in the early stage of the process (in the beginning of the 28 days) there is no need to hurry. Thus, other parts which are towards the end of the 28 days are prioritized over the other parts. However, this can mean that delays are incurred early on in the process. Another issue with other departments handling combustor parts is communication. Sometimes parts have already been handled but the combustor is not transported back to the combuster department, or the department is not notified that the part is finished. This leads to unnecessary waiting times, where both parties are waiting for the other party to do something. According to the Combustor department the high TAT is mainly caused due to the “outings’ of combustor components to other departments.

The combustor department is the only department within ES that is capable of brazing, this means that other parts or components that need brazing will be brought to the combustor shop for this task. This happens for two parts: coffee machines that are used within the cabin and need mending of a hole, and the HPC stator. However, according to the department these are so few and infrequent that they are not considered to be of large influence on the TAT.

Method
The general process of combustor maintenance has already been described. However, some details have not been discussed. These methods, mostly enabling processes, will be discussed below.

The combustor maintenance process occurs on a first in first out (FIFO) basis, and no real planning occurs. In general the line manager knows a combustor will come in for maintenance a week ahead of time, and is expected to know whether or not the shop can handle the demand. There is a longer term planning, however this is perceived as unreliable and is therefore not used. The capacity is around 15 combustors with a variety in types, the shop can not handle 15 combustors of the same type. If the shop is full combustors might be outsourced, but this hardly ever occurs. Especially during 2015 the demand has been very low, so the number of combustors in the shop is not an issue.

A daily planning is made in the morning for both the early and late shift. In this planning the focus is on “top priorities”, as the department is not yet able to make sure the parts are on time at the beginning so the combustors can be calmly pulled through the system. Furthermore knowing that a combustor is coming in is one thing, knowing the state of the combustor is another thing. And only once the state is known can a proper planning be made.

To keep track of which combustor is where a tracking system has been devised within the department. It consists of a large whiteboard with a coloured plasticized A4-sheet for each combustor that is in the shop. Each sheet contains the projectnumber and the date by which the combustor should be finished, the sheets are organised based on the end date. Furthermore each sheet has a table whith a row for each combustor part and a column for each workshop and a column for parts that have been marked PV (product disturbance) or parts that have been repaired. Figure 2.12 shows an example of the sheet, as can be seen there are magnets placed on the sheet. These magnets show at which workshop the following task should be performed.

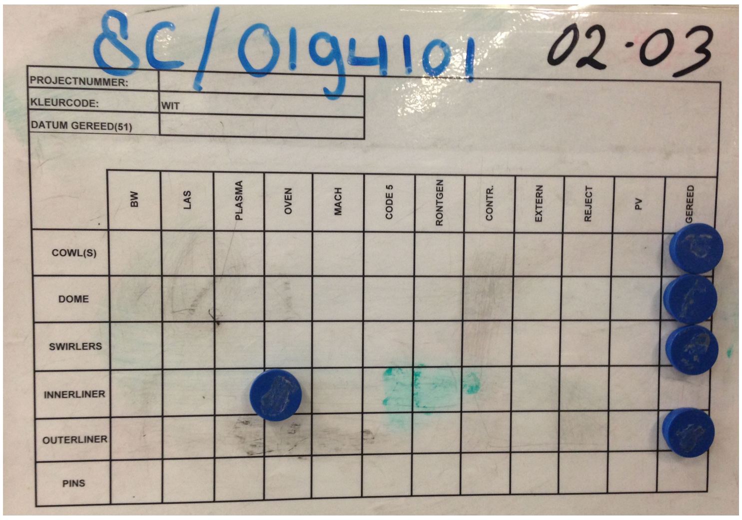


Figure 2.12: Combustor tracking page

After a task has been completed by a mechanic the part is stored in a storage rack. The storage rack consists of 5 shelves, one for each combustor part, and each combustor has its own place in the cupboard marked with a plasticized A4-sheet that matches the sheet on the tracking board. Once the part is put down the mechanic checks what the next step is and places the magnet on the accompanying square. The mechanic can then look at the board to see which combustor has a task that can be carried out by this mechanic (based on skills) and can take this combustor from the rack.

This system seems slightly time-consuming, especially due to combustors being placed in the rack after each task. Furthermore, it encourages mechanics to pick whichever task they would like to do. If a mechanic prefers to do a welding task over a benchworking task he will probably look for a welding task, even if this combustor has a later finishing date than a combustor that needs a benchworking task to be fulfilled. Also this system does not take into account whether or not certain combustors have a longer, more complex maintenance route than others, nor does it take into account the specified TAT per phase. For instance a combustor that has a late completion date might have to be started at day one to have a chance of being finished on time, while a combustor that has a very close completion date might not need to be handled straightaway. What's more, there is no clear instruction or agreement of the order in which maintenance should be performed. There are no agreements on which item should be handled first by a mechanic.

There is a solution to this that has been introduced within the combustor shop, but is not yet followed by everyone. Namely, the WVL-list. This list is based on the SAP planning per phase per part. Every morning a new list is printed and the parts that need repair most urgently are listed at the top, while less urgent parts are more towards the bottom of the list. If two parts have the same completion date the part that has a longer, more complex route is given priority over the simpler route. Furthermore, the completion date per phase is used in order to make sure that the parts are completed on-time throughout the phases. The system determines the completion date per phase based on the start date of the new phase (when entered in sap) and the agreed TAT for that phase. However, the wvl does not correct the end date per phase if the TAT is exceeded for a previous phase. So the actual completion date will be postponed within the WVL even though the TAT for the complete combustor is then exceeded.

In addition to the WVL list each combustor part is given a daynumber (e.g. 01-01 is 1) , this number stands for the date at which the part should be completed (as determined by the WVL). This daynumber is added to a sheet that is placed with the shop traveller. By doing this every mechanic can see which combustor needs to be handled first at a glance, namely the lowest number. When the part enters a new phase a new daynumber is given.

Another thing to take into account with the methodology is the following. Before repair is started the combustor is disassembled and prepared for maintenance. Preparation consists of cleaning (HPW that removes plasma), and oven (this softens the material so that work can be performed on the material). The preparation route timing is highly dependent on external departments. There are only 5 days scheduled for this process. However, two steps are hard to plan as these are outsourced to other departments. If a combustor comes in on Thursday and is ready for the oven on Friday, so it can stay in the oven for 24 hours, this does not interfere with the 5 days. However, if the combustor is placed in the oven on Monday instead of Friday the combustor will always be late (the 5 days are already over after Monday). Furthermore, combustor receipt on Friday is always an issue as you will only have a maximum of 3 working days to perform the preparation. Combustor parts that need (re)ordering can only be ordered once the 'Z51' route is started. If parts are required to be exchanged through a service bulletin they can also not be ordered in advance, even though this maintenance is known to be performed in advance.

Work on a component is determined based on repairs needed. Depending on defects certain repairs are determined. These repairs are defined through a work bill which has been designed by the engineering department. Each repair requires certain steps, these steps for all the repairs of the component are combined in the shop traveller. The shop traveller defines tasks and their sequence. The shop traveller is followed until the combustor repairs have been finished. If extra damages occur during the process the traveller is adapted and a new traveller is added to the existing traveller, which is then marked 'VOID'. This can lead to mix-ups and confusion as to what is to be done, as it is not always clear which traveller to use at first glance. Rework is systematically part of the repairs and traveller. If "rework" is unnecessary certain steps are skipped. A question to be asked is: why not do things right the first time? Or why not repair all defects (i.e. tears) even though they are within limits (these tears might grow during the repair process).

The work and repairs a part needs are determined by inspections. Inspection activities are carried out to determine the quality of a component at several instances during the maintenance process. Inspections can only be carried out by the inspectors and happen at least at the beginning and the end of each phase. The inspections carried out at the beginning of the phase are to define the state and the quality of the part. This is done in order to see what maintenance is necessary, but also to define the state in which it was received. The parts are tested and measured to see whether the shape, size and condition is within predefined margins. If the part is within the margins, no maintenance is necessary. If the part is outside of the margins maintenance will need to be performed. The inspections at the end of the phase are to ensure that the combustor has been restored to a serviceable state, and again this is done by seeing if the parts are within predefined margins.

There are also inspections that are carried out during the maintenance process. These inspections are performed to see whether or not it is possible to perform the next task. For instance certain tears in the material need to be welded properly before the part can be put in the oven. If the tears are not within certain margins more tearing may occur during or after the oven and rework is needed. In these instances inspections are performed as a sort of preventive measure.

One of the issues within the process is that there are so few inspectors. If there is only one inspector and 5 parts need inspection at least 4 parts will have to wait before maintenance can continue. Furthermore there are so many inspections, the question arises whether or not all of these inspections are actually necessary.

Lastly, roll-call should be discussed. Every morning at 8:30 all skillmanagers within ES meet up with the planning and control group (PCG). Each of the engines in the engine shop is discussed; what is its status, which parts might cause a delay, is there an issue with the part/engine, what causes this issue and how can the problem be solved. Every workcentre can say where they have an issue, and if possible other departments can offer their services. Furthermore, a skillmanager can say that one of his parts is currently in another department but that this part really needs to be processed as soon as possible in order to prevent delays, the other department can then say whether or not this part can be handled sooner, and if so when it will be handled. These agreements are then marked on the board, and the following day they are discussed again to see if all has gone according to agreement. These meetings ensure all skillmanagers are on the same page, and aware of the engine progress. The idea is that the skillmanagers communicate this roll-call with their own linemanagers and, if necessary with the mechanics.

Measurement

The combustor maintenance process is not actively measured within the combustor department. What is measured within the department is the progress of the combustor maintenance through scans in SAP. These scans provide “time-stamps” for the completion of each task. Within the combustor process quality is actively measured. Things such as process cost and productivity are measured by other departments. This section will discuss the factors that are measured within the combustor department, and the TAT, which is not measured within the department but is relevant to this analysis.

The data that SAP generates is processed by a data analyst who sends the monthly performance data for Z51 to the LSS office who use this to make the monthly scorecard. Per part they review whether Z51 has been performed within the time span of 28 days. This gives an incomplete overview of incomplete data. If all parts in a combustor except one are on time the combustor will still be late, furthermore if all combustor parts have been repaired within the 28 days for Z51 the combustor might still be late as we do not know whether performance during the other phases was on time.

Furthermore, the tasks that are performed on each combustor, and the replacing parts that have been used are tracked in order to make the bill for the customer. The normative time defined in SAP is used to build up the bill. The more time an activity takes, the more a client is charged. If the time performance differs from the predefined time by only a few minutes no changes are made to the bill. However, if there is a large deviation this time will be adapted in SAP. If the large deviation occurs frequently a permanent change might be made to the time duration definition. It might be noted that the process times will not be defined to take less time as this might have a negative effect on the bill.

As mentioned earlier, every morning a roll call takes place. During this roll call the skillmanagers meet in order to discuss their work progress. This helps monitor the engine repair process. Furthermore, lists are presented showing the parts progress per engine and the time to delivery date. This allows the departments to discuss their issues, furthermore priorities are given. For example, the combustor part is about to be late if it is not treated in the oven within the morning. The oven manager can say whether or not this is possible and the combustor part is prioritized. By having this roll call people know where there is possible slack and where ropes need to be tightened.

As mentioned before, colour is assigned to each combustor. A storage space within the rack, and a ‘tracking’ system are linked to this colour. The tracking system indicates where in the shop the combustor is located/which task it is undergoing. However, 15 different colours are needed, which means that shades are used and it is not always clear which colour is which. The idea is that the sheet has a certain colour and the sticker on the rack has the same colour (including the name of the colour). However, the shades don’t always coincide, and as there is no colour name on the tracking sheet confusion can occur.

Inspections are the factor in the process that ensure the combustor parts are of the required quality. As such, inspections can be seen as a measurement of quality. However, these inspections are incorporated in the maintenance process in such a way that they are considered part of the maintenance method.

Fishbone Diagram
The issues found within the observations have been summarised in a fishbone diagram as shown in Figure 2.13.

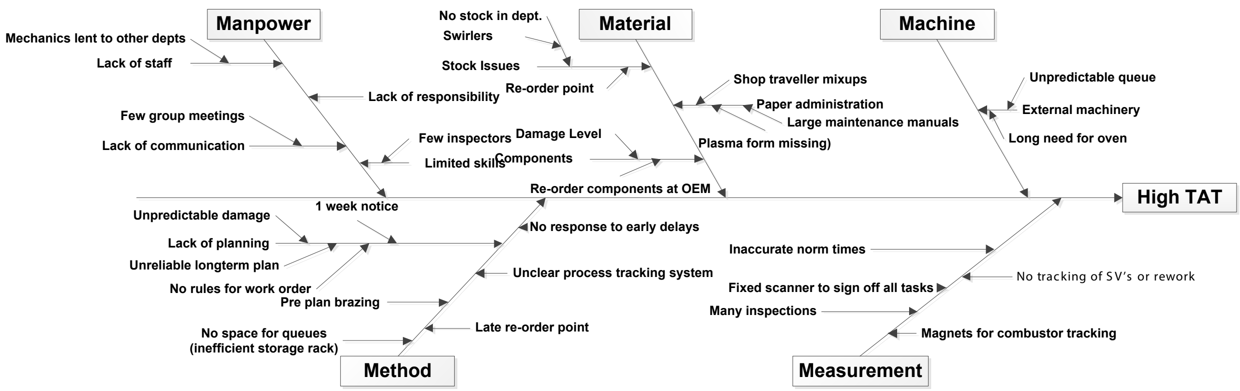


Figure 2.13: Fishbone diagram for combustor maintenance

2.2.3. Practice Research Conclusion

Within ES combustor repair has been identified as the main bottleneck in the engine maintenance process. The main issue is the high TAT of combustor maintenance. The process as discussed in this chapter consists of six maintenance phases. The combustor module is brought to the shop where it is inspected, and, if necessary, disassembled, cleaned, repaired and reassembled. The required TAT for combustor maintenance is 36 days. Furthermore, the combustor department performs inspections on combustors that have been externally repaired.

The focus of the analysis will be the CFM56-7B combustor as the AFI engine shop in Paris is “full capable” to carry out maintenance on the 7B combustors. Hence, TAT needs to be reduced for these combustor repairs first. The observations regarding the current state have been carried out according to the 5M’s. It has become clear that the process is not highly planned, and there is no consensus on which part needs maintenance when, and which task is carried out by whom. There are strict rules on the maintenance routes that need to be carried out.

It seems that the value drivers, the elements that are most influential to TAT, can be found within Manpower, Material and Method. Within Manpower the mechanics’ productivity and availability influences the TAT, along with their skills, in other words the capabilities of the people within the department influence TAT. Within Material the spare and extra parts management influences the TAT along with the availability of necessary paperwork. Most important is the state and type of the combustor components.

The people within the process carry out most of the maintenance, and thus influence the capacity.

Finally, the whole method of maintenance influences the TAT due to the different maintenance phases and the many inspections and the large variety of maintenance tasks throughout these maintenance phases, shortly summarised as the routing. Together with these factors the availability and organisation of skills have been explicitly identified by the combustor department as a factor that influences TAT, this can be translated to the planning.

The factors influential to TAT are listed below. It should be noted that the first three factors are value drivers and that planning and routing are part of the maintenance process that are influenced by the value drivers and management.

- Capabilities
- Components
- Capacity
- Routing
- Planning

2.3. Criteria & Variables Found

From literature and practice ideas and factors have been identified that are part of maintenance and process improvement. A general factor that is considered of important is the process TAT, and this thesis is looking to identify which value drivers determine TAT. Hence, the value drivers are variables of this research. The analysis that will be made of the ES combustor maintenance will help establish if, and to what extent the value drivers influence the combustor maintenance process. In this sense the main criterion is that the factors have a demonstrable influence on TAT.

Literature regarding TAT within aircraft maintenance is scarce. One source has been found that directly linked lean MRO to improving TAT, hence declaring the use of lean fit for the purpose of this thesis. Other sources have not directly linked lean to TAT improvement but they have identified factors that influence TAT. For instance Samaranayake [2006] suggests that improving planning on resources within certain workcentres can improve TAT. Thomas [2015] suggests that standardising maintenance practices can stabilise TAT.

LSS identifies five categories in which influential factors to the process might be found, the so-called 5M's. Within these categories the practice research has pinpointed components, capacity and capabilities as the main value drivers. Routing and planning are also considered influential to tat, but more on a management level.

The factors planning, standardisation and capacity, are part of LSS theories, and are considered to be influential to process performance. Taking the findings on MRO TAT, and combining these with the findings of lean and the practice research leads to the idea that planning and capacity are a few of the variables that are relevant to this research.

Furthermore, according to Slob, there are three factors essential to MRO, namely: capacity, tools and materials [Beelaerts van Blokland et al., 2012]. There needs to be enough capacity to handle the demand, and in order to realise maintenance the correct tools and materials should be available. Tools are part of the machinery, and as established from the practice research, in the case of combustor maintenance the machinery can be seen as capabilities. Furthermore in combustor maintenance the materials are the components. Therefore, capacity, capabilities and components are the main variables that require investigation of their relation to TAT.

Thus, summing up the criteria and variables found in the preliminary research, the main criterion is influence on the engine TAT. The variables that will be investigated are the maintenance routing, capacity, capabilities, planning and components.

2.4. Conceptual Framework

The main criterion and variables that are of most influence to the process have been identified. Therefore improving these factors should have a positive influence on the maintenance process, in turn improving TAT. A conceptual framework has been constructed, using these variables. The framework shows the relationships between these factors and the maintenance process.

The conceptual framework can be seen as a model of the engine MRO process. According to Morrison models provide a 'tool for investigation' that allows the user to learn about the world and theories [Morrison and Morgan, 1999]. As such a tool it can be used to investigate the relationships between factors that are believed to influence TAT.

Figure 2.14 depicts the relevant value drivers and how they influence the maintenance process The blue blocks are the value drivers, and the green blocks are indirect influencers. The conceptual framework should provide an answer to the first research question. However, this framework has not been tested, and therefore this answer is currently hypothetical. By verifying and validating the framework the answer can be accepted.

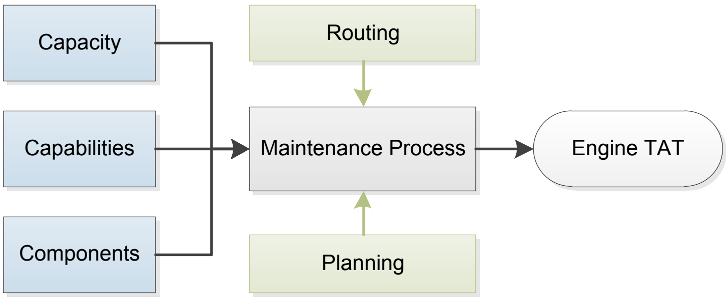


Figure 2.14: Conceptual framework for engine MRO

The second sub research question can be answered after analysis in which the relationships and their influence on each other have been analysed and can thus be determined. The verification and validation can be performed by investigating how and if these factors influence TAT. By performing a case-study, analysing the combustor maintenance process at ES and the role of the identified factors, the model can be tested on a real-life situation, which will verify the model to be fit for purpose. This will also allow the second research question to be answered. By then investigating to what extent the factors influence the TAT within the combustor maintenance process the framework can be validated, this will in turn answer the third research question.

3 Problem Analysis

This chapter will analyse the problem the combustor maintenance department faces. As such it should help to provide the answers to the third and fourth sub-research questions. The chapter will start by analysing the maintenance process in order to define the current state and main issues within the combustor department. The influence of each of the factors identified in the model will be determined, along with their relationships. This allows a better understanding of the causes of high TAT, and will help establish the main value drivers. The chapter will conclude with the main issues that require improvement.

The analysis will be performed using various LSS tools. For LSS the ultimate goal is a controlled process that is continually evaluated in order to improve the process where necessary. A controlled process means that the process is carried out in a controlled or standardised manner, and that the output is under statistical control. This can be achieved by reducing waste, operating based on customer pull and a single piece flow through the process.

According to Arnheiter and Maleyeff [Arnheiter and Maleyeff, 2005], a LSS company would include the main points of lean management and six sigma as follows:

- Maximize the value-added operations;
- Constantly evaluate incentive systems that ensure optimisation across the value stream;
- Implementation of a decision making process that takes into account customer impact;
- Make decisions based on data driven methodologies;
- Use methodologies that minimise quality variation;
- Create and implement education and training throughout the company.

Thus, the data obtained should be analysed not only to identify how TAT is influenced, but also to provide a basis for decision making. George [2003] suggests analysing the previously collected data and information in order to determine the source of delays and waste and exploring cause-and-effect relationships. Franchetti [2015] suggests value added process analysis; throughput, capacity and demand analysis; and Pareto analysis for improvement opportunities. Taking this into account the analysis performed should focus on value added activities, variation and waste.

Histograms, probability plots, and scatter plots are the main tools that will be used. The aim of the analysis is to identify whether the process is stable and under control with little variation in the output. The statistical analysis will be performed using statistical software, Minitab 17.

3.1. Maintenance Process

This section will discuss the current maintenance process as carried out within the ES combustor department. In order to do so data has been collected from SAP. From this data all maintenance carried out within the department from 2-1-2014 until 3-1-2015 has been extracted. This data is then used first to determine the input, after which the on-time performance for each component that has entered the system is determined. After this, the combustor repairs for the 7B combustors will be analysed in order to determine the current state of the combustor process. The outcomes of this analysis will be used to create a value stream map that illustrates the process as carried out by the combustor department.

3.1.1. Input

In order for maintenance to take place combustors arrive at the combustor department. The rate at which the combustors enter the system are relevant for the capacity, as this determines the distribution of 'pressure' on the system. Appendix D shows which combustors have arrived on which date, along with the normative maintenance time and the TAT.

Figure 3.1 shows the input of different combustor types and the total input per month throughout 2014. The data can be found in Table F.1 in appendix F. In total 90 combustors have come to the combustor shop. As can be seen the input is neither constant throughout the year for the total, nor for any of the combustor types. It becomes clear that the department does not use a buffer system to ensure a steady release of combustors into the system. This means that within the department the unstable input causes fluctuations in capacity and flow.

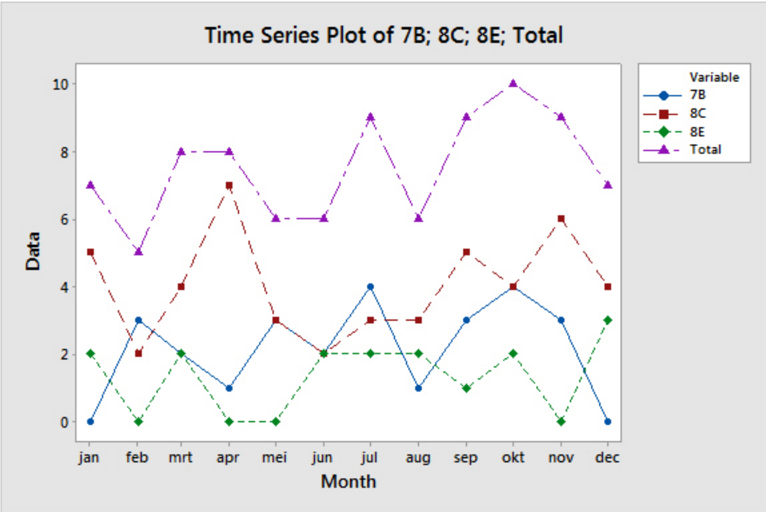


Figure 3.1: Combustor Input 2014

In agreement with the combustor department it has been decided that the focus of the problem analysis will lie with the 7B combustors. Figure 3.2 shows a histogram of the input of the 7B combustors per month throughout 2014. It shows that the input varies between 0 and 4 combustors per month, with a mean of 2.17.

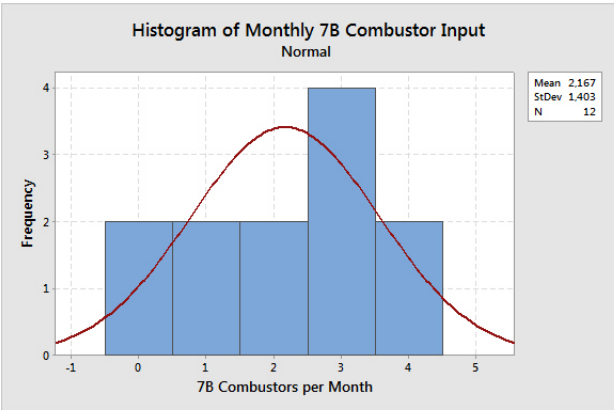


Figure 3.2: 7B Combustor Input Per Month 2014

3.1.2. Combustor Maintenance

This section will discuss the 7B combustor maintenance performance. First the general performance is discussed, after which the in-house and external repairs will be discussed. Finally, the data of the two groups will be combined in order to make a comparison of the behaviour and dependencies of the two.

For each combustor the maintenance start-date, phases, and completion date are known. Furthermore, the available data shows which tasks are performed by whom, in which sequence, and on which date a task is completed for each component. Using this information an overview of the combustor maintenance TAT can be given, including the TAT per phase. The TAT for each component that has entered the combustor department is shown in Appendix D, along with total on-time performance for each component type.

In order to determine what makes up the combustor maintenance TAT, the complete maintenance routes should be analysed. Information is needed on the maintenance route; whether this is similar for each combustor; if performance is on-time; how many combustors were delivered on time; and if the on-time performance is constant. Finally, the component or maintenance phase that regularly causes a high TAT should be determined. This section will analyse and discuss these factors. Table E.2 in Appendix a:j gives an overview of these factors.

Combustors do not just enter the combustor department for maintenance, they also enter the department after they have been externally repaired, in which case they are submitted to an overhaul inspection. This leads to a distinction between in-house and outsourced repairs. For each of the 7B combustors that have had an in-house repair, the actual and planned TATs have been defined. Based on the start and completion dates of each phase for every combustor component it is possible to create a graph, that can be used to visually determine whether or not the combustor is delivered on-time.

From the graph it becomes clear which component has the the latest Z51 completion date and is thus the critical part. Assembly cannot start until maintenance for this component is completed. The longest normative maintenance time for the critical component can be determined, that is, the time it should take for all tasks to be carried out subsequently without breaks. This normative time can then be translated to the expected TAT in working days. This is done by defining the daily productive working hours, and dividing the normative time by this productivity. Within KLM E&M per working day the productive hours are said to be 10.8 hours out of 16. The working days expected for maintenance can be compared to the actual TAT by means of the normative percentage of TAT. Based on this value the waiting time can be defined.

Waiting time in this context is defined as the time spent by a component waiting until it is handled. The relationship between waiting time, TAT and normative maintenance time is as follows:

TAT= Normative time + waiting time

An example of a maintenance overview graph is given in Figure 3.3. In the figure the TAT of each maintenance phase can be seen for each component. For combustor 7B-174790 the complete TAT is 39 days. This means that this combustor has been delivered 3 days late. Looking at the phases it can be seen that phase 02X-Z11, is performed in 1 day. Z01 and Z11 are also performed within 1 day, and Z42 varies per component. The Z42 TAT for the inner and outer liner is 2 days, and 6 days for all other components. Z52 is performed only on the outer liner, inner liner and the dome, and for all three components the TAT differs. The inner liner is repaired within the 28 days reserved for Z51, the other two parts exceed this time-frame. Finally, assembly is performed within 1 day. As the outer liner takes longest to complete, even though it had a short Z42, this component proves to be on the critical path for this combustor. The *Assembly wait* bar shows the amount of time each non-critical component has to wait until assembly.

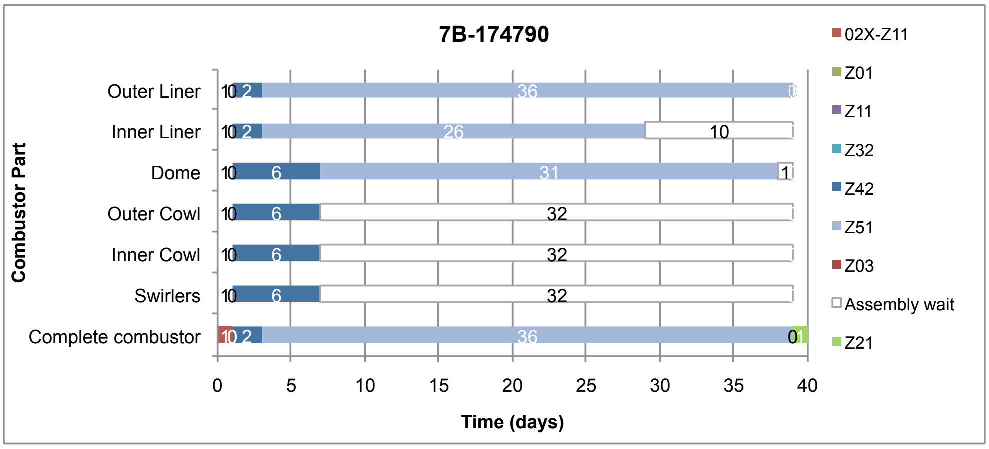


Figure 3.3: Combustor 7B-174790 Maintenance TAT

In Figure 3.4 the TAT for each combustor that enters the department is shown in order of arrival. A red line marks day 36, and another red line marks day 5. These red lines mark the handshake TAT for the in-house repairs and the inspections for the external repairs. As can be seen the TATs vary greatly, and it seems that the TATs vary at two different levels; one part of the combustors has a TAT between 0 and 15 days, and another component varies somewhere between 25 and 60 days.

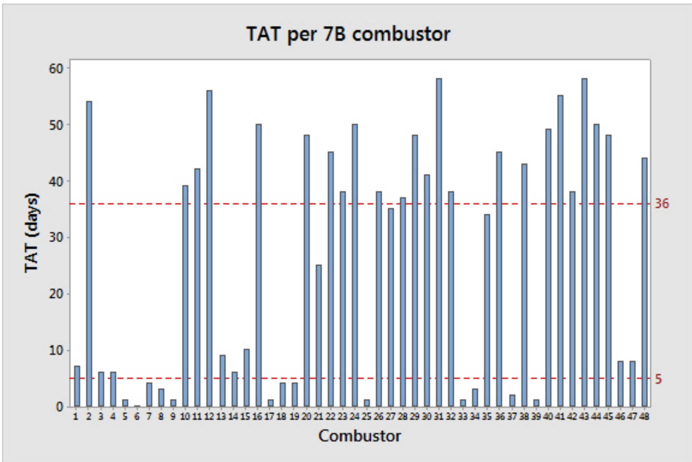


Figure 3.4: Bar Chart of TAT for all 7B Combustors

The histogram in Figure 3.5 confirms this observation as there is one set of bars between 0 and 15, and the other bars lie between 33 and 63 except one bar that lies between 21 and 27. This can be largely explained by the inclusion of the external or outsourced repairs in this set. The standard deviation is very large at 21.3 days. Given the average TAT of 26.9 this means that 64% of all combustors is delivered between 5.6 and 48.2 days. As the process should be focussed on a TAT around 36 days, this variation is very high. As the TAT and process for external repairs is highly different from the other combustors these should be considered separately. Ideally the average would be 36 days or less for the repairs, and 5 days or less for the inspections, both with a standard deviation of 0, meaning that the process is constant and all combustors are delivered on-time.

Using a normal probability plot the distribution of TAT can be tested. The data should form a single line if it is normally distributed, and is scattered around the graph if this is not the case [Gygi and Williams, 2012]. As can be seen in Figure 3.6 the TAT is not distributed normally, as the dots do not form a line but rather look like a rotor. The two groups, external and in-house repairs are likely each at other ends of the line, moving around one centre value. This indicates that there might be a lot of waste. Furthermore, Six Sigma can only be used when data is normally distributed, which means that the

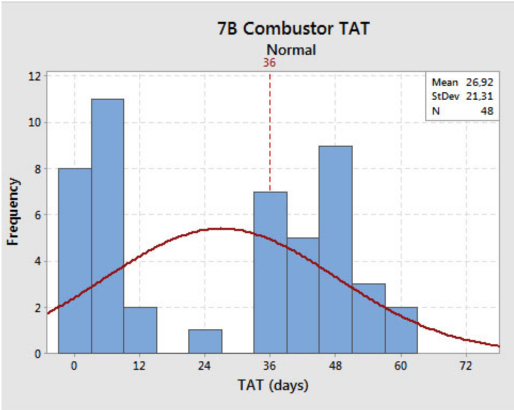


Figure 3.5: Histogram of TAT of Handled Combustors

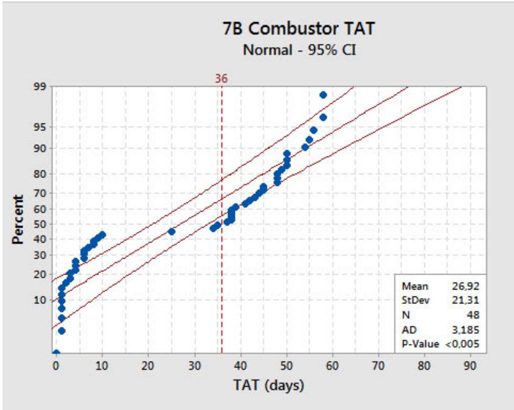


Figure 3.6: Probability Plot of Handled Combustors

performance should be stabilised before Six Sigma tools can be applied [Waard, 2007]. Put simply, the TAT line in the probability plot should be straightened using lean tools. LSS tools can be applied to stand up the curve, indicating a constant process, after which the line should be shifted left, indicating a reduced TAT [Six and Muller, 2015].

After collecting the data and seeing the complete maintenance routes for all 7B combustors within the combustor department a distinction has been made between in-house and external repairs. The in-house repairs include combustors with a regular maintenance route and combustors that have followed an exceptional maintenance route, where assembly has taken place before completion of the last part. The external repairs include combustors that have only entered the department for an inspection after an external repair. This because both groups have a different process, and TAT “goal”.

The following sections will first discuss in-house repairs, after which the parts that have been maintained externally will be discussed. For each of the repair types the goal is to determine whether the process is stable (shows little variation), whether waste is present, and if there are specific factors such as process disruptions, and outsourced repairs that influence TAT.

In-house Repairs

It has been found that the in-house repairs consist of regular and exceptional repairs. These are discussed into depth in Appendix F. From this analysis it has become clear that these repairs are similar regarding their maintenance route, TATs and critical components. As such it is interesting to combine the data for both in order to see to what extent they can be considered to be similar. This comparison will be carried out through a bar chart, histogram, probability plot and scatterplots.

Figure 3.7 shows the TAT for each of the completed combustors, organised in chronological order. A high variety can be seen in TAT, and there is no general trend that seems to be linked to time.

A histogram is created in order to see how the TAT is distributed. This is shown in Figure 3.8. The values seem to have a normal distribution around the mean of 44.7 days, with a standard deviation of 8.1. The mean is quite a bit higher than the handshake of 36 days. The standard deviation is also quite high, due to the relatively large spread of TATs. In order to improve performance both the standard deviation and the mean should be reduced.

To see if the TAT of 25 days is an outlier, and to check if the distribution is normal a probability plot has been made, as can be seen in Figure 3.9. This graph shows that the distribution is quite normal, but the tail veers off towards the left, and the base is also positioned to the left of the line. This graph clearly illustrates that almost 90% of the combustors are late and their values lie in a range of about 20 days, whereas the three on-time combustors lie within a range of 10 days.

Now that it is established that the in-house combustor TAT shows a (roughly) normal distribution, that

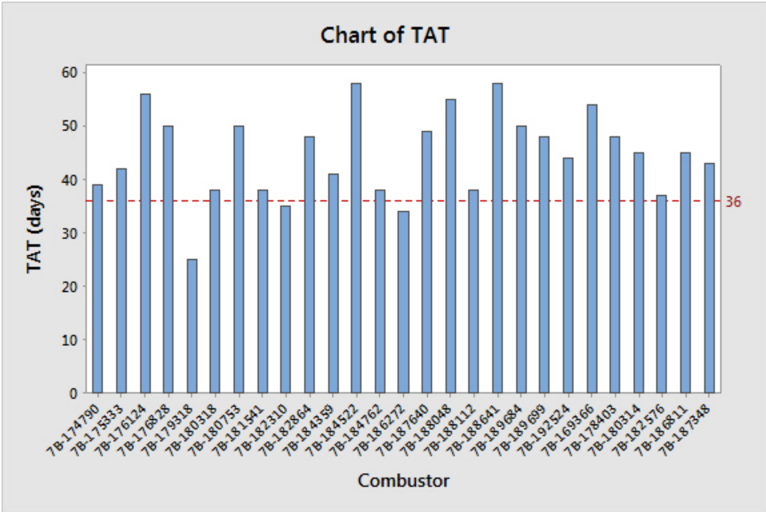


Figure 3.7: Bar chart of Handled 7B-Combustors

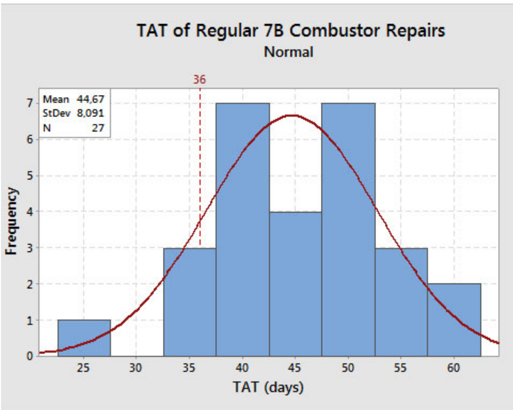


Figure 3.8: Histogram of Handled Combustors

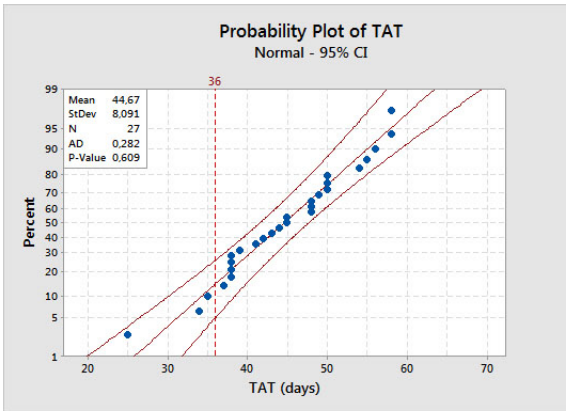


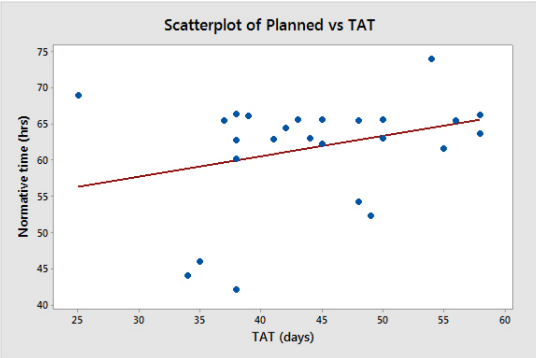
Figure 3.9: Probability Plot of Handled Combustors

the average TAT is too high and the range of the TAT is too wide, lean and Six Sigma tools should be used to “stand the line up and shift it”. In order to determine which factors might be influential to the TAT scatter plots are made to establish whether the TAT shows a correlation to certain factors such as the planned norm time and PVs.

Figure 3.10 shows that there is some correlation between the TAT and the planned normative maintenance time (thus the normative time for the planned longest route). The regression line shows that as the normative time increases the TAT becomes higher. However, there are quite a few values that are scattered around the graph. As such it can be concluded that the TAT is dependent on the planned normative time, albeit on a very low level. It is possible that the dependency is influenced by different types and amounts of waste in the different combustor maintenance processes.

One of the factors that is assumed to influence TAT is the number of process disturbances or PVs. Figure 3.11 shows how the presence and number of PVs in a maintenance route influence the total TAT. As can be seen, the correlation between the two factors is very small as many data points are scattered across the graph. Roughly, as the number of PVs in a repair increases, the TAT increases. It is logical that PVs influence TAT, however, the dependency is probably influenced by high amounts of waste.

Aside from the presence of PVs the TAT of these PVs might also influence TAT. In quite a few cases the TAT for the PV is extremely high, or non-existent. Therefore, the TAT for PVs are not considered, as they do not seem to be tracked properly. The PVs should be properly monitored and tracked. Further-



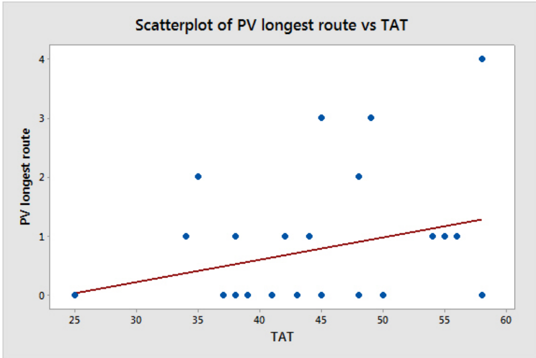


Figure 3.10: Scatterplot of Planned Norm Time and Actual TAT

Figure 3.11: Scatterplot of Process Disruptions and TAT

more, the available information should be stored and evaluated in order to see how the PVs influence the maintenance process and TAT.

In conclusion the combustor in-house maintenance process can be said to produce a fairly normally distributed output. However, this output has a large spread, and a high average and standard deviation. Hence, the process is likely to contain a lot of waste. Factors that influence TAT are PVs and normative times, however, the extent of their influence is small. Assuming that normative times are accurate there is a lot of waiting time or waste in the process. The causes of the waiting times and waste should be identified in order to improve process performance.

Outsourced Repairs
Some combustors can not be repaired by the combustor department and are repaired externally by other MRO companies. ES remains responsible for the quality of the combustor. Therefore, outsourced components are inspected after external maintenance. This inspection is performed within maintenance activity code Z03. The normative time that is set for this activitiy is always 1.5 hours, and the handshake is to perform Z03 within 5 days. In Appendix F these repairs have been analysed more extensively.

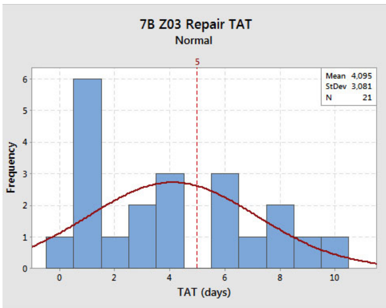


Figure 3.12: Histogram of TAT per Z03 Inspection

The outsourced components require very little work or time in the combustor department as they only require an inspection to verify their quality. However, the time in which such an inspection is performed is highly variable, as can be seen in Figure 3.12 the distribution of the TATs for the completely outsourced combustors leads to believe that the TAT is influenced by the urgency of the need for the combustor. This is also reflected in the low TATs for the outsourced components, as these components are always finished within handshake TAT and the complete combustors for which a componentis outsourced are the only combustors that have been completed on time. Finally, the high discrepancy between the normative time and TAT suggests that there is a lot of waste in this process. As this process exists of only one task there is no need for further analysis of this process itself. It is assumed that the causes for waste within Z03 activities are similar to those within the regular repairs, and can hence be resolved using similar solutions.

Combustor Repair Conclusion
For each combustor in the data set both the actual and planned maintenance times have been determined. For each combustor the maintenance route was evaluated; was it a regular route, were there exceptions (i.e. did assembly take place before the completion of certain components), or was maintenance outsourced and carried out externally? Furthermore, it has been checked whether or not each combustor was completed within the required TAT of 36 days for the full maintenance route, or 5 days for the external repair. And, which combustor component was on the critical path, or took the longest to repair, and which component was planned to take longest. Table 3.1 summarises the findings of the collected data.

Table 3.1: Summary of Combustor Repairs

	7B			Actual Critical Part				Planned Critical Part			
	Handled	*On time*	*PV*	*Outer Liner*	*Inner Liner*	*Dome*	*components at same time*	*Chamber*	*Outer Liner*	*Inner Liner*	*Dome*
Reg	21	3	49	11	4	1	5	0	1	9	11
Exception	6	0	17	5	2	1	0	0	0	2	4
Z03	21	13	0					21			
Total	48	16	66	16	6	2	5	21	1	11	15

As can be seen in Table 3.1, from the 27 combustors with an in-house repair six are found to be an exception, and an additional 21 combustors have come to the combustor department after an external repair. From the summarised data one can see that from all the 7B combustors viewed only 33% was completed within the predefined TAT. If one looks at the in-house repairs, only 11% of the 7B combustors has been completed on time.

It has been found that the swirlers and cowls are never critical components. This is due to the fact that these components never go through phase Z51. What's more, it can be seen that the outer liners are most frequently on the critical path, whilst regarding normative repair times the dome would be expected to be on the critical path. As such it can be concluded that the type and damage to the component directly influence TAT.

In conclusion the combustor in-house maintenance process and inspection process for external repairs is variable, and shows a high average and standard deviation. The process is likely to contain a lot of waste. The difference between the planned normative times and maintenance routes and the actual TAT is very large. This discrepancy is believed to be waiting time and is thus considered waste. On average the waiting time is about 90% of the TAT.

These findings indicate that the process is unpredictable, and the current planning method is not sufficient, or is not used properly. PVs and normative times are found to have an influence on the TAT albeit almost negligible. Due to this it is concluded that the process contains a lot of waste. Furthermore, the data of the Z03 process gives reason to believe that once a combustor or componentis late, little effort is made to quickly complete the remaining tasks. The causes of the waiting times and waste should be identified in order to improve process performance. Further analysis is required regarding the repair process. This will be done by analysing the in-house repairs. It is assumed that the single Z03 task will be similar to the individual tasks within the repair process.

3.2. Current State

The preliminary analysis of the combustor repairs allows a Value Stream Map (VSM) to be created using the available data. A value stream map is a tool that shows the material and information flows, and helps identify value and waste. According to Rother and Shook [2003], 'a value stream is all the actions (both value added and non-value added) required to bring a product through the main flows essential to every product'. In order to come to a future state, the current maintenance situation should be analysed, which can be done through making a "current-state" VSM. This section will first show the

VSM made with the combustor department, after which a current state VSM will be made.

According to Franchetti, lean examines all forms of waste in an organisation in order to reduce cost. The value is evaluated from the end customer's perspective, and a key tool is a VSM. The VSM shows the flow of the product through the process from the customer's perspective. Any process the customer is not willing to pay for, or does not add customer value should be eliminated and every activity is categorized as "value-added" or "non-value-added" accordingly [Franchetti, 2015]. Furthermore, according to George[2003], a VSM allows the time-traps in the process to be visualised.

Together with the mechanics, skill manager and department manager a value stream map of the combustor maintenance process was made. This map was based on an exceptionally long Z51 maintenance route of a combustor component that was handled by the department (128 tasks), but was marked "Void" halfway through the process. As such it is not useful for the definition of the current state. However, as the VSM session was conducted with most of the department it was useful for the department to gain insight in the process, and discuss where possible wastes might occur. The notes of this session can be found in Appendix B.

Using the available data a current-state map is drawn of the 7B combustor maintenance that has been previously used as an example. The VSM shows door-to-door flow in the department, and processes are grouped together rather than showing each process step. This VSM is based on all maintenance phases rather than on a single phase. In Figure 3.13 the current-state VSM is shown. In the map the process supplier, the process customer, the process phases and the process control group are identified along with the physical and information flows.

The supplier and customers, in this case engine disassembly, a-prep and the end-customer are shown using a "factory" symbol. Each process is identified using a process box. This process box contains the number of people that execute the process. The data regarding a process or external party is shown in data boxes below each item. The arrows that come from and go to the external parties show the transfer of finished goods, the method of shipment is by pushcart which is shown with the pushcart symbol. The triangles between processes show where possible inventory. The push between process tasks is shown with the dashed arrows.

Information flows are also an important part of the map. According to Rother and Shook [2003], a question to ask is: *How can information flow so that one process only makes what the next process needs when it needs it?*. Throughout the process both digital and physical information can be identified. The digital information is shown with the bolted arrows, and the physical information is shown with the regular arrows. Finally at the top centre is the process control group which uses SAP to manage the processes within ES.

The databoxes per process phase contain information on the duration and productivity of the phase. HS stands for handshake time, the time which is allocated per phase, this is followed by the actual time spent on this phase in days, the normative time allocated per phase in minutes, the working time spent during the phase, the number of tasks during this phase, and finally the number of components that go through the phase. This is different from the data suggested by Rother and Shook [2003], such as the up-time and changeover time necessary for machines, and for instance the number of product variations are not directly relevant. The data they suggest is relevant for a production process where each componentfollows the same production line and has to wait for the componentahead to be completed. However, the components within the combustor maintenance process do not all follow the same route, and are not solely processed by machines that execute the same operation continuously. Hence, changeover time and up-time are not the most relevant factors in deciding what the future state will be.

The line at the bottom of the VSM shows the actual TAT in days, and the normative times of the combustor, in minutes, which can be seen as the time in which the combustor has actually been handled. Looking at Z51 the normative time is approximately 24 hours, whereas the TAT for that phase is 36 days. This indicates waste.

The map clearly shows that there is a lot of waste in the process, as the processing time is much lower than the actual TAT. The VSM illustrates that the TAT is mainly caused by the internal performance, as in general not a lot of waiting occurs due to inventory or late deliveries. Furthermore, there is very little planning and communication between the phases. It becomes clear that spare components are ordered at a relatively late point in the process, and that relatively little inventory is needed. The inventory between Z51 and Z21 will always exist as these are the combustor components that have already been repaired but are waiting for assembly. Furthermore, it becomes very clear where most of the waiting time exists, namely during Z51.

As discussed in Chapter 2, only Z42 and Z51 are value added components of the process, all other phases are non-value added. However, in some cases these phases might be necessary. In order to determine this the tasks within each process phase should be evaluated, which will be done in the following section.

3.3. Value Drivers

In chapter 2 an analytical model has been designed that identifies the value drivers and factors that influence the maintenance process and in turn TAT. The previous section has led to the definition of the current state in the form of a VSM. This section should show if the identified factors really do influence TAT, and how they are related to each other. Figure 3.14 shows the analytical framework and the factors that have been identified.

3.3.1. Routing

In order to understand how maintenance takes place, and to identify how routing influences TAT the maintenance routes should be analysed. As discussed in the previous section this will be done for the in-house repairs of 7B combustors. For each of the combustor repairs the critical maintenance route will be evaluated in order to find out if waiting time occurs especially during specific phases or if the waiting time is related to task sequencing.

For each combustor the complete maintenance route has been determined based on subsequent tasks performed on a combustor and its critical component. For each phase the start date is available, and for each task an end date is available. Using these dates the TAT per task and per phase can be determined for each component, as well as the complete combustor In order to determine the TAT per task four assumptions are made:

1. A task is assumed to start directly after the preceding task is finished;
2. All tasks performed on one day are assumed to be performed without waiting time between these tasks, as there no end-times are available;
3. It is assumed that each task is carried out in the normative time;
4. The TAT is assumed to consist of normative maintenance time and waiting time.

The consequence of the first and second assumption is that the TAT is automatically allocated to the first task finished on the date after completion of the preceding task. Another consequence, as can be seen further on, is that when a maintenance phase that has a handshake of one day is started at the end of a day, and is finished the following day, the component will be considered late even though maintenance might have actually been carried out within the normative time. The last assumption means that if a task has a TAT of 1 day (10.8 hours) and the normative time for this task is one hour, the waiting time is 9.8 hours.

Table 3.2 is an excerpt of the data used to determine a maintenance route and it illustrates how the TAT is determined between tasks within a phase. The subsequent rows contain subsequent tasks.

The table shows which capability is required for a task, which exact task is performed, how the tasks are ordered, and the normative time allocated to the task (both in minutes and hours). This information is used to see if for instance a lot of the waiting time occurs at Q702 (benchworking). Aside from this

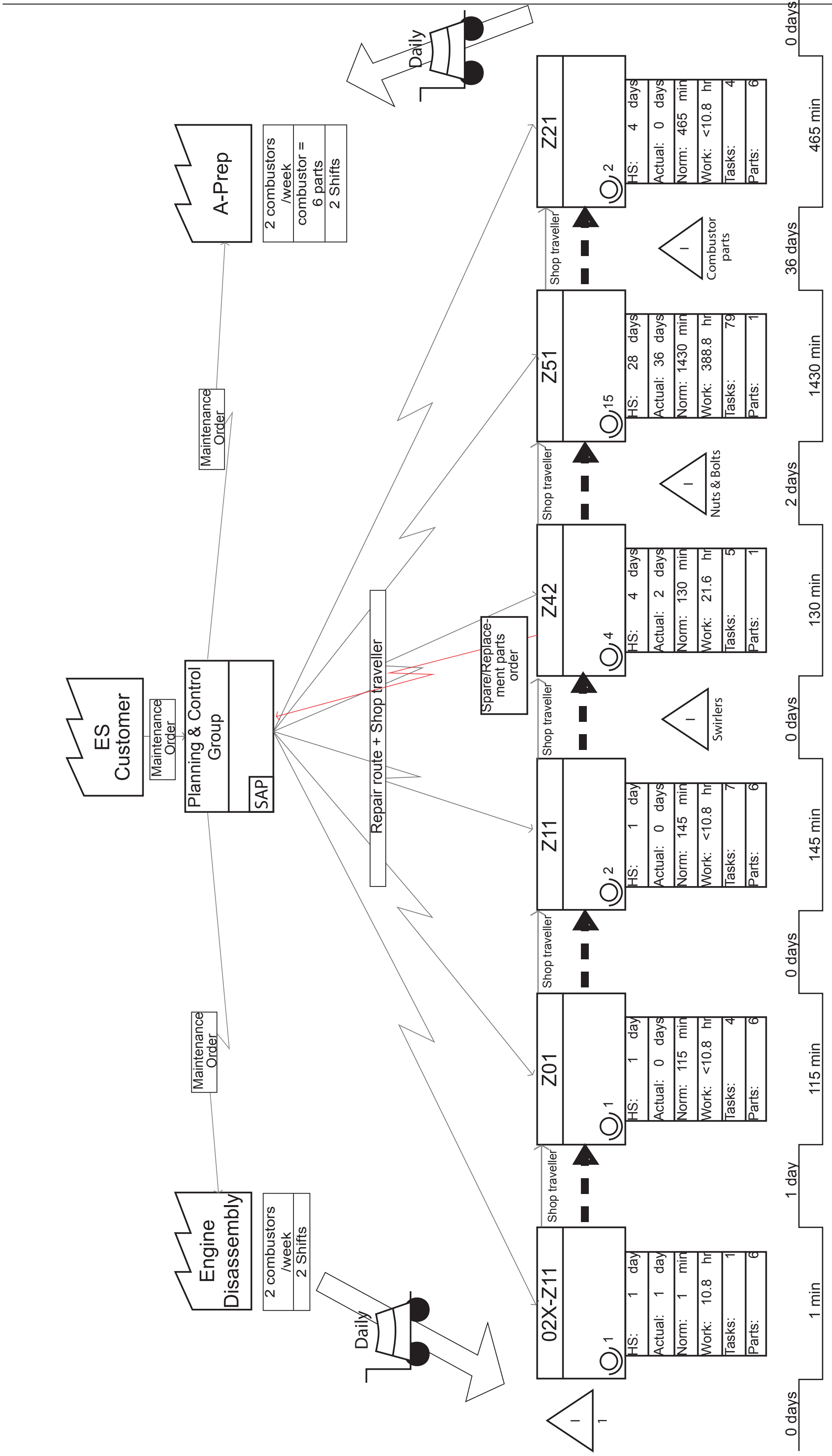


Figure 3.13: Combustor Department Current-State

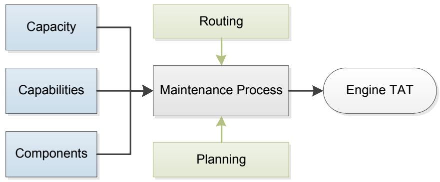


Figure 3.14: Conceptual Framework for Engine MRO

Table 3.2: Example of Available Data Used to Determine TAT Per Step

Capability	Task	Service Order	Duration (min)	Duration(hrs)	Finish Date	TAT(days)
Q428	5-2 TASK.E	120	45	0.75	20-2-2014	0
Q702	5-2 TASK.F	140	15	0.25	21-2-2014	1
Q034	5-2 TASK.G	160	5	0.08	21-2-2014	0
Q034	8-2 TASK.A	200	15	0.25	21-2-2014	0
Q702	8-2 TASK.B	220	50	0.83	21-2-2014	0
Q683	8-2 TASK.C	240	40	0.67	24-2-2014	3

information it is known during which phase a task is carried out, this helps to determine how much time is usually spent on a phase.

Phases

Each combustor component goes through several of the maintenance phases, and not all components follow a complete maintenance route. Figure 3.15 summarises this process for these 27 complete combustors. As can be seen the complete combustor enters the combustor department during phase 02X-Z11 or phase Z01. During phase Z11 the combustor is disassembled and the separate components continue on their individual maintenance routes. The cowls and the swirlers never go through phase Z51, and not all components enter during phase 02X-Z11 (this can be seen in the row depicting the amount). In phase Z21 all components are assembled, which is why Z21 only starts after all components are completed. For each component that goes through a phase the TAT is determined, along with the on-time performance. As can be seen the on-time performance for certain phases is quite high, but as the on-time performance accumulates the total combustor on-time performance is only 11%.

As on-time performance depends on the component with the longest maintenance time, the evaluation of each phase will be performed on the critical components. The data and discussion of this evaluation is presented in Appendix G. The main findings from the evaluation will be presented below.

It has been established that for certain phases the number of tasks is always the same, as is the normative time for these tasks. Table 3.3 shows that this is the case for all phases except phase Z42 and Z51 as these phases show varieties in tasks and duration. It should be noted that phase 02X-Z11 is not carried out by the combustor department in all cases, and it only consists of one task with a normative time of 1 minute. As can be seen assembly is expected to be most time consuming with a normative time of 465 minutes for only 4 tasks. Furthermore, if a complete maintenance route is carried out it will consist of at least 17 tasks and will take 726 minutes, which translates to 12.1 hours of work. This means that the basic maintenance could be carried out in little over a day, using KLMs productive hours, or in a single day when considering working hours.

Table 3.3: Constant Phases

Phase	02X-Z11	Z01	Z11	Z42	Z51	Z21	Total
Tasks	1	4	7	-	-	4	**17**
Norm (min)	1	115	145	-	-	465	**726**

It should be determined if there are phases of the process that have a constant performance, and if

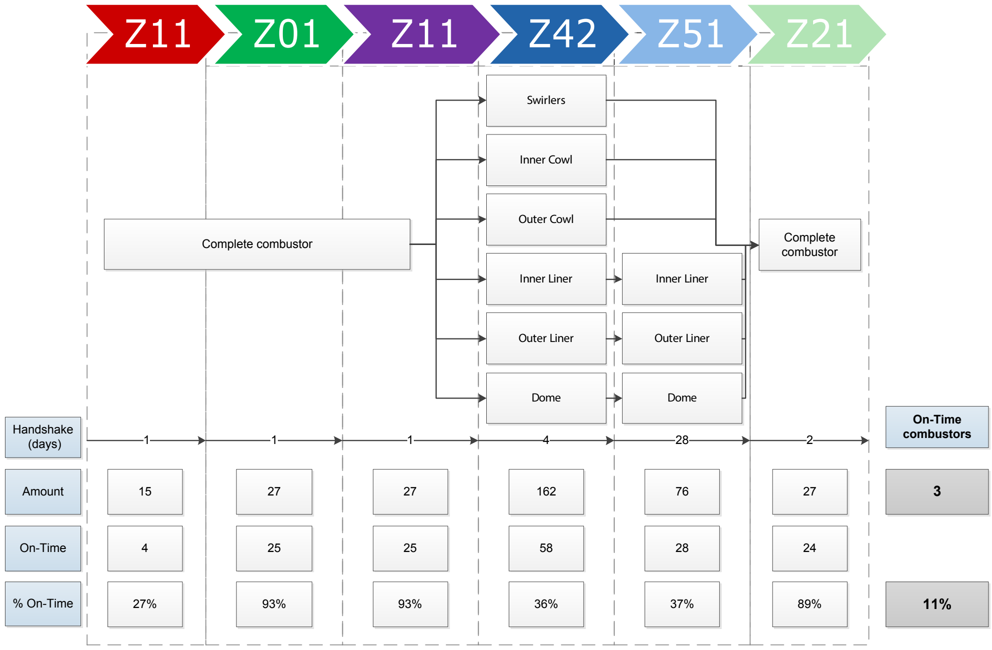


Figure 3.15: maintenance route Visual Summary of On-time Performance per Phase

performance is on-time. Table 3.4 shows the internal handshake TAT per phase. The handshake TAT is compared to the average normative times per phase. In the cases of Z42 and Z51 this is an average, in the other cases it is the actual normative time (as this is always the same). By comparing these times we can see that in most cases the normative time is only a fraction of the handshake time, Z21 is an exception with a normative time that is 72% of the handshake TAT.

Table 3.4: Internal Handshakes for TAT per Phase Compared to Normative Times per Phase

Time/Phase	**Z11**	**Z01**	**Z11**	**Z42**	**Z51**	**Z21**	**Sum**
HS (days)	1	1	1	4	28	1	36
Average Norm	1	115	145	170.8	2306.7	465	3203.5
Norm vs HS	0%	18%	22%	7%	13%	72%	14%

The on-time performance per phase differs between phases, as can be seen in Table G.4 of Appendix G. For phase 02X-Z11 the component was maintained within the handshake tat of 1 day only 27% of the time. Given the fact that this one task should take very little time this is very surprising. For Z01 and Z11, the on-time performance is quite high at 93%. On-time performance is poorest for phases Z42 and Z51 which both have an on-time performance of 19% . Z21 has an on-time performance of 78%, even though the difference between normative maintenance time and the handshake was so small.

In order to determine the variation of TATs a histogram and probability plot is made for each phase. The analysis for each individual phase can be found in Appendix E. In order to compare the performance of the different phases a probability plot containing all phases has been made. This section will discuss the summary of the findings.

Figure 3.16 shows the probability plots of all phases. It is clear that Z51 has the highest TAT. Phases Z21, Z01 and Z11 show the lowest TATs. In this plot all TAT distributions seem normal, however, this is not the case for the three phases with the lowest TATs. The phases that need most improvement are phase Z42 and Z51 as these phases take up the largest share of TAT. Furthermore, the fact that Z21 has a good on-time performance, even though this phase has the smallest margin, should also be investigated further. Is this because the norm times for this phase are too high? Is it because this phase is carried out by a single person? Or is it because this phase is used to compensate for lost

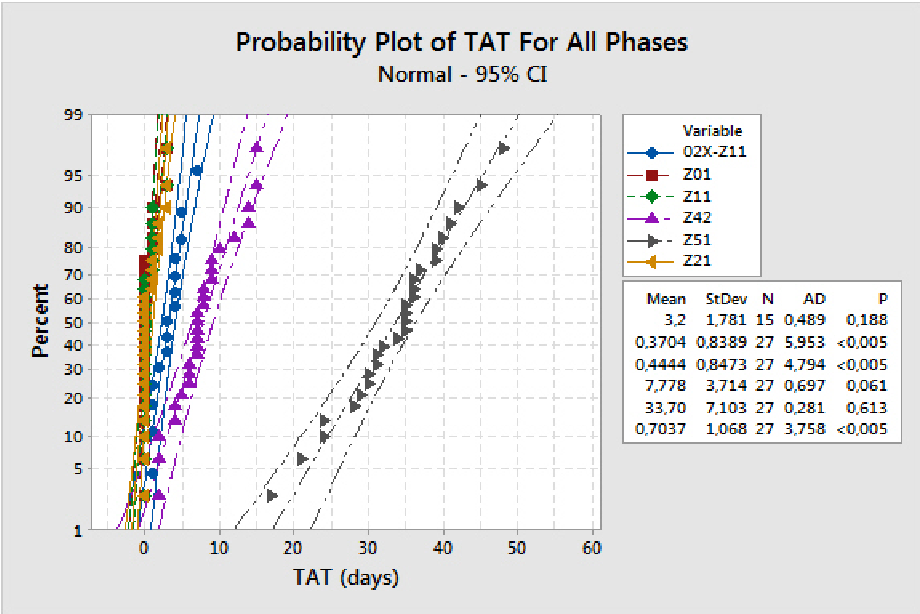


Figure 3.16: Probability Plot of TAT for All Phases

time? However, this will not be investigated further within this thesis.

In order to see whether the on-time performance and TAT of phases Z42 and Z51 combined form a good indicator of on-time combustor performance these TATs are compared. This comparison can be seen in Table F.8 of Appendix F. If phase Z42 and Z51 are not completed within 32 days (the combined handshake TAT for these phases) the combustor will be late. On average the TAT for Z42 and Z51 combined makes up 93% of the total combustor TAT. Therefore these phases have most influence on the total TAT, and further analysis should focus on these phases.

Conclusion Phases It can be concluded that the maintenance phases vary depending on the combustor component type and damage. There are only three components that require Z51 maintenance, namely the inner liner, the outer liner and the dome. Furthermore phases Z42 and Z51 have the greatest influence on TAT, as they make up 93% of the TAT and together require most maintenance time. Phase Z42 shows fairly similar tasks and normative maintenance times for each combustor and component. Phase Z51 shows greatest variety in number of tasks and normative maintenance times, and for this phase the maintenance route is mainly determined by state the component.

The other phases are similar for each combustor, require relatively little maintenance time and make up only a small share of the total TAT. As these phases are always similar it would be expected that performance would be more consistent. However, as the probability plots show for these phases, that is not the case. However, for phase Z42 and Z51 the spread of TAT is larger. This can be due to the unpredictable nature and length of the maintenance route within these phases. Therefore, it can be said that the length and predictability of the maintenance route has an influence on TAT.

Task Sequencing

As discussed in Chapter 2, the various tasks and capabilities required for maintenance are irregularly interspersed within the process. The same is true for waiting time. Figure 3.17 shows an example of the maintenance route for Combustor 7B-188112 and illustrates this. The figure shows where in the process different tasks and techniques are used, and how long this takes. As can be seen, there is a high variety in capabilities and sequence. However, the waiting time is so large compared to the tasks, not all tasks can be seen.

Figure 3.18 shows the route without waiting times to compare the two. It shows much more tasks, and a higher variety of different tasks that follow each other. This is mainly because the waiting time is so

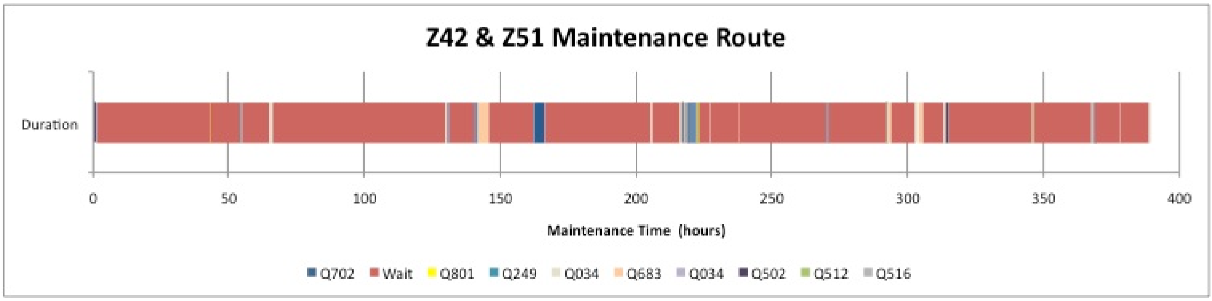


Figure 3.17: Bar chart of the Normative Time per Task and actual Waiting Time for Combustor 7B-188112

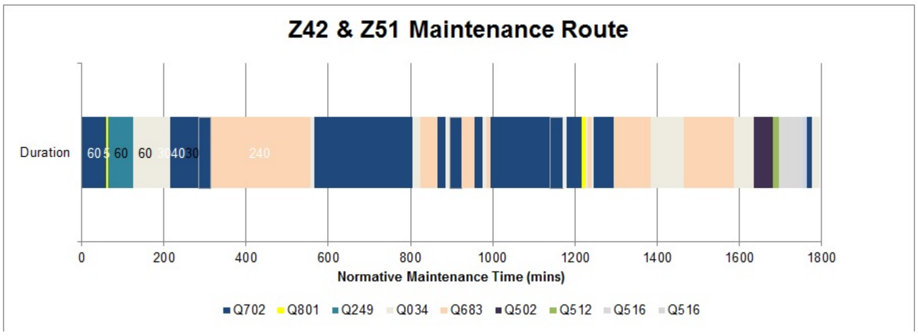


Figure 3.18: Bar chart of the Normative Time per Task for Combustor 7B-188112

large that smaller tasks become invisible in Figure 3.17. Comparing the two figures illustrates what the effect is of the waiting time, where in the process it occurs and how much longer the TAT becomes. It should be noted that this is the combustor with least tasks during the maintenance route. This route would be expected to have relatively little variety and waiting time. However, this combustor still shows a lot of waiting time and the TAT performance is longer than demanded. Therefore it can be assumed that for combustors with a longer maintenance route this will occur even more.

As the required capabilities are scattered throughout the maintenance route either the people that carry out the tasks need to be able to perform many different capabilities in order to continuously carry out maintenance for one part. Or, the people should focus only on carrying out one capability for various components. As the majority of tasks requires only a few capabilities, it would make sense to have people carry out maintenance for one component requiring different capabilities. Furthermore, this would be in line with lean one-piece-flow. However, if mechanics can not carry out all required capabilities, a component will have to wait at certain times until a mechanic that does have the required capability can carry out the next task. Thus, the routing sequence determines the required capacity of the required capabilities. The sequence will also influence planning, as the correct capacity and capabilities should be made available at the required time. Furthermore, not being able to carry out certain tasks disrupts the flow, and therefore the sequencing of tasks causes waste.

Routing Conclusion

This section has discussed how the phases and task sequences within a maintenance route influence the maintenance process and TAT. The routing is found to be determined by the combustor component. Depending on its type and damage the component requires different maintenance routes and phases. Phases Z42 and Z51 consist of most tasks, and comprise the largest share of TAT. The maintenance route comprises many tasks that require different capabilities, and 90% of the TAT consists of waiting time. Throughout a maintenance route the tasks require various capabilities, depending on the capabilities of the mechanics this influences the capacity and hence influences both the required planning and available capabilities.

3.3.2. Components

This section will discuss if the combustor component type has an impact on the maintenance process. As discussed in previous sections different maintenance tasks are carried out for different combustor components. This section will determine how the maintenance phases and tasks vary for each component type.

Section 3.3.1 has shown that the maintenance tasks for all phases except phases Z42 and Z51 show similar maintenance tasks and times for each combustor. This could be explained by the fact that during these phases individual components are handled rather than a complete combustor. As the maintenance routes analysed are for different components it is possible that the variation in tasks and normative times are related to this. In order to determine this the number of tasks and the normative times have been compared for each combustor part.

For Z42, as can be seen in Table 3.5 the number of tasks and the normative maintenance times vary depending on the type of component. However, variation in tasks and TAT is also possible for similar components. This not only shows that the number of tasks per componentis not always the same, it also shows that the normative time per task can vary.

Table 3.5: Maintenance Tasks and Normative Times per componentfor Phase Z42

Part	Tasks	Norm (min)	Occurrence
Dome	4	185	5
Inner Liner	4	185	1
	5	185	5
	6	185	1
		230	1
	7	232	2
Outer Liner	5	130	8
	6	175	4

For phase Z51 the variation is much larger, as shown in Table 3.6. The variation is smallest for the dome, and largest for the outer liner.

This demonstrates that the number of tasks and the normative times do depend on the component type. However, as there are quite a few varieties of tasks and norm times it is likely that something other than the components also influences the number of tasks and the norm time per step. This is probably the damage, as the variation within Z42 where the component is prepared for maintenance is less than the variation within Z51 where the damage is actually repaired. Unfortunately, no data is available on the damages and repairs needed for the combustors that have been evaluated. Hence, this can not be further analysed. Aside from the damages that might affect the number of tasks and normative time, it is also a possibility that the nature of the tasks with a similar amount and normative time varies.

3.3.3. Capacity

One of the value drivers is the maintenance capacity. In order to see what influence the available capacity of the combustor department has on TAT this will be analysed in the following section. The capacity of the combustor department is determined not by the speed and capacity of machinery, but by the available mechanics and their capabilities. Therefore, capacity can be considered as available man-hours.

For 2014 the work performed per day, and the available mechanics per day are known as shown in Table 3.7. In 2014 the combustor department has been open 268 days, and 47 different people have worked in the department. Together these people have performed 15905 tasks with a total normative time of 7571 hours. Not all maintenance carried out has been carried out on combustors but also on coffeepots, and the HPC Stator. In total these tasks had a normative maintenance time of 169 hours.

Table 3.6: Maintenance Tasks and Normative Times per componentfor Phase Z51

Part	Tasks	Norm (min)	Occurrence
Dome	48	1610	1
	61	2343	1
	87	3018	1
		3058	1
	94	3228	1
Inner Liner	94	2695	1
	98	2735	1
	103	2815	1
	105	2815	2
	107	2855	2
	110	3065	1
	113	2955	1
	129	3520	1
Outer Liner	71	1125	1
	86	1190	1
	103	1810	1
	105	1848	1
	111	2248	2
	112	1430	1
		2248	2
	115	2293	1
	117	2230	1
	123	2438	1

This is only 2% of the total time spent on maintenance within the department, so this has little influence on the capacity available for combustor maintenance.

Table 3.7: Maintenance activities within the Combustor Department

	Mechanics	Capabilities	Tasks	Time (hrs)
Combustor	47	20	15794	7402
HPC Stator	22	5	42	9
Coffeepot	15	1	114	160
Total	49	20	15905	7571

The capacity of the department is determined by the available working hours, which is a combination of the opening hours and the available mechanics. It is assumed that each person works an 8 hour shift, and that at least one task is performed within that shift. However, as discussed during the previous chapter, not all people have the same capabilities, and thus not everyone can carry out the same tasks. Hence, the capacity is limited by available skills. Therefore, it is relevant to know not only how many people are available, but also which people are available. This section will discuss the available capacity, the use that is made of this capacity and which tasks take up most of the capacity.

Available Capacity
Not all mechanics that have performed work in 2014 are actually part of the combustor department. Only 23 of the 47 people mentioned earlier are actually combustor mechanics. The number of mechanics who are part of the combustor department can be compared to the total number of people that have worked in a day. This is done in Appendix E. In general the difference between the two is not very large, and the maximum number of total people working on a day is 13, whereas the maximum is 12 for the combustor mechanics. Therefore the people that are not part of the combustor department are not considered part of the capacity for the combustor department.

Knowing how many mechanics have worked in a day allows the capacity of the department to be determined. The capacity can be defined as:

Capacity (hours) = People from 2400 x Available Working Time.

As every person in the department works an 8 hour shift, which includes two 15 minute breaks, the available working time is 7.5 hours. In Figure 3.19 a time series plot is shown which visualises the daily capacity. As can be seen, the daily capacity fluctuates greatly with a minimum of 0 hours, to a maximum of 90 hours on a day. The minimum of 0 can be explained not by the regular weekend (as these days have not been analysed) but by a weekend day where a task was performed by a mechanic that is not part of the combustor department. It is possible that this is mainly to do with a task being signed off a bit after 24:00 on Friday night, and is therefore not considered relevant for the capacity analysis.

Figure 3.20 shows a histogram of the people that have worked for the 2400 department. On average 7.4 people work per day, with a maximum of 12 people and 90 hours. This means that the average capacity should be 55.5 hours per day.

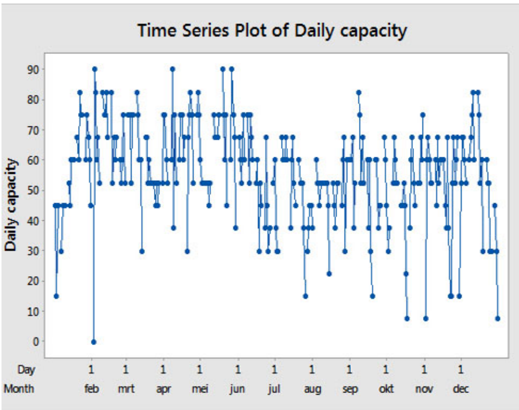


Figure 3.19: Time Series Daily Capacity 2014

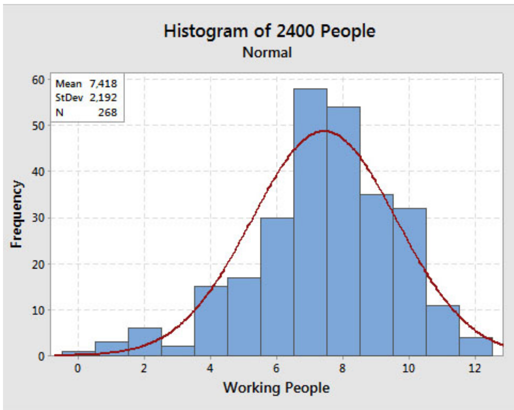


Figure 3.20: Histogram of People Working in Dept. 2400 in 2014

On average, for 2014 the capacity is 55.6 hours per day, as shown in Figure 3.21. It would be expected that the capacity would be somewhat constant around 52.5 and 60 hours, as two shifts of 4 people would be the regular staffing of the department, according to the skill managers. Taking in to account that it is possible that some days a person takes leave or attends training, it is possible that there are only 7 people available. However, quite frequently the capacity is higher or lower. The minimum capacity can be said to be 7.5 hours, which has occurred three times, this might also be due to a late registration. The maximum capacity of 90 hours has occurred four times. It is interesting to see that the histogram has empty bars, this is due to the bars having a size of 5 and the intervals in capacity are 7.5. It can be said that the capacity of the combustor department is not constant.

Figure 3.22 shows a probability plot of the capacity. As can be seen, the values do not have a normal distribution. This is to be expected as the capacity only increases in increments of 7.5 hours. Furthermore, if one looks at the daily fluctuations of the capacity (as can be seen in Figure 3.19), there is no pattern to be discerned in the fluctuations. This makes it difficult to predict the capacity and plan accordingly, which may cause issues with the TAT.

In general it seems that there are quite a few people available. However, it is interesting to see how much use is made of this available capacity and whether the capacity is available at the right times. This can be determined by looking at the available work. The work performed per day can be seen as the available work, and is expressed in normative hours. The work done per day is determined by the tasks completed on a day and the normative times for these tasks. As can be seen in 3.23 the

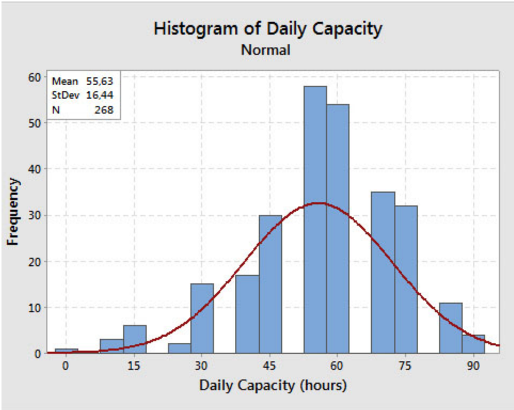


Figure 3.21: Histogram of Daily Capacity in 2014

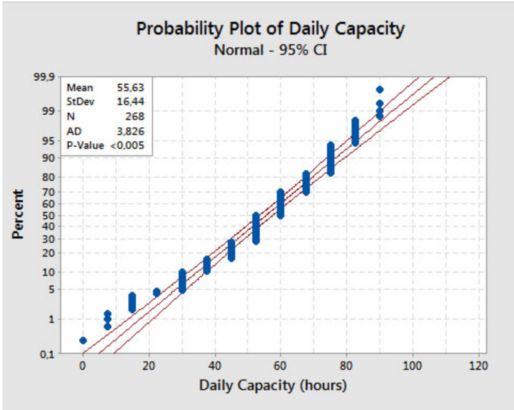


Figure 3.22: Probability Plot of Daily Capacity in 2014

daily work performed varies between 75.3 and 0.2 hours. This is a great spread of work performed, and it is less than the highest available work hours. However, this histogram does not indicate in which instances the high work hours were performed. Most frequently around 30 hours of work are realised, with the mean being 28.3 hours.

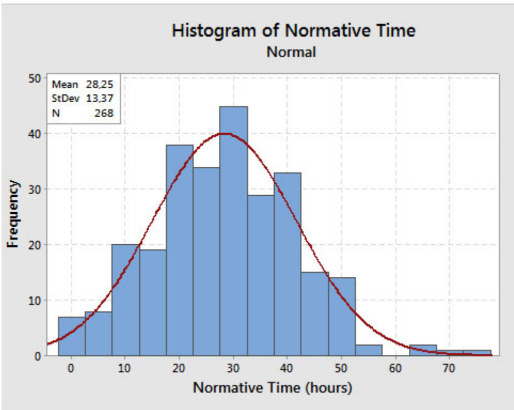


Figure 3.23: Histogram of Work Performed in 2014

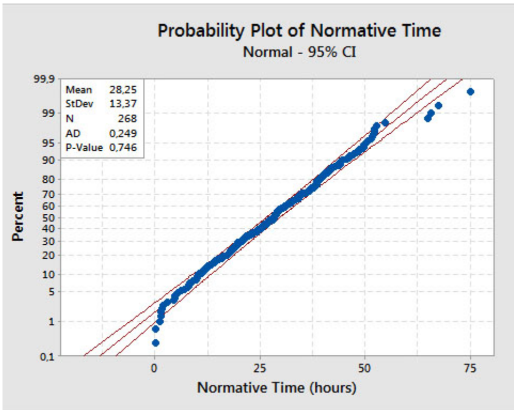


Figure 3.24: Probability Plot of Work Performed in 2014

In order to see whether the performed work is distributed normally a probability plot has been generated as shown in Figure 3.24. As can be seen the work performed has a normal distribution with a total of 7 outliers on both ends of the slope. The high spread and outliers on both ends of the slopes indicate a lot of waste in work performance.

It is interesting to see if there is a relationship between the work performed and the available capacity. It would be expected that as the capacity increases the work performed increases. If this is true the available capacity has an influence on TAT, as the performed work influences the TAT.

Figure 3.25 shows the relationship between the daily capacity and the work performed. As can be seen the data points are grouped together, and the two factors show a slight positive correlation. This means that as capacity increases it can be expected that more work will be performed, and thus the TAT will be improved. However, this does not say anything about the efficiency or effectivity of the capacity. If there is a higher capacity through more people, this does not mean that waste is reduced, it might even increase waste. Therefore, it is relevant to identify how the capacity is utilised.

Conclusion Available Capacity The mechanics that have worked within the department on a daily basis varied between 0 and 12 people per day spread over two shifts. On average there are 55.6 available work hours. Furthermore, on average 28.3 hours of work are performed which indicates that

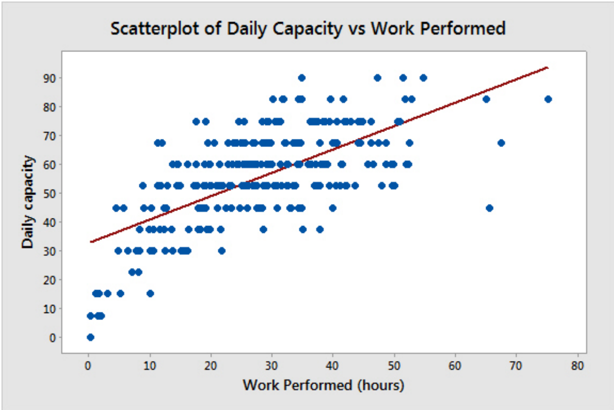


Figure 3.25: Scatterplot Daily Capacity and Work Performed

people do not work all the time that they are available. The capacity and the work performed do show a positive correlation, indicating that as capacity increases the performed work increases. However, increasing capacity by increasing the available work hours does not mean that the performance is improved or that waste is reduced.

Utilisation

In order to compare the work done to the available capacity, a time series is plotted in which the daily capacity and work performed are compared. Figure 3.26 shows this. Even though the graph seems chaotic as both the available capacity and the work done vary greatly, it becomes claer that that the work performed is generally less than the available capacity.

The utilisation rate can show how supply and demand between work and available resources are

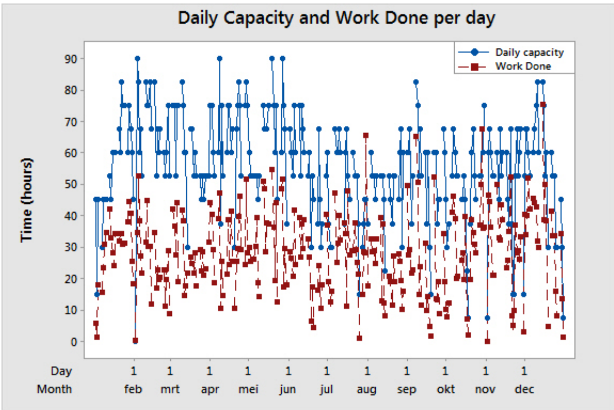


Figure 3.26: Time Series Daily Capacity and Work Performed

distributed. After determining the daily capacity and the work done per day, the utilisation rate can be determined. In order to see to what extent the capacity is utilised, the capacity is compared to the normative times of the activities carried out per day. This comparison gives the utilisation rate, which can be defined as follows:

$$\textbf{Utilisation Rate} = \frac{NormativeTime(hrs)}{Capacity(hrs)}.$$

The assumption is made that the normative times are correct. The utilisation rate per day is identified for 2014. During this period the rate ranges between 9% and 102%. This means that in some cases the remaining capacity was 91%, and relatively little work was performed, or that there was too much work to perform for the available mechanics. The latter case is strange as the work has been performed even though there was not sufficient capacity. In these cases mechanics might have worked very effectively or have given up their break time. It is also possible that for these cases the work could be completed in less time than predetermined by the normative times.

Figure 3.27 shows the histogram of the utilisation rate. As can be seen the rate varies, and has an average of 52%. In general less hours of work are performed than available, as there is only one instance in which the utilisation rate is larger than 100%.

This is also shown in the probability plot of Figure 3.28. Here it can be seen that the utilisation

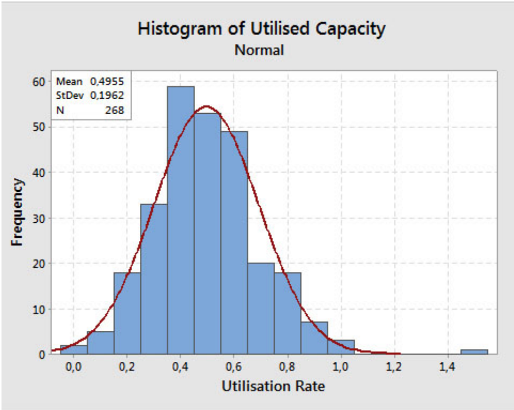


Figure 3.27: Histogram of Utilised Capacity in 2014

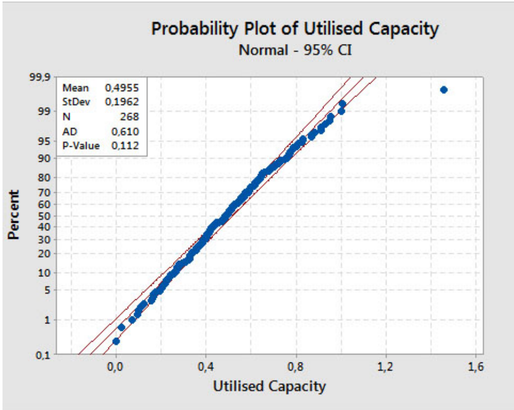


Figure 3.28: Probability Plot of Used Capacity in 2014

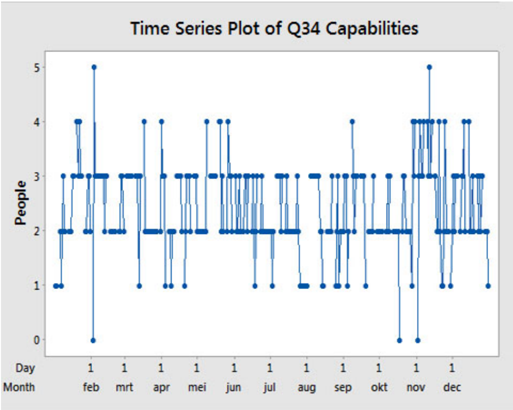
rate has a normal distribution, but the tail of the slope veers of to the right, closer to the 100% utilisation. This means that there is some waste within the use of capacity, and both ends of the utilisation spectrum signify waste. Too much capacity leads to waste as people have a lot of time on their hands to complete things. Too little capacity leads to waste as additional sources might be used in order to get things done in time, leading to additional costs or unnecessary queues arising due to the lack of capacity. Either way, a smaller variation should be created by having a more constant utilisation rate.

Conclusion Utilisation The utilisation rate is highly variable, but does have a normal distribution. However, the probability plot shows that the tail of the slope veers of at both ends, indicating waste within the performance and availability of resources. In general there is a lot of capacity, and relatively little work performed. However, the cause of the waste is not yet identified.

Time-Traps

In general it seems there is more than enough capacity available to complete the work. However, the TAT is frequently high, and the cause is still unidentified. It is too easy to say that the low utilisation rates are due to mechanics in the combustor department being lazy. There is a possibility people are prevented from performing as much work as they are capable of. It could be there is not enough capacity to carry out the capabilities that have been identified as time-traps. Therefore, these capabilities will be further analysed. According to the skill managers there is a lack of skill coverage, meaning that the distribution of capabilities is not sufficient to perform all the required tasks. They think that due to a lack of certain capabilities components have to wait. This section will try to identify how the available work is distributed amongst the available capacities.

The number of mechanics and their combined skill sets can be identified for each working day. However, the most relevant capabilities are those whose tasks form time-traps (these will be further discussed in Section3.3.4). Therefore, it is relevant to know how many mechanics are available that have these particular capabilities. Figures 3.29, 3.30, and 3.31, show the variation in people present with their respective capabilities. As can be seen, with a few exceptions, every day at least one person is available for each of the required capabilities. This would mean that at least 7.5 hours per day could be spent on tasks requiring this capability. However, the mechanics do not work exclusively on one capability every day, in general they alternate between different tasks.



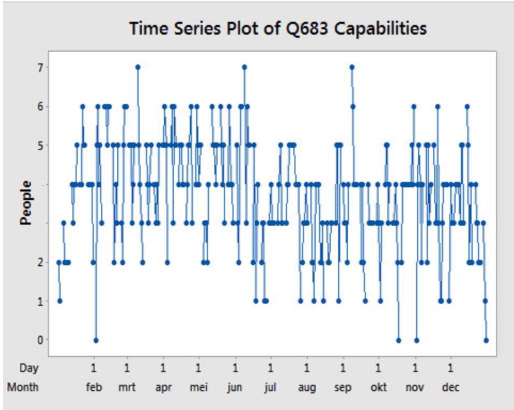


Figure 3.29: Time Series of Available Q34 Capability per Day Figure 3.30: Time Series of Available Q683 Capability per Day

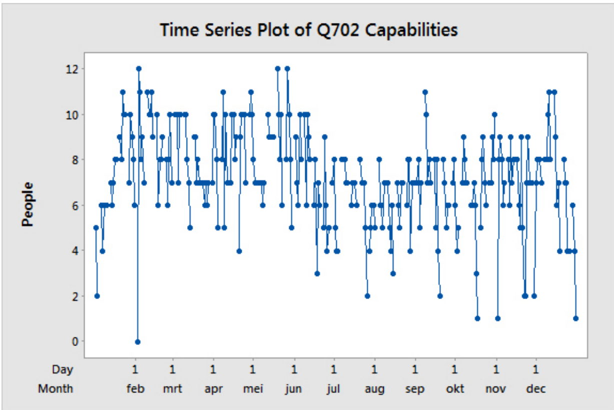


Figure 3.31: Time Series of Available Q702 Capability per Day

As the available mechanics and capabilities vary daily, every day should be analysed to see how the capacity is distributed amongst the mechanics. However, it is more relevant to see how the capabilities are distributed. For instance, how many people possess the skills for all three time-traps, and how many hours a year are the time-trap capabilities required. This will be done in section 3.3.4.

In 2014 7571 hours of work has been performed on 15905 tasks. In total 2015 hours (27% of the total time) were spent on Q034, 1414 hours on Q683 (19%), and 3167 hours on Q702 (42%). It is surprising that the least people are capable of performing Q034 tasks, even though the second largest group of tasks requires this capability.

If we now look at the number of tasks each of these time-traps requires it can be seen that 5635 (35% of the total tasks) tasks were done for Q034 , 1996 (13%) for Q683, 5889(42%) for Q702. On average 1 person with Q034 capabilities carries out 9 Q34 tasks and 3.2 hours of Q34 work per day. For Q683 this is 2 tasks in 1.5 hours, and for Q702 this is 3 tasks in 1.6 hours. For Q034 on average 2.4 people carry out tasks, for Q683 this is 3.7, and for Q702 this is 7.2 people.

Tasks do not become available at set times, nor do they always become available at the moment a person with that skill is available. Therefore, it may happen that either a mechanic or a component has to wait before the next task can be carried out, and it is difficult to dedicate mechanics to carrying out a single capability.

Thus, it is relevant to compare the availability of the capabilities to the demand. The demand is the work available for maintenance. Following the maintenance route of a combustor an indication can be made of what can be performed when.

It has been found that tasks are not equally distributed. Even though people are present, they cannot always perform work as they have to wait for a component to become available to them. Similarly, components have to wait to be handled until a person is available to complete the required task. Thus, even though the available capacity is enough to complete the available tasks, the capacity can not be utilised if the required capabilities are not available. Due to the mismatch between required and available capabilities, not all components can continue their maintenance route.

Due to the variable maintenance route, required and available capabilities, components can not continuously follow a maintenance route, nor can the capacity be used to the fullest. Furthermore, it has been found that if one simply continues working on one component and no planning is made of whom should perform what when, choices will be made based on gut-feelings or preference. This means that it is very likely that the capacity is not used to its full potential as there is no clear overview of the effects the made decisions have. If mechanics or skill managers do not know ahead of time which components are available when they can not anticipate that only working on one component causes waiting time for others. If a planning is made regarding the available capabilities and tasks these factors can be better balanced.

It has been found that Q034 forms a large bottleneck in the maintenance route, as even though one inspector is available during a shift other components remain waiting. It should be noted that Q034 takes place largely at the beginning and end of each phase. Furthermore, it only takes one task of a capability that is not available to leave a component waiting for a complete shift. This probably explains why both Q034 and Q683 form time-traps as not everyone possesses these skills and these tasks do occur quite frequently. Taking into account that 37% of the tasks are Q702 tasks, 35% are Q34 tasks, and 13% are Q683 tasks, it makes sense that if there are few of these capabilities there will be waiting times.

Everyday at least one person capable of Q702 was available. Therefore the waiting time within Q702 tasks might not be due to a lack of available capabilities. However, Q702 tasks occur so frequently that it is not unlikely that Q702 tasks have to wait whilst other tasks are given priority. For instance if one mechanic focusses on Q034 tasks for different components and the task following Q034 is Q702, this componentand Q702 task will have to wait. This automatically shifts the waiting time to the Q702 task. The same might also be true for Q683. This can be investigated by looking at the maintenance routes carried out in 2014.

Capacity Conclusion
In conclusion for the capacity, there are enough available work hours in which to complete the combustor maintenance. However, there is a lot of variation in possible maintenance routes, task sequencing, capacities, and capabilities. This, in combination with a lack of a predetermined work sequence for the mechanics, leads to inefficient use of the available resources. Furthermore, there are very few people available that have the Q034 skill. As this task occurs frequently throughout every combustor repair it allows waiting times to add up, both before and after carrying out a Q034 task. Therefore, the Q034 capability forms the main bottleneck within the combustor maintenance process. It should be noted that Q034 tasks are inspections, and it is debatable if these inspections are all necessary as the inspections do not add value to the product.

3.3.4. Capabilities
This section will discuss the influence of the required and available capabilities on the maintenance process. The required capabilities are related to the tasks and capability required to carry out the maintenance route. The available capabilities are related to the mechanics' capabilities and their availability to carry out the required tasks. Both will be discussed in this section.

Required Capabilities
In order to determine which capabilities are regularly required for maintenance, the maintenance routes for the 7B combustor will be analysed. The routes will be evaluated based on the different skills that are required for each task, these required skills are referred to as capabilities. In order to find out at what point during maintenance the high TAT arises, and where the most waiting time exists for the 27 combustor components the number of tasks, the normative time and the TAT per capability will

be evaluated. First, the different capabilities used during maintenance will be defined, after which the maintenance routes will be evaluated.

Table 3.8 shows the different capabilities that are required during combustor maintenance. As can be seen, 23 different capabilities can be used during maintenance. As mentioned during Chapter 2, not all maintenance tasks are performed by the combustor department. If, for instance, heavy machinery is needed to carry out a task, the component is sent to another department within ES. Hence, the table also shows within which department a certain skill is carried out. Department 2400 is the combustor department, and department 2700 is the "Grote Machinale" or large machinery department.

Table 3.8: Capability types and departments

2400		**2700**	
Code	**Definition**	**Code**	**Definition**
Q033	Inspection/Repair	*Q249*	UHPW Stripping
Q034	Inspection	*Q428*	Carrouselathe turning
Q071		*Q434*	Drilling/Milling
Q114	PVM101 Code 7	*Q512*	Drygrit Plasma & Galvano
Q116	PVM101 Code 10	*Q516*	Plasma Spray Robot
Q224	Steamcleaning	*Q518*	Plasmaspray
Q244		*Q717*	717PVM
Q254		*Q800*	Vacuum Oven Brazing
Q502	Preparation	*Q801*	Vacuum Oven Solution HT
Q683	Nickel/Cobalt alloy welding	*Q802*	Vacuum Oven Aging Treatment
Q685	Brazing	#	Administration
Q702	Benchwork		

From the maintenance routes for each critical component the tasks have been categorised based on the required capabilities. For each combustor the number of tasks, the normative maintenance time and the TAT per skill are defined. Tables G.5 through G.10 in Appendix a:e show this for each combustor. From this data the total waiting time, and the waiting time per combustor is determined.

Table 3.9 shows a summary of the total tasks, normative time and waiting time per capability, along with the ratio of normative time to TAT. Along with the number of tasks, total normative time, TAT and waiting time for all capabilities and combustors.

Table 3.9: Amount of Tasks, Normative Time and TAT per Maintenance Capability

Amount/Capability	**#**	**Q033**	**Q034**	**Q114**	**Q116**	**Q224**	**Q249**	**Q428**	**Q434**	**Q502**	
Tasks	213	1	722	39	39	31	34	195	38	27	
Norm (mins)	3105	10	10144	445	395	255	1570	8380	4170	580	
TAT (days)	15	0	364	1	2	2	46	143	49	4	
Wait (days)	10.2	0.0	348.3	0.3	1.4	1.6	43.6	130.1	42.6	3.1	
Norm % of TAT	32%	100%	4%	69%	30%	20%	5%	9%	13%	22%	
Amount/Capability	**Q512**	**Q516**	**Q518**	**Q683**	**Q685**	**Q702**	**Q717**	**Q800**	**Q801**	**Q802**	**Total**
Tasks	31	59	60	287	11	781	154	19	75	20	**2836**
Norm (mins)	380	1930	1500	8741	220	22982	4462	193	790	200	**70452**
TAT (days)	32	0	37	81	6	225	5	15	78	15	**1120**
Wait (days)	31.4	0.0	34.7	67.5	5.7	189.5	0.0	14.7	76.8	14.7	**1016.1**
Norm % of TAT	2%	100%	6%	17%	6%	16%	100%	2%	2%	2%	**10%**

From the table it becomes clear that the total TAT is 1120 days, and the waiting time is 1016.1 days. The normative time is only 10% of the TAT, which means that overall, the TAT consists of 90% waiting time. Furthermore, in some cases there is no waiting time. In these cases the maintenance has been performed in less time than the normative maintenance time. For instance Q516 has always been performed in less than one day, therefore the TAT is automatically 0.

Figures 3.32 to 3.35 show bar charts of the tasks, normative time, TAT and waiting time for each skill type. These bar charts, along with table 3.9 show there is quite a variety in the number of tasks per capability. For instance, Q033 only occurs once, and Q702 occurs 781 times. The normative maintenance time varies between 10 minutes and 22982 minutes, this is again for Q033 and Q702 respectively. Finally the TAT varies from 0 to 364 days which is for Q033 and Q034 respectively. This means that Q033 hardly occurs but in case it does occur it is carried out very efficiently. Capability Q034 doesn't occur most frequently, nor does it have the highest normative time, but it does account for the highest TAT. It is not surprising that the most waiting time occurs within this skill.

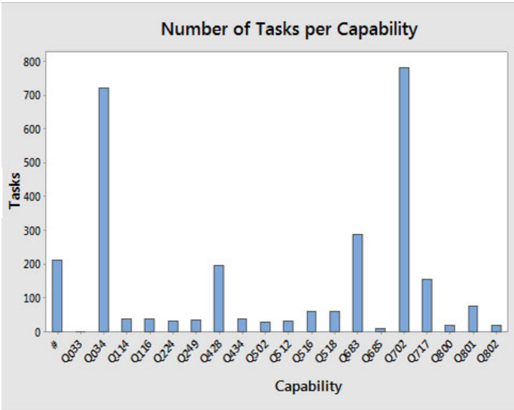


Figure 3.32: Bar Chart of Tasks per Capability

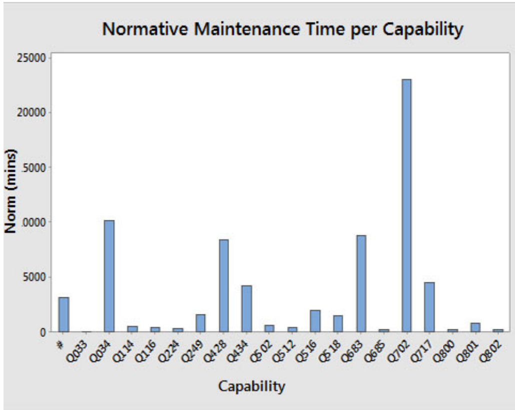


Figure 3.33: Bar Chart of Normative Time per Capability

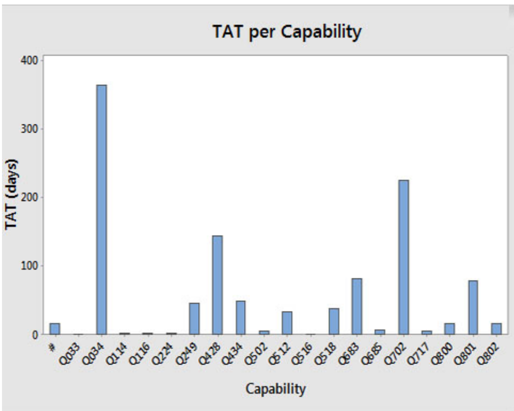


Figure 3.34: Bar Chart of TAT per Capability

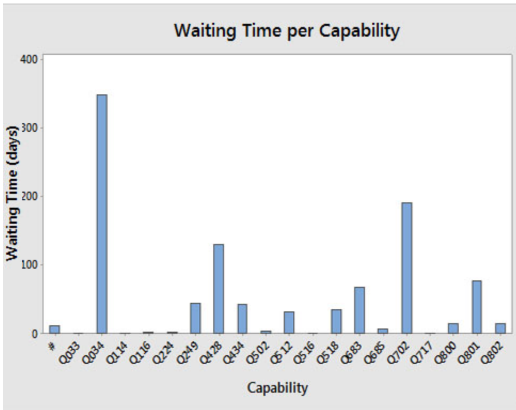


Figure 3.35: Bar Chart of Waiting Time per Capability

According to George [2003], in any process with an efficiency of 10% or less, as is the case with the combustor process where the normative time only takes up 10% of the total TAT, less than 20% of the activities cause 80% of the process lead time, or TAT. George calls these activities time-traps, and identifying these time-traps can help process improvement. As a small number of activities cause a large sum of the TAT it makes sense to focus on these activities. Improving performance on these tasks is likely to have the largest effect on the whole process. This 80% to 20% ratio is also known as the 80-20 rule, or Pareto Principle. Which, according to Defeo and Juran [2010] 'states that for any given effect, there are a number of contributors. These contributors make unequal contributions'. A Pareto analysis is a suggested LSS tool, that is used to identify these activities or time-traps. In such an analysis the activities are arranged in descending order of cumulative percentage [Defeo and Juran, 2010]. A Pareto analysis has been performed to identify where most tasks, normative times, TAT and waiting time occur. In these charts the bars show the total occurrence of for instance tasks per capability, and a line shows which capabilities together are responsible for 80%.

The distribution of tasks per capability is analysed in order to define how many tasks require a certain capability. As discussed in the section Process Flow and Value in Chapter 2, the different capabilities are rarely grouped, and the maintenance process might benefit from creating one-piece flow from the capability perspective, carrying out one capability at a time for one component. Therefore, it is relevant to know which tasks occur frequently in order to see which tasks should be grouped together. As can be seen in Figure 3.36 78% of the tasks lie with 5 different capabilities; Q702, Q034, Q683, #, and Q428. Furthermore, Q702 and Q034 make up a 53% of all tasks.

By performing a Pareto analysis on the normative times it becomes clear which capabilities should be

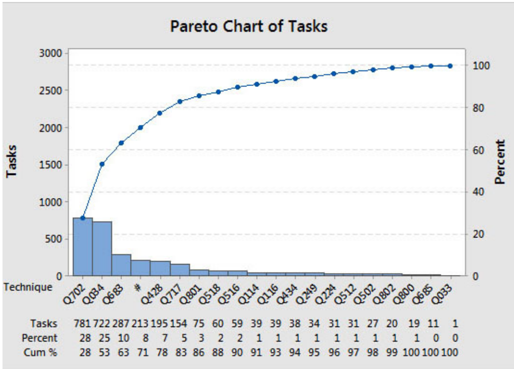


Figure 3.36: Pareto Chart of Tasks per Capability

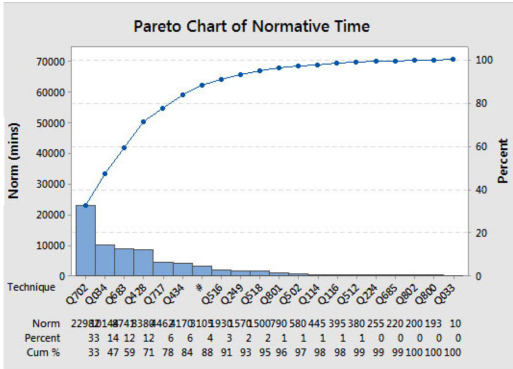


Figure 3.37: Pareto Chart of Normative Time per Capability

most time consuming. As the normative times and the actual TATs are known to vary, the normative times are not yet relevant themselves. However, it is interesting to compare their distribution to that of the TAT, in order to see if there are similarities. Figure 3.37 shows the distribution of normative times per capability. As can be seen Q702, Q034, Q683, Q428, and Q717 make up 78% of the TAT. It is not surprising that the first three capabilities are similar to the capabilities for the tasks, as it is to be expected that more tasks require more time. Furthermore, it is logical that the # tasks do not require a lot of normative time as these tasks only consist of simple administration. This is also why Q717 is within the 80% of normative time as this capability is in the 83% for the number of tasks. However, the assumption that more tasks leads to a higher normative time is not entirely correct as the order in which the tasks are organised beyond 83% is different for both pareto diagrams. Furthermore, we can see that relatively less time is allocated to Q034 tasks than for Q702 tasks.

Figure 3.38 shows the distribution of TAT per capability. As can be seen 80% of TAT lies with Q034, Q702, Q428, Q683, and Q801. Capabilities Q034 and Q702 form 53% of the total TAT. Q702 would be expected to have the highest share of TAT, and it is surprising that Q034 causes 33% of TAT as this is not the capability with most tasks, nor does it have the highest normative times. This means that either the normative times are incorrect for Q034, or that a lot of wastes occur with this capability. Another possibility is that Q702 might be carried out more efficiently. However, as discussed in section 3.3.3, the discrepancy between the two is caused by the lack of Q034 capabilities.

As the difference between TAT and normative times is said to be waiting time, a Pareto chart can be used to see for which capability the largest waiting times occur. Figure 3.39 shows that 80% of the waiting time lies with Q034, Q702, Q428, Q801 and Q683. These are similar to the tasks that cause 80% of TAT, although the order for Q683 and Q801 are switched. Furthermore, it is interesting to note that the waiting time for Q34 and Q72 almost equal their TAT.

As the focus of the analysis should lie with the factors that influence the maintenance process and TAT, the focus of the analysis should lie with the tasks that cause the highest TAT. As the waiting time is a form of waste, and waste reduction should improve TAT, the capabilities that have most waiting time have been identified. These waiting times are found to be almost as large as the TAT. Hence, Q034, Q702, Q428, Q801 and Q683 should be further explored for improvement.

As shown in Table 3.8 not all of the tasks that need further exploration are performed within the com-

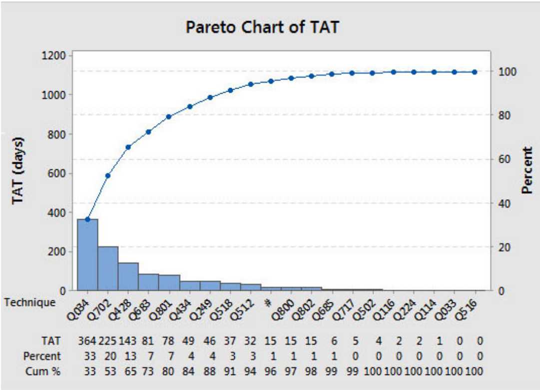


Figure 3.38: Pareto Chart of TAT per Capability

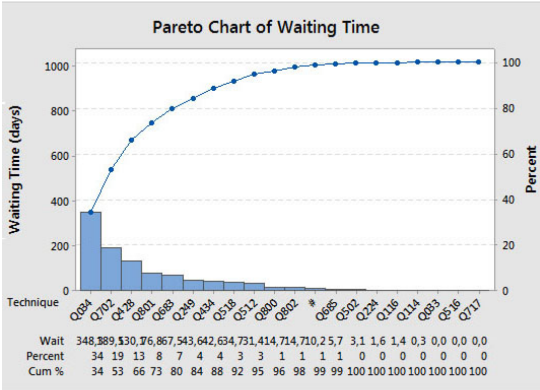


Figure 3.39: Pareto Chart of Waiting Time per Capability

bustor department. As this analysis is carried out for the combustor department, and can only instigate changes within this department, the focus of further improvement should lie with the capabilities that are performed within the combustor department. Hence, the focus will lie with Q034, Q702, and Q683. This does not mean that the other capabilities such as Q428 and Q801 do not require improvement, but the combustor department is not responsible for these processes and can therefore not change them at their own accord. Therefore, the department should focus on their own performance. Department 2700, as the owner of the external processes, should be informed of the effect their activities have on combustor maintenance, and should be requested to reevaluate their performance. Furthermore, the combustor department should find a means of communication with these departments in order to signal possible delays and take this into account in their own planning and performance.

Conclusion Required Capabilities It can be concluded that not all capabilities are required equally throughout a maintenance route. It has been decided to focus on the capabilities that are available within the combustor department. 63% of the total tasks performed are Q702, Q034 and Q683 tasks. The same is true for the normative maintenance time where these three capabilities amount to 59% of the total normative time. For the TAT and waiting time this is slightly different, but within dept. 2400 Q034, Q702 and Q683 make up 60% of the TAT and the waiting time.

Furthermore the TAT and normative times have been found to differ greatly. This difference is prescribed to waiting time. On average, 90% of the TAT is waiting time. If waiting time is reduced, the TAT will also immediately be reduced. The reason for the large share of waiting time has to be determined, and might possibly be caused by the repair routing, or a lack of capacity.

Available Capabilities

This section will discuss the capabilities of the mechanics that work within the combustor department in relation to the capacity. Depending on their capabilities mechanics can carry out specific maintenance tasks. If they do not possess the required capability they can not carry out these tasks.

Of the 47 people that have carried out work within the combustor department, not all are actually part of the department. These people are either from the engineering department and have signed off a task that was no longer necessary or needed additional expertise, or the people work for another department and have carried out an administrative task after a task on a combustor was carried out within their department. In Appendix H the number of tasks and capabilities carried out by each of these people are summarised in Table **??**. In this table it can be seen that a few people carry out very few capabilities or very few tasks. These people can be considered to be from another department, and hence can not be part of the combustor department capacity. The people who are not part of the combustor department have been determined by identifying who performed only one capability less than ten times, or who carried out ten tasks or less in total. This leads to a total of 23 people that are said to work in the combustor department. Their skills are shown in Table 3.10.

From this table it can be seen that certain capabilities are rarely carried out by people from the combus-

Table 3.10: Matrix of Capabilities and Mechanics

Mech	#	Q33	Q34	Q71	Q100	Q114	Q116	Q224	Q244	Q254	Q434	Q502	Q516	Q682	Q683	Q685	Q702	Q801	Total
A	x										x						x		3
B														x	x		x		3
C	x		x	x	x	x	x	x	x	x		x	x				x	x	13
D						x	x												2
E						x	x					x		x	x		x		6
F	x			x	x			x	x			x					x		7
G	x			x				x	x	x		x					x		7
H				x	x				x	x		x		x	x		x		8
I			x			x	x					x			x		x		6
J	x			x	x	x	x	x	x	x		x		x	x		x		12
K	x				x	x			x	x	x		x				x		8
L						x	x								x		x		4
M						x	x								x		x		4
N	x		x		x	x	x	x	x	x							x		9
O	x																x		2
P	x		x											x			x		4
Q	x	x	x	x		x	x	x	x	x					x	x	x		12
R	x																x		2
S	x										x								2
T	x			x	x	x	x	x	x	x		x			x	x	x		12
U	x			x	x			x	x	x		x			x		x		9
V	x		x					x									x		4
W	x					x	x				x								4
Total	16	1	6	9	8	11	11	10	10	9	3	10	1	4	11	2	20	1	**143**

tor department. Q801 is carried out by only one person, as is the case for Q033 and Q516. Therefore, tasks requiring these capabilities, in the rare case they do arrive, are likely to form bottlenecks for throughput. Furthermore, it should be noted that person P is actually not a person but "not assigned". In these cases a task is finished but no note is made of who completed this task.

In total 6 mechanics are capable to carry out Q034 tasks, all of them are also capable of carrying out Q702 tasks, and 3 of them are also capable of carrying out Q683 tasks. For Q683 there are 11 capable people, 3 of whom are capable of carrying out Q034, and all are capable to carry out Q702 tasks. There are 20 people that are capable of carrying out Q702, 11 of whom can carry out Q683 and 3 of whom can carry out Q702. Figure 3.40 gives an overview of which people can carry out the time-traps. As can be seen everyone that carries out Q034 and Q683 can carry out Q702, and there are three people that have all three capabilities. Therefore, 11 people can carry out a maximum of 2 time-trap capabilities, and 6 people can only carry out one (Q702). As many tasks consist of Q034 and Q683 capabilities it seems strange that there are not more people capable of performing these tasks.

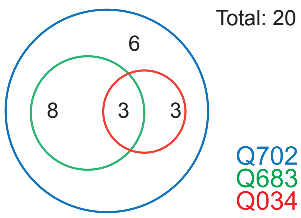


Figure 3.40: Venn Diagram of Capabilities per Skill

Capabilities Conclusion

The three capabilities that have the most tasks, highest TAT and longest waiting time are Q034, Q683 and Q702. These capabilities can be considered time-traps. However, it has been found that not every mechanic is capable of performing the time-trap tasks. Of the 23 mechanics in the combustor department 20 are capable of performing Q702, 11 are capable of performing Q683 and only 6 mechanics are capable of Q034. As most waiting time exists with Q034 and least mechanics are capable of this task it is likely that a large share of the waiting time is caused by this factor. Therefore Q034 can be seen as the bottleneck for the combustor department.

3.3.5. Planning

Planning in the case of the combustor maintenance process entails the planning of resources and time. Knowing how many combustors require maintenance, how long this maintenance will take, which capabilities are required when, and which capabilities and capacity is available allows a planning to be made. However, none of this happens within the combustor department at the moment. Section 2.2.2 in Chapter 2 discusses how planning occurs within the combustor department. Section 3.3.3 has shown the effect planning can have on the execution of the maintenance route. In general the lack of planning is expected to lead to a sub-optimal execution of maintenance leading to additional waiting time and thus increasing TAT. However, this can not be quantified as no data is available to compare the planning to the actual performance.

3.3.6. Main Issues Regarding Value Drivers

Each of the five factors influencing TAT has been analysed and the main issues for each of these factors has been discussed. It has been found that all factors do indeed have an effect on TAT. It has become clear that the components capacity and capabilities are the value drivers, and that routing and planning indirectly influence the TAT. Throughout the analysis it has also become clear that the factors are dependent on, or influence other factors. The relationship between the factors will be shown in this section along with the main issues. This will then help to answer the fourth research question of how the value drivers are related to each other.

The maintenance route determines which tasks are performed in which sequence. As each task has a predetermined maintenance time the combination of these tasks should add up to the TAT. It is expected that the longer the maintenance route and the higher the normative time the higher the TAT becomes. However, as shown in section 3.1.2 this is not necessarily the case due to additional waste within the process. It has been found that the total maintenance time per combustor makes up 14% of TAT. The routing is determined by components. Depending on the type of component and the damage it has incurred repairs are required and a maintenance route is determined. The maintenance route in turn influences the required maintenance capacity and capabilities. These factors are influenced as the type of maintenance required determines the length and type of repair. This then determines how many hours of maintenance, and how many capabilities are required.

Furthermore, the routing influences the planning as depending on the routing the necessary capacity and capabilities need to be made available. At the same time the planning influences the execution of the routing as the planning should determine when which component should be handled, and when it should wait in order to help other components along the route. However, the planning does not influence the routing itself, it only influences the timing of the route.

Capacity determines the work that can be done within the available time, and as such is a value driver. Therefore, the higher the capacity the more work can be performed. The amount of work performed in a day determines the TAT, and therefore the capacity influences TAT. On average 50% of capacity is utilised. The capacity is determined by the available capabilities, the components that require maintenance and their required routing. These factors determine how many work hours are required and how many work hours per capability are available. Planning and capacity both influence each other, as depending on the capabilities that are made available through planning the capacity is determined. Whilst at the same time the available capacity will influence the planning as depending on which capacities are available certain tasks can or can not be carried out.

The components determine the maintenance route. Depending on their type and state the maintenance route is determined. Different components require different routes, and different damages require different repairs. These repairs determine the required repair tasks and time, thus influencing TAT. As such the components are value drivers. The repairs required also determine which capabilities are required to carry out these repairs. The required capacity and planning are therefore also influenced by the components, as depending on the required time and capabilities part of the capacity is used and choices regarding planning should be made to match the available capabilities with the demand.

The available capabilities influence the capacity and TAT, and thus can also be considered a value driver. Within the required and available capabilities Q034, the inspections, have been identified as the bottleneck for process performance. Due to this capability being frequently required, but rarely being sufficiently available waiting time occurs and increases as components have to wait until maintenance can continue.

Finally, the planning influences the capacity and the available capabilities by planning which people with which capabilities should work when and on what. However, routing, required capacity and capabilities influence planning as these factors determine what is required regarding available capacity and capabilities and how this should be matched to the routing of the different components. There are signs that planning influences TAT, however this has not been proven directly.

Table 3.11 shows a table in which relationships between the various factors are indicated. As can be seen the capacity only influences planning, and is influenced by all factors. Whereas the components have an influence on all factors but are not influenced by any. The planning is also influenced by all factors, and it influences all factors other than the components.

Table 3.11: Matrix of Relationships Between Influencing TAT Factors

Factor	**Routing**	**Capacity**	**Components**	**Capabilities**	**Planning**
Routing	-	x		x	x
Capacity		-			x
Components	x	x	-	x	x
Capabilities		x		-	x
Planning	x	x		x	-

Using Table 3.11, the conceptual framework can be adapted to incorporate these relationships. Figure 3.41 shows the framework that includes the relationships between the factors. The black lines show how the factors influence the process and TAT. The grey arrows indicate which factors have an influence on others. Routing and Planning are marked in green with green arrows as they indirectly influence the process, capabilities and capacity, mainly through management.

It should be noted that the relationships between factors have not been quantified. In some cases the

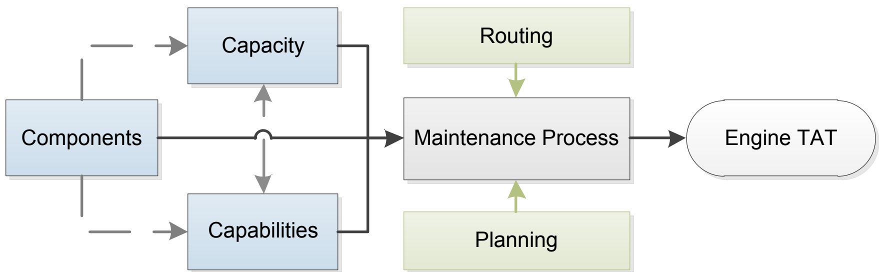


Figure 3.41: Conceptual framework for engine MRO including relationships

relationship has already been shown during the analysis. For other cases this relationship will have to bee shown during the process simulation.

After having identified the main issues within maintenance and the relationships between the critical factors these factors can be addressed during the design of the future state, which should resolve the issues at hand in order to suggest how the current performance can be improved. This will be done in the following chapter.

3.4. Conclusion

The problem the combustor department has regarding TAT has been analysed. The factors that influence TAT have been identified, along with their relationships. The problem analysis has been performed in order to identify the wastes in the process according to LSS methodologies. Furthermore, as suggested by TOC literature, a bottleneck, Q034, has been identified.

It can be concluded that the TAT for maintenance is too high and is not distributed normally. This indicates the presence of waste within the process. The data for in-house repairs shows a large difference between the normative maintenance times and the actual TAT. The process is unpredictable, and the current planning method is not sufficient.

Furthermore, the process is divided into several phases, which do not seem to interact with each other regarding planning nor do all of the phases add value. Out of the six phases identified, only two phases actually add value. These two phases are Z42 and Z51, which incidentally cause the highest share of TAT and are the most unpredictable. Phase Z51 is the only phase that shows a great variation in number of tasks and normative maintenance time required, and is therefore most difficult to anticipate and plan. Furthermore, throughout the maintenance phases many non-value added tasks can be found such as the inspections.

The routing and phases depend on the component types and damage. There are only three components that require phase Z51, and these components are the critical part. The maintenance route consists of various tasks requiring different capabilities. The capabilities are irregularly sequenced throughout the maintenance route, which is a cause of waste as it causes waiting time if the correct capability is not available at the right time. This has a strong influence on capacity, the required planning and available capabilities. In total 90% of the TAT has been identified as waiting time. The largest share of waiting time can be found within three time-trap capabilities: Q034, Q683 and Q702.

The capacity in available working hours is generally more than the work performed. Therefore, the total capacity is believed to be sufficient. However, the available mechanics fluctuate. This is shown in the utilisation rate. The utilisation rates are highly variable and indicate waste in both use of capacity and work performed. One of these wastes is caused by the lack of available capabilities. Not all mechanics have the capabilities to perform all tasks. Very few people are capable of performing Q034 tasks. Therefore components with Q034 tasks frequently have to wait before they can be handled. The waiting time accumulates as other time-trap tasks frequently follow Q034 tasks. The Q034 capability is therefore identified as the main bottleneck.

Finally, through the problem analysis relationships between the factors within the conceptual framework have been identified. This has led to an adapted conceptual framework as shown in Figure 3.41. This model will be validated in the following chapter.

4

Modeling and Simulating a Future State

In the previous chapters the value drivers have been identified and captured in a conceptual model, and the current state has been defined. This chapter will focus on the influence and effects of these value drivers, in order to determine which changes might improve TAT. This will be done by simulating the current state process, and testing changes to the value drivers. By doing so the answer to the third and fourth sub-research question should be confirmed, and the fifth and sixth sub-questions should be answered.

The aim of the future state is to define a process which will ensure all combustors are on-time. Ideally KLM should be able to realise this with low implementation and execution costs, and improve the utilisation rate of the available capacity. Therefore the influence of the value drivers will be tested regarding TAT and utilisation rates.

This chapter will first discuss how combustor maintenance will be simulated. This is followed by the issues found with each of the value drivers and possible solutions to these issues, after which simulation test scenarios can be defined. These scenarios are then simulated and the results are compared to identify the effects of changes on the value drivers. Finally a future state will be designed that incorporates changes to the value drivers in order to achieve an ideal state. A complete discussion of the simulation model, validation and verification can be found in Appendix I.

4.1. Simulation

The simulation model that will be created will contain only discrete events, as combustors arrive at certain points in time, mechanics arrive and leave for work at regular intervals, and tasks are performed once new parts and tasks become available. Furthermore, simulation might be stochastic or deterministic, based on whether or not random events and variation occur. The combustor maintenance process is stochastic, as maintenance is unpredictable in nature. However, when using historical data to create a current state the simulation model will be deterministic, as the arrival time and maintenance routes are known.

In order to create a successful simulation model one must understand the problem and situation at hand, must determine which system is to be modeled, what the objectives of the simulation model are, which elements are within or outside of the scope, what are the model inputs and outputs, and finally it should be determined what the model will contain exactly. Simulation models 'yield the output of the system for a given input'[Shannon, 1992], and as such can only serve as a tool to analyse system behaviour under the specified conditions. In addition, optimum values for a set of control variables under predefined inputs can be found using a simulation model. As such, the simulation results might lead to the definition of an ideal future-state.

The following sections will briefly discuss the software that is used to carry out the simulation, along with the requirements for the simulation model. It will become clear what should be the outputs of the model, and how these outputs will be generated. Finally the simulation model will be discussed along with the validation and verification of the model.

4.1.1. Simio

There are many tools that can be used to create a discrete event model and carry out simulations, both for commercial and scientific use. Examples are Simio, Arena, ProModel. Simio is object oriented whilst Arena and ProModel are process oriented. According to Pegden [2007] a process orientation has proven to be very effective in practice, but an object orientation has the potential to be more natural and easier to use. The object orientation allows the system to be modelled using the objects that make up the system, such as workers and machines and allowing these to interact. Due to the ease of use it has been decided to use Simio to create the simulation model. Furthermore, within Simio the decisions made within the system can be visualised by animation. This allows the model to be verified as the user can see what goes on in the system. In the case of combustor maintenance the components can be tracked throughout their maintenance process. The simulation model will be discussed in detail in Appendix I.

In Simio, all models are built using objects that are derived from the same base object. There is a Simio Standard Library which contains various objects that can be used in the model. These standard objects might be changed in order to fit the model needs. The behaviour of objects in the model is based on processes consisting of individual process steps that are executed by tokens. Tokens carry out process steps on behalf of their related objects, and as objects might have several related objects that can carry out different processes this provides modeling flexibility. Additional process steps or behaviour might be added using add-on processes [Schriber et al., 2013].

Simio makes use of entities, which are units that 'instigate and respond to events. An event is an instantaneous happening that changes the state of a model'[Schriber et al., 2013]. In the case of combustor maintenance both the combustor and its components can be entities, and an event might be the arrival of the combustor at the shop. The resources within Simio signify system elements that provide a service, such as the mechanics in the combustor department. In general a resource has a capacity, so entities compete in order to make use of the available resources, and might be required to wait, creating queues (as is the case in reality).

A simple process within Simio in which an entity enters a system, is processed and leaves the system would be built using an entity, and a source, server and sink that are connected by nodes. The source 'creates' the entity based on either stochastics, a specific date or an event. The entity is then transported across the node connected to the server. At the server the entity is 'processed', which means that the server holds the entity for a given time (either based on stochastics or predefined), and the entity is 'delayed' for that amount of time. After processing the entity is then transported over the node that leads to the sink, where the entity is 'destroyed' upon entering. Each of the objects mentioned here has properties that can be changed in order to achieve the desired system behaviour. This will be discussed in further detail during the model design, verification and validation, which can be found in Appendix I.

4.1.2. Model

A complete description of the model requirements, design, verfication, validation and sensitivity analysis can be found in Appendix I, this section will summarise the main findings. The simulation model is designed to represent the current state maintenance process as closely as possible. In order for the model to correctly do this, it must be designed to carry out the process on a task level rather than on the phase level which has been used in the flow-charts that until now. Figure 4.1 shows the flowchart for the process as executed by the model. Each task is carried out by a server, which represents the required capability. Furthermore assembly and disassembly of components is carried out by using simio combiners and a separator. As the model has to make each combustor component individually the components are combined before the maintenance process is started. Then, once the components are disassembled the combustor is separated at the separator so that each component can continue its individual maintenance route, after which it will move to the combiner, where all components are combined once the last component has entered the combiner queue.

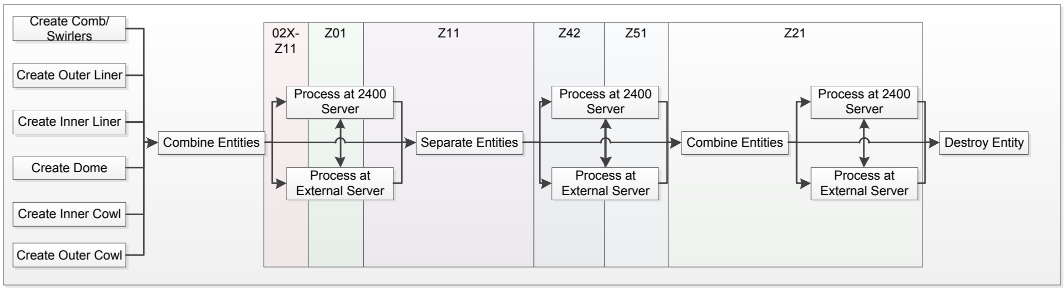


Figure 4.1: Model process flowchart

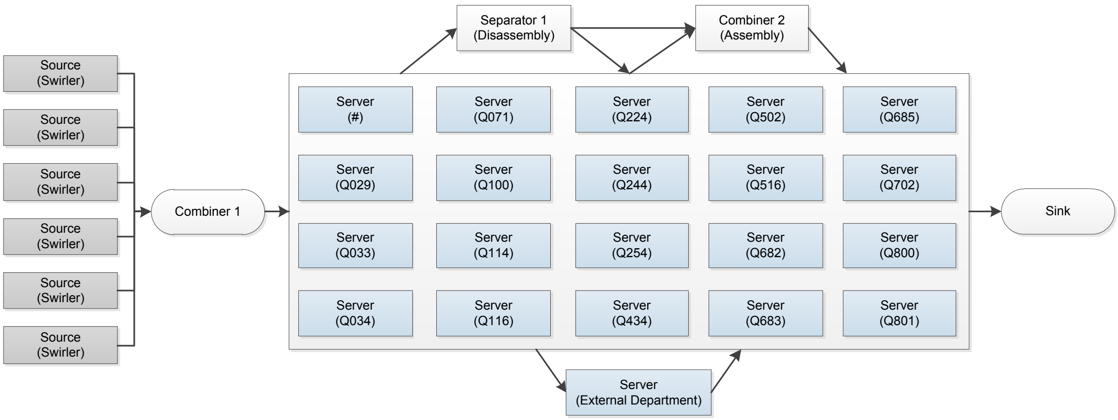


Figure 4.2: Model Entity flowchart

Figure 4.2 shows a flowchart of the model in which it can be seen how the model entities or components can move through the system. All servers are interconnected, as components require different capabilities in any given order, to ensure readability the 2400 servers are shown to be part of the department and the connection lines have been removed. If this is compared to Figure 4.1 the servers are part of the process at 2400 or external server steps.

In order for the model to correctly represent the process not only should the components be able to move trough the system in a similar way to reality, the inputs and outputs of the model should also be similar. Figure 4.3 shows how the inputs and outputs of the model are related to the combustor department. For example the model worker represents a mechanic and the mechanics capabilities and availability are modelled through defining a capability list and schedule for the worker. Iterative verification was performed in order to ensure that the model could correctly carry out the defined behaviour of the components and mechanics, and that the components would follow the correct maintenance routes including assembly and disassembly.

The base model is constructed so that it will match the current state of the combustor department. As such the validation has been performed by comparing the model output to the analysis results of the current state analysis. The combustor TATs were compared as well as the utilisation rates of the mechanics and the servers. It has been found that whilst the model does offer the possibility of simulating the presence and capabilities of all mechanics that have been active during the test period this does not lead to the required TAT. This is because the model can not exactly replicate who carried out which task and at which moment, the match the model makes between available and required capabilities differs from reality, and as such the TAT will differ. Therefore, the base model has been validated using 4 mechanics with limited capabilities that represent the actual mechanics and their capabilities (the exact capabilities are listed in Table D.14 in Appendixa:i).

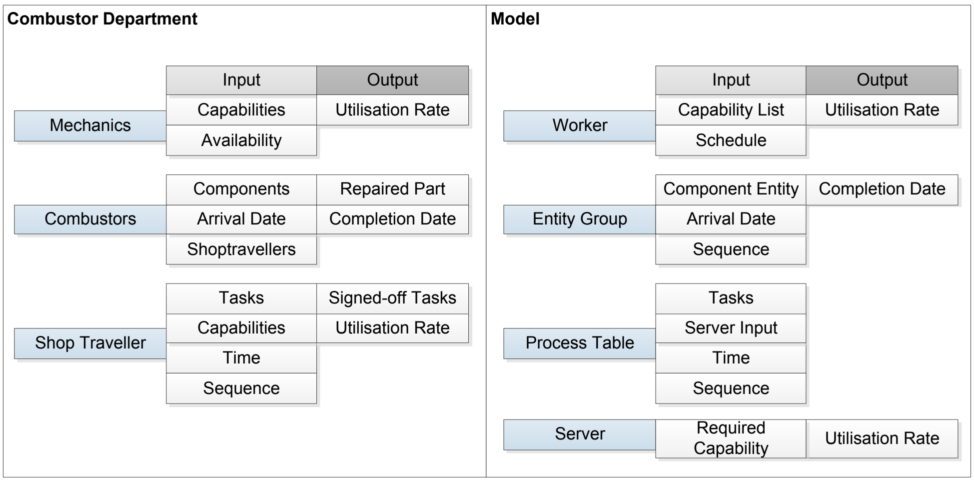


Figure 4.3: Maintenance Process Objects

The utilisation rates have not been used to validate the model as they do not match the utilisation rates of historic data, but it has been found that the mechanic utilisation rates can be used to analyse process alternatives. The model making use of the real available mechanics has resulted in a slightly lower TAT than the current state. This shows that the available mechanics are not productive due to the bad match between available and required capabilities. The validated base model assumes that the available and required capabilities are matched, and that all mechanics carry out the task with the earliest due date. Taking this into account the model capacity can be used to test the required capacity and productivity.

Figures 4.4 and 4.5 show how the base model performs compared to the current state. As can be seen the histogram and probability plot do not exactly fit. However, the means and standard deviation are considered to be quite similar. In order to test if this is in fact the case statistical tests are performed on both the complete data set as well as for each combustor type individually.

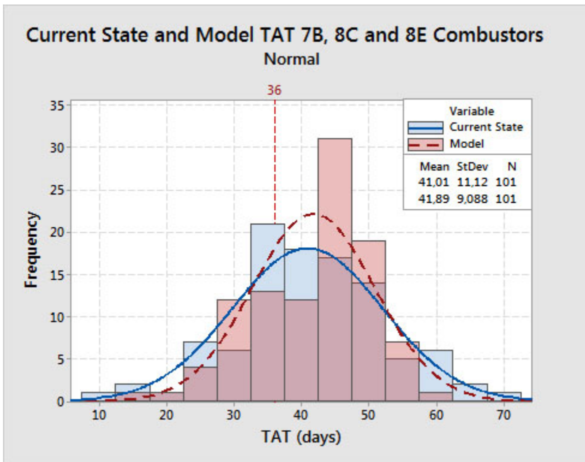


Figure 4.4: Histogram of Current State and Model TAT

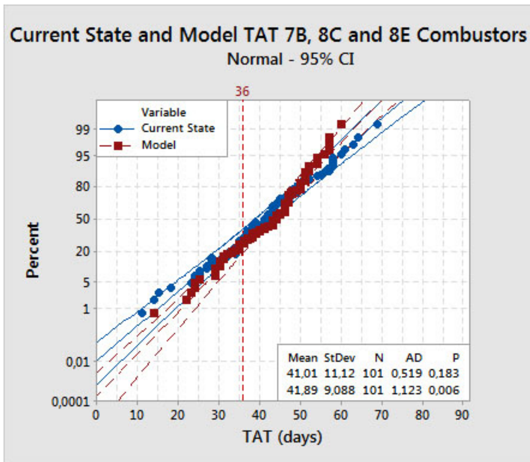


Figure 4.5: Probability plot of Current State and Model TAT

Using statistical t-tests the average TAT for all components processed has been validated, and is considered the same for both the base model and the current state. The same is true for the means of each of the combustor types. It has been found that regarding the combustors, the model TAT resembles the current state best for 8C combustors, and least for 8E combustors. The results of the t-tests can be found in appendix J. Furthermore the model generates a much lower average TAT for Z03 combustor repairs, as well as for HPC Stators and coffee cans. As especially the non-combustors have only been added to the model to better represent the pressure on the system these differences can be neglected for this analysis. However, it is recommended that the processes for these components are further analysed. It is likely that the lower TAT is due to the fact that these components are mostly maintained in external departments, and that the external department is not adequately modelled to represent these processes.

However, the model can not be completely validated solely based on how well the output TAT matches the current state TAT. A sensitivity analysis is also part of validation, and will be discussed in the following section.

4.1.3. Sensitivity Analysis

The Base scenario, which is the validated model, is built to represent the current state performance as closely as possible. However, the current state performance is far from ideal. Therefore it is relevant to know if it would be at all possible for the model to simulate changes to the process. Sensitivity analysis, according to Saltelli et al. [2008], 'is the study of how uncertainty in the output of a model can be attributed to different sources of uncertainty in the model input'. As such, the input parameters are varied where possible in order to demonstrate the relative influence of the input on the outcome of the model.

During the model validation many changes to the model have been made in order to realise a TAT that was as close to reality as possible. In order to define a base case these variables have been changed and tested in order to fit the current state as closely as possible. During these tests it was found that the model is highly sensitive to changes, as even a small change has a direct effect on TAT. However, the same is true for the process in reality so this is not necessarily a negative thing. The variables changed during the validation are not all within the scope of analysis. Therefore these factors will not be discussed into depth, and it might be recommended that the influence of these variables will be investigated during further research.

A structured sensitivity analysis has been carried out after the model was validated regarding TAT. This analysis has sought to investigate the model or process sensitivity to changes regarding the value drivers. Appendix I discusses this analysis, and includes graphs that visualise the results. The model data that is used as the basis of this analysis can be found in Appendix K. This section will only briefly discuss the conclusions of this analysis.

The model variables that have been tested are listed below. The main value drivers that are tested are capacity and capabilities, as it is not possible to test the influence of the components. In addition to the value drivers the influence of routing and entity arrivals have been tested.

- Mechanics:
  - Availability & Capacity
  - Capabilities
  - Dedicated to a capability
- Server capacity
- Combustor arrival times
- Combustor maintenance routes

Of the variables tested, it has been found that capacity has the largest effect on TAT (shown in Figure 4.6). A distinction has been made between the combustor department capacity and the external department capacity. The combustor department capacity has a larger influence than external capacity. The external capacity is only of significant influence (TAT change of >1 day), if the number of workdays is reduced.

The combustor department capacity consists of servers and mechanics. It has been found that variations in server capacity could not be properly made and tested. It is therefore advised to analyse this

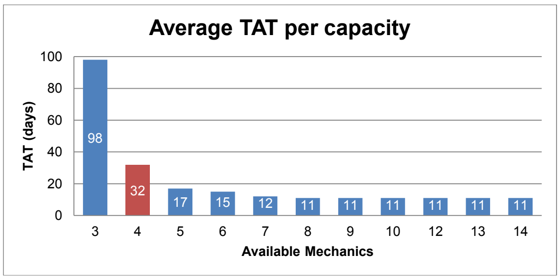


Figure 4.6: Average model output TAT for capacity of multi-skilled mechanics

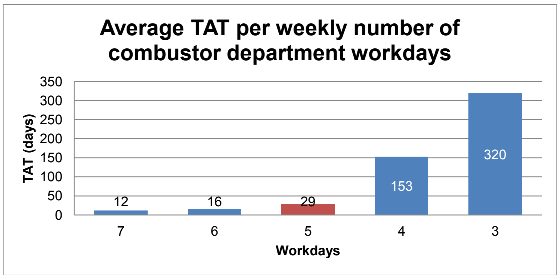


Figure 4.7: Average model output TAT for combustor department workdays

during further research as the consequence for the model is that only one task can be carried out at a time for each capability, and it should be possible to see the effect of multiple tasks of one capability being carried out simultaneously. The capacity of available mechanics has been tested regarding multi-skilled mechanics, mechanics that are capable of all tasks. It has been found that the average TAT reduces exponentially as the number of mechanics is increased from 3 to 14 mechanics, where the difference between 8 and 14 mechanics is negligible (shown in Figure 4.7. Furthermore the number of workdays per week only has an influence when the workdays are decreased.

After capacity the capabilities are most influential. It should be noted that only the bottleneck capabilities Q034 and Q683 have been tested (shown in Figure 4.8 and 4.9). Depending on the changes made regarding available capabilities the changes to TAT can vary. It was found that especially having mechanics dedicated to carrying out tasks of one particular capability has a large effect on TAT, as TAT increases as the number of dedicated mechanics increases. This is expected as dedicating mechanics to a specific capability reduces the overall capacity available for other tasks.

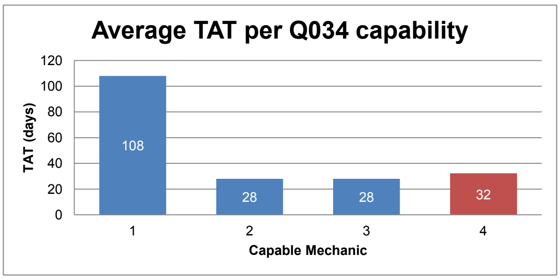


Figure 4.8: Average model output TAT for Q034 capabilities

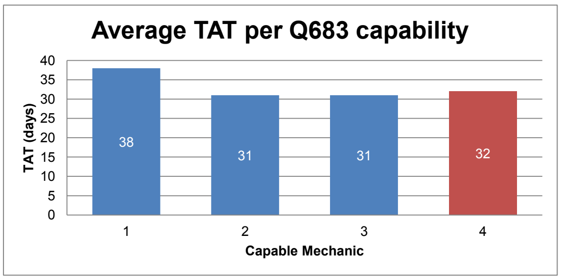


Figure 4.9: Average model output TAT for Q683 capabilities

Furthermore, the sensitivity analysis shows that there is an optimum to be found regarding the available mechanics and the available capabilities. Limiting the availability of a bottleneck capability to only one capable mechanic causes the TAT to increase 246% for Q034 and 21% for Q683. A TAT reduction can be realised between 2 and 3 capable mechanics out of 4 (3-10%), whereas the average TAT increases when all mechanics are capable of all tasks. It would be expected that having all mechanics capable of the bottleneck capabilities would allow for the lowest TAT. However, this is not the case. An explanation might be that reducing the bottleneck capabilities allows other mechanics to carry out more non-bottleneck tasks allowing the capable mechanics to focus on the bottlenecks. Further research on the available capabilities is advised in order to explain this.

Testing for the combined capabilities by testing various sets of available Q034 and Q683 capabilities does not show great changes in TAT (this is shown in Figure 4.10). For the scenarios tested the maximum increase in TAT is 11% and the maximum reduction is 6%. However, even though the effect is not very large the specific capability sets reduces the necessity of every mechanic being capable of all tasks. Therefore, even though the TAT effects might not be large the financial costs of implementing a solution with a specific capability set should be lower as less investment in training is required.

Changes to the arrival pattern of the combustors does have an influence on TAT. It was found that the greatest increase in TAT was for the combustors that arrived most consistently, which is unexpected. As the combustor arrivals are not considered value drivers the arrivals have not been tested extensively. It is recommended that this is investigated during further research, and it would be interesting to test how the model will behave when combustors arrive randomly.

Finally, changes to the maintenance route were not extensively tested as limited changes were possible. Two alternative routes were tested, namely a maintenance route in which excessive Q034 tasks were removed, and a route where subsequent tasks of the same capability were grouped to be carried out directly after each other. It has been found that grouping tasks increases TAT, and that reducing Q034 tasks reduces TAT. Combining the two also reduces TAT but not significantly compared to only reducing inspections.

Sensitivity Conclusion

In conclusion it has been found that changes to the previously defined value drivers capacity and capabilities do have an influence on TAT. Changes to capacity have the largest effect, whereas the effect of changes to capability depend on the changes that have been made. It can be said that there is a minimum of required capabilities. Once there are fewer capabilities available than the minimum TAT will be greatly increased. By having created a model that has been verified and validated the fifth research question has been answered. It is possible to create a model that can simulate the current process. And due to the variables that can be changed in the model it is possible to test the effects of changes to the value drivers.

4.2. Future State

After the influence of the value drivers has been determined and testing the model sensitivity to changes regarding these factors it is possible to investigate how TAT can be reduced to a maximum of 36 days, and even to see what might reduce the tat to a maximum of 24 days. This section will discuss the possible solutions that KLM ES might adopt for an improved future state. The required capacity, maintenance route and capabilities will be determined to ensure all combustors are completed within 36 days. Furthermore, the number of multi-skilled mechanics required to be able to perform maintenance within 24 days will be investigated in order to see what system changes are required to realise this additional TAT reduction.

The sensitivity analysis has determined that capacity and capabilities are most influential to TAT. Therefore the future state should be generated first by increasing the capacity. If there is a large difference in TAT between two capacities it is possible to see if changes to the available capabilities will allow TAT to be reduced further for the lower capacity. In addition to that the maintenance route might be changed.

In the base case a constant capacity of 4 mechanics with limited capabilities generated an average TAT of 28.5 days. From sensitivity it was determined that a constant capacity of 4 multi-skilled mechanics generates a TAT of 32 days. Upon further inspection it becomes clear that only 53% of the components arrive on-time in this scenario. It is clear that this scenario does not perform well enough. However, when investigating a capacity of 5 mechanics the average TAT is 16.2 days. As the difference between these scenarios is so large a 4+ scenario will be generated to see if this might sufficiently improve TAT.

In Appendix I an additional sensitivity test has been performed to see how much changes to both capacity and routing might reduce TAT. Figure 4.10 shows how different capability sets can influence TAT. As can be seen capability set P (Table 4.1) shows the largest reduction in TAT compared to a constant multi-skilled capacity of 4. As the sensitivity analysis has shown that reducing Q034 tasks might improve TAT this has also been tested for capacity set P. As Figure 4.11 shows this reduces the average TAT to 19.6 days. This is almost 9 days less than the average TAT for the base scenario. As such this scenario might be considered as scenario 4+.

Table 4.1: Mechanic capability set P

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x		x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4			x	x	x	x	x	A

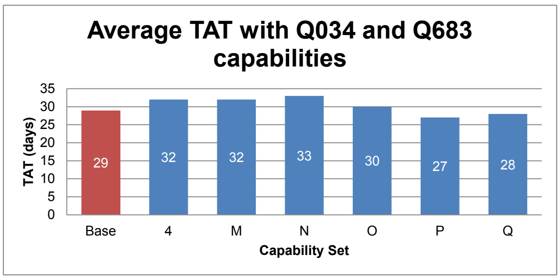


Figure 4.10: Average model output TAT for combinations of Q034 and Q683 capabilities

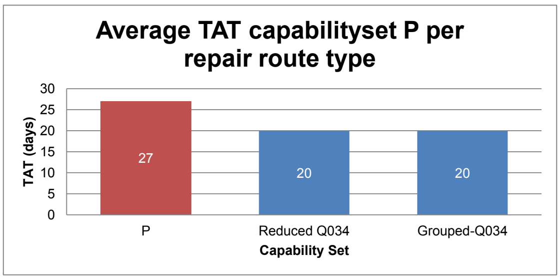


Figure 4.11: Average model output TAT for capability set P and adapted maintenance routes

Table 4.2 shows the average TAT, on-time performance and maximum TAT for the base scenario, a capacity of 4,5,6 and 7 multi-skilled mechanics and for scenario 4+, with 4 mechanics, capability set P, and a maintenance route with reduced inspections. Detailed results for this comparison can be found in Appendix M. As can be seen the Base and Capacity 4 are not sufficient. In the scenarios with 6 and 7 mechanics all components are on time. The constant capacity of 7 might also be further investigated to determine if this capacity will suffice for TAT 24. For a capacity of 5, 99% of the components are on time with a maximum TAT of 38. For scenario 4+ 96% is on time with a maximum TAT of 39.

Table 4.2: Performance per tested Future State capacity

Capacity	Base	4	5	6	7	4+
Average TAT	28.5	31.0	16.2	14.9	11.6	19.6
% On-time	60%	53%	99%	100%	100%	96%
Max	60	60	38	36	30	39

In order to determine which scenarios will suffice for TAT 36 and TAT 24 the combustor TATs are further investigated. Appendix L shows histograms and probability plots for all components, and for 7B, 8C and 8E combustors for each scenario. For capacity 5 (Figure 4.12) only one combustor is late, with a TAT of 39 days. All other combustors and components have a maximum TAT of 32 days. If 100% on-time performance is required this scenario does not suffice. However, taking into consideration that in this scenario many components are completed within 1 day, it might be possible to manage 100% on-time performance with the given capacity if the combustor that is about to become late is prioritised over other combustors with a longer time to go.

With a capacity of 6 mechanics the highest TAT is 36 days (Figure 4.13), and therefore all combustors are on-time. Furthermore, looking at the combustor probability plots, it becomes clear that all combustors have a normal distribution, which is a sign of a constant performance and little waste.

For the capacity of 7 mechanics all components are delivered within 30 days (Figure 4.14). Furthermore, a bit more than 95% of components are delivered within 24 days. All 8E combustors are delivered within 24 days, for both the 7B and 8C combustors 3 combustors are completed later than 24 days.

For the 4+ scenario (Figure 4.15) 95% of components are delivered within 36 days. All 8E combustors are delivered within 36 days (with the highest TAT being 36 days), for both the 7B and 8C combustors 3 combustors are completed later than 36 days. This scenario does not suffice regarding on-time perfor-

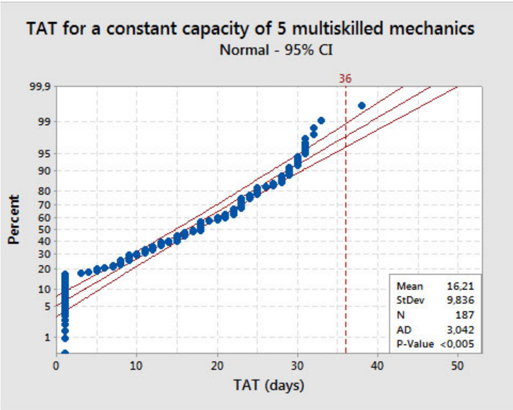


Figure 4.12: Combustor TAT for a constant capacity of 5 multiskilled mechanics

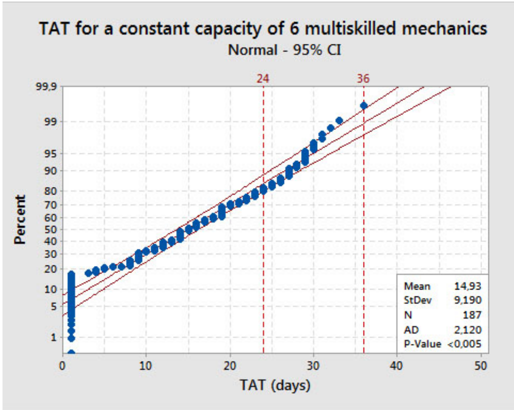


Figure 4.13: Combustor TAT for a constant capacity of 6 multiskilled mechanics

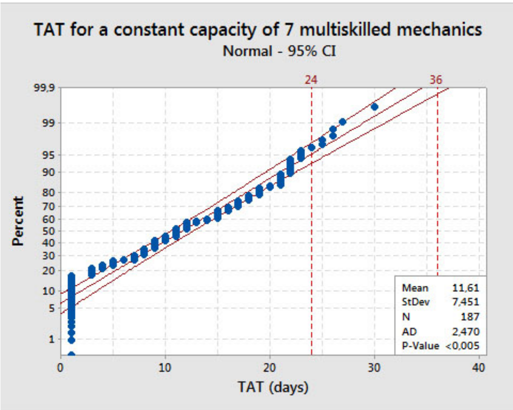


Figure 4.14: Combustor TAT for a constant capacity of 7 multiskilled mechanics

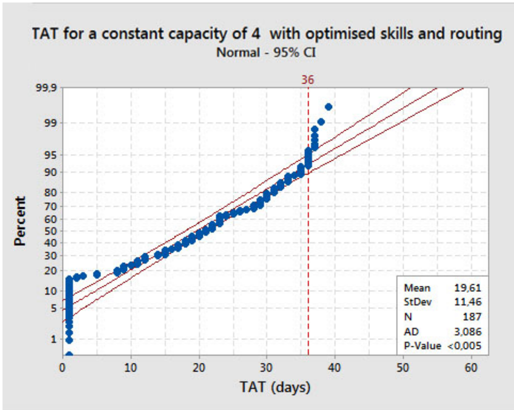


Figure 4.15: Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

mance. Comparing this scenario to both the base and a constant capacity of 4 multi-skilled mechanics does clearly illustrate that changes to capabilities and routing have a significant influence on TAT. In this case it can be seen that the on-time performance is increased by 36-43%. Furthermore, Table 4.3 shows how the mechanic utilisation rates are changed between the scenarios. The average utilisation rate in scenario 4+ is reduced by 5% compared to scenario 4. However, these utilisation rates are much higher than the current state utilisation. As such, the mechanics are required to work harder, but it is expected that this should not be a problem as long as the supply and demand of capabilities is correctly done.

Table 4.3: Mechanic utilisation rates per scenario

Worker	**4**	**4+**	**5**
A	98%	93%	81%
B	96%	94%	80%
C	97%	93%	101%
D	96%	87%	87%
E	-	-	69%
Average	97%	92%	84%

Extrapolating the findings regarding scenario 4+ would mean that if the capabilities for scenario 5 where changed or the inspections were reduced scenario 5 will allow a 100% on-time performance for a TAT of 36 days. Applying both changes should even further improve the average TAT. Finally applying the same steps to the capacity of 7 mechanics should ensure that 100% on-time performance for a TAT of 24 days can be realised. Increasing the capacity to 8 mechanics or more will not significantly improve the on-time performance for TAT 24 as in all these cases the maximum TAT is 29 days.

Whilst analysing the possibilities for a future state the last sub-research question has been answered. TAT can be improved by changes to capacity, capabilities and maintenance route. The combustor department future state should allow 100% on-time performance, and all combustors should be completed within 36 days. If the findings are extrapolated it is expected that with reduced inspections and specific capacities a constant capacity of 5 mechanics per day would suffice. However, taking into account that in the current state on average 7.5 mechanics are present daily and the on time performance is very poor it is suggested that the combustor department will make use of a constant capacity of 6 multi-skilled mechanics per day. It is strongly recommended that the combustor department seeks to reduce the inspections in the maintenance route to further improve performance and reduce pressure on this bottleneck capability. Furthermore, in order to realise a maximum TAT of 24 days 7 multiskilled mechanics will not suffice. However it is possible that when reducing inspections and optimising the available capabilities TAT will be sufficiently improved to achieve the required maximum.

Figures 4.16, 4.17, 4.19 and 4.18 show the histograms for all combustors, and for each combustor type with a constant capacity of 6 multi-skilled mechanics. As can be seen in all cases all combustors are completed within 36 days.

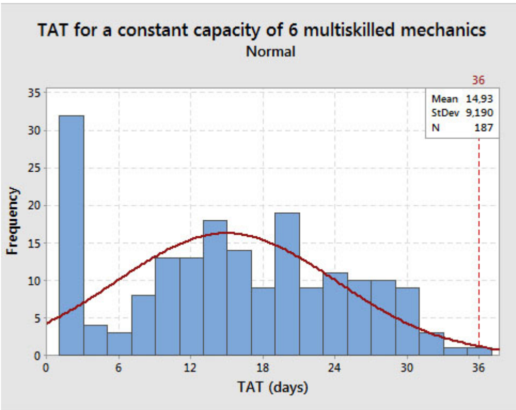


Figure 4.16: Combustor TAT for a constant capacity of 6 multi-skilled mechanics

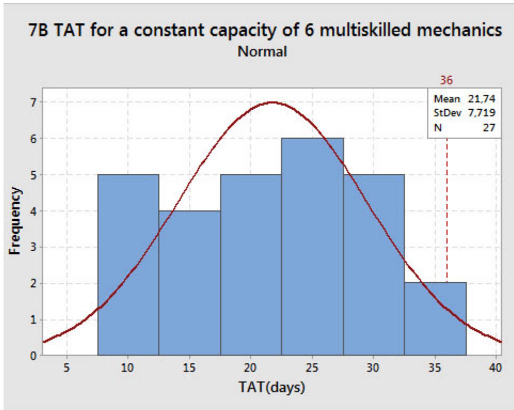


Figure 4.17: 7B Combustor TAT for a constant capacity of 6 multiskilled mechanics

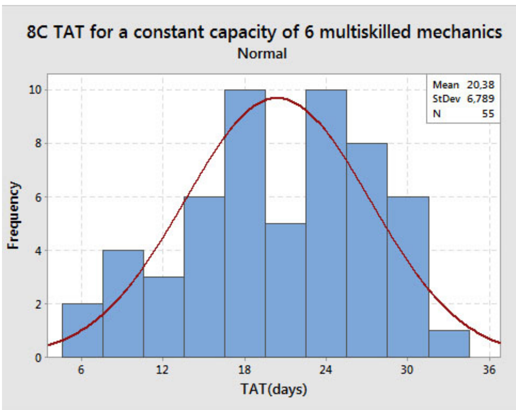


Figure 4.18: 8C Combustor TAT for a constant capacity of 6 multiskilled mechanics

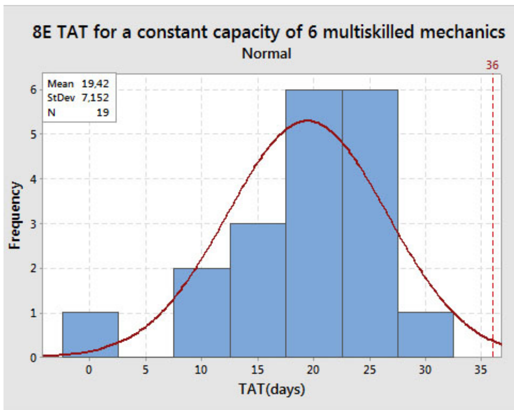


Figure 4.19: 8E Combustor TAT for a constant capacity of 6 multiskilled mechanics

Finally, it has been shown that it is almost impossible to fully utilise the available mechanics, but the average utilisation rates of possible future state scenarios are much higher than the current utilisation rates. This is mainly explained by the model capability to efficiently match supply and demand where this was found to be lacking in the current state. Therefore it is recommended that the combustor department will make use of a system that can dynamically show mechanics which components should be handled when.

4.3. Conclusion

This chapter sought to design a future state and to answer the fifth and sixth sub-research question by means of modelling and simulation. By using the available combustor maintenance data and translating the combustor maintenance process flowchart a Simio current state model was designed. The model has been verified and validated by means of historical data and use of statistical t-tests to ensure the average model output TAT was similar to the current state TAT. The Base model makes use of a far lower number of available mechanics than the actual current state. This is due to a constant capacity and the model making an efficient match between available and required capabilities. As such the model operates under the assumption that the supply and demand of capabilities is dynamically matched throughout the day based on components with the earliest due date being handled first.

The simulation model allows the current state to be reproduced, and changes to the system to be tested, and by doing so this has answered the fifth sub-research question. A sensitivity analysis regarding the value drivers has been performed to investigate their influence on TAT. It has been found that changes to capacity, capabilities and routing have a direct influence on TAT. Capacity has the largest influence, followed by capabilities. It has been found that mainly a lack of available bottleneck capabilities has a large negative effect on TAT. Thus, increasing the available capabilities has a positive effect on TAT. However, it has been determined that allowing all mechanics to perform work on all tasks limits this positive effect. Finally reducing the number of inspections in the combustor maintenance routes also allows TAT to be reduced.

Finally, combining the sensitivity analysis results has allowed for a few future state scenarios to be designed. This shows how TAT can be improved, and as such answers the final sub-research question. It has been found that a capacity of 6 multi-skilled mechanics will allow the future state to have 100% on-time performance for a TAT of 36 days. It has been found that it is not possible to realise 100% on-time performance for a TAT of 24 days with multi-skilled mechanics alone. However, it has been found that on-time performance can be increased with 36-43% by optimising the mechanic capability set and reducing the inspections. Therefore it is possible that a capacity of 7 or 8 mechanics will allow 100% on-time performance for TAT 24. The same is true for a capacity of 5 mechanics, but taking into account the current state performance and its average use of 7.5 mechanics per day it is more realistic to require 6 mechanics.

5

Conclusions & Recommendations

This is the concluding chapter of the thesis and will thus discuss the conclusions and recommendations that have been derived from the research. The conclusions will be structured in such a way that the answers to each of the research questions is answered, after which recommendations for further research are given. The chapter will conclude with a personal reflection.

5.1. Conclusions

This section will discuss the conclusions of this research by providing the answers to each of the research questions. First the main question will be answered, after which each of the sub-questions that has led to this answer will be discussed.

5.1.1. Main Research Question

The main research question that this thesis sought to answer is as follows:**What are the value drivers that determine the turnaround time of the aircraft engine combustor maintenance repair and overhaul process from a Lean Six Sigma perspective?**

It has been found that the value drivers that determine the combustor TAT are components, capacity and capabilities. The damage to the components determines the required repair. The maintenance route designed to carry out the repair dictates which tasks should be performed, and which capabilities are required and how long repair should take. The capacity influences TAT as depending on the required and available capacity work can be carried out on-time or components have to wait to be handled. The same is true for the capabilities, each task requires a certain capability and depending on whether a mechanic with that capability is available a task can be carried out or a component has to wait.

5.1.2. Sub-Question 1

The first sub-question is *How is combustor maintenance performance measured?*

It has been found from both literature and practice research that the main performance indicator for maintenance is on-time performance. This is determined by measuring the turnaround time, which is the time from process start to process completion. From an LSS perspective a 100% on-time performance should be realised. At KLM E&M the required TAT for maintenance is 36 days, and the on-time performance for combustor maintenance was less than 30% throughout 2014. Within the combustor maintenance TAT starts after the combustor component has been received and the TAT is completed after the combustor is reassembled and the final inspection has been performed.

5.1.3. Sub-Question 2

The second question *How is combustor maintenance carried out?*

From literature general information on aircraft and aircraft engine maintenance was found, but no specific information on combustor maintenance. Therefore the description of combustor maintenance is based solely on observations and interviews at KLM E&M ES. It has been found that the combustor maintenance process consists of six phases, as shown in figure 5.1. A complete combustor arrives, is inspected, then it is disassembled and each combustor component goes through its own maintenance process. As can be seen not all combustor components go through a complete maintenance process. Based on the state of a component it is determined whether a complete repair (Z51) is necessary. It has been found that in general only 3 components require a complete repair. Namely the inner and outer liners and the dome. All other parts only go through maintenance preparation after which they are ready for assembly.

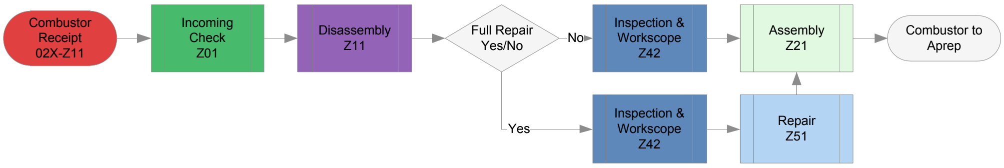


Figure 5.1: Combustor maintenance process flowchart

Maintenance is carried out based on task cards, or a shop traveller, which define which tasks should be performed and in which sequence. The tasks that need to be performed are described in maintenance manuals which specify exactly what needs to be done, and how. For each of the maintenance phases a new shop traveller is created. For all phases except phase Z42 and Z51 the tasks on the traveller are always the same. The tasks in phases Z42 and Z51 depend on both the type and the damage of the component. This makes the maintenance process hard to predict and control. Especially phase Z51 shows large variation in required maintenance time and tasks, and also shows a large variation in on-time performance.

Most tasks within combustor maintenance are performed by mechanics. As such it has been determined that the capacity of the combustor department is determined by the number of available mechanics. Furthermore, each task specifies which capability is required to perform that task and what the normative time required to complete this task is. Each mechanic has a specific set of capabilities and based on these capabilities the mechanic can handle a certain set of tasks. It has been found that the current capacity within the combustor department is highly variable, and that there are certain required capabilities that form bottlenecks, either due to their frequency or due to the lack of their availability.

5.1.4. Sub-Question 3

The third sub-question follows from the analysis of the combustor maintenance process, and is as follows: *Which value drivers are most influential to combustor maintenance?*

From both literature and practice research it was possible to define components, capacity and capabilities as the main value drivers for combustor maintenance. However it was also found that planning and the maintenance route are also factors that influence the combustor engine maintenance process. However, these factors mainly have an indirect influence. Planning helps determine the available capacity and capabilities, and also determines how these resources should be used. The maintenance route influences the required capacity and capabilities but depends on the damage of the components.

A conceptual framework was created that includes the value drivers and indirect factors, this formed the basis of the current state process analysis. After in depth analysis of the performance of this process it was found that components, capacity and capabilities are most influential to the process and as such are most critical to improvement of the process. The combustor components do have a direct influence on the process. However their influence depends on the damage and maintenance needed on these components, and this can not be directly influenced. The influence of capacity and capabilities has been confirmed during the sensitivity analysis in Chapter 4.

5.1.5. Sub-Question 4

The fourth question: *How are the value drivers related to each other?* has also been answered during the current state analysis.

It has been found that the value drivers directly influence TAT, and capabilities and capacity influence each other. Both are influenced by the components as these determine the required repair and thus capacity and capabilities required. Capacity and capabilities determine how much work can be performed, and which tasks can be performed depending on the match between required and available capacity and capabilities. Furthermore, routing and planning are part of the process and both influence and are influenced by capacity and capabilities. The routing and planning determine which capacities and capabilities are required and available. The conceptual framework has been extended to include the relationships between the factors (see Figure 5.2).

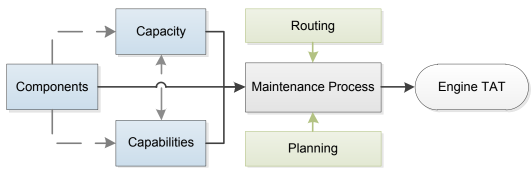


Figure 5.2: Conceptual framework for Engine MRO Including Relationships

5.1.6. Sub-Question 5

Can a model be created that simulates the current process in order to test changes to the value drivers?

This is possible. A Base model has been created that simulates the current state of the maintenance process. The model has been verified and validated based on the average TAT for combustors, and a sensitivity analysis has been performed to see how sensitive the model is to changes. Furthermore this sensitivity analysis was extended to determine how sensitive the model is to changes regarding the value drivers.

It should be noted that the Base model was validated with a constant capacity of 4 mechanics with a limited set of skills. The model is capable of correctly simulating the available mechanics and their capabilities, however the average TAT generated with this model was less like the current state than the Base model output. As such the current state model operates under the assumption of a constant capacity. Another assumption of the model is that planning is carried out to properly match the required and available capabilities and capacity.

The model demonstrates that changing the capacity and available capabilities influences the turnaround time and utilisation of process resources (servers and mechanics). Changes to the maintenance route in which the route was simplified or reduced also directly caused changes to the TAT and utilisation. It was difficult to test the effect of planning as the simulation model automatically plans which maintenance is carried out when, and it was not possible to make all possible choices and planning random. However, it has become clear that both TAT and bottlenecks are reduced if mechanics reevaluate which task they should perform for which combustor after each task they complete.

5.1.7. Sub-Question 6

All previous questions allow the final sub-question to be answered. *How can TAT be improved?*

By using the findings from the sensitivity analysis it has been found that TAT can be improved by increasing the overall capacity, ensuring a constant capacity and by increasing the bottleneck capabilities. It was assumed that having all mechanics capable of performing all tasks would have the most positive effect on TAT. However, it has been shown that this is not the case. For a capacity of 4 mechanics only two mechanics are required to be capable of all tasks, and two mechanics are required to be capable of all but one bottleneck capability (either Q034 or Q683). Furthermore an additional TAT reduction can be realised by reducing the number of inspections that are performed throughout the Z51 maintenance phase.

For the combustor department a future state should be designed that will allow 100% on-time performance. This can be realised by providing a constant capacity of 6 multi-skilled mechanics. However, it has been found that by optimising the skillset of 4 available mechanics and by reducing the inspections an additional reduction of TAT of 35% can be realised (improving the on-time perfomance by 36-43%). Therefore it might be possible to realise 100% on-time performance with 5 mechanics. However, keeping in mind that in the current state on average 7.5 mechanics were required daily it is advised to provide a constant capacity of 6 mechanics and to see if the available skills and routing can be optimised to further improve TAT. This can be done by testing changes in the maintenance model.

5.2. Recommendations

During this research observations have been made regarding aircraft engine combustor maintenance and the way this process is carried out. Furthermore a model has been made that can simulate the current state process and can be used to determine the influence of changes to the main value drivers. The model, as has been mentioned during the validation and sensitivity analysis has limitations, and the combustor maintenance process at KLM E&M is far from ideal. As such recommendations may be made for further research and to KLM in order for them to further improve their process.

5.2.1. Recommendations for Further Research

Very little was found in literature regarding lean six sigma applied engine maintenance. This thesis has defined a conceptual framework that identifies the main value drivers for TAT in combustor maintenance. It is recommended that further research is done to see if the conceptual framework is applicable to the maintenance process of other components, engine maintenance, and other maintenance processes in general. As other components with similar tasks have already been processed by the model it is likely that this is true. However, many of these components are mainly repaired in external departments which have not (yet) been adequately modeled for these components.

It is recommended that the simulation model is tested more extensively. As maintenance is unpredictable in nature, stochastics might be used to represent uncertainties in the process such as the damage and required repair, and the arrival of combustors. The simulation model that represents the combustor maintenance process is based on historical data. As such it is recommended that the model is tested while making use of stochastics for the combustor arrivals and necessary maintenance routes in order to see how the model and process will respond to these uncertainties. Furthermore, by doing so it might be possible to predict the effects of different maintenance routes or new components. Other factors that might be tested in the model are changes in the amount of work available. For instance what happens if 50 combustors arrive simultaneously, and what happens if a new combustor arrives every day.Further points are the effects of changing the handling sequence of the entities, workers and servers, and the way priorities are given to certain components.

Also the model should be further developed regarding work in the external departments, and their workloads. Another thing to develop is the server capacity of the servers in the combustor department. It was found impossible to increase the server capacity whilst still having both servers and workers show correct off-shift behaviour. It is likely that this can be resolved with an add-on process. However, I was not able to do so. Once this has been developed the sensitivity and effect of increasing server capacity should be tested in order to determine if it is useful to carry out multiple tasks of the same capability simultaneously, and if so to what extent should this be possible. Another thing that should be enabled in the model is the prioritisation of for instance Q034 tasks over other tasks, and the possibility for mechanics to reject an offered task in order to be available for the next inspection task to become available.

Finally, further research might be carried out regarding the influence of planning on the maintenance process, and more specifically it might be interesting to research if there is an ideal method to match required and available capabilities and incorporate due dates and priorities e.g. longer maintenance routes. If there is such a method, it might be interesting to develop a tool that can determine this on a daily (or more frequent) or even dynamic basis so that the process can carried out as efficiently as possible and can be easily adapted to changes. It is possible to use the simulation model to plan this. However, this might not be practical for day-to-day use.

5.2.2. Recommendations for KLM E&M

This research has been carried out because of KLM E&M's request to analyse the performance within their engine shop. There are many recommendations for KLM regarding combustor maintenance in particular, and engine maintenance in general. First of all I believe that KLM ES would benefit from creating a clear overview of the lower level engine maintenance processes and how these are related to each other. Furthermore, everyone within the engine shop should be aware of these relationships so that communication between different departments can be improved and people are more aware of the bigger picture.

Another thing regarding process overviews is the way processes are managed and performance is tracked. For instance, while doing my research it took me months to finally realise that the combustor department on-time performance was based solely on the performance of phase Z51, which is only one part of combustor repair. Furthermore, this performance was based on combustor components, whereas it takes six components to make a combustor and it takes only one late component to have a late combustor. This should be changed. In relation to the clearer overview it should become more clear which components become available for repair at what point during engine maintenance, and when these components are again required. By doing so it should be possible to have a better planning and more clarity on where there is room for slack, and where there is none.

Regarding the combustor maintenance a few things are recommended. First of all the accuracy of normative maintenance times should be tested. Not only are there large discrepancies between normative and actual maintenance times, the mechanics believe that the normative times are frequently incorrect. If this is tested this will make the mechanics feel heard, regardless of the outcome. Another thing is the PV's and out of stocks. These are not adequately registered, nor are they properly tracked. By making note of such events and their causes, and by regularly evaluating this it might be possible to determine frequent issues and to take action accordingly.

The combustor department should reevaluate the maintenance routes. It is very likely that these have 'grown' over the years due to consequent rework or lack of quality. By looking into what is strictly necessary, and what might be carried out differently altogether, it might be possible to reduce maintenance times, bottlenecks and unnecessary tasks. Furthermore, it is strongly recommended that the combustor department seeks to reduce the inspections in the maintenance route. There are so many inspections throughout the process, whilst this does not add value but does form a bottleneck that something has to be changed. The department might consider better monitoring the quality of work (by doing random testing or something other than a routine inspection), or improve the skills of the mechanics that are capable in order to prevent the low quality that has resulted in the inspections.

Finally the combustor department should improve their planning. Capacities should be better planned, the availability of capabilities, but also who performs which tasks and when, and when should spare parts or new components be ordered.

5.3. Personal Reflection

This section contains my personal reflection on the research process. When looking back at my internship I have learned two things. First, theory and practice are two very different things. It seems to me that research is conducted from a very idealistic mindset, namely that of investigating a problem and trying to find an ideal solution. However, in practice there is no time (taken) to look into all the details and puzzle until the ideal solution is found. Decisions are frequently taken based on gut-feeling or previous experience. For me the balance between the two was very interesting as I wanted to help KLM as fast as possible, but at the same time I wasn't really doing 'proper' research.

The second thing I learned was that you can have the most brilliant idea or solution, but that there is no way it is going to work if there is no will to listen or change. I really enjoyed and learned a lot from walking around on the shop floor. When I first came I saw all the guys think, 'oh there's another suit coming to tell us what to do, with no idea what we're doing.' By my walking around, asking questions and listening to the mechanics I feel that I gradually earned trust, which allowed me to better understand the process, as I got honest answers, and at the same time allowed me to be critical of what they were doing, and could make the department understand that changes are necessary and that they don't directly mean bad things (as everyone's afraid of losing their position).

Regarding research I have gained a lot of knowledge, of theory, of conducting research but also about myself. Considering the fact that I have analysed process performance and have familiarised myself with lean and six sigma. I believe that if I were to apply my own research to my thesis process I will find a lot of waste, and a lot of room for improvement, not to mention my on-time performance. This makes me feel a bit like a hypocrite. However, I do believe that doing research is an iterative process in which new knowledge is gained, and new insights are found continuously. But an important part of research is also making choices and sticking to them, which is something I find very hard. I was afraid to make clear choices regarding my topic, which is why it has taken me a long time to finally have a clear course of action and a focus.

Furthermore I have found that throughout the process I may have focussed too much on the details and might have lost sight of the bigger picture. I focussed on details thinking that this would really have an effect on the outcome. However, looking back I can see that many of the things that I thought important at the time are only very small parts of the bigger picture. The 80/20 rule definitely applies here as well. After looking at the research question, rereading this report and what actually adds to answering that question, I was able to either move things to the appendix or remove sections altogether because they were not entirely relevant to the question.

At the same time these details have allowed me to get a thorough understanding of the problem. For instance in the case of the model, where I tested many scenarios that produced 'near' fits to the current state. It is likely that these near fits would have yielded approximately the same outcome. But, by tweaking the variables I was able to generate a fit of which I was confident that it represented the system properly, and in the process I gained a better understanding of the model and its limitations.

I am very glad to finally be done. My research has been a series of ups and downs and twists and turns but I believe that in the end I have actually ended up with a report that can actually add value. Especially to KLM, but also possibly for research as I have been able to identify value drivers that I have not been able to find previously described in literature regarding this context. Furthermore, I am very pleased with the fact that I have built a simulation model, and that it actually works. Considering that I had no modelling/simulation experience before December, and that combustor maintenance is fairly detailed, I believe I have done quite well in the short time of learning how simulation works and building the model.

Bibliography

S. Ackert. Engine maintenance concepts for financiers. *Macquarie AirFinance, Mar*, 2010.

Federal Aviation Administration. *Pilot's Handbook of Aeronautical Knowledge*, volume 1. U.S. Department of Transportation, 2008.

E.D. Arnheiter and J. Maleyeff. The integration of lean management and six sigma. *The TQM magazine*, 17(1):5–18, 2005.

P. Ayeni, T.S. Baines, H. Lightfoot, and P. Ball. State-of-the-art of'lean'in the aviation maintenance, repair, and overhaul industry. *Proceedings of the Institution of Mechanical Engineers, Part B: journal of engineering manufacture*, 2011.

W.W.A. Beelaerts van Blokland, A. De Waard, and R. Curran. Design of a lean mro business process for epcor. In *Conference proceedings of the 26th Congress of International Council of the Aeronautical Sciences (ICAS), 2008, 1-9 (2008)*. American Institute of Aeronautics and Astronautics, AIAA, 2008.

W.W.A. Beelaerts van Blokland, C. Slob, and R. Curran. The development of a performance assessment method to evaluate and optimize the value of material flows in a mro environment. *Journal of Aerospace Operations*, 2012.

M. Ben-Daya, D. Ait-Kadi, Salih O. Duffuaa, J. Knezevic, and A. Raouf. *Handbook of maintenance management and engineering*, volume 7. Springer, 2009.

M.R. Bowers and G. Adams. Turbo toc. *APICS magazine*, February 2008.

CEN. Nen-en 13306:2010, 2010.

B. Clegg, M.P.J. Pepper, and T.A. Spedding. The evolution of lean six sigma. *International Journal of Quality & Reliability Management*, 27(2):138–155, 2010.

S. Conger. Six sigma and business process management. In *Handbook on Business Process Management 1*, pages 127–146. Springer, 2015.

J. Defeo and J.M. Juran. *Juran's Quality Handbook: The Complete Guide to Performance Excellence 6/e*. McGraw Hill Professional, 2010.

W. Edwards Deming. Out of the crisis, massachusetts institute of technology. *Center for advanced engineering study, Cambridge, MA*, 510, 1986.

H. W. Dettmer. *Goldratt's theory of constraints: a systems approach to continuous improvement*. ASQ Quality Press, 1997.

David M Ferrin, Martin J Miller, and David Muthler. Lean sigma and simulation, so what's the correlation?: V2. In *Proceedings of the 37th conference on Winter simulation*, pages 2011–2015. Winter Simulation Conference, 2005.

G. Fishman. *Discrete-event simulation: modeling, programming, and analysis*. Springer Science & Business Media, 2013.

M.J. Franchetti. *Lean Six Sigma for Engineers and Managers: With Applied Case Studies*. CRC Press, 2015.

M.L. George and M. George. *Lean six sigma for service*. McGraw-Hill New York, NY, 2003.

E.M. Goldratt. *Theory of constraints*. North River Croton-on-Hudson, NY, 1990.

A. Gortenmulder and J. Wiggelinkhuizen. Cbbsc es january 2015. KLM internal presentation, January 2015.

C. Gygi and B. Williams. *Six sigma for dummies*. John Wiley & Sons, 2012.

K.M. Henderson and J.R. Evans. Successful implementation of six sigma: benchmarking general electric company. *Benchmarking: An International Journal*, 7(4):260–282, 2000.

P. Hines, M. Holweg, and N. Rich. Learning to evolve: a review of contemporary lean thinking. *International journal of operations & production management*, 24(10):994–1011, 2004.

AT Kearney. Achieving customer satisfaction through logistics excellence. *Managing Service Quality: An International Journal*, 4(2):47–50, 1994.

J.P.C. Kleijnen. An overview of the design and analysis of simulation experiments for sensitivity analysis. *European Journal of Operational Research*, 164(2):287–300, 2005.

Air France KLM. Annual report air france-klm 2014, 2015.

J. Levitt. *Lean maintenance*. Industrial press, 2008.

SIMIO LLC. Simio reference guide, 2014.

S. Mi Dahlgaard-Park and T. Bendell. A review and comparison of six sigma and the lean organisations. *The TQM magazine*, 18(3):255–262, 2006.

M. Morrison and M.S. Morgan. Models as mediating instruments. *Ideas in Context*, 52:10–37, 1999.

D. Nave. How to compare six sigma, lean and the theory of constraints. *Quality Progress*, 35(3):73–80, 2002.

A. Parida and U. Kumar. Maintenance performance measurement (mpm): issues and challenges. *Journal of Quality in Maintenance Engineering*, 12(3):239–251, 2006.

G. Parry, J. Mills, and C. Turner. Lean competence: integration of theories in operations management practice. *Supply Chain Management: An International Journal*, 15(3):216–226, 2010.

C.D. Pegden. Simio: a new simulation system based on intelligent objects. In *Proceedings of the 39th conference on Winter simulation: 40 years! The best is yet to come*, pages 2293–2300. IEEE Press, 2007.

H. Pham and H. Wang. Imperfect maintenance. *European Journal of Operational Research*, 94(3): 425–438, 1996.

T. Pyzdek and P.A. Keller. *The six sigma handbook*, volume 486. McGraw-Hill New York, NY, 2003.

Shams-ur Rahman. Theory of constraints: a review of the philosophy and its applications. *International Journal of Operations & Production Management*, 18(4):336–355, 1998.

M. Rother and J. Shook. *Learning to see: value stream mapping to add value and eliminate muda*. Lean Enterprise Institute, 2003.

A. Sahay. *Leveraging information technology for optimal aircraft maintenance, repair and overhaul (MRO)*. Elsevier, 2012.

A. Saltelli. Sensitivity analysis for importance assessment. *Risk Analysis*, 22(3):579–590, 2002.

A. Saltelli, M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, M. Saisana, and S. Tarantola. *Global sensitivity analysis: the primer*. John Wiley & Sons, 2008.

P. Samaranayake. Current practices and problem areas in aircraft maintenance planning and scheduling: interfaced/integrated system perspective. In *INDUSTRIAL ENGINEERING AND MANAGEMENT SYSTEMS, Proceedings of the 7th asia-pacific conference in bangkok, UWS, Sidney*, pages 2245–2256, 2006.

R.G. Sargent. Verification and validation of simulation models. In *Proceedings of the 37th conference on Winter simulation*, pages 130–143. winter simulation conference, 2005.

T.J. Schriber, D.T. Brunner, and J.S. Smith. Inside discrete-event simulation software: how it works and why it matters. In *Simulation Conference (WSC), 2013 Winter*, pages 424–438. IEEE, 2013.

R.E. Shannon. Simulation: a survey with research suggestions. *AIIE Transactions*, 7(3):289–301, 1975.

R.E. Shannon. Introduction to simulation. In *Proceedings of the 24th conference on Winter simulation*, pages 65–73. ACM, 1992.

L.A. Shay. Aviation week announces 2015 mro of the year award winners. *Aviation Week and Space Technology - MRO Edition*, April 2015.

V. Six and W.H. Muller. Green belt course. KLM internal presentation, May 2015.

R.D. Snee. Lean six sigma-getting better all the time. *International Journal of Lean Six Sigma*, 1(1): 9–29, 2010.

A. Stander, M. Boersma, B. Wennink, M. de Vries, R.J. de Boer, and M. Overeijnder. Applying proven methods in a new environment: the case of lean in business aviation mro. In *In Air Transport and Operations: Proceedings of the Third International Air Transportation and Operations Symposium*, 2012.

B.P. Sunjka and S.F. Murphy. Lean implementation within south african aircraft maintenance organisations. *International Journal of Lean Enterprise Research*, 1(1):59–80, 2014.

A.J. Thomas, R. Mason-Jones, A. Davies, and E.G. John. Reducing turn-round variability through the application of six sigma in aerospace mro facilities. *Journal of Manufacturing Technology Management*, 26(3):314–332, 2015.

W.T. Truscott and W.G. Truscott. *Six sigma: Continual improvement for business: A practical guide*. Routledge, 2003.

A. de Waard. The design and implementation of a lean business process at epcor. Master's thesis, TU Delft, 2007.

K.J. Watson, J.H. Blackstone, and S.C. Gardiner. The evolution of a management philosophy: The theory of constraints. *Journal of Operations Management*, 25(2):387–402, 2007.

J.P. Womack and D.T. Jones. Beyond toyota: how to root out waste and pursue perfection. *Harvard business review*, 74(5):140, 1996.

J.P. Womack and D.T. Jones. *Lean thinking: banish waste and create wealth in your corporation*. Simon and Schuster, 2003.

A
Combustor Department Observations

This appendix contains observations done during two tours that were received of the combustor department. The first has taken place on 25-03-2015, the second on 01-04-2015. I was guided through the combustor repairs workshop by Aad van Kessel. Aad van Kessel is responsible for Engine HW&QEC, he is the skill manager of both the combustor and tube bending departments. He shares this function with Rob Keizer and they rotate day/night shifts every other week.

Aad showed me the combustor workshop, along with other departments and machinery that are necessary for the combustor maintenance but are located within different departments. During the tour I was informed about which work is done at the combustor workshop. Furthermore I asked questions relating to my observations. The following is an account of what I have noticed during this tour.

The engine workshop is open 5 days a week from 7.10 to 00.00. Work is divided into two shifts, an early shift from 7.10 to 15.40 and a late shift from 15.30 to 00.00. During the 10 minute overlap in shifts the handover of work and information takes place between the two groups.

Combustor repair is located in shop PL4. The repair is divided into two parts; Z42 - preparation, and Z51 – maintenance. The combustor department is dependent on 4 external departments and machines:

- The oven
- Grote machinale (large machinery)
- High pressure cleaning
- Plasma and Welding

A.1. Observations 25-03-2015

A.1.1. Capacity

- KLM E&M at Schiphol-Oost provides maintenance for GE engines only. Currently repairs are performed for CFM56-7 and CF80-C and E engines. Different skills are required for the different engines. According to Mr Van Kessel KLM is better at CFM56-7 engine repairs, and is slower for the 80C engines etc. They have only started repairs on these engines 2 years ago. Possibly if E&M continues at this pace they will not be able to beat or compete with their competitors as they are currently slower and more expensive.
- Regarding capacity the combustor shop is able to handle about 15 combustors at a time. However, it can only handle a mix of combustor types. They could not handle 15 combustors of the same type at once.

A.1.2. Preparation

- Preparation consists of cleaning (HPW that removes plasma), and oven (this softens the material so that work can be performed on the material).
- The preparation route timing is highly dependent on external departments. There is only 5 days planned for this process. However two steps are hard to plan as these are outsourced to other departments.

  - If a combustor comes in on Thursday and is ready for the oven on Friday, so it can stay in the oven for 24 hours, this does not interfere with the 5 days. However, if the combustor is placed in the oven on Monday instead of Friday the combustor will always be late (the 5 days are already over after Monday).
  - Furthermore combustor receipt on Friday is always an issue as you will only have a maximum of 3 working days to perform the preparation.
- Combustor parts that need (re)ordering can only be ordered once the ‘Z51’ route is started.
  - If parts are required to be exchanged through an SB they can also not be ordered in advance even though this maintenance is known to be performed in advance.

A.1.3. Workscope

- Work on a component is determined based on repairs needed. Depending on defects certain repairs are determined. These repairs are defined through a work bill which has been designed by the engineering department. Each repair requires certain steps, these steps for all the repairs of the component are combined in the shop traveller.
- The shop traveller defines tasks and their sequence. The shop traveller is ‘followed’ until the combustor repairs have been finished.
- If extra damages occur during the process the traveller is adapted and a new traveller is added to the existing traveller, which is then marked ‘VOID’.
  - This can lead to mix-ups/confusion as to what is to be done as it is not always clear which traveller to use at first glance
- Rework is systematically part of the repairs and traveller. If ‘rework’ is unnecessary certain steps are skipped.
- A question to be asked is: why not do things right the first time? Or why not repair all defects (i.e. tears) even though they are within limits (these tears might grow during the repair process).

A.1.4. Progress tracking

- Every morning a roll call takes place. During this roll call the skill managers meet in order to discuss their work progress. This helps monitor the engine repair process, furthermore lists are presented showing the parts progress per engine and the time to delivery date. This allows the departments to discuss their issues, furthermore priorities are given. For example, the combustor part is about to be late if it is not treated in the oven within the morning. The oven manager can say whether or not this is possible and the combustor part is prioritized. By having this roll call people know where there is possible slack and where ropes need to be tightened.
- A colour is assigned to each combustor. A storage space (rack) and a ‘tracking’ system are linked to this colour. The tracking system indicates where in the shop the combustor is located/which task it is undergoing. However 15 different colours are needed, which means that shades are used and it is not always clear which colour is which. The idea is that the sheet has a certain colour and the sticker on the rack has the same colour (including the name of the colour).
  - However, the shades don’t always coincide and as there is no colour name on the tracking sheet confusion can occur.
- The attitude at other departments is that if the part is in the early stage of the process (in the beginning of the 28 days) there is no need to hurry. Thus, other parts which are towards the end of the 28 days are prioritized over the other parts. However this can mean that delays are incurred early on in the process.

A.1.5. Skills

- People manually move combustor parts. If one part is heavy and the mechanic is not in shape he will be less likely to pick up a task that involves lifting or moving around the part.
- There is an issue with skills: not everyone has the same skills or the same level of skills. Some people can only be used for a limited number of tasks. Furthermore some people are better at a certain skill than others. And people prefer to hand over or leave the work to more skilled people. An example of this is welding: not everyone is equally good at welding

- Furthermore it is not clear what weld is ideal. In some cases a rough and thorough weld will suffice, but frequently a thorough and ‘pretty’ weld is made. This could cost unnecessary time.
- Every six months a new certificate is required per weld type, as a proof of ability. If one welder can perform three types of welds 6 tests should be done per year. This means it is expensive to teach or allow everyone to weld. Planning and billing:
- There is no clear instruction or agreement of the order in which maintenance should be performed. There are no agreements on which item should be handled first by a mechanic.
- A time duration is defined for each maintenance activity. This time is used to build up the bill. The more time an activity takes, the more a client is charged. If the time performance differs from the predefined time by only a few minutes no changes are made to the bill. However, if there is a large deviation this time will be adapted in SAP. If the large deviation occurs frequently a permanent change might be made to the time duration definition. For instance an older engine requires longer maintenance as it is usually more damaged.
  – It might be noted that the process times will not be defined to take less time as this might have a negative effect on the bill.

A.1.6. Staff

- There is little trust among the mechanics according to their managers. They don’t rely on each other and do not trust others to do their jobs well.
- There is an issue with staffing. Mechanics from departments that have sufficient staff are ‘lent’ to other ‘understaffed’ departments.
  – For instance, the current inspectors from the combustor department are outsourced to another department. Only one inspector per shift is available to the combustor department.
  – In case it is very busy a mechanic that used to be an inspector but now works in a different department can occasionally be called upon. However, if he is not available only one person is available for all the checks.
- Mechanics choose which task to do.
  – The result is that mechanics pick the tasks they prefer, and leave more difficult tasks to others or for a later time.
  – Another result is that if one mechanic is working on a certain chain of tasks towards the end of the day no one will continue/take over this chain of tasks during the late shift. Hence this part is left unattended until the next morning, when the mechanic can continue his work.

A.1.7. Issues concerning identification and information

A combustor part moves around the shop and is always accompanied by the shop traveller. However this traveller can not be taken into the oven for instance. When the traveller and part are temporarily separated mix-ups or issues might arise regarding the match between the traveller and the part.

Issues also arise when the part is plasma sprayed. Along with the part a small plate is sprayed. This plate is then tested in order to verify if the plasma spray was of the right quality. Once the plate has been tested a quality form is filled out that indicates the quality of the spray. This form should always accompany the combustor part, and is needed to verify that the combustor is ready for release. However it occurs that either the plate or the form gets lost. If the plate gets lost the whole part has to be plasma sprayed again, if the form gets lost only the plate needs to be retested. In both instances this causes extra time and costs to be made in order to validate the engine quality. Even if this work has been done, the engine assembly can only take place once the form is available (the form is found, the test is redone or the plasma has been reapplied)

At the combustor station this happened. The form was lost, so the combustor could not be released for aprep. What’s more is that the combustor was already reassembled. If the form had not been found the combustor might have to be disassembled in order for the part to be re-sprayed. In this case the combustor was already finished on 24/3 (the deadline date) but it could only be handed over on 15/3 at 13.30 due to the lost form(found at 11.30) and required administration.

A.2. Observations 01-04-2015

On April 1st I went back to the combustor workplace. After one of the main observations that there are many inspections embedded in the repair process my supervisor told me that Harold F. Dodge has once said 'You can not inspect quality into a product.' That is to say, a quality inspection is only a control of the quality of the process performance. An inspection shows whether or not the process has been performed to specification. The inspection itself does not improve the quality of the product nor does it improve the quality of the process. It only shows whether or not the performance is up to par. Hence, the quality should be produced by the process rather than adding extra inspections to the process.

According to W. Edwards Deming 'routine 100 per cent inspection to improve quality is equivalent to planning for defects, acknowledgement that the process has not the capability required for the specifications. Inspection to improve quality is too late, ineffective, costly' [Deming, 1986]. This is true for the combustor repair process. Inspections have gradually been added to the process in order to ensure the quality. One inspection is mandatory as this is needed to verify the repair has been performed as it should and to demonstrate to all parties involved (GE, customers and KLM) that the quality is of the required standard. All other inspections have been added after certain steps in the process failed to meet the required quality. However as Deming continues 'it is important to carry out inspection at the right point for minimum total cost.' This notion I believe is very relevant to the maintenance process at the combustor workplace. It is very likely that not all inspections that are currently done are necessary or done at the point at which it is most efficient.

Furthermore, Deming continues on the responsibility for quality. If the inspectors are responsible for the quality (which is the case for combustors) they are the ones that are concerned with the quality. This leads to the mechanics performing their work for performance's sake rather than performing their work to the required quality as they are not held responsible for the quality of their performance. The inspectors are held responsible for the work of the mechanics. If quality is to improve the ones that are responsible for the quality should also be held accountable for the quality.

Quality and inspection are an interesting form of waste, and require more research. Aside from the quality and inspections I had a few other questions/issues that I would like to further explore. Another issue that arose from the vsm session and my last meeting was the skill coverage. If mechanics have more skills they will be able to perform more subsequent process steps, hence eliminating waiting time. Hence it might be relevant to explore the capabilities of each of the mechanics in the department in order to see what tasks might be allocated to which mechanic.

Furthermore, I wanted to know how the shop traveller is generated. I.e. how are the steps in the traveller related to the repairs specified by the manuals and travellers. And of course, what is in the manuals and what do they look like. It would be interesting to investigate what is required by GE, by law and by KLM with regards to the repairs. Another point of interest is the shop capacity. How many engines can be handled. They say 15, but is this at any given time, per week or per month?

A.2.1. Meeting Skillmanagers

Z03 is disassembly, this happens in stage 1 of the MRO process. Z51 (the repair stage) is currently 28 days but it should be 25 days (this is a demand from Jan Willem van Woerdekom, the production unit manager repairs for engine services). The total time for engine MRO is 36 days. These 36 days are built up according to the steps and activities as shown in Figure A.1 and Figure A.2. However if the days reserved for the different stages are added up the total adds up to 37 days instead of the aimed 36 days.

Figure A.1: Stages MRO Process

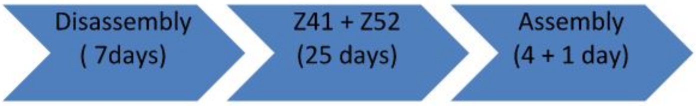


Figure A.2: Activities MRO process related to stages

Break times are at set times for all mechanics. (what would be the right term for mechanics? Note that in this case mechanics refer to: benchworkers, inspectors etc). GE provides the engine manual. The engine manual prescribes the necessary repairs. The KLM Engineering department determines the steps that are needed to perform the necessary repairs. There are certain repairs that KLM cannot perform, and does not want to develop. These repairs are then outsourced.

The so called 'voorroute' (pre route) is an inspection and disassembly of the module (combustor), crack control and UHPW and oven are also parts in the repair preparation. According to the data analysis by Willem Hamer the transition from Z42 (the heavy preroute) and Z51 (the main route) takes a lot of time. The inspectors are responsible for this transition. You try to get the combustors through Z42 as fast as possible, as this directly influences your TAT (there's 5 days scheduled for this part of the route). However, once Z51 is started they have a lot of time again so they leave the parts that still have a lot of time to go and give preference to parts that are in a hurry towards the end of the time to go until assembly.

Per motor type and per module (CG) engineering has appointed a responsible engineer. When do you reject anything? Jan: 'When this is needed.' Loops have been included in the 'routekaart' (shop traveller) because rework was structurally necessary. The repeated steps are marked as 'in case necessary' leaving it up to the mechanics to decide whether or not the 'rework' is necessary/applicable. This is actually the responsibility of the inspector. There are two types of repairs; light, with a minimal inspection/resizing; and heavy, which is per definition a larger repair route.

A PV is a product verstoring (product disruption). The work centre asks for a PV when they can not continue their work on a specific item for whatever reason. The PV is a status that is then applied to this item and allows for monitoring why something is not happening as it should. For instance the damage to the item is heavier than anticipated and communication with the involved parties is necessary in order to make a decision on whether or how to continue.

Once a PV notification is started the issue has to be resolved within a limited time. If this can not be done feedback is needed as to why this is not possible. In the pre-route a PV should be solved within 4 hours, in the main route a PV should be solved within 48 hours. According to Aad less time should be given for the PV during the main route.

After the first inspection of the combustor parts there are several options; the parts can be accepted for internal repair, external repair or they can be rejected. The cowls hardly need repair, and if they do E&M can usually perform the repairs themselves. Sometimes the cowls are rejected, but nonetheless this is never a showstopper.

A repair is performed due to the following reasons:

- Client demand/wish
- Service bulletin
- Item did not pass the inspection

The combination of these repairs determines the repair route.

Crack inspection can be performed by the bench worker, however the inspector has to perform this inspection and can not always perform this inspection right away.

Stamps are used on the shop traveller to show that a task has been performed. If a previous task has not been stamped, the subsequent task can not be performed. Sometimes the stamps are forgotten and the subsequent tasks should not be performed because the required work before this task has not been performed. Simultaneous with the stamps a scan is used to track progress in SAP. This scan is also a requirement in order to be able to continue subsequent tasks. If one continues to work without the scan it is impossible to register the subsequent steps in SAP.

However sometimes one person performs several subsequent tasks and only stamps/scans them when they have finished their sequence. This can lead to a data inaccuracy once the sap data is used for analysis. Furthermore in case someone forgets to scan/stamp their work and does not notify others that they have performed this task a risk exists that the same task is performed again by another. Another option in the case of the stamps is that once the repairs have been completed and the traveller is checked it turns out that stamps are missing and people decide to stamp these tasks even though they are not 100 per cent sure that this task has been performed. This may lead to defects or other issues with the part.

A 0-stand (0-level) is a situation where the replacement parts that are needed are unavailable. Replacement parts can be nuts and bolts and the swirls are frequently redeveloped and hence need ‘upgrading.’ Sometimes a larger part needs replacement, but this is usually only in the case of a service bulletin requirement.

In the QEC department, where both Aad van Kessel and Rob Keizer are both also line manager, the mechanics are all trained to be able to perform multiple tasks/skills. According to them both this is extremely helpful as this allows the mechanics to deployed for multiple purposes. They both agree that it would be very useful to have multi-skilled combustor department employees, they would like to create a so called functional factory. They feel that this would be a very useful investment in their employees and that it would pay itself back very quickly due to the time it would save and the motivation it would give their employees (with some exceptions), and hence improve the quality of work. However the downside to this education of employees is that you also lose them in time as many of the skills you teach them can be applied well in other departments (e.g. welding).

Regardless of this possibility Aad feels that it would be ideal to have at least 8 employees that are capable of performing all tasks. However he also notes that this is not really an option as not all employees are willing to be multi-skilled and some people would have to be laid off or reemployed into another department; KLM’s policy until recently was to ‘keep the family together’ meaning that people are not easily let go.

NOTE: times mentioned for different maintenance activities are noted as mentioned during the meetings, this does not necessarily coincide with the handshakes/prescribed times)

B

Combustor Department Value Stream Mapping Sessions

This appendix contains the notes and observations made during a value stream mapping session with with the combustor department; Jan de Vreede, Aad van Kessel and 8 or 9 mechanics.

The VSM was made using brown paper and post-its. The process was based on the longest route as defined by the shop traveller. The focus was on the part between the preparation and the end of the route where the combustor moves to external departments. The VSM map started at the last point in the combustor department before an ‘outing’ to the oven in another department. From there the process was mapped toward the start of the process.

The process is shown in Figure B.1. Inspections were marked with orange post-its, other maintenance tasks were marked yellow, the first and last steps have been marked pink. The map starts at the top right, however, due to the large number of process steps rather than forming a line the map has become U shaped.

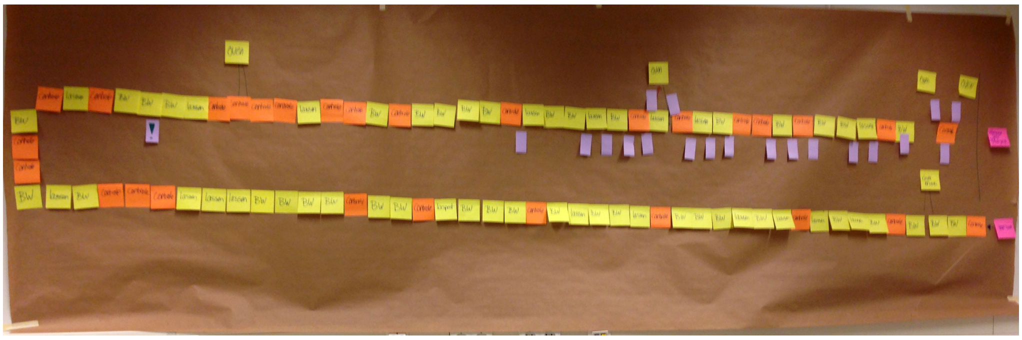


Figure B.1: Department Value Stream Map

As can be seen the route consists of very many steps. The complete route that this map is based on consists of 128 different steps. At first sight it seems that there is a lot of repetition. However this is not necessarily a repetition of sequences, but it is probably because of different tasks assigned to different process steps. E.g. the bench working process can have tasks ranging from A to Z. The repair manual is needed to see what is required and why (this manual will be present during the next session).

Are there potential waiting times? If so, where? The waiting times have been identified with the purple post-its. However a discussion arose about where waiting times existed. Some said that potential waiting times occurred between every step, while others said that this is not necessary. However the consensus was reached that every task change could lead to waiting time. Hence the purple markings stopped as these were no longer necessary. Different post-its mean possible waiting time.

Those that said waiting times between different steps are not necessary explained that it is possible that one person performs subsequent tasks on the same part. In this case no waiting time is needed as a mechanic can continue to work on the part. However this does depend on the persons skill set.

Furthermore the waiting times depend on several factors:

- A queue can arise for the use of the machinery
- A switch can be made between mechanics:
  - Is the person with the skill available
  - Does the person with the skill pick up the part
- A shift changes during the subsequent tasks and no none in the following shift picks it up. The person who started it finishes it the next morning.

Another observation is that many inspections are performed and there is no directly visible pattern in their occurrence. Could these inspections be eliminated? Again there were different answers; one party said that this can not be done as this is prescribed by the engineering department. The other party thought that this might be done if activities were clustered more. However an argument against this was that if you do this and the quality is not sufficient you would have to redo the whole cluster of activities.

This led to the next question: can activities be clustered? Again a party argued that this could not be done because this is prescribed by engineering. They build up the manual (and have done this in accordance with the mechanics for the CFM56-7 engine repairs some time ago). The route is determined by the necessary repairs and certain steps are prescribed per repair.

Another question is whether it is possible to group steps from different repairs in order to limit the process steps and inspections and in turn to limit the process time. A remark made by the attending mechanics was that one group of steps is always linked to welding, namely the bench work before welding and oven after welding.

C

Meeting Bart de Bakker 01-04-2015

Bart de Bakker is the production and capacity planner at the engine services department. He can provide me with the SAP data on the activities involved in the combustor repair process.

In SAP a serial number is allocated to a part in order to follow it through the repair process. For instance the combustor will get a serial number. However, if a part is either extremely expensive, can become extremely hot or runs very fast, as is the case for the combustor parts the part gets a so called part number. This part number is needed to track the progress of the individual part.

If you start looking at the data from a certain date onwards you should note that it is possible that some engines are in the middle of the repair process. Hence it would make sense to take a certain engine as a starting point.

PV notifications and orders on hold are not contained in the data set. However you should take these into account otherwise the dataset is incomplete. i.e. you don't know why certain orders have not been finished etc.

Table C.1: Column Headings Data File

Service Order	**MaintActivityType**	**Base unit**	**Service product qty**	**CS ord creation date**
Equipment	Part Name	Operation start date	Operation finish	Techniekcode
WBS element	**Operation (Service O**	**Work Center**	**Part (ES only)**	**type**
Operation description	Duration	duur (hrs)	TAT (days)	TAT (hours)

Table C.1 shows the headings of the different columns in the data file. The headings that are relevant to the data analysis will be discussed in the meeting notes.

The tasks that are performed during the combustor maintenance are tracked in SAP by means of scans. Once a task has been finished and scanned the next step is automatically started by SAP. This means the time for the following task starts running, however this does not mean that the task is actually started. Hence the data Bart has is based on these scans that mark the time between the end of one task and the end of the next.

A unique service order number is allocated each of the combustor parts. The service order number is to a part for the duration of the maintenance. I.e. if it has a service order number and the repair is finished, the next time the part comes in it will get a new service order number. The Maintenance Activity Type is the code for the part of the process. For instance Z51 is the hoofdroute and Z42 is the pre-route for the heavy repairs.

A WBS element is a tag that is allocated to an element. For instance, 7B/0186117-41X is a WBS element, where 7B signifies the type of engine, the number between the forward slash and the dash is the sales order number, and the 41X signifies the module. The WBS element remains the same throughout the engine's life.

The combustor department at E&M can repair the combustors for 7B, 8C and 8E engines. The module codes that correspond to the engine types can be found in Table C.2.

Table C.2: Engine Type vs combustor modules

Engine Type	Combustor Module
7B	42X
8C	41X
8E	41X

The Work Centre is the department that executes a task. For instance work centre 2400 is the combustor department. However some tasks of the combustor repairs are performed in work centres other than the combustor department. For instance the UHPW cleaning is performed in WC 2700. The operation service order is a number that defines the sequence of tasks that are performed for each service order.

The techniekcode is the code for a specific technique centre within a work centre. For example Q034 is an inspection

The Operation description is a specific task within a technique centre. This task is determined by the shop traveller and the description of the task can be found in the repair manual. The repair instructions are the regulations for the repairs and include the task descriptions. Here you will be able to find what the operation descriptions mean.

For each task there is a norm time which is noted in SAP. This norm time is supposed to approach the touch time. However, as the touch time is not measured for every activity ES makes use of these norm times to estimate the time spent on a certain activity. In some cases the time spent on the task differs greatly from the norm time, in these cases the skill managers ask for an adjustment in SAP. However these adjustments are usually incidental. In the case that the time needed for a task structurally differs from the norm time a permanent adjustment can be made. However a request for this should be made to mr. Mantjes, and this is not done frequently.

It might be advisable to spend a day timing the activities in order to validate the norm times. Furthermore the norm times are used to build up the customer invoice. (my assumption is that the more tasks and time needed for repairs the higher the bill will be). In some cases the norm times are changed in order to create an invoice to fit the customer's budget.

It would also be advisable to seek out spare parts; how many there are within the process, which parts, where they are stored and what they are stored for.

D Simulation Input Data

This appendix contains the data that has been used as an input for the simulation of process alternatives. In order to determine the complete capacity required all parts that have been at the combustor department for maintenance should be identified. along with their normative maintenance times. It is also necessary to know when the part has entered the combustor department in order to be able to realistically simulate the maintenance alternatives. Furthermore, in order to compare the performance of the alternatives to the actual performance of 2014 the TAT for each of these parts must be known.

Tables D.30, D.31, D.32, D.33 and D.34 show the start date, normative maintenance time and TAT for each combustor, the HPC stators and Coffee Cans. Furthermore the on time performance is shown along with the average TAT.

D.1. Scenario Information

This section contains tables that briefly list the main variable inputs for the various sensitivity analysis tests. This will be followed by tables containing the various mechanic capability sets.

Table D.1: Base scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
Base	A	5	1	1	5	124

Table D.2: External capacity scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
1	A	5	1	2	5	124
53	A	5	1	3	5	124
54	A	5	1	4	5	124
2	A	5	1	5	5	124
3	A	5	1	6	5	124
4	A	5	1	7	5	124
5	A	5	1	10	5	124
6	A	5	1	50	5	124
7	A	5	1	1	7	124
8	A	5	1	1	4	124
9	A	5	1	1	3	124
55	A	5	1	1	2	124

Table D.3: 2400 Capacity scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
56	A	6	1	1	5	124
57	A	7	1	1	5	124
58	A	4	1	1	5	124
59	A	3	1	1	5	124
10	0	5	1	1	3	124
11	0	5	2	1	3	124
12	0	5	10	1	3	124
60	0	5	50	1	3	124
13	0	5	Infinity	1	3	124

Table D.4: Optimised scenario P information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
69	P	5	1	2	5	1234
70	P	5	1	2	5	1234

Table D.5: System capacity scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
14	0	5	Infinity	Infinity	3	124
15	0	5	10	10	3	124
16	0	5	5	5	3	124

Table D.6: Multiskilled Mechanics scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
17	B4 (MS)	5	1	2	5	1234
18	10(MS)	5	1	2	5	12345678910
19	12(MS)	5	1	2	5	123456789101112
20	12(MS)	5	1	2	5	123456789111012
21	9(MS)	5	1	2	5	123456789
22	8(MS)	5	1	2	5	12345678
23	7(MS)	5	1	2	5	1234567
24	6(MS)	5	1	2	5	123456
25	5(MS)	5	1	2	5	12345
26	3(MS)	5	1	2	5	123
27	16(MS)	5	1	2	5	123456789111012
28	15(MS)	5	1	2	5	123456789111012
29	14(MS)	5	1	2	5	123456789111012
30	13(MS)	5	1	2	5	123456789111012

Table D.7: Mechanic capabilities scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
31	C	5	1	2	5	1234
32	D	5	1	2	5	1234
33	E	5	1	2	5	1234
34	F	5	1	2	5	1234
35	G	5	1	2	5	1234
36	H	5	1	2	5	1234
37	I	5	1	2	5	234
38	J	5	1	2	5	24
39	K	5	1	2	5	234
40	L	5	1	2	5	24

Table D.8: Worker priority scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence	Additional Info
41	B4 (MS)	5	1	2	5	1234	Worker1 priority
42	B4 (MS)	5	1	2	5	1234	Worker1&2 priority
43	B4 (MS)	5	1	2	5	1234	Worker1 priority Add-on
44	B4 (MS)	5	1	2	5	1234	Worker priority smallest value due
45	B4 (MS)	5	1	2	5	1234	Worker priority largestvalue

Table D.9: Alternative routing scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence	Additional Info
46	A	5	1	1	5	124	reduce Q034
47	A	5	1	1	5	124	Grouped
48	A	5	1	1	5	124	Grouped-Q034

Table D.10: Alternative arrivals scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence	Additional Info
49	A	5	1	1	5	124	A
50	A	5	1	1	5	124	B
51	A	5	1	1	5	124	C
52	A	5	1	1	5	124	D

Table D.11: Alternative arrival Scenarios

Schedule	Type
A	All Combustors arrive on the 3rd of the month they originally arrived in
B	Until July sunday 4 combustors arrive, after this 3 combustors arrive each Sunday
C	Half of the combustors arrives on the 3rd of the month they originally arrived in, the other half arrives 14 days later

Table D.12: Capability sets scenario information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
64	M	5	1	2	5	1234
65	N	5	1	2	5	1234
66	O	5	1	2	5	1234
67	P	5	1	2	5	1234
68	Q	5	1	2	5	1234

Table D.13: Ideal capabilities information

Scenario	Mech	Workdays	Server Cap	Ext Cap	Workdays	Worker Sequence
69	P	5	1	2	5	1234
70	P	5	1	2	5	1234

D.1.1. Mechanic Capabilities

Table D.14: Mechanic capability set A

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x		x				M
2					x	x		A
3	x	x	x					M
4							x	A

Table D.15: Mechanic capability set C

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2		x	x	x	x	x	x	A
3		x	x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.16: Mechanic capability set D

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2		x	x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.17: Mechanic capability set E

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x	x	x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.18: Mechanic capability set F

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x		x	x	x	x	x	A
3	x		x	x	x	x	x	M
4	x		x	x	x	x	x	A

Table D.19: Mechanic capability set G

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x		x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4	x		x	x	x	x	x	A

Table D.20: Mechanic capability set H

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x	x	x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4	x		x	x	x	x	x	A

Table D.21: Mechanic capability set I

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x							M
2		x	x	x	x	x	x	A
3		x	x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.22: Mechanic capability set J

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x							M
2		x	x	x	x	x	x	A
3	x							M
4		x	x	x	x	x	x	A

Table D.23: Mechanic capability set K

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1		x						M
2	x		x	x	x	x	x	A
3	x		x	x	x	x	x	M
4	x		x	x	x	x	x	A

Table D.24: Mechanic capability set L

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1		x						M
2	x		x	x	x	x	x	A
3		x						M
4	x		x	x	x	x	x	A

Table D.25: Mechanic capability set M

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2			x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4			x	x	x	x	x	A

Table D.26: Mechanic capability set N

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x		x	x	x	x	x	M
2		x	x	x	x	x	x	A
3	x		x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.27: Mechanic capability set O

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2		x	x	x	x	x	x	A
3	x		x	x	x	x	x	M
4		x	x	x	x	x	x	A

Table D.28: Mechanic capability set P

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2	x		x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4			x	x	x	x	x	A

Table D.29: Mechanic capability set Q

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x	x	x	x	x	x	M
2		x	x	x	x	x	x	A
3	x	x	x	x	x	x	x	M
4			x	x	x	x	x	A

D.2. Combustor Input

Table D.30: Performance information 7B combustor

Combustor	Start	Norm (min)	TAT (days)
7B-169363	2-1-2014	90	7
7B-169366	24-2-2014	10904	54
7B-171379	2-1-2014	90	6
7B-171814	9-1-2014	90	6
7B-172459	8-1-2014	5565	23
7B-172469	20-1-2014	90	1
7B-172922	28-1-2014	90	0
7B-173055	31-1-2014	90	3
7B-173332	17-2-2014	90	1
7B-174790	29-1-2014	6653	39
7B-175333	13-2-2014	9121	42
7B-176124	3-3-2014	6841	56
7B-176244	17-3-2014	90	9
7B-176503	17-4-2014	90	6
7B-176822	25-4-2014	90	10
7B-176828	10-3-2014	8994	50
7B-176861	23-4-2014	90	1
7B-177542	5-5-2014	90	4
7B-178048	5-5-2014	90	4
7B-178403	17-4-2014	10251	48
7B-179318	5-5-2014	5038	25
7B-180314	12-5-2014	4755	45
7B-180318	12-5-2014	8874	38
7B-180753	10-11-2014	9174	50
7B-181062	26-6-2014	90	1
7B-181541	9-6-2014	7668	38
7B-182310	4-7-2014	4185	35
7B-182576	30-6-2014	9636	37
7B-182864	24-6-2014	8971	48
7B-184359	21-7-2014	8199	41
7B-184522	20-10-2014	8379	58
7B-184762	28-7-2014	9022	38
7B-185456	1-10-2014	90	1
7B-186117	6-10-2014	90	3
7B-186272	25-8-2014	4116	34
7B-186811	19-9-2014	7347	45
7B-187335	27-10-2014	90	2
7B-187348	25-9-2014	9532	43
7B-187595	13-11-2014	90	1
7B-187640	23-10-2014	6424	49
7B-188048	29-9-2014	9091	55
7B-188112	6-10-2014	3976	38
7B-188641	6-10-2014	9162	58
7B-189684	3-11-2014	7446	50
7B-189699	25-11-2014	5611	48
7B-191293	30-12-2014	90	8
Average			27.4
On-time			23
Late			23
Total			46
% on-time			50%

Table D.31: Performance information 8C combustor

Combustor	Start	Norm (min)	TAT (days)
8C-165302	15-1-2014	546	27
8C-171235	2-1-2014	1694.9	15
8C-171590	6-1-2014	3852.9	18
8C-171591	7-4-2014	6497.2	52
8C-172061	9-1-2014	3787.9	14
8C-172214	13-1-2014	3813.9	11
8C-172574	8-1-2014	4467.9	27
8C-172987	6-1-2014	5525.2	35
8C-173014	6-1-2014	5471.6	37
8C-173019	2-1-2014	5568.9	34
8C-174051	22-1-2014	6181.4	51
8C-174108	7-4-2014	6680.2	49
8C-174372	21-1-2014	3456.2	41
8C-174612	11-2-2014	6489.2	36
8C-174734	30-1-2014	5604.2	34
8C-175191	13-2-2014	4848.3	42
8C-175964	21-2-2014	4002.2	45
8C-175965	24-2-2014	6534.2	60
8C-176317	25-2-2014	5272.2	38
8C-177163	13-3-2014	4660.2	47
8C-177464	24-3-2014	7627.2	52
8C-177979	4-4-2014	7469.2	42
8C-178449	20-4-2014	3885.2	36
8C-178744	28-4-2014	5412.2	42
8C-178772	10-4-2014	7372.2	61
8C-179257	28-4-2014	6730.2	45
8C-180312	6-5-2014	7751	64
8C-181214	21-5-2014	5922.2	37
8C-181567	26-6-2014	3469.2	34
8C-181657	27-5-2014	5929.2	44
8C-183126	27-6-2014	5798.2	38
8C-184041	22-7-2014	0	0
8C-184113	14-7-2014	5577.2	36
8C-184727	22-7-2014	4995.2	35
8C-185193	6-8-2014	6284.2	35
8C-185875	21-8-2014	5459.2	32
8C-185988	18-8-2014	120	21
8C-186077	25-8-2014	6087.2	28
8C-186495	26-8-2014	6164.2	28
8C-186522	8-10-2014	6670.2	57
8C-186678	8-9-2014	7035.2	43
8C-186679	15-9-2014	5790.2	37
8C-187638	24-9-2014	80	0
8C-187758	23-10-2014	4199.2	28
8C-187821	23-9-2014	6595.2	63
8C-188108	7-10-2014	7112.2	69
8C-188109	6-10-2014	5889.2	43
8C-188681	27-10-2014	6730.2	57
8C-189867	4-11-2014	6954.2	41
8C-190256	10-11-2014	5954.2	43
8C-190415	10-11-2014	6351.6	58
8C-191014	19-11-2014	6402.2	28
8C-191114	24-11-2014	6304.2	50
8C-191153	1-12-2014	2061.3	42
8C-191266	9-12-2014	5559.2	43
8C-191712	29-12-2014	5677.2	24
8C-191714	11-12-2014	8283.2	46
8C-193051	29-12-2014	6661.2	35
Average			40.6
On-time			17
Late			30
Total			47
% on-time			36%

Table D.32: Performance information 8E combustor

Combustor	Start	Norm (min)	TAT (days)
8E 172863	14-1-2014	6940	24
8E 174110	16-1-2014	4829	25
8E 174207	20-1-2014	5492.5	44
8E 176409	7-3-2014	7294	49
8E 177153	19-3-2014	5872.5	43
8E 178060	7-4-2014	4678.5	37
8E 181089	6-6-2014	5267.5	34
8E 181652	27-5-2014	6630.5	37
8E 183259	30-6-2014	6037.5	44
8E 183555	4-7-2014	7198.5	39
8E 185110	1-8-2014	5362.5	35
8E 185519	11-8-2014	4568.5	28
8E 186468	26-8-2014	6531	42
8E 189023	21-10-2014	8545.5	58
8E 189404	23-10-2014	6130.5	43
8E 191289	26-11-2014	140	43
8E 191673	18-12-2014	5813.5	39
8E 191681	9-12-2014	4643.5	35
8E 192087	29-12-2014	5672.5	49
Average			39.4
On-time			6
Late			13
Total			19
% on-time			32%

Table D.33: Performance information coffee cans

Coffee Can	Start	Norm (min)	TAT (days)
41905579	10-1-2014	55	12
41905582	10-1-2014	55	12
41910974	24-1-2014	55	39
41917639	7-2-2014	85	55
41925160	26-2-2014	55	29
41933078	17-3-2014	55	106
41948608	18-4-2014	55	13
41953805	5-5-2014	55	57
41958592	19-5-2014	55	39
41958594	19-5-2014	55	43
41959389	20-5-2014	15	1
41959391	20-5-2014	15	1
41959392	20-5-2014	15	1
41962148	28-5-2014	55	34
41990024	25-8-2014	55	15
41991494	28-8-2014	55	20
41993716	3-9-2014	55	14
41994765	8-9-2014	55	9
41994769	8-9-2014	55	9
41999917	23-9-2014	55	66
42004173	3-10-2014	55	61
42021093	10-11-2014	55	29
42022391	13-11-2014	55	26
42023901	18-11-2014	55	22
42028319	28-11-2014	55	41
42029357	2-12-2014	105	41
42036303	19-12-2014	32	5
42038347	24-12-2014	17	7
Average			28.8
On-time			18
Late			10
Total			28
% on-time			64%

Table D.34: Performance information HPC Stator

HPC Stator	Start	Norm (min)	TAT (days)
172863	13-1-2014	40	0
174207	11-2-2014	40	1
176409	18-3-2014	40	9
177153	11-4-2014	40	10
178060	28-4-2014	40	8
183555	15-7-2014	40	13
186468	4-9-2014	40	19
189023	29-10-2014	40	22
189404	3-11-2014	40	17
191289	8-12-2014	40	28
191673	30-12-2014	40	16
191681	22-12-2014	40	14
Average			13.1
On-time			12
Late			0
Total			12
% on-time			100%

E

Combustor Repair Data

This appendix will discuss how data has been collected from SAP and how this data is used.

E.1. Data Collection

As discussed in the Chapter 2 the SAP system is used to track the end of each task, along with the sequence of tasks. The data SAP provides are hence collected and used to track the performance of the combustor department. This section will discuss how the data has been collected and how it is used to determine the current state at the combustor department.

The data per task as stored in SAP can be seen in Table E.1. This data links the combustor part numbers to the complete combustor, the maintenance phase, the maintenance task and where it is carried out, the person that has carried out the task, the date the task was planned to take place and the date the task has been finished. The information was obtained from an interview which can be found in Appendix C.

Table E.1: SAP data table

Service Order	**Maint Activity Type**	**Base unit**	**Service product qty**	**CS ord creation date**	**WBS element**	**Operation (Service O)**	**Work Centre**	**Part (ES only)**
41794209	Z51	EA	1	10-4-2013	7B/0154624-42X	5644	2400	#
Part Name	**Operation start date**	**Operation finish**	**Capability Code**	**Operation description**	**Person**	**Name**	**Duration**	**Pnr**
LINER-OUTER COMBUSTION CHAMBER	19-8-2013	16-4-2014	Q702	2-2 TASK.C	13647	D. Dors	40	13647
Equipment	**Duration (hrs)**	**Year & Month**	**Order and Line number**					
100247090	0,667	201404	41794209-5644					

The parts of the data that are relevant to the analysis are mentioned below, along with a brief explanation:

Maintenance Activity Type This is the maintenance phase in which the task takes place.

Service product qty The number of parts this unit consists of, for instance a set of swirlers will have a quantity greater than one.

CS ord creation date The date at which the service order has been created, this is also the planned start date for the first task within the maintenance phase.

WBS element This shows the element, 7B is the type of engine the number after the / is the administration number, used for the customer bill, and finally -41X shows the module type.

Operation (Service Order) This is the sequence of tasks. For instance the first task is 010 and the next task is 020, the step size is 10 in case rework is needed and extra tasks need to be added to the shoptraveller.

Work Centre This is the workcentre number, e.g. 2400 is the combustor department.

Equipment This number is linked to the part type.

Part Name The name, or type of the part.

Operation start date The date at which the task should start, this is the date SAP has planned for the start of the task. However, as can be seen in the example, this date can not always be relied upon.

Operation finish date The date the task has been finished and scanned.

Capability Code This is the type of task that is performed, it coincides with the workshop within a workcentre. For instance Q034 is an inspection

Operation description This is the task. 2-2 means that the task is described on page 2 of maintenance manual number 2. The task to be carried out is bewerking D.

Person This is the personnel number of the person who carried out the task.

Duration The normative time for the task in minutes.

Personnel number This is the personal identification number for the mechanic.

Duration (hrs) The normative time for the task in hours.

Year & Month The year and month in which the task has been finished. This can be used for instance to identify which tasks have been completed within a certain month.

Order and Line number The ordernumber and operation service order combined.

This information can then be used to track the route the complete combustor has gone through during maintenance. The WBS element is used to identify the individual combustors. Each part of a single combustor has the same engine type and administration number, the module type can differ for the same combustor, depending on the phase. Thus, the combustors are grouped based on the first parts of the WBS element. Then the maintenance activity type is used to group the tasks according to the maintenance phase. The tasks are then organised based on the operation service order or the order and line number so the sequence of tasks is in the right order. This allows the complete turnaround time for the combustor to be determined based on the CS order creation date of the first task performed on the combustor and the operation finish date of the last task performed on the combustor.

Furthermore, this information can give an insight of the work in progress at any given time within the workshop, the productivity of the workshop personnel (e.g. how many tasks have they completed in a day), and the variety of skills each person actually performs compared to their actual skills.

E.2. 7B Combustor Repair Data

The data that has been collected regarding combustor maintenance can be organised according to combustor number. Based on this number, an overview can be made of each combustor's repair route, the TAT, which part is critical in on-time performance, and how many process disruptions (PV's) have occurred. Table E.2 gives an overview of these factors. As can be seen combustors do not just enter the combustor department for maintenance, they also enter the department after they have been externally repaired, in which case they are submitted to an overhaul inspection. So the total number of combustors that enters the department is 48 instead of the 27 that were mentioned earlier. However, 21 of these combustors do not enter the department for maintenance as they are repaired externally, hence the agreement for their TAT is 5 days rather than 36. In total 16 out of 48 combustors are delivered on-time which is only 33% of the total.

Table E.2: Combustor maintenance overview

Combustor	Repair Type	TAT	On-Time	Critical Part	Combustor	Repair Type	TAT	On-Time	Critical Part
7B-169363	External	7	0	Chamber	*7B-181062*	External	1	1	Chamber
7B-169366	exception	54	0	Outer Liner	*7B-181541*	Regular	38	0	Outer Liner
7B-171379	External	6	0	Chamber	*7B-182310*	Regular	35	1	Outer Liner
7B-171814	External	6	0	Chamber	*7B-182576*	exception	37	0	Outer Liner
7B-172469	External	1	1	Chamber	*7B-182864*	Regular	48	0	Inner Liner
7B-172922	External	0	1	Chamber	*7B-184359*	Regular	41	0	Outer Liner
7B-172925	External	4	1	Chamber	*7B-184522*	Regular	58	0	Outer Liner
7B-173055	External	3	1	Chamber	*7B-184762*	Regular	38	0	Inner Liner
7B-173332	External	1	1	Chamber	*7B-185456*	External	1	1	Chamber
7B-174790	Regular	39	0	Outer Liner	*7B-186117*	External	3	1	Chamber
7B-175333	Regular	42	0	Outer Liner	*7B-186272*	Regular	34	1	Outer Liner
7B-176124	Regular	56	0	Outer Liner	*7B-186811*	exception	45	0	Outer Liner
7B-176244	External	9	0	Chamber	*7B-187335*	External	2	1	Chamber
7B-176503	External	6	0	Chamber	*7B-187348*	exception	43	0	Dome
7B-176822	External	10	0	Chamber	*7B-187595*	External	1	1	Chamber
7B-176828	Regular	50	0	Dome & Inner	*7B-187640*	Regular	49	0	Outer liner
7B-176861	External	1	1	Chamber	*7B-188048*	Regular	55	0	Outer Liner
7B-177542	External	4	1	Chamber	*7B-188112*	Regular	38	0	Dome & Outer
7B-178048	External	4	1	Chamber	*7B-188641*	Regular	58	0	Dome & Inner
7B-178403	exception	48	0	Outer Liner	*7B-189684*	Regular	50	0	Inner Liner
7B-179318	Regular	25	1	Dome	*7B-189699*	Regular	48	0	Dome & Inner
7B-180314	exception	45	0	Inner Liner	*7B-189953*	External	8	0	Chamber
7B-180318	Regular	38	0	Inner Liner	*7B-191293*	External	8	0	Chamber
7B-180753	Regular	50	0	In, Out & Dome	*7B-192524*	Regular	44	0	Outer Liner
On-Time Average		26.9	**16** 33%						

E.2.1. Maintenance Phases

In order to determine the variation of TATs for each phase, histograms and probability plots per phase are made.

Phase 02X-Z11 is only carried out in 15 cases, and has a TAT between 1 and 7 days. This is remarkable given the short normative time that stands for this activity and the fact that the handshake is 1 day. The distribution of TATs is normal as shown in both the histogram (Figure E.1) and the probability plot (Figure E.2). The TAT of 7 days can be singled out both in the histogram and the probability plot, even though it is still within the normal range of the graph. As the probability plot shows, the values are all fairly close to the line with an exception of the 7 day TAT and a few of the 1 day TAT values. As there are several occurrences for different TATs for each different day a vertical line is created for each

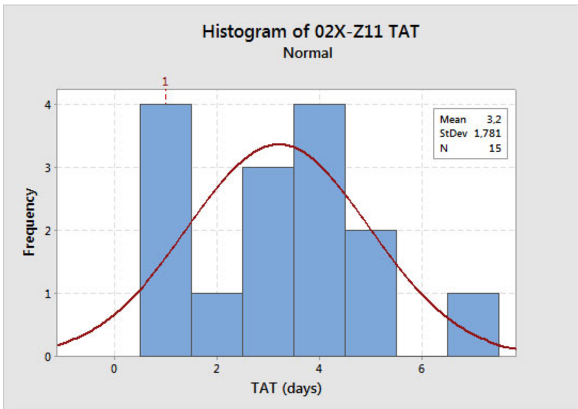


Figure E.1: Histogram of TAT for Phase 02X-Z11

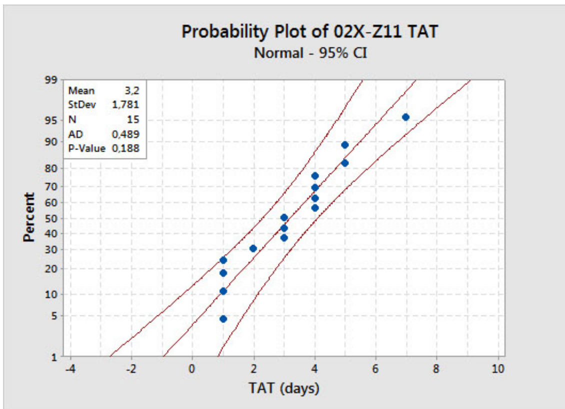


Figure E.2: Probability Plot of TAT for Phase 02X-Z11 of these days, which prevents the dots from forming a sloped line. This is due to the fact that TAT is discrete. The graph mainly indicates waste due to the comparison to the Handshake TAT and the fact that less than 30% of the values is within this TAT. Furthermore, the average TAT is 3.2 days and the standard deviation is 1.8, which means that the handshake TAT is removed by more than 1 standard deviation from the mean.

Phase Z01 is mostly performed in less than a day, as can be seen in both the histogram (Figure

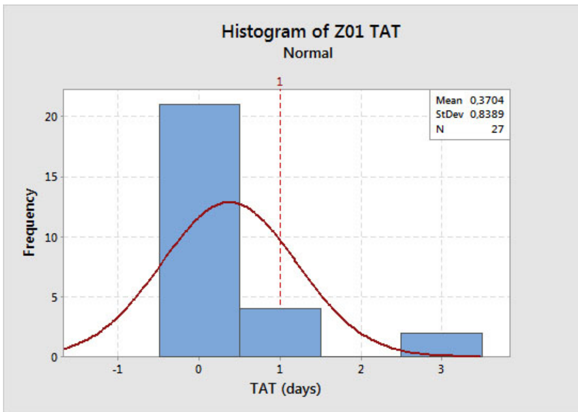


Figure E.3: Histogram of TAT for Phase Z01

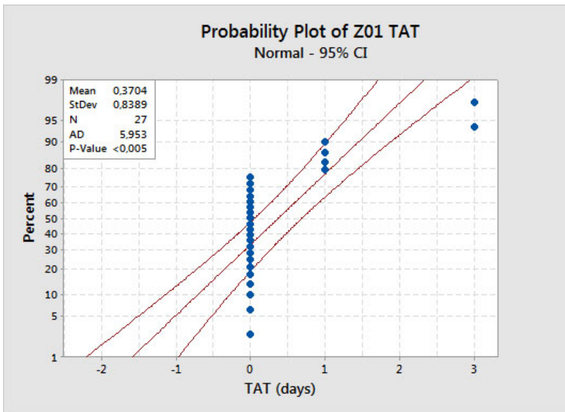


Figure E.4: Probability Plot of TAT for Phase Z01

E.3) and the probility plot (Figure E.4). The average TAT is 0.37 days, and the standard deviation is 0.84. This means that the TAT is realised in 93% of the cases. Furthermore, the TAT of 3 days can be seen to be an outlier. However, this TAT may be caused by Z01 starting on a friday, after which the part is automatically put down for two days due to the weekend. Furthermore, even though the on-time performance is high the distribution is not normal, as many values fall outside the normal distribution as shown in the probability plot. This is again due to the use of integers rather than more accurate values. However, all in all the performance seems very good, and does not leave much room for improvement. Hence the focus will lie with other parts of the maintenance process rather than with phase Z01.

Phase Z11 shows results similar to Z01, even though a TAT of 0 days is realised less frequently

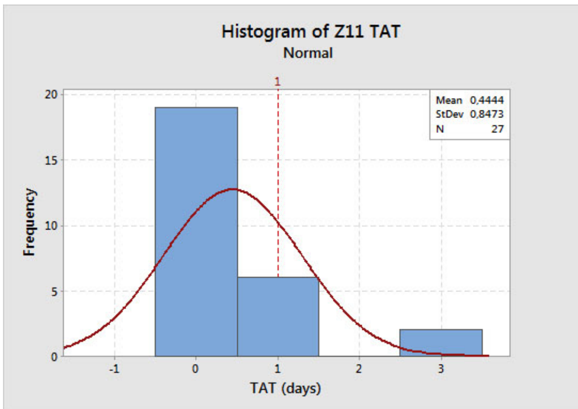


Figure E.5: Histogram of TAT for Phase Z11

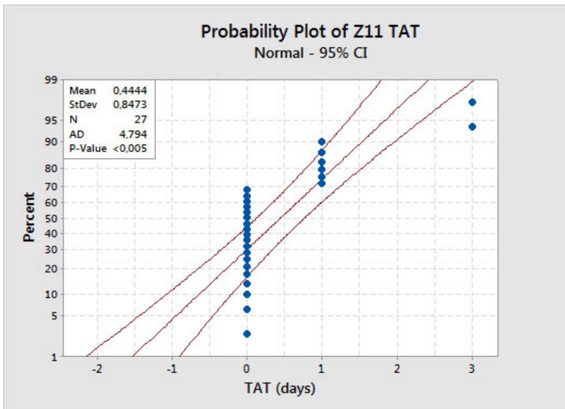


Figure E.6: Probability Plot of TAT for Phase Z11

the number of on-time combustor is equal. As shown in Figures E.5 and E.6 the average TAT is 0.44 and the standard deviation is 0.85. Again the distribution is not normal, due to the integers and there are two outliers with a TAT of 3 days. The performance of this phase is again deemed sufficient to focus the analysis on other phases. It should be noted however that the TAT for Z01 and Z11 are not necessarily the same for the same combustor.

The variation of TAT for phase Z42 ranges between a TAT of 2 days and a TAT of 15 days. As

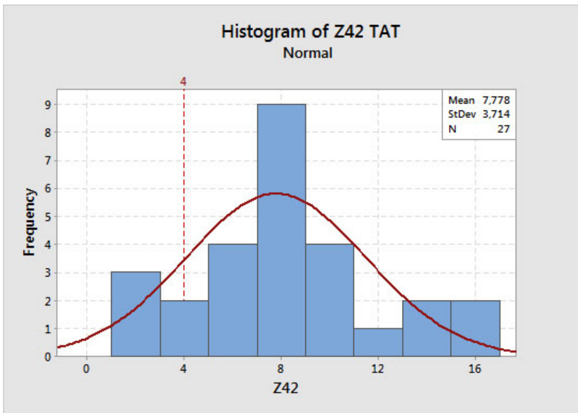


Figure E.7: Histogram of TAT for Phase Z42

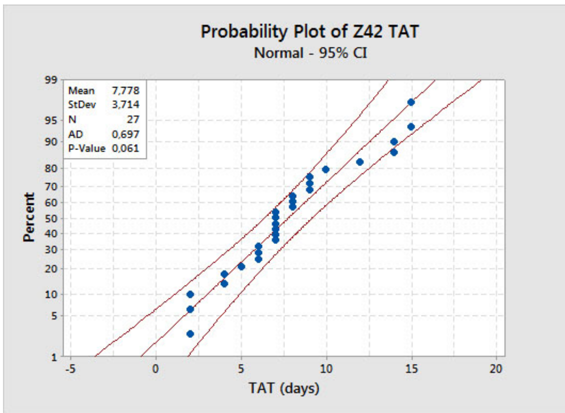


Figure E.8: Probability Plot of TAT for Phase Z42

the histogram in Figure E.7 shows the TAT is most frequently in bin 7-9. The average TAT is 7.8 days and the TAT is distributed normally about this mean. The standard deviation is 3.7, which means that the handshake TAT is just outside one standard deviation from the mean. Due to the use of integers the values in the probability plot in Figure E.8 can not form a sloped line. However, most values are within the normal range, hence the plot can be said to be normal. Furthermore, a TAT of 4 days (the handshake) is only realised once. For Z42 the range and average of the TAT need to be reduced. Therefore, phase Z42 requires further analysis to see what causes the variable TAT.

Phase Z51 shows a range of TATs from 17 to 48 days, this is the largest range so far and can be ex-

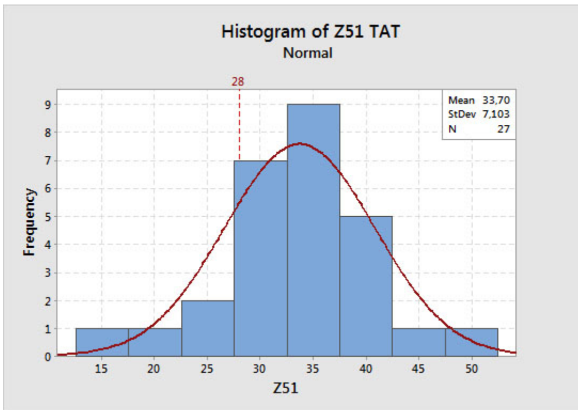


Figure E.9: Histogram of TAT for Phase Z51

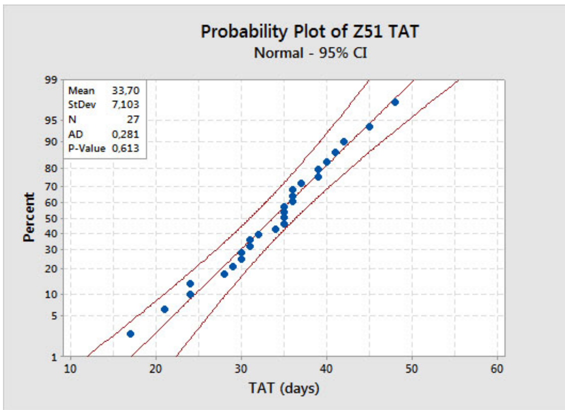


Figure E.10: Probability Plot of TAT for Phase Z51

plained by the high range of maintenance times within this phase. However, the on-time performance is very low. As the histogram in Figure E.9 shows the average TAT is 33.7 days and the standard deviation is 7.1. This means that the handshake TAT of 28 days is within one standard deviation of the mean, but as the mean is quite large this is still not close enough. What's more is that a TAT of 28 days is only realised once. Figure E.10 shows that the distribution of values is normal as all values are fairly close to the line. However, the spread of values should be reduced, and the slope needs to become steeper. This is why Z51 requires further analysis. It should be noted that if the TAT of Z51 is larger than 28 days, regardless of the on-time performance of the other phases, the combustor will almost always be finished late. Furthermore, if this process is improved, it is mostly likely to have the largest effect on the overall TAT as it currently has the highest TAT of all phases.

Finally, phase Z21 is the phase with a relatively high on-time performance, as can be seen in Figure E.11. The average TAT is 0.7 days, and the standard deviation is 1.1. This means that the handshake TAT is within about 0.3 standard deviations from the mean. As expected from the histogram the probability plot in Figure E.12 shows that the TAT is indeed not normally distributed. This is again due to

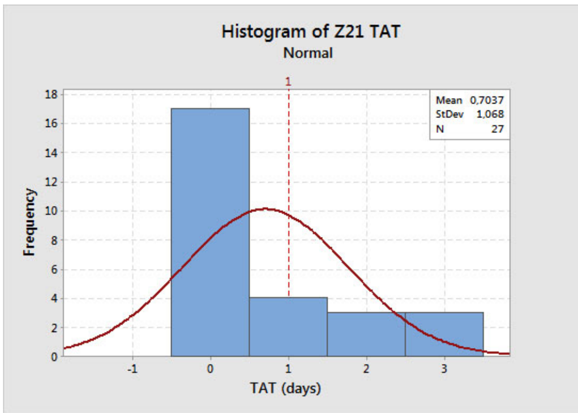


Figure E.11: Histogram of TAT for Phase Z21

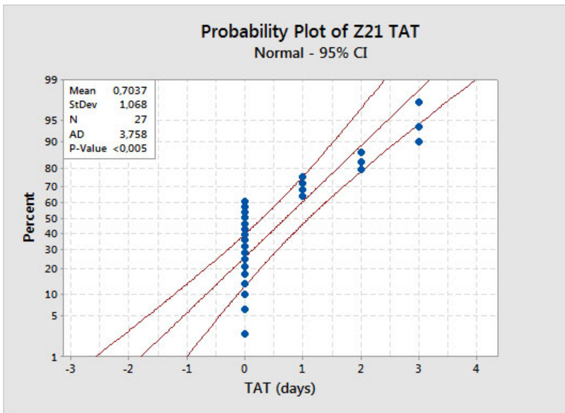


Figure E.12: Probability Plot of TAT for Phase Z21

the use of integers. Also there are three instances of a 2 day TAT, this means that this TAT is not as such due to the weekend, but very likely due to waste. However, as Table 3.4 showed, the ratio of normative time to handshake TAT leaves little room for waste, which makes it all the more interesting to find out why this phase has such a high on-time performance.

E.2.2. Available Mechanics

Not all mechanics that perform work in the combustor department are actually part of this departmen. In Figures E.13 and E.14 this comparison is given in a bar chart for 2014. As can be seen the number of people working varies, along with the difference in total people and 2400 people. For the people working in 2400 the people working vary between 0 and 12 per day, whereas in total the numbers vary from 1 to 13 people a day.

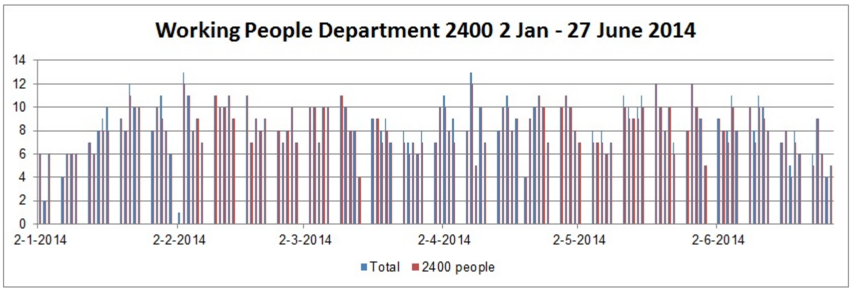


Figure E.13: Bar chart of people working in dept. 2400 from January-June

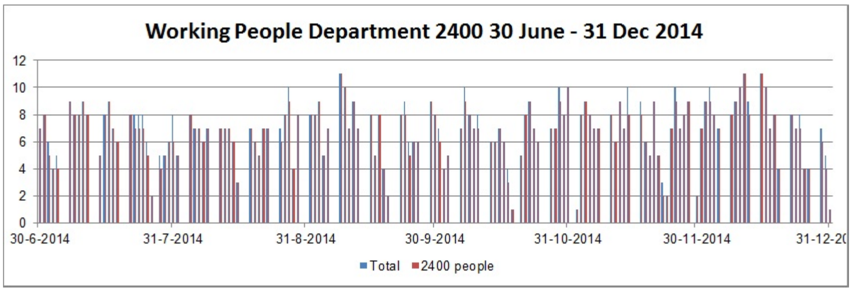


Figure E.14: Bar chart of people working in dept. 2400 from July-December

s

F

Process Analysis

This appendix contains the detailed process analysis that has been carried out during the problem analysis in Chapter 3.

F.1. Input

Table F.1 in appendix F shows the number and type of combustors that have come in to the combustor department for maintenance throughout 2014. In total 90 combustors have come to the combustor shop, this is an average of about two combustors per week.

Table F.1: Received Combustors 2014

Month	**7B**	**8C**	**8E**	**Total**
Jan	0	5	2	7
Feb	3	2	0	5
Mar	2	4	2	8
Apr	1	7	0	8
May	3	3	0	6
Jun	2	2	2	6
Jul	4	3	2	9
Aug	1	3	2	6
Sep	3	5	1	9
Oct	4	4	2	10
Nov	3	6	0	9
Dec	0	4	3	7
Total	26	48	16	**90**

F.2. Repairs

F.2.1. Regular In-house Repairs

In total 21 combustors have followed a regular maintenance route. These will be discussed into more detail in this section. For each of these combustors the TAT has been determined, as well as on-time performance. Furthermore, the component on the critical path, and the normative maintenance time for this component has been determined both in hours and working days. Using the normative working days (including weekends) the normative percentage of TAT has been calculated, which in turn is used to calculate waiting time.

Of the combustors that followed a complete maintenance route only 3 were delivered on time, this is only 15% (see Table F.2). TAT varies between 25 and 58 days and there does not seem to be a regular trend within the TATs. In order to see how much the TAT varies, a histogram is made. Figure F.1

shows a histogram of the TAT. The mean is 33.67, and the standard deviation has a value of 8.78. This means the spread of values is quite large, and thus it is likely that waste exists within the process.The table also shows which component was on the critical path, and what the normative maintenance time for the critical component was in both hours and working days. Using the normative working days and including the weekends the normative percentage of TAT has been calculated, which in turn is used to calculate waiting time.

Table F.2: 7B Combustor Regular Repair Information

Combustor	On-time	TAT (days)	Critical Component	Norm (hrs)	Working days	Norm % of TAT	Wait
7B-174790	0	39	Outer Liner	38.1	3.5	9%	91%
7B-175333	0	42	Outer Liner	51.8	4.8	11%	89%
7B-176124	0	56	Outer Liner	51.8	4.8	9%	91%
7B-176828	0	50	Dome & Inner Liner	65.5	6.1	12%	88%
7B-179318	1	25	Dome	69.0	6.4	26%	74%
7B-180318	0	38	Inner Liner	60.2	5.6	15%	85%
7B-180753	0	50	Inner & Outer & Dome	63.0	5.8	12%	88%
7B-181541	0	38	Outer Liner	45.1	4.2	11%	89%
7B-182310	1	35	Outer Liner	33.3	3.1	9%	91%
7B-182864	0	48	Inner Liner	62.9	5.8	12%	88%
7B-184359	0	41	Outer Liner	51.8	4.8	12%	88%
7B-184522	0	58	Outer Liner	45.2	4.2	7%	93%
7B-184762	0	38	Inner Liner	66.4	6.2	16%	84%
7B-186272	1	34	Outer Liner	34.1	3.2	9%	91%
7B-187640	0	49	Outer liner	52.3	4.8	10%	90%
7B-188048	0	55	Outer Liner	55.7	5.2	9%	91%
7B-188112	0	38	Dome & Outer Liner	42.0	3.9	10%	90%
7B-188641	0	58	Dome & Inner Liner	66.2	6.1	11%	89%
7B-189684	0	50	Inner Liner	65.3	6.1	12%	88%
7B-189699	0	48	Dome & Inner Liner	54.2	5.0	10%	90%
7B-192524	0	44	Outer Liner	53.3	4.9	11%	89%
On-time	**3**						
Average	15%	44.5		53.7	5.0	12%	88%

A probability plot, shown in Figure F.2, is generated to check if the distribution of the data is nor-

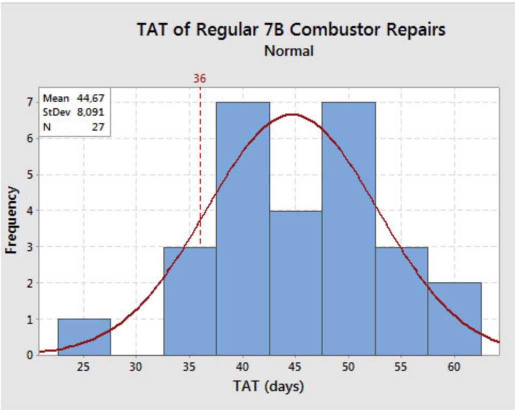


Figure F.1: Histogram of the Regular Repair TAT

mal. As can be seen the distribution is near normal, as all the TATs are positioned roughly along the line and fall within the boundaries. However, there are a few outliers at either ends of the line, and the line is not yet straight. This confirms that there are likely still wastes within the process.

It is interesting to see the probability plot of the regular repair TAT compared to the probability plot

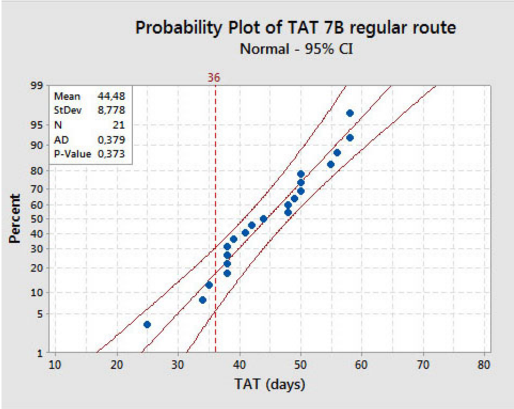


Figure F.2: Probability Plot of Regular Repair TAT

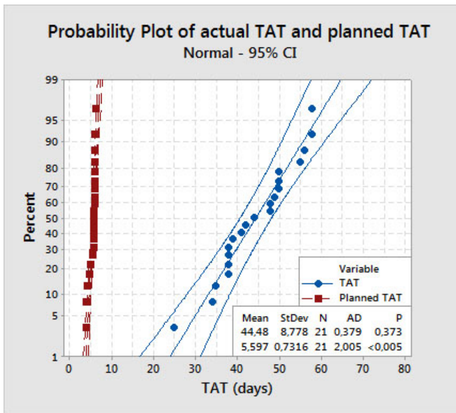


Figure F.3: Probability Plot of Norm. and Regular Repair TAT

of the normative repair TAT, as shown in Figure F.3. The normative TAT shows a fairly clear line that stands up and is moved towards the left of the actual TAT, much like the lean shift suggested during the KLM Green Belt Training. The normative TAT hence shows a possible future state for the TAT.

Furthermore, on average, the normative maintenance time for the critical component is only 53.7 hours for the complete maintenance route. This time translates to 5 working days. This is a planned maintenance time of 7 days, which amounts to only 12% of the actual TAT. If the normative times are assumed to be correct this means that on average 88% of the process consists of waiting time. This seems a very high percentage, and it seems likely that the normative times are not entirely correct. However, even quadrupling the normative times would still lead to more than 50% waiting time. Therefore it is reasonable to assume that incorrect normative times are not the cause of the high TAT. Hence, the normative times will used for the remainder of the data analysis to compare the planned maintenance time to actual TAT.

It is possible that there is one component that is always on the critical path, whilst another component has the largest normative maintenance time. Therefore the critical components are also looked into. Figure F.4 shows a pie chart of how the critical components and their combinations are distributed. As can be seen, the outer liner is the component that is most frequently on the critical path for maintenance. The dome is the critical component only once, and the inner liner is on the critical path 4 times. On three occasions the dome and inner liner were on the critical path together, meaning that the TAT for Z42 and Z51 combined was equally long for both parts. The same has occurred once for the inner and outer liners and the dome, and for a dome and an outer liner. This is interesting, as the different parts always have different normative maintenance times.

Table F.3 shows the normative times for the maintenance of each of the combustors that followed a full maintenance route, along with the number of PV's for the longest actual route, the duration of these PV's, and the total number of PV's for the complete combustor maintenance. In total 49 PV's occurred during regular combustor maintenance. At least one PV has occurred for each combustor, with an average of 2.3 PV's per combustor. During maintenance of the critical component 15 PV's occurred within 9 combustors. For three combustors these PV's caused waiting time. In one instance the waiting time was 36 days, however it is likely that this is only because the PV was not signed off rather than that it took such a long time to resolve. Hence, it can be said that PV's do occur regularly, but that they rarely have an affect on the total combustor TAT as this has only occurred 1 in 7 times.

Furthermore, the table shows which component has the longest normative maintenance time, and how much time the complete maintenance route would cost. Again this normative time is translated to working days and is compared to the actual TAT for the combustor. In four cases the normative main-

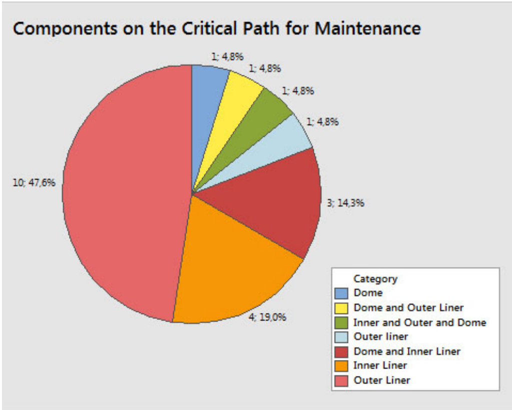


Figure F.4: Pie chart of the Components on the Critical Path of Regular Repair

Table F.3: 7B Combustor Regular Repair Normative Route Information

Combustor	**Planned Norm (hrs)**	**Working days**	**Weekend**	**Norm % of TAT** excl. weekend	**Norm % of TAT** incl. weekend	**Longest Norm**	**PV** critical com-po-nent	**PV** duration	**#PVs**
7B-174790	66.0	6.1	2		21%	Dome	0		2
7B-175333	64.4	6.0	2		19%	Inner Liner	1	0	3
7B-176124	65.5	6.1	2		14%	Dome	1	0	6
7B-176828	65.5	6.1	2		16%	Dome	0		2
7B-179318	69.0	6.4	2		34%	Dome	0		1
7B-180318	60.2	5.6	2		20%	Inner Liner	0		1
7B-180753	63.0	5.8	2		16%	Inner Liner	0		2
7B-181541	62.7	5.8	2		21%	Inner Liner	0		1
7B-182310	46.0	4.3	0/2	12%	18%	Dome	2	2	3
7B-182864	65.5	6.1	2		17%	Dome	0		2
7B-184359	62.9	5.8	2		19%	Inner Liner	0		3
7B-184522	63.6	5.9	2		14%	Inner Liner	4	2	5
7B-184762	66.4	6.2	2		21%	Inner Liner	1	0	2
7B-186272	44.0	4.1	0/2	12%	18%	Dome	1	365	3
7B-187640	52.3	4.8	0/2	10%	14%	Outer Liner	3	0	4
7B-188048	61.6	5.7	2		14%	Inner Liner	1	0	2
7B-188112	42.0	4.0	0/2	10%	16%	Dome	0		1
7B-188641	66.2	6.1	2		14%	Dome	0		1
7B-189684	65.5	6.1	2		16%	Dome	0		1
7B-189699	54.2	5.0	2		15%	Dome	0		1
7B-192524	63.0	5.8	2		18%	Inner Liner	1	0	3
Average PV	60.5	5.6	2	11%	18%		0.715	41	2.349

tenance time amounts to 5 working days or less. In such cases it depends on when the maintenance is started whether or not a weekend is componentof the total maintenance time. This affects the ratio between the actual TAT and the normative TAT. As can be seen the average normative working days are 5.6 days, which is about 18% of the actual TAT. In the four cases without a weekend the normative time is only 11% of the actual TAT. Figure F.6 shows how the normative TAT for the planned critical component compares to the actual TAT in days, as can be seen the normative TAT is only a fraction of the actual TAT.
Another factor that might influence TAT is process disruption. If the process is seriously disrupted a PV is made, so that the issue can be resolved. Hence, the PVs for every maintenance route should

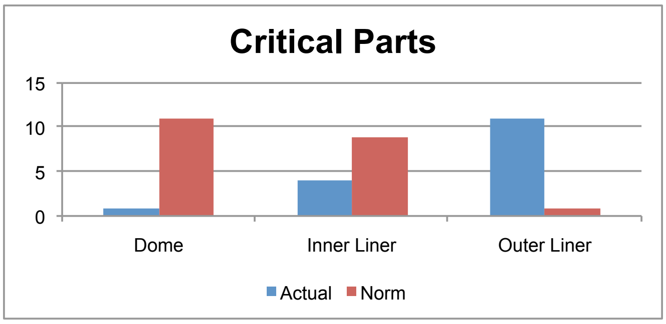


Figure F.5: Count of Components on Critical Path

be checked along with their influence, which is done in Appendix F. It has been found that PV's occur regularly, but that they rarely have an effect on the total combustor TAT.

Furthermore, the component with the longest normative maintenance time can be identified to determine the complete normative maintenance time. The average normative working days are 5.6 days, which is about 18% of the actual TAT. Figure F.6 shows how the normative TAT for the planned critical component compares to the actual TAT in days. As can be seen the normative TAT is only a fraction of the actual TAT.

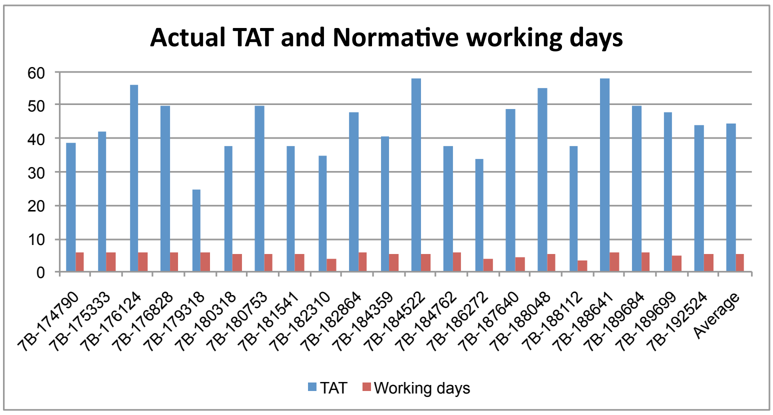


Figure F.6: Bar chart of Actual TAT and Normative TAT Per Combustor

For the regular maintenance route it can be concluded that the TAT regularly exceeds 36 days, and that the outer liner is most frequently the critical component. Furthermore, it can be seen that there is a large discrepancy between the normative times and the actual TAT, and that the planned TAT shows different normative times and critical components. Finally it can be seen that PV's regularly occur throughout the maintenance routes but they do not seem to highly affect TAT.

F.2.2. Exceptional In-house Repairs

Aside from the combustors that follow a regular maintenance route there are combustors that have had an exceptional maintenance route. That is to say, these combustors were assembled before maintenance of the last component was completed. In general maintenance for these components was carried out as regular, except the components that were completed after assembly have been replaced by a spare part.

Unfortunately there is no information available on why assembly has taken place before the final component was completed, nor is it visible whether or not the component has been replaced or exchanged (even though this is almost certainly what has happened). Furthermore, it is also not clear how, and at what point in the process the decision to continue without this component has been made.

There have been 6 combustors with an exceptional maintenance route. Of these 6 none were completed on-time, as illustrated in Figure F.7. The average TAT for these repairs was 45.3 days with a normative time of 61.1 hours for the critical component. This amounts to an average of 5.7 working days. Compared to the actual TAT this is only 13%, and thus the average waiting time is 87%. The ratio of waiting time to the normative time is similar to that of the regular maintenance route.

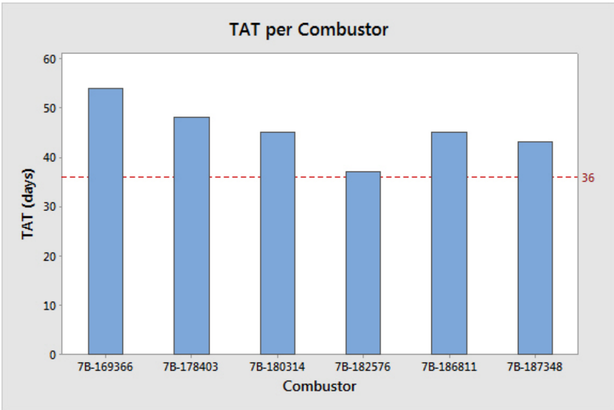


Figure F.7: Bar chart of the Exceptional Repair TAT

As shown in Figure F.8 the outer liner is again most frequently on the critical path, whilst the dome

Table F.4: 7B Combustor Exceptional Repair Information

Combustor	On-time	TAT	Norm (hrs)	Working days	Norm % of TAT	Wait	Critical Component
7B-169366	0	54	65.9	6.1	11%	89%	Outer Liner
7B-178403	0	48	65.2	6.5	13%	87%	Outer Liner
7B-180314	0	45	62.2	5.8	13%	87%	Inner Liner
7B-182576	0	37	56.3	5.2	14%	86%	Outer Liner
7B-186811	0	45	51.8	4.8	11%	89%	Outer Liner
7B-187348	0	43	65.5	6.1	14%	86%	Dome
On-time	0						
Average	0	45.3	61.1	5.7	13%	87%	

and outer liner are on the critical path only once. Furthermore, none of the parts have the same TAT for Z42 and Z51. As with the regular combustors the Dome is most frequently the component with the longest planned normative maintenance time, and the outer liner is not on the planned critical path at all.

So far these combustor repairs seem to be similar to the regular combustor repairs. It is assumed that these components have been exchanged for spare or newly available components in order for assembly to take place. It seems logical that a PV would occur when a component needs to be exchanged, however no note of this has been made in the available data.

It has been found that on average the planned normative maintenance time is 66.36 hours, or 6.1 working days, which is 18% of the complete TAT. The percentage of the normative maintenance time is similar to that of the combustors with a regular maintenance route. Furthermore, on average 2.8 PV's occurred for each combustor.

From Table F.5 it can be seen that the assembly date of each combustor is before the completion date of the last part. Why and how this has happened could not be determined from the available data. It is

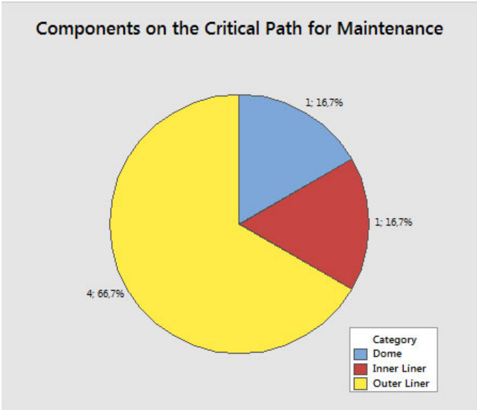


Figure F.8: Pie chart of the Components on the Critical Path of Exceptional Repair

assumed that these parts have been exchanged for spare or newly available parts in order for assembly to take place. Besides the assembly and completion dates Table F.5 shows which components have the longest normative maintenance time and what this maintenance time is both in hours and working days.

Table F.5: 7B Combustor Exceptional Repair Normative Route Information

Combustor	Planned Norm (hrs)	Working days	Norm % of TAT	Longest Norm	Assembly Date	Last Part	Completion Date	PV
7B-169366	74.0	6.9	16%	Inner Liner	16-4-2014	Outer Liner	7-5-2014	2
7B-178403	65.5	6.1	17%	Dome	4-6-2014	Outer Liner	25-7-2014	6
7B-180314	62.2	5.8	17%	Inner Liner	27-6-2014	Outer Liner	30-6-2014	4
7B-182576	65.5	6.1	22%	Dome	7-8-2014	Outer Liner	12-8-2014	1
7B-186811	65.5	6.1	18%	Dome	5-11-2014	Outer Liner	6-11-2014	2
7B-187348	65.5	6.1	19%	Dome	7-11-2014	Dome	12-12-2014	2
Average PV	66.4	6.1	18%					2.8 17

Very little can be said how the component requiring longer maintenance has influenced TAT. From data it becomes clear that this has occurred, and what the additional TAT is for these components. Figure F.9 shows how the actual, additional and normative TATs for the exceptional components compare. As can be seen the additional time for each of the components varies between a day and 51 days, and the normative time is only a fraction of the TAT for the part.

In order to determine how the exceptional process varies both a histogram and a probability plot have been made. The histogram in Figure F.10 shows that the data can be categorised in three boxes that are not all adjacent. This means that even though there is a normal curve in the graph the data is still quite variable. Furthermore, the standard deviation is 5.6 around an average of 45.3, meaning that 84% of the data exceeds the TAT of 36 days, as the TAT is removed from the mean by more than one standard deviation.

The probability plot of Figure F.11 shows that the values are distributed fairly normally. However, rather than forming a line the TATs are organised similar to an s-shape. Furthermore, there is quite some variation. Hence the exceptional process needs to be stabilised and improved quite a lot before reaching the agreed TAT.

Of the exceptional components it can be said that in case a componentis completed after assembly has taken place the combustor will not be on-time. In all other respects the process is quite similar to

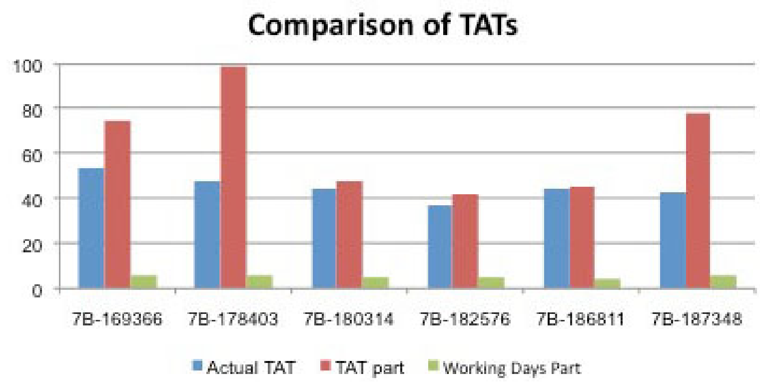


Figure F.9: Bar Chart of the Exceptional componentTAT compared to Actual TAT and Working Days

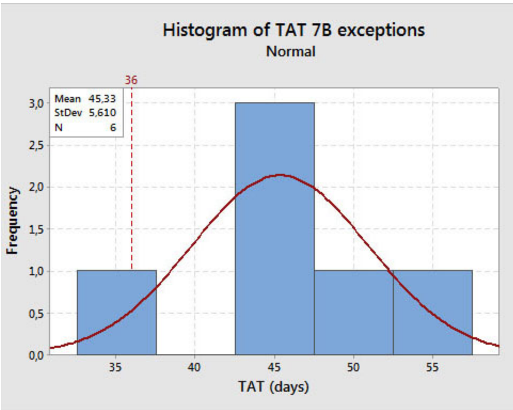


Figure F.10: Histogram of the Exceptional Repair TAT

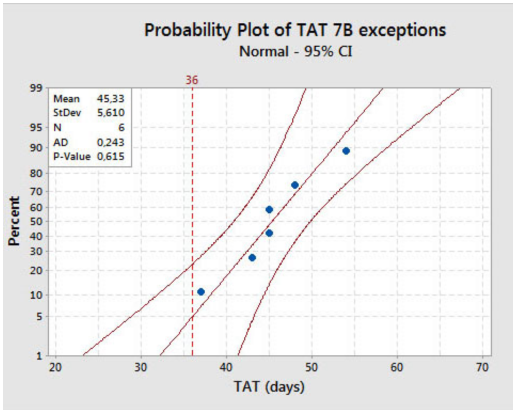


Figure F.11: Probability plot of the Exceptional Repair TAT

the regular process. Furthermore, there is no explanation of why or how the decision was made for assembly to take place before completing the last part.

F.2.3. Outsourced Repairs

Some combustors can not be repaired by the combustor department and are repaired externally by other MRO companies. ES remains responsible for the quality of the combustor. Therefore, outsourced components are inspected after external maintenance. This inspection is performed within maintenance activity code Z03. The normative time that is set for this activitiy is always 1.5 hours, and the handshake is to perform Z03 within 5 days. Table F.6 shows the combustors that have been outsourced, along with the time it has taken to perform the inspection, whether this was done on-time, how much the normative time is compared to the actual TAT, for which componentthis occurred, and if a PV occurred.

As can be seen 13 out of 21 combustors were inspected within the available TAT, and the average TAT was 4.1 days. So far this is the only instance in which the average TAT is lower than the handshake TAT. However, the average normative time compared to the actual TAT was 11% meaning that 89% of the time is waiting time. Furthermore, no PV's have occured during Z03. Furthermore, Z03 has taken place only for the combustion chamber, which is the complete combustor.

Figure F.12 shows that the TAT is distributed quite normally, and that the inspections were either performed in 4 days or less, or 6 days or more. This makes it seem almost as if this happens on purpose, that an effort is made to keep the TAT under 5 days, and if the inspection is going to be late it no longer matters how long it takes. The standard deviation is 3.1, which shows that the spread around the mean is small compared to the other standard deviations. But, is relatively quite large compared to the handshake TAT which is 5 days. Furthermore, the inspection is performed in one day exceptionally

Table F.6: 7B Combustor Outsourced Repair Information

Combustor	On Time	TAT	Norm % of TAT	PV	part
7B-169363	0	7	2%	0	chamber
7B-171379	0	6	2%	0	chamber
7B-171814	0	6	2%	0	chamber
7B-172469	1	1	14%	0	chamber
7B-172922	1	0	100%	0	chamber
7B-172925	1	4	3%	0	chamber
7B-173055	1	3	5%	0	chamber
7B-173332	1	1	14%	0	chamber
7B-176244	0	9	2%	0	chamber
7B-176503	0	6	2%	0	chamber
7B-176822	0	10	1%	0	chamber
7B-176861	1	1	14%	0	chamber
7B-177542	1	4	3%	0	chamber
7B-178048	1	4	3%	0	chamber
7B-181062	1	1	14%	0	chamber
7B-185456	1	1	14%	0	chamber
7B-186117	1	3	5%	0	chamber
7B-187335	1	2	7%	0	chamber
7B-187595	1	1	14%	0	chamber
7B-189953	0	8	2%	0	chamber
7B-191293	0	8	2%	0	chamber
On time	13	4.1	11%		
PV				0	

frequently, which explains the peak of the second bin.

In order to see how normal the distribution is a probability plot has been made, as can be seen in

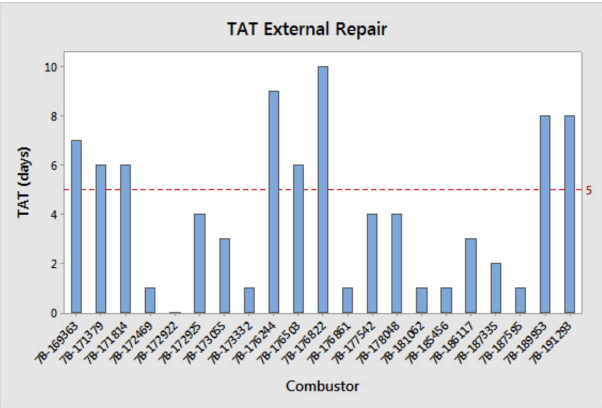


Figure F.12: Bar chart of the Outsourced Repair TAT

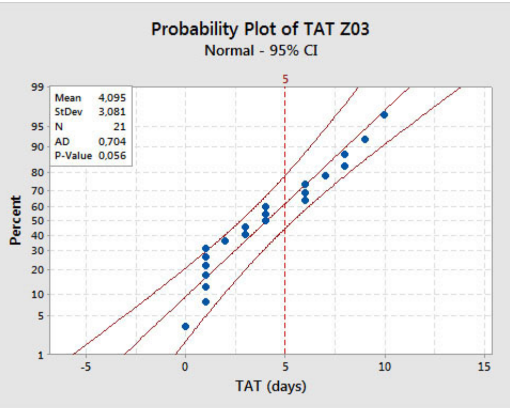


Figure F.13: Probability Plot of Outsourced Combustors

F.13. This plot shows that the data is not quite normally distributed as the data has a sort of tail at the bottom due to the frequent occurrence of a 1 day TAT. This implies that there is some waste. However, in this case only a small shift to the left is necessary as the TATs are close to the handshake TAT compared to the other types of repairs.

As the normative time is so small and always the same, it is interesting to see how this compares to the actual TAT. As Table F.6 already showed, there was one instance in which the inspection was completed within a day, and the TAT and normative time are thus said to be equal. Figure F.14 shows that the normative TAT is so small compared to the actual TATs that it is almost invisible.

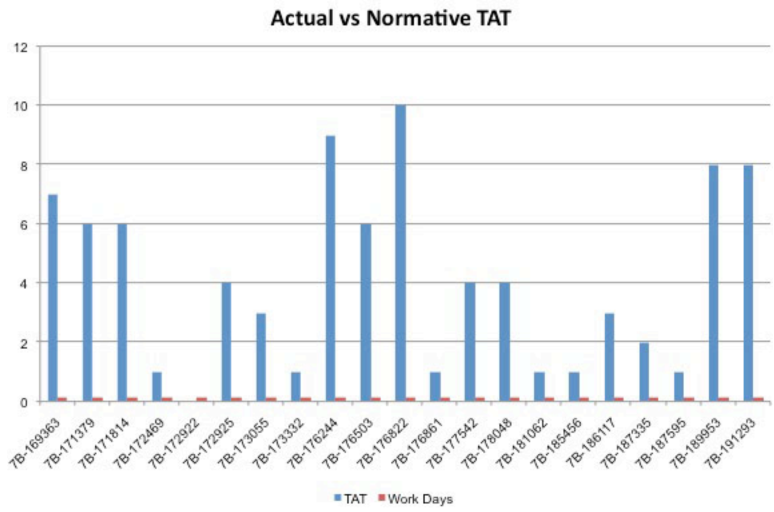


Figure F.14: Bar chart of Actual TAT and Normative TAT per Combustor

Aside from the inspections of outsourced combustors, there are also combustor components that are outsourced whilst maintenance for the rest of the combustor occurs within the department. This has been the case in 6 instances. As shown in Table F.7 in this case 50% of the combustors is on time. This the highest on-time performance found so far. This implies that outsourcing maintenance for a componenthas a positive influence on TAT. Especially as these on-time combustors are the only three 7B combustors with an in-house repair that have been completed on-time. Unfortunately the sample is too small to draw any conclusions regarding the overall process. It is, however, an interesting fact that might be interesting for further analysis. Furthermore, the normative time for the Z03 inspections is significantly lower than the Z03 for complete external repairs and depends on the component type. Z03 for the outer liner is 0.3 hours, and Z03 for the inner liner is 0.1 hour. Another interesting fact is that the components that have been outsourced are never the critical components. This could mean that the external repairs are performed quicker than the internal repair, or that these components have been exchanged rather than repaired externally. Unfortunately this can not be determined from the available data.

Table F.7: 7B Combustor components External Repair

Combustor	Repair	TAT	On-time	Critical Component	External Part	TAT Z03	Norm Z03
7B-179318	Regular	25	1	Dome	Outer Liner	0	0.3
7B-180314	Exceptional	45	0	Inner Liner	Outer Liner	3	0.3
7B-182310	Regular	35	1	Outer Liner	Inner Liner	0	0.1
7B-186272	Regular	34	1	Outer Liner	Inner iner	0	0.1
7B-188112	Regular	38	0	Dome and Outer Liner	Inner Liner	1	0.1
7B-189684	Regular	50	0	Inner Liner	Outer Liner	0	0.3
Average		37.8	50%			0.7	0.2

In order to see to which extent the normative time influences the TAT a scatterplot is made. This plot shows whether or not the TAT has a correlation with the normative time. Figure F.15 shows the relationship between the two. The regression line shows a slight correlation that indicates as the normative time increases TAT increases. However, the data points are organised around highly different normative times, and the TATs for each of these normative times also differ. Especially the differences in TAT around the normative time of 1.5 hours lead to the notion that the TAT has very little dependency on the normative time.

The outsourced components require very little work or time in the combustor department as they only require an inspection to verify their quality. However, the time in which such an inspection is performed

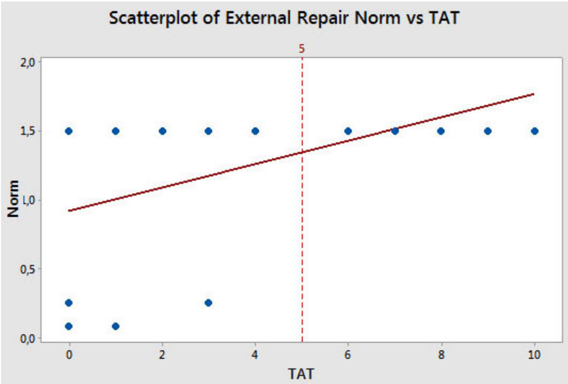


Figure F.15: Scatterplot of Actual TAT and Normative TAT

is highly variable, the distribution of the TATs for the completely outsourced combustors leads to believe that the TAT is influenced by the urgency of the need for the combustor. This is also reflected in the low TATs for the outsourced components, as these components are always finished within handshake TAT and the complete combustors for which a componentis outsourced are the only combustors that have been completed on time. Finally, the high discrepancy between the normative time and TAT suggests that there is a lot of waste in this process. As this process exists of only one task there is no need for further analysis of this process itself. It is assumed that the causes for waste within Z03 activities are similar to those within the regular repairs, and can hence be resolved using similar solutions.

F.3. Value Drivers

F.3.1. Maintenance Phases

In order to see whether the on-time performance and TAT of phases Z42 and Z51 combined form a good indicator of on-time combustor performance these TATs are compared. This comparison can be seen in Table F.8, where it becomes clear that if the phase Z42 and Z51 are not completed within 32 days (the combined handshake TAT for these phases) the combustor will be late. Furthermore, on average the TAT for Z42 and Z51 combined makes up only 93% of the total combustor TAT. Therefore these phases have most influence on the total TAT, and further analysis should focus on these phases.

F.3.2. Tasks Following Q034

As a mechanic can choose between focussing on one component at a time, or focussing on carrying out one capability for various components. The latter is generally the case for Q034 tasks. An inspector (as the name already implies), continuously carries out inspection (Q034) tasks. In this case a component is handled, after which it is put back in the storage rack until someone else comes along to perform the next task. When this happens, the following task immediately incurs waiting time. As determined, there are very few people with Q034 skills, but there are many Q034 tasks that occur at different moments throughout the different maintenance routes. As there are usually only between 2 and 5 other mechanics within the department, and there are on average 2 combustors with 6 components each in the department, it is likely that once a Q034 task has been finished, the component has to wait before the next task is carried out.

Therefore, it is relevant to explore if Q683 and Q702 tasks frequently follow Q034 tasks, as this might explain why waiting time arises so much for these tasks, even though there seems to be sufficient capacity. In order to find out if and how many times Q034 tasks are followed by Q683 and Q702 tasks each combustor maintenance route has been analsyed and the instances in which these follow ups have occurred have been counted. Table F.9 shows in how many cases this has happened for each combustor type. Furthermore, the instances in which Q034 tasks follow Q034 tasks have also been counted.

Table F.8: Comparison of Complete Combustor TAT and Phase Z42 & Z51 TAT

Combustor	Z42 & Z51 TAT (days)	On-time	Complete TAT (days)	On-time	%Z42 & Z51 of TAT
7B-174790	38	0	39	0	97%
7B-175333	40	0	42	0	95%
7B-176124	54	0	56	0	96%
7B-176828	44	0	50	0	88%
7B-179318	24	1	25	1	96%
7B-180318	38	0	38	0	100%
7B-180753	48	0	50	0	96%
7B-181541	37	0	38	0	97%
7B-182310	32	1	35	1	91%
7B-182864	45	0	48	0	94%
7B-184359	37	0	41	0	90%
7B-184522	56	0	58	0	97%
7B-184762	34	0	38	0	89%
7B-186272	29	1	34	1	85%
7B-187640	45	0	49	0	92%
7B-188048	55	0	55	0	100%
7B-188112	36	0	38	0	95%
7B-188641	52	0	58	0	90%
7B-189684	44	0	50	0	88%
7B-189699	37	0	48	0	77%
7B-192524	39	0	44	0	89%
7B-169366	49	0	54	0	91%
7B-178403	44	0	48	0	92%
7B-180314	43	0	45	0	96%
7B-182576	35	0	37	0	95%
7B-186811	43	0	45	0	96%
7B-187348	42	0	43	0	98%
On-time		3		3	

As Table F.9 shows, in total 6559 Q034 tasks have occurred, 4615 of which have been followed

Table F.9: Tasks Following Q034 Tasks

Combustor	Q034 Tasks	Q034	Q702	Q683	Total
7B	2310	949	720	253	1922
8C	3240	982	809	122	1913
8E	944	584	146	25	755
Coffeecan	65	15	10	0	25
HPC Stator	0		0	0	0
Total	6559	2530	1685	400	4615

by either three of the time-trap tasks, this is about 70% of the Q034 tasks. This means that, as it is likely that the tasks after Q034 tasks incur waiting time, it is likely that these tasks have waiting time. Unfortunately it is unclear whether subsequent Q034 tasks are carried out in one go, or that waiting time can exist between these tasks as well. However, as seen during the example of the 7B-169366 combustor if these subsequent tasks, which occur frequently at the start of a maintenance route, are carried out in one go a lot of additional waiting time occurs for other components. Therefore, it is likely, as this also is at the start of the maintenance route, that other Q034 tasks are prioritised. Hence, the waiting time can accumulate throughout the Q034 tasks and the following Q683 and Q702 tasks. This partially explains how Q034 forms a bottleneck and allows the waiting time to accumulate within a maintenance route.

The waste within utilisation and capacity has been found to lie within the so-called time-traps. For each of these capabilities there are many tasks and a relatively high amount of normative maintenance time. In theory there are enough mechanics with the required time-trap capbilities present every day. However, mechanics are not able to perform only one capability per day, and not every mechanic is capable of performing all available tasks for each of the capabilities they focus on. From the 23 people within the department 20 are capable of performing Q702, 11 people are capable of performing Q683 and 6 people are capable of performing Q034. In total 3 people are capable of performing all three time-trap capabilities. After looking at a maintenance route and the available work it was determined that a mismatch arises between the available work and the available capabilities causing components to remain waiting for the correct capability to become available. Q034 has been determined to be the main bottleneck as almost every componenthas to wait until this capability becomes available. This creates a cumulative waiting time as Q034 tasks are frequently followed by other time-trap tasks.

A factor that influences both TAT and the waiting time for the bottleneck is the planning. Due to a lack of planning, the possible bottlenecks within the available tasks can not be anticipated and the outcome is likely to be less efficient, and might cause additional waiting time.

F.3.3. Available Capbilities

It is also relevant to know how the available capabilities influence TAT. As this can not be directly determined it is relevant to compare the work done to the capabilities. If there is a relationship between the work performed and the available capabilities it is likely that the capabilities and TAT have a relationship as TAT is influenced by the work performed.

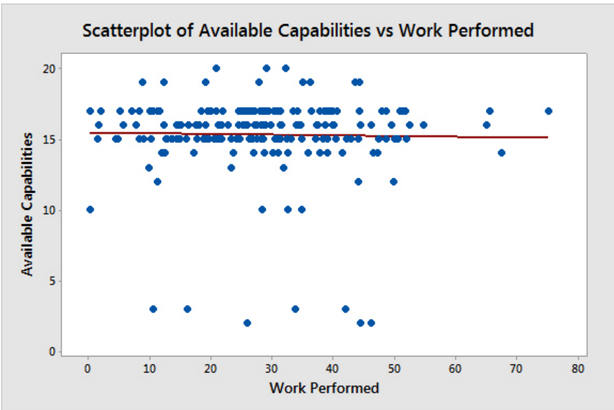


Figure F.16: Scatterplot Available Capabilities and Work Performed

Figure F.16 shows a slight negative correlation. However, as can be seen it does not mean that if there are more available capabilities less work is performed. The capabilities required are determined by the routing and the the state of the components.

G

7B Combustor Repair Data

This Appendix contains the data that has been used for the analysis of the combustor repair routes.

Table G.1: Number of tasks per combustor maintenance phase per 7B combustor including the critical part

Combustor	Z11	Z01	Z11	Z42	Z51	Z21	sum	Part
7B-174790	1	4	7	5	112	4	133	Outer Liner
7B-175333	1	4	7	5	112	4	133	Outer Liner
7B-176124	0	4	7	5	112	4	132	Outer Liner
7B-176828	1	4	7	4	87	4	107	Dome
7B-179318	0	4	7	4	94	4	113	Dome
7B-180318	0	4	7	4	94	4	113	Inner Liner
7B-180753	0	4	7	7	103	4	125	Inner Liner
7B-181541	0	4	7	5	105	4	125	Outer Liner
7B-182310	0	4	7	5	71	4	91	Outer Liner
7B-182864	0	4	7	5	107	4	127	Inner Liner
7B-184359	1	4	7	5	111	4	132	Outer Liner
7B-184522	1	4	7	6	103	4	125	Outer Liner
7B-184762	1	4	7	5	110	4	131	Inner Liner
7B-186272	1	4	7	5	86	4	107	Outer Liner
7B-187640	1	4	7	6	117	4	139	Outer Liner
7B-188048	0	4	7	6	123	4	144	Outer Liner
7B-188112	1	4	7	4	48	4	67	Dome
7B-188641	1	4	7	4	87	4	107	Dome
7B-189684	1	4	7	7	113	4	136	Inner Liner
7B-189699	1	4	7	4	61	4	81	Dome
7B-192524	1	4	7	6	115	4	137	Outer Liner
7B-169366	0	4	7	6	129	4	150	Inner Liner
7B-178403	0	4	7	5	105	4	125	Inner Liner
7B-180314	0	4	7	5	105	4	125	Inner Liner
7B-182576	0	4	7	5	98	4	118	Inner Liner
7B-186811	1	4	7	5	111	4	132	Outer Liner
7B-187348	1	4	7	6	107	4	129	Inner Liner
Average	1	4	7	5.1	98.7	4	121.6	

Table G.2: Normative maintenance time (in minutes) per maintenance phase for the critical part

Combustor	**Z11**	**Z01**	**Z11**	**Z42**	**Z51**	**Z21**	**Sum**
7B-174790	1	115	145	130	1430	465	2286
7B-175333	1	115	145	130	2248	465	3104
7B-176124		115	145	130	2248	465	3103
7B-176828	1	115	145	185	3018	465	3929
7B-179318		115	145	185	3228	465	4138
7B-180318		115	145	185	2695	465	3605
7B-180753		115	145	232	2815	465	3772
7B-181541		115	145	130	1848	465	2703
7B-182310		115	145	130	1125	465	1980
7B-182864		115	145	185	2855	465	3765
7B-184359	1	115	145	130	2248	465	3104
7B-184522	1	115	145	175	1810	465	2711
7B-184762	1	115	145	185	3065	465	3976
7B-186272	1	115	145	130	1190	465	2046
7B-187640	1	115	145	175	2230	465	3131
7B-188048		115	145	175	2438	465	3338
7B-188112	1	115	145	185	1610	465	2521
7B-188641	1	115	145	185	3058	465	3969
7B-189684	1	115	145	232	2955	465	3913
7B-189699	1	115	145	185	2343	465	3254
7B-192524	1	115	145	175	2293	465	3194
7B-169366		115	145	185	3520	465	4430
7B-178403		115	145	185	2815	465	3725
7B-180314		115	145	185	2815	465	3725
7B-182576		115	145	185	2735	465	3645
7B-186811	1	115	145	130	2248	465	3104
7B-187348	1	115	145	230	2855	465	3811
Average	1	115	145	170.8	2306.7	465	3332.7

Table G.3: TAT per maintenance phase (days) for the critical part

Combustor	Z11	Z01	Z11	Z42	Z51	Z21	sum
7B-174790	1	0	0	2	36	0	39
7B-175333	1	0	0	4	36	1	42
7B-176124	1	1	14	40	0	56	3103
7B-176828	4	1	1	9	35	0	50
7B-179318	0	0	7	17	1	25	4138
7B-180318	0	0	7	31	0	38	3605
7B-180753	1	1	9	39	0	50	3772
7B-181541	1	0	9	28	0	38	2703
7B-182310	0	3	8	24	0	35	1980
7B-182864	0	0	6	39	3	48	3765
7B-184359	4	0	0	2	35	0	41
7B-184522	2	0	0	14	42	0	58
7B-184762	4	0	0	2	32	0	38
7B-186272	3	0	0	8	21	2	34
7B-187640	4	0	0	15	30	0	49
7B-188048	0	0	7	48	0	55	3338
7B-188112	1	0	1	12	24	0	38
7B-188641	5	0	1	7	45	0	58
7B-189684	3	0	0	15	29	3	50
7B-189699	7	0	0	6	31	3	47
7B-192524	5	0	0	4	35	0	44
7B-169366	3	0	8	41	2	54	4430
7B-178403	3	0	10	34	1	48	3725
7B-180314	0	0	7	36	2	45	3725
7B-182576	0	1	5	30	1	37	3645
7B-186811	3	0	0	6	37	0	46
7B-187348	1	0	3	7	35	0	46
Average	3.2	0.4	0.4	7.8	33.7	0.7	44.8

Table G.4: On-time Performance Per Phase

Combustor	02X-Z11	Z01	Z11	Z42	Z51	Z21
7B-174790	1	1	1	1	0	1
7B-175333	1	1	1	1	0	1
7B-176124		1	1	0	0	1
7B-176828	0	1	1	0	0	1
7B-179318		1	1	0	1	1
7B-180318	1	1	0	0	1	38
7B-180753	1	1	0	0	1	50
7B-181541		1	1	0	1	1
7B-182310		1	0	0	1	1
7B-182864	1	1	0	0	0	48
7B-184359	0	1	1	1	0	1
7B-184522	0	1	1	0	0	1
7B-184762	0	1	1	1	0	1
7B-186272	0	1	1	0	1	0
7B-187640	0	1	1	0	0	1
7B-188048		1	1	0	0	1
7B-188112	1	1	1	0	1	1
7B-188641	0	1	1	0	0	1
7B-189684	0	1	1	0	0	0
7B-189699	0	1	1	0	0	0
7B-192524	0	1	1	1	0	1
7B-169366	0	1	0	0	0	54
7B-178403	0	1	0	0	1	48
7B-180314	1	1	0	0	0	45
7B-182576	1	1	0	0	1	37
7B-186811	0	1	1	0	0	1
7B-187348	1	1	0	0	0	1
Total	4	25	25	5	5	21
% On-time	27%	93%	93%	19%	19%	78%

Table G.5: Number of Maintenance Tasks per capability for Critical Combustor Part During Phase Z42 and Z51 (part 1)

Combustor	#	Q033	Q034	Q114	Q116	Q224	Q249	Q428	Q434	Q502
7B-174790	6		25			1	1	4		1
7B-175333	12		33			1	1	8		1
7B-176124	12		33			1	1	8		1
7B-176828	2		27			1	1		3	1
7B-179318	3		27			2	1		3	1
7B-180318	6		22	4	4	1	1	11	2	1
7B-180753	6		25	3	3	2	2	12	2	1
7B-181541	8		35			1	1	4		1
7B-182310	7		19				1	4		1
7B-182864	6		24	4	4	2	1	12	2	1
7B-184359	13		33			1	1	6		1
7B-184522	14		24				2	12		1
7B-184762	6		24	5	4	2	1	13	2	1
7B-186272	16		20				1	6		1
7B-187640	14	1	31				2	8		2
7B-188048	17		33			1	2	8		1
7B-188112			17				1			1
7B-188641	3		27			1	1		3	1
7B-189684	6		28	3	3	3	2	12	2	1
7B-189699	1		20				1		3	1
7B-192524	11		35		1	1	2	8		
7B-169366	7		33	4	4	3	1	12	2	1
7B-178403	6		24	4	4	2	1	11	2	1
7B-180314	6		24	4	4	2	1	11	2	1
7B-182576	6		22	4	4	1	1	12	2	1
7B-186811	13		33				1	1	6	1
7B-187348	6		24	4	4	2	2	12	2	1
Total	213	1	722	39	39	31	34	195	38	27

Table G.6: Number of Maintenance Tasks per capability for Critical Combustor Part During Phase Z42 and Z51 (part 2)

Combustor	Q512	Q516	Q518	Q683	Q685	Q702	Q717	Q800	Q801	Q802	Tot
7B-174790	1	1	4	13	1	22		3	1		*84*
7B-175333	1	2	4	14	1	32		1	3	3	*117*
7B-176124	1	2	4	14	1	32		1	3	3	*117*
7B-176828	1	3		12		36		1	3		*91*
7B-179318	1	3		13		39		2	3		*98*
7B-180318	1	2		7		24	12		3		*101*
7B-180753	1	2		7		29	12		3		*110*
7B-181541	2	2	4	17	1	29		4	1		*110*
7B-182310	2	2	4	9	1	24			2		*76*
7B-182864	1	2		8		30	12		3		*112*
7B-184359	1	2	4	14	1	32		1	3	3	*116*
7B-184522	1	2	12	9	1	29			2		*109*
7B-184762	1	2		9		30	12		3		*115*
7B-186272	2	2	6	9	1	25			2		*91*
7B-187640	2	3	4	13	1	37		1	3	1	*123*
7B-188048	1	2	6	14	1		34	1	4	4	*129*
7B-188112	1	3		8		19			2		*52*
7B-188641	1	3		12		36		1	3		*92*
7B-189684	1	2		8		34	12		3		*120*
7B-189699	1	3		8		24		1	2		*65*
7B-192524	1	2	4	14		35		1	3	3	*121*
7B-169366	1	2		10		38	12		5		*135*
7B-178403	1	2		8		29	12		3		*110*
7B-180314	1	2		8		29	12		3		*110*
7B-182576	1	2		7		25	12		3		*103*
7B-186811	1	2	4	14	1	32		1	3	3	*116*
7B-187348	1	2		8		30	12		3		*113*
Total	31	59	60	287	11	781	154	19	75	20	***2836***

Table G.7: TAT (days) per capability for Critical Combustor Part During Phase Z42 and Z51 (part 1)

Combustor	#	Q033	Q034	Q114	Q116	Q224	Q249	Q428	Q434	Q502
7B-174790	0		19			0	0	5		0
7B-175333	0		6			0	0	5		0
7B-176124	0		24			0	4	8		0
7B-176828	0		19			0	3		6	0
7B-179318	1		9			0	1		0	0
7B-180318	0		13	0	0	0	1	18	1	0
7B-180753	1		10	0	0	0	4	6	2	0
7B-181541	0		16			0	0	3		0
7B-182310	0		6				1	1		0
7B-182864	0		13	0	0	0	0	13	6	0
7B-184359	3		16			0	1	3		0
7B-184522	0		23				6	14		0
7B-184762	0		17	0	2	0	0	5	0	0
7B-186272	5		12				0	1		0
7B-187640	0	0	15				6	1		0
7B-188048	0		25			0	5	3		0
7B-188112			11				1			3
7B-188641	0		13			0	1		6	1
7B-189684	0		8	0	0	0	4	5	2	0
7B-189699	0		8				0		3	0
7B-192524	0		5		0	1	2	6		
7B-169366	0		16	1	0	0	0	11	1	0
7B-178403	0		19	0	0	0	1	7	3	0
7B-180314	0		9	0	0	1	1	10	3	0
7B-182576	0		10	0	0	0	1	9	1	0
7B-186811	5		15				0	1	7	0
7B-187348	0		7	0	0	0	3	8	8	0
Total	15	0	364	1	2	2	46	143	49	4

Table G.8: TAT (days) per capability for Critical Combustor Part During Phase Z42 and Z51 (part 2)

Combustor	Q512	Q516	Q518	Q683	Q685	Q702	Q717	Q800	Q801	Q802	Tot
7B-174790	1	1	4	13	1	22		3	1		*84*
7B-175333	1	2	4	14	1	32		1	3	3	*117*
7B-176124	1	2	4	14	1	32		1	3	3	*117*
7B-176828	1	3		12		36		1	3		*91*
7B-179318	1	3		13		39		2	3		*98*
7B-180318	1	2		7		24	12		3		*101*
7B-180753	1	2		7		29	12		3		*110*
7B-181541	2	2	4	17	1	29		4	1		*110*
7B-182310	2	2	4	9	1	24			2		*76*
7B-182864	1	2		8		30	12		3		*112*
7B-184359	1	2	4	14	1	32		1	3	3	*116*
7B-184522	1	2	12	9	1	29			2		*109*
7B-184762	1	2		9		30	12		3		*115*
7B-186272	2	2	6	9	1	25			2		*91*
7B-187640	2	3	4	13	1	37		1	3	1	*123*
7B-188048	1	2	6	14	1		34	1	4	4	*129*
7B-188112	1	3		8		19			2		*52*
7B-188641	1	3		12		36		1	3		*92*
7B-189684	1	2		8		34	12		3		*120*
7B-189699	1	3		8		24		1	2		*65*
7B-192524	1	2	4	14		35		1	3	3	*121*
7B-169366	1	2		10		38	12		5		*135*
7B-178403	1	2		8		29	12		3		*110*
7B-180314	1	2		8		29	12		3		*110*
7B-182576	1	2		7		25	12		3		*103*
7B-186811	1	2	4	14	1	32		1	3	3	*116*
7B-187348	1	2		8		30	12		3		*113*
Total	31	59	60	287	11	781	154	19	75	20	***2836***

Table G.9: Normative Time (mins) per capability for Critical Combustor Part During Phase Z42 and Z51 (part 1)

Combustor	**#**	**Q033**	**Q034**	**Q114**	**Q116**	**Q224**	**Q249**	**Q428**	**Q434**	**Q502**
7B-174790	0		305			10	45	120		15
7B-175333	0		438			10	45	395		30
7B-176124	0		438			10	45	395		30
7B-176828	60		453			10	60		370	45
7B-179318	60		453			20	60		370	45
7B-180318	205		305	45	40	5	45	520	240	10
7B-180753	205		327	35	30	15	90	550	240	10
7B-181541	5		448			10	45	120		15
7B-182310	0		285				45	120		15
7B-182864	205		325	45	40	15	45	550	240	10
7B-184359	200		438			10	45	195		30
7B-184522	10		300				90	360		15
7B-184762	205		325	60	40	15	45	565	240	10
7B-186272	0		300				45	180		0
7B-187640	200	10	415				90	375		45
7B-188048	200		438			10	90	255		30
7B-188112			310				60			45
7B-188641	120		493			10	60		370	45
7B-189684	205		367	35	30	25	90	550	240	10
7B-189699	0		350				60		560	45
7B-192524	0		448		15	10	90	395		
7B-169366	205		465	45	40	20	45	550	145	10
7B-178403	205		325	45	40	15	45	520	240	10
7B-180314	205		325	45	40	15	45	520	240	10
7B-182576	205		305	45	40	5	45	550	240	10
7B-186811	200		438				10	45	195	30
7B-187348	205		325	45	40	15	90	550	240	10
Total	3105	10	10144	445	395	255	1570	8380	4170	580

Table G.10: Normative Time (mins) per capability for Critical Combustor Part During Phase Z42 and Z51 (part 2)

Combustor	**Q512**	**Q516**	**Q518**	**Q683**	**Q685**	**Q702**	**Q717**	**Q800**	**Q801**	**Q802**	**Tot**
7B-174790	15	60	100	303	20	512		45	10		*1560*
7B-175333	10	60	100	323	20	862		10	45	30	*2378*
7B-176124	10	60	100	323	20	862		10	45	30	*2378*
7B-176828	15	70		650		1440		5	25		*3203*
7B-179318	15	70		785		1500		10	25		*3413*
7B-180318	15	80		170		820	355		25		*2880*
7B-180753	15	80		190		880	355		25		*3047*
7B-181541	20	60	100	393	20	682		50	10		*1978*
7B-182310	20	60	100	128	20	437			25		*1255*
7B-182864	15	80		200		890	355		25		*3040*
7B-184359	10	60	100	323	20	862		10	45	30	*2378*
7B-184522	15	120	300	128	20	602			25		*1985*
7B-184762	15	80		380		890	355		25		*3250*
7B-186272	0	0	150	128	20	472			25		*1320*
7B-187640	25	120	100	173	20	782		10	30	10	*2405*
7B-188048	10	60	150	323	20		912	10	65	40	*2613*
7B-188112	15	70		540		740			15		*1795*
7B-188641	15	70		650		1440		5	25		*3303*
7B-189684	15	80		220		940	355		25		*3187*
7B-189699	15	70		540		865		8	15		*2528*
7B-192524	10	60	100	323		932		10	45	30	*2468*
7B-169366	15	80		455		1230	355		45		*3705*
7B-178403	15	80		200		880	355		25		*3000*
7B-180314	15	80		200		880	355		25		*3000*
7B-182576	15	80		170		830	355		25		*2920*
7B-186811	10	60	100	323	20	862		10	45	30	*2378*
7B-187348	15	80		200		890	355		25		*3085*
Total	380	1930	1500	8741	220	22982	4462	193	790	200	***70452***

H

Capabilities

This appendix contains a table showing how many tasks each mechanic has performed within the combustor department per required capability.

Table H.1: Matrix of Tasks per Person and Capability I

	#	Q029	Q033	Q034	Q071	Q100	Q114	Q116	Q224	Q244	Q254	Q434	Q502	Q682	Q683	Q685	Q702	Tot Tasks	Tot Cap
A	6											6					1	13	3
B														2	32		16	50	3
C	55			1920	1	2	25	7	5	5	5		4				138	2167	11
AA							5	1							1			7	3
BB	2																	2	1
D							20	9										29	2
CC																		0	0
E							24	11					3	3	147		127	315	6
F	3				56	15			8	4			18				546	650	7
DD				1														1	1
G	1				19				1	12	1		21				136	191	7
EE	6																	6	1
FF																	2	2	1
GG																		0	0
H					13	1				4	2		7	5	387		444	863	8
HH							3	3								1		7	3
I				16			5	3					1		8		20	53	6
J	1				16	1	47	17	7	4	3		13	14	257		171	551	12
II													1					1	1
K	25				74	21			9	50	10		138				1202	1529	8
JJ	1																	1	1
L							1	8							2		3	14	4
M							8	5							10		3	26	4
KK																	1	1	1
LL													2				2	4	2
MM													1					1	1
N	50			2270		3	50	19	10	3	15						101	2521	9
NN																	1	1	1
OO																	1	1	1
O	75																1	76	2
PP																	2	2	1
P	54			3											1		7	65	4
Q	77		1	1143	3		106	41	4	3	2				62	3	50	1495	12
R	5																6	11	2
S	6											6						12	2
QQ	1																1	2	2
SS				3													1	4	2
TT													2					2	1
UU							1	1										2	2
VV																	1	1	1
WW		1																1	1
XX																	4	4	1
YY	1																	1	1
ZZ														2				2	1
AB							3	2										5	2
T	27				65	41	355	157	15	31	14		53		822	25	2094	3699	12
U	22				16	8			15	13	16		24		267		803	1184	9
V	2			279					1								4	286	4
W	2						8	3				2						15	4
Tot Tasks	422	1	1	5635	263	92	661	287	75	129	68	14	288	26	1996	29	5889	15876	
Tot People	22	2	2	9	10	9	16	16	11	11	10	4	15	6	13	4	31		

I
Model Validation & Verification

This Appendix will discuss the model of the process built in SIMIO. In order to ensure the simulation model correctly represents the process and to verify and validate the model a base scenario is made. In order to do so a thorough understanding of the process is required, which has been achieved throughout the research via interviews, observations, data analysis and process mapping. This section will discuss the base model design and its verification and validation.

I.1. Model Requirements

In order for a model to be successful it is important to define the objectives of the model and simulation before the model is designed. By doing so choices can be made regarding required outputs, the required system input, the scope and possible assumptions to be made. The objective of the simulation model is to assess process performance of the combustor maintenance process, and to be able to see the effects changes to the might have on this performance. This section will discuss what the model requires and what it should entail.

The objectives of the model are in line with the objectives of this research, and seek to provide a clear overview of the combustor maintenance process as carried out by the KLM E&M combustor maintenance department. Furthermore, the aim is to confirm that the value drivers as defined in the previous chapters are in fact influential to the maintenance process. Furthermore, the aim of the model is to answer the fifth and sixth sub-research questions. After defining the objectives the required outputs, the input and scope of the model can be defined, which will be done in the following sections.

I.1.1. Required Outputs

In order to assess process performance within the combustor department the model should be able to determine the TAT per combustor and the utilisation rates of both capabilities and mechanics. By doing so the model will be able to answer if and how many combustors are completed on-time, and where the time-trap capabilities lie. Furthermore, it would be helpful if the model could help identify bottlenecks within the process, this can be done by determining the number of components waiting before a certain capability is carried out, and the time these components spend in the waiting queue.

I.1.2. Scope

The combustor maintenance process is quite extensive, and is part of the engine maintenance process. As the main focus is on the combustor turnaround time and the utilisation rates of the mechanics and capabilities it is not necey to model all elements that are present in reality. Therefore it has been decided to focus only on the maintenance process carried out within the combustor department. This entails all maintenance tasks that take place within the combustor department, including work on combustors and non combustors. Additional activities that mechanics might carry out during their workday will not be considered, nor will process disruptions and out of stock events be considered to occur as there is no available data on these events. Furthermore, it is assumed that all required resources are present (including spare parts and things such as nuts and bolts). Finally tasks that are part of combustor maintenance but are performed in external departments have to be part of the model, but as these departments are not considered all external capabilities will be considered as one identical external capability in order to simulate the time spent in external departments.

I.1.3. Input

As the combustor maintenance process has been analysed using data for all maintenance activities carried out on combutors and within the combustor department during 2014, this data will also serve as an input for the combustor maintenance simulation model. This data includes all tasks that have been performed, their normative maintenance time, on which date the task was completed, and which mechanic has performed the task. The tasks (specifically their required capability), and normative maintenance times will be used as an input. However, the maintenance dates are not included, except the maintenance start dates for the complete combustors. Furthermore, the mechanics that carry out the tasks are not specifically included. In order to simulate the activities of the mechanics the daily available capacity and capabilities that have been established during the analysis are used as an input, as well as the utilisation rates for the mechanics.

I.2. Design

It has become clear that the general combustor maintenance process consists of 6 phases, as shown in the flowchart in figure I.1. However, each of these phases consist of a variable number of tasks which depend on both the type and damage of the combustor and its components. This means that it is not possible to create a model based on just the maintenance phases. Therefore, as with the current state analysis, the simulation model will be organised according to the required capabilities. The tasks carried out in external departments will be grouped as one required capability. Figure I.2 shows the process flowchart of the simulation process.

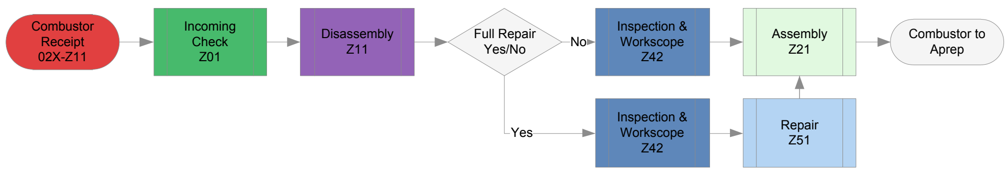


Figure I.1: Combustor maintenance process flowchart

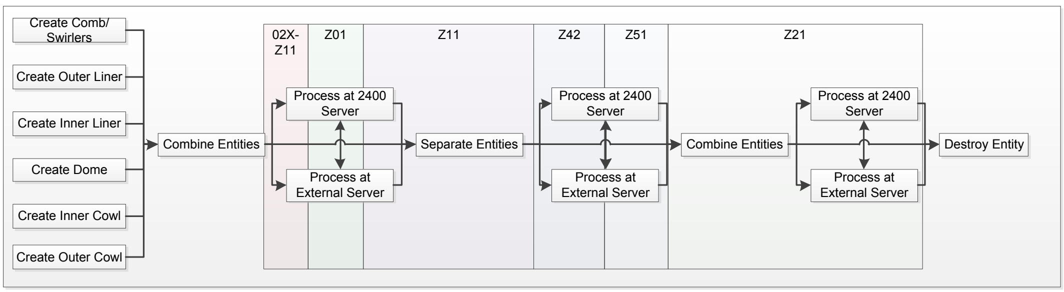


Figure I.2: Model process flowchart

Maintenance tasks will be executed by available mechanics with the required capabilities. Simulating these tasks, the mechanics capabilities and the capacity (determined by available mechanics) will be done using Simio objects. Table I.1 shows the objects available in Simio that will be used to represent these elements. Figure I.3 shows how the objects of the actual process, such as the mechanics, combustors and shop-travellers are translated into the model and what the inputs and outputs regarding these objects are.

As mentioned in section 4.1.1, Simio makes use of entities. For each combustor component a separate

Table I.1: Simio Standard Object Library [LLC., 2014]

Name	Description
Source	Creates entities that arrive to the system.
Sink	Destroys entities and records statistics.
Server	Models a multi-channel service process with input/output queues.
Combiner	Combines entities in batches.
Separator	Separates entities from batches.
Worker	Carries entities between Fixed objects and processes entities at a fixed location.
Basic Node	A simple intersection of Links.
Transfer Node	An intersection where entities set destination and wait on Transporters.
Path	A pathway between two Nodes where entities travel based on speed.

entity is made, each of these entities is then “created” by a source on the combustor arrival date. A source has been created for each component type. The combustor components can be linked to each other using a combiner, so the components together behave as one complete combustor. A separator can then separate the components once disassembly takes place, and the components are then re-assembled using a combiner. Simio allows entities to be given specifications which can then be used to link the entities that are part of one combustor to ensure that the correct components are assembled and ‘reassembled’.

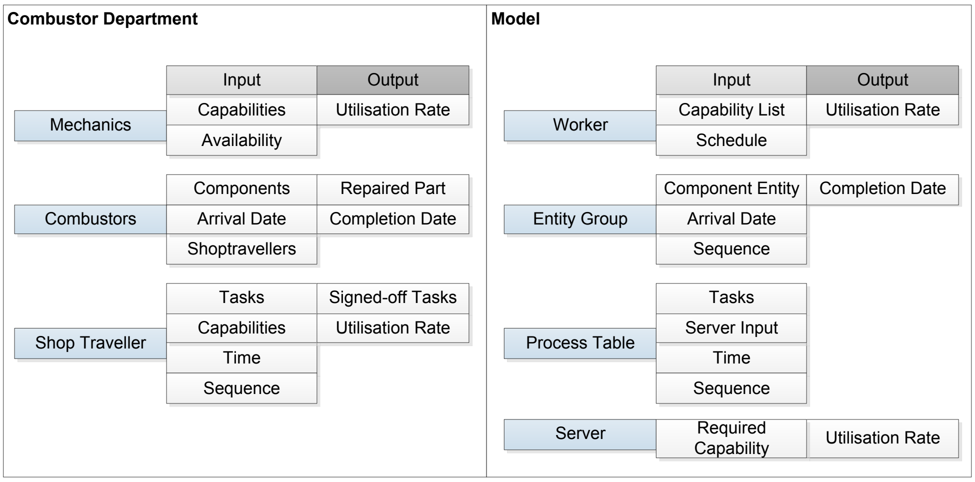


Figure I.3: Maintenance Process Objects

The entities are processed at a server, this signifies a task being performed on the combustor. Tasks are categorised based on the required capabilities and as such the server will signify a specific capability. The server can only process the entity if a worker (which simulates the mechanic) is available to come to the server for processing. Combustors and components are moved around the department by mechanics, who place the components at the workstation specified for the task that is defined by the shop-traveller. This is simulated by the entity being transported over the available nodes to the required server. If the server is occupied, or there is no worker available the components are placed in a queue in front of the server. It is possible to specify rules for selection of the queued components (for instance FIFO, or based on a specific priority). After processing the component is placed in the outgoing queue where it waits until a mechanic picks up the component and takes it to its next destination.

Tasks are performed by mechanics, who are simulated with Workers. For each of the workers in the model a schedule can be defined to determine when the mechanic is present within the shop (date, time and working hours). A worker receives requests for work from the server, which requests the nearest available mechanic from a list that contains the mechanics with the required capability. The mechanic selection can also be specified to be random, or based on a preferred order for instance.

It should be noted that the model assumes that only one mechanic at a time can work at a server. This means that only one task of one capability is performed at a time. In reality it is possible that several mechanics perform an inspection simultaneously, or that several mechanics are performing bench-work tasks at the same time.

Each component and combustor is handled according to the shop-traveller. Simio allows the required time and capability for each task on the shop-traveller to be entered into a table which is then linked to the component entity. The sequence of tasks is the sequence in which the entity is moved from server to server, and the time for processing is the time the entity is delayed ("processed") at the server. Entities and workers move through the shop via paths that connect to transfer nodes which in turn connect all servers to each other.

Finally, when all tasks are performed on the combustor the combustor is completed and moved to aprep. This is simulated by the sink, which "destroys" the entity. Both the sink and the source keep track of which entity has been created or destroyed and at what time this occurred by means of a so-called tally statistic. This allows the turnaround time for each combustor to be determined. Furthermore, the source can create entities based on a list or based on stochastics. In the case of the base model the source will create entities based on a list, which defines the time and date for each combustor arrival, and as such can mimic the actual arrival of the combustors as determined within the combustor maintenance data. For each combustor component the date at which it enters the combiner is tracked, this allows the end date for Z51 to be determined. The same can be done for components leaving the separator, allowing the start date for Z42 to be determined. However, the data for Z42 and Z51 start and finish is considered to detailed for the current scope.

Besides defining the TAT for each combustor and component, it is also possible to track the utilisation rates of both the mechanics and the capabilities. This can be done in Simio by using so-called expression labels which can show what the average utilisation has been for that server or mechanic throughout the model run. Simio allows expressions to be returned of values that are automatically tracked and generated during a model run. Furthermore, for each server the number of components in the queue can be shown both as a dynamic output during the model run or as a final result that can show the average, minimum or maximum number of components in the queue. The average time spent by the components in the queue can also be determined.

I.2.1. Run Length & Replications

The run length defines the time-period that the simulation spans. As the analysis of the combustor maintenance process has covered the 2014 data it would be logical to have the time-span coincide with this duration. However, the simulation run starts with an empty system, and in order for the model to properly reflect performance covering a year the pressure on the system (the components that require maintenance) should be realistic. As such the combustor will never enter an empty system, and there are always other parts present. Therefore the simulation run should start well before the first combustor of 2014 enters the system in order for other combustors to arrive and 'fill up the system' so to speak. The same goes for the combustors leaving the system. The last combustor that has entered the system in 2014 should not be the only combustor in the system after 1-1-2015. Therefore additional combustors have been added to the system arriving from 3-11-2013 until 13-2-2015. The model will run from 3-11-2013 until 1-4-2015 to ensure all combustors have been completed. However, it should be noted that combustor processing on 30-12-2013. This is later than the combustor arrival but as such the system performs most like the current state in 2014 during the model analysis of 2014. Utilisation rates of servers and workers are determined for 2014 only. Furthermore, as the model is deterministic the model only needs to be run once to generate the required data. Additional replications should (and do) lead to the same results.

I.3. Verification

Sargent [2005] has defined verification as ‘ensuring that the computer program of the computerized model and its implementation are correct.’ This means that the model does not contain errors and that it correctly carries out the process, which can be done by checking the logic and structure of the model. In the case of the combustor maintenance it should be checked to see if all the combustor maintenance tasks are performed in the correct sequence with the correct duration and that all combutor components are linked as specified.

The verification of the maintenance model has been a continuous and iterative improvement process to make a representative model. The data used as an input for the model is the data for combustor maintenance of 2014. As this data has already been thoroughly analysed the input data can be assumed to be correct. For each combustor the task sequence and duration is known along with the start date. By checking whether all these tasks are executed sequentially and the start date and task durations are as specified it has been verified that the model correctly processes the input data. In addition to this, the components of one combustor should be created on the same date and time, and should be correctly linked together so the model can create the correct batches before maintenance starts and when the combustor is reassembled. Furthermore, each component should follow its specified task sequence. This has been verified by first only processing a single combustor and checking if all components and tasks were correctly handled, and later several combustors were followed throughout their maintenance route whilst there were several combustors in the system to see if the correct components were combined and handled as specified.

Simio allows both servers and workers to be available for processing on a schedule basis. This should allow for a simulation of the working hours and available mechanics. As such neither the servers nor the mechanics should be able to perform work once the department is closed, or the mechanic is scheduled as not present. After finding out that this did not work as required, with mechanics working 30% of the time that they should be off-shift, it was determined that standard Simio behaviour is to have mechanics finish their task in overtime before actually leaving the server. In order to resolve this a so-called add-on process was added that allowed off-shift behaviour for the server, allowing it to reevaluate its activities whilst going off-shift. This process allowed the server to stop processing the ‘active’ component, release the required mechanic, record the remaining processing time, and to place the component into the server queue so that it can continue its process once a server and a mechanic are available again. As such all elements of the model are carried out by SIMIO correctly and without errors, and the model can thus be considered verified.

I.4. Validation

Having a verified model allows the model to be validated. The validation of a model according to Sargent [2005] is generally confirming that the computerised model ‘within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model’. This means that the outcomes of the model should be sufficiently accurate in order to determine the effects of changing the factors deemed influential to combustor maintenance. In addition to this the validity of the model regarding its possible predictive or planning value might be checked.

A frequently used approach is that of the team developing the model to decide whether or not the model is valid. In this case however, process experts have been consulted in order to deem the model fit for purpose. According to Sargent [2005] there are various methods that can be used to validate the model. Here the choice has been made to use historical data for the validation.

The historical data verification will be done by comparing the outputs of the model to the outputs of the current state analysis. The model is valid if the outputs of the model are within a reasonable range of the current state outputs. The outputs that can be compared are the total average TAT, the average TAT per combustor type, and the standard deviations for these values. Furthermore, the average utilisation rates of both the mechanics/workers and the capabilities/servers can be compared. TAT and utilisation rates will each be specifically discussed.

There are three basic approaches to compare the simulation model output to the actual current state performance according to Sargent [2005]. Namely the subjective use of graphs, or the objective use of confidence intervals, and the use of hypothesis tests. It is clear that the use of objective methods is preferable, especially due to the LSS approach this thesis aims to take, but this is frequently impossible due to insufficient available system data and/or the required statistical assumptions can not be satisfied. The TAT will be evaluated subjectively using 2-sample t-tests to determine if the data populations differ significantly. The 2-sample t-test uses a Student's t-distribution to perform a hypothesis test, in this case the hypothesis that the two means of the current state and the model are similar will be tested. According to Pyzdek and Keller [2003] 'the t statistic is commonly used to test hypotheses regarding means'.

The utilisation rates will be compared subjectively as there is too little data for statistical analysis, i.e. there is only one average utilisation rate output for both the servers and mechanics. In addition to this the model has been validated at face value, to see whether the model and its behaviour are considered reasonable. Each of the output types will be compared below. For brevity only two possible models are tested and discussed in depth. During the validation process many variables have been changed and tested, from available mechanics, capabilities and working hours, to processing sequences and priority rules. It has been found that the model is quite sensitive to changes regarding the processing sequences and priority rules, and as such these factors will remain as they have been defined in the validated model.

I.4.1. TAT

As TAT is the main KPI for combustor maintenance, the model's TAT performance is the most important factor for validation. The TAT performance of the model will be validated based on the 7B, 8C and 8E regular repair data. Other repairs such as Z03 and other components will be briefly discussed at the end of this section.

The mean and standard deviation of the model TAT for all combustors should be as close to reality as possible. First the data will be graphically assessed using a histogram, and probability plot to see if the data is visually similar. If this is the case, a 2-sample t-test will be used to determine if the average difference between the current state and model data is significantly different or due to random chance. The model will be considered valid if the means do not differ. All tests will be performed using Minitab.

In total 101 combustors have been processed by the combustor department and the model throughout 2014. Figures I.4 and I.5 show how the two data sets are distributed. As can be seen in the histogram the model does not completely fit the current state. The histograms largely overlap, and at first glance their centres and variablity seem similar, but the model shows a higher TAT more frequently than the current state, and the current state is more frequently lower. Furthermore, the maximum TAT of the model is lower than the current state. The probability plot shows that the two data sets are quite similar and that there are no real outliers. The current state shows an average TAT of 41.01 days with a standard deviation of 11.12. The model mean is 41.89 and standard deviation is 9.08. As such the model output seems to reproduce the current state sufficiently for the purpose of monitoring the influence of value drivers. It should be noted that even though the distribution of the current state is not normal (as can be seen by the p value that is >0.05) it is still possible to perform a 2-sample t-test as the distribution is not highly skewed.

In order to completely validate the model the means are compared using a 2-sample t-test in Minitab. The p-value is 0.538, this is larger than the 0.05 level of significance, and therefore the means do not significantly differ. As such the model can be considered valid. Furthermore, the 95% certainty interval, which is associated with estimating the difference in means from sample data, shows that the true difference in means is between -3.70 and 1.94. This means that if the experiment were repeated it can be said there is a chance of 95% that the found mean will lie within this range of the current state mean.

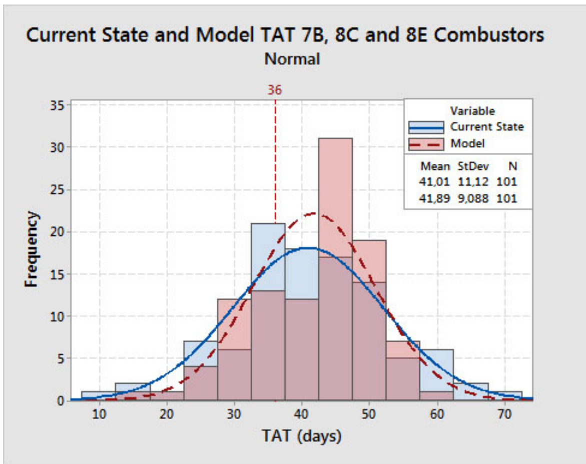


Figure I.4: Histogram of Current State and Model TAT

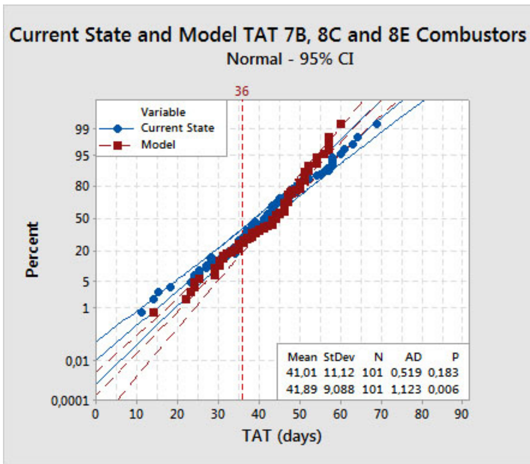


Figure I.5: Probability plot of Current State and Model TAT

As the current state and model for all combustors are not extremely similar it may be investigated how well the model performs for each combustor type. Appendix J shows the histograms and sample t-test outcome summaries for each of the combustor types. Visually the combustor histograms are deemed valid, as they all show the same centre and roughly the same variability. However, the 7B model histogram lower TAT is more to the right of the current state lower TAT. For the 8C combustor the highest model TAT is to the left of the highest current state TAT. And for the 8E combustor the histogram has a lower variability than the current state.

For the 7B combustor the current state mean is 43.89 days with a standar deviation of 9.108 and the model mean is 44.74 with a standard deviation of 8.032. According to the 2-sample t-test the means do not differ significantly as the p-value is 0.717. The 95% confidence interval lies between -5.54 and 3.84 and as such the model can be validated regarding the 7B combustor TAT.

For the 8C combustors the current state mean is 40.16 with a standard deviation of 12.64, the model mean is 40.49 with a standard deviation of 10.21. The 2-sample t-test produces a p-value of 0.882 meaning the means do not significantly differ. Finally the 95% confidence interval lies between -4.67 and 4.02. As such the model is also considered valid regarding the 8C combustor TAT. Furthermore, the model has the closest approach to actual performance for this combustor

Finally the mean for the current state 8E combustor TAT is 39.37 with a standard deviation of 8.408, this is 41.89 and 5.877 for the model TAT. This is the largest difference within the combustor data-set. However, the 2-sample t-test shows a p-value of 0.291 and as such the means do not significantly differ, however it should be noted that the dataset is quite small (19, where the minimum requirement is 15). Therefore it is possible that the results are not entirely accurate. The 95% confidence interval lies between -7.32 and 2.27. As such the model can also be validated for the 8E combustor TAT.

The data for Z03 repairs, HPC stator and Coffee-can repairs is also available. The histograms showing the performance are found in Appendix J in Figures J.8, J.9, and J.10. It has been found that these components are maintained much faster in the model than in reality. The HPC stator and Coffee-can repairs are carried out mainly in external departments and have mainly been added to the model to properly simulate the load they impose on the system. As such it is not important for the model validation if these repairs are carried out according to reality. Furthermore, as these components are mainly repaired externally it is likely that the external repairs are not correctly simulated, and that this causes the shorter maintenance time. It is therefore recommended that the external departments are more closely modeled during further research.

I.4.2. Mechanic Utilisation

The model that has been validated regarding TAT does not contain the available mechanics and capabilities as they were present and available in reality during 2014 as this did not generate the required TAT. Instead the availability and capabilities of the workers are modelled according to the average availability and capabilities in 2014. There are 7 capabilities that not all mechanics can perform, Table I.2 shows which mechanic has each of these capabilities. Furthermore the table shows during which shift each mechanic is available.

Table I.2: Base Model Worker Capacity and Shift

Worker	Q034	Q683	Q033	Q114	Q502	Q682	Q516	Shift
1	x	x		x				M
2					x	x		A
3	x	x	x					M
4							x	A

As the mechanics are not simulated like the current state the mechanic utilisation can not be directly used to validate the model. However, as can be seen in Table I.3, the average work performed daily in both the current state and the model is very similar, and shows only 2.5% difference. As the average work performed daily is so similar it is possible to consider the model valid on this point.

Table I.3: Current State and Model Comparison Regarding Daily Available Mechanics and Capacity

	Current State	Model
Available Mechanic	7.4	4
Available Hours	55.6	30
Utilisation Rate	52%	97%
Work performed (hours)	28.3	29.0

Taking into account the utilisation rate and available mechanics and hours it can be said that the workers in the model are almost twice as productive as the mechanics. And as such one worker in the model may represent two mechanics in the current state. This is not relevant for the validation, however it is important to keep this in mind whilst designing a future state as this means that either mechanics should become more productive, or the number of mechanics required by the model should be adjusted to fit the productivity level of the required mechanics.

During the process of validation a test scenario similar to the validated model was generated that used the actual available mechanics and their capabilities. This model generated a lower average TAT performance, but had a much larger variance, and as such was not validated (see Figures I.6 and I.7). However, as shown in Table I.4 the number of mechanics available and the average work performed per person are similar, and only differ by 5.6%. From this output it can be concluded that the model can correctly simulate mechanic availability and performance.

Table I.4: Current State and Test Comparison Regarding Available Mechanics and Performed Work

	Current State	Test Model
Total Available Mech	49	49
Average mechanics per day	7.4	7.8
Productive Hours	7.5	7.5
Work performed (hours)	28.3	31.4
AverageUtilisation	52%	41%
Work per person	3.8	4.0

If the test model can correctly simulate mechanic availability and performance it is strange that the

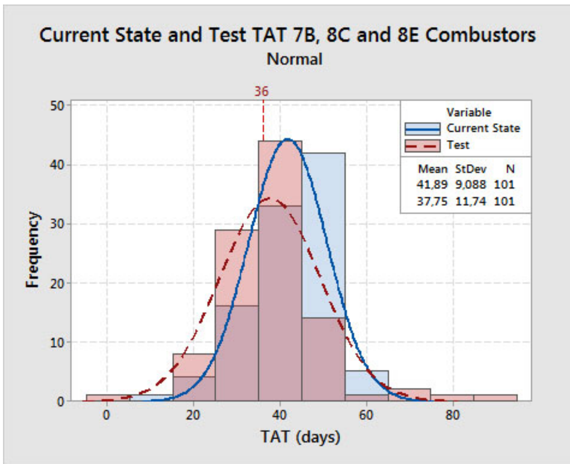


Figure I.6: Histogram of Current State and Test Model TAT

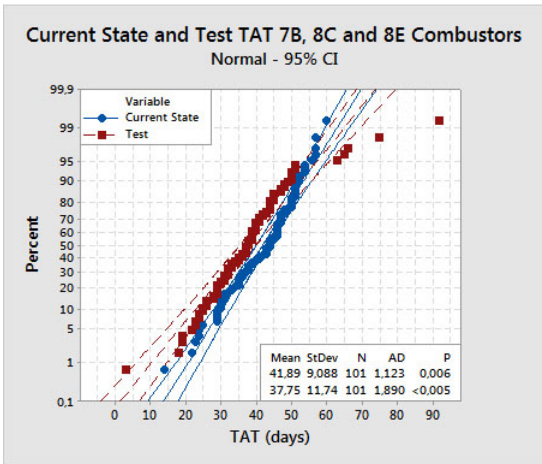


Figure I.7: Probability plot of Current State and Test Model TAT

average TAT is lower than the current state average, and that the variability of the test TAT is larger. The lower average TAT is likely to be caused by the higher efficiency of the mechanics. This sounds strange as the work per person is similar for both current state and the test model. However, there is a limit to the available work, and once all work has been done the system will be empty until new work arrives. Regardless of the efficiency the total work performed on average will be the same for equal inputs over the same time-span. It is therefore possible that the test model completes work at a higher rate, leading to a a lower TAT and a system that is more frequently empty, whilst still maintaining the same work performed on average per person as in the current state.

The large variability is possibly due to required capabilities not being present. As this is all predefined and rigid it is not possible, as would be in reality, to flexibly solve the problem of a component having to wait a long time. Mechanics from other departments might be called in or the component might be outsourced.

I.4.3. Server Utilisation

The server utilisation is a measure of how many hours of work have been performed on a specific capability compared to the available working time (7.5 hours per shift). During the analysis it was found that for 7B combustor repairs 27% of the total normative time was required for Q034, 19% for Q683 , and 42% for Q702. However, the model does not only process 7B combustors, and the output does not allow for the distinction between times spent by the server on different combustor types. Therefore, the model can not be validated by comparing the current state data to the model output.

This does not mean that the required capabilities are carried out differently by the model than in the current state, and that the model is invalid on this point. The two can simply not be compared using the analysis data. Knowing that the servers only carry out the tasks allocated to them from the input list using the normative process time it can be assumed that the model will produce the same outputs as defined by the input. Furthermore, Table I.5 shows the utilisation rates per server. As can be seen in the model Q034, Q702 and Q683 are also the capabilities that are most frequently required.

Table I.5: Utilisation Rates per Server

Server	#	**Q029**	**Q033**	**Q034**	**Q071**	**Q100**	**Q114**	**Q116**	**Q224**	**Q244**
Utilisation Rate	7%	0%	0%	100%	14%	1%	38%	22%	5%	10%
Server	**Q254**	**Q434**	**Q502**	**Q516**	**Q682**	**Q683**	**Q685**	**Q702**	**Q800**	**Q801**
Utilisation Rate	1%	1%	24%	0%	1%	61%	1%	93%	0%	0%

I.5. Sensitivity Analysis

The Base scenario, which has been discussed as the model for validation before, is built to represent the current state performance as closely as possible. However, the current state performance is far from ideal. Therefore it is relevant to know if it would be at all possible for the model to simulate an improved process. Sensitivity analysis, according to Saltelli et al. [2008], 'is the study of how uncertainty in the output of a model can be attributed to different sources of uncertainty in the model input'. As such, the input parameters are varied where possible in order to demonstrate the relative influence of the input on the outcome of the model.

Most frequently sensitivity analysis is carried out using the one-at-a-time (OAT) method. In this method all parameters are kept constant, and changes are made to one parameter at a time to see the influence this parameter are on the model outcome. However, the downside of this method is that does not show how the factors interact. In order to find out how this occurs the factors should be changed simultaneously [Kleijnen, 2005]. Both Kleijnen [2005] and Saltelli [2002] suggest that OAT is not an ideal method. However, for the purpose of creating an understanding of the simulation model as used here OAT is deemed sufficient to explore the influence of variables.

During the model validation many changes to the model have been made in order to realise a TAT that was as close to reality as possible. Simio allows a wide range of variables to be defined and changed. In order to define a base case these variables have been changed and tested in order to fit the current state as well as possible. During these tests it was found that the model is highly sensitive to changes, as even a small change has a direct effect on TAT. This is mainly due to the maintenance process, as each time a task is completed a mechanic makes a choice which component will be handled next, and the consequence is that each part that is available but is not handled directly incurs waiting time. Depending on the choices mechanics make the TAT for each component, and in turn each combustor are influenced. The same occurs within the model.

The sensitivity analysis can be carried out both structured and iteratively. Whilst developing the model many of the variables within Simio were changed and tested in order to come to the best fit Base model, this was mainly an iterative process. It has been found that changes to the way servers and mechanics rank the components in the queue regarding which component will be handled first has an influence on TAT that can not be ignored. The same is true for the way priority is used, and the sequence in which mechanics are 'requested' to the server. However, these factors are not within the scope of analysis and as such have been changed only to realise the best possible match between the base model and the current state. For the base model, and all tests performed regarding sensitivity to value driver changes the ranking has been kept the same. All servers handle components based on a dynamic ranking in which the smallest priority value is handled first. The priority value has been defined as the due date, and as such the server handles components based on which component should be completed first. In the case of servers requesting mechanics this is done based on which capable mechanic is closest to the server.

However, the purpose of this sensitivity analysis is to define the sensitivity of the system rather than the model with respect to variable changes. The input variables that will be investigated are listed below.

- Mechanics:
  - Availability(amount and times)
  - Capabilities
  - Dedicated to a capability
- Server capacity
- Combustor arrival times
- Combustor repair routes

Changes to each of these variables have been investigated. The different scenarios and parameters for variable changes are listed in Appendix D, and the TAT results of each scenario can be found in

Appendix K. The most influential changes will be compared regarding the average combustor TAT using bar charts to visualise the relative difference.

I.5.1. Capacity

This section will discuss the model sensitivity to capacity changes regarding the available mechanics, but also regarding the server capacities. It should be noted that the 2400 department server capacities are limited to 1. It is expected that increasing this capacity will allow TAT to be further reduced. However, it has not been possible to test this in combination with the add-on processes that are used to disable mechanic off-shift working. This is a limitation to the current model. Further research might look into adding this possibility to the model, and testing the effects. All tests have been performed using the validated model as the base. The main point to which changes are compared is marked in red in each of the graphs.

First of all the sensitivity regarding working days has been tested. This has been done in order to see how much effect changes regarding the workdays of the combustor department has, and how much effect this would have if it were changed for the external department. As can be seen in Figures I.8 and I.9 reducing the number of workdays has a much larger effect than adding workdays. As expected, due to the focus on combustor maintenance activities, the external department working days have less influence on the average TAT than changes to the workdays within the combustor department. Reducing the 2400 shop opening hours to three days per week causes an increase of TAT of 1018% or 291 days. Whereas a 7-day workweek reduces TAT by 59% or 17 days. For the external department changes lie within a 425% increase in TAT for 2 workdays, and a 0% reduction for 7 workdays.

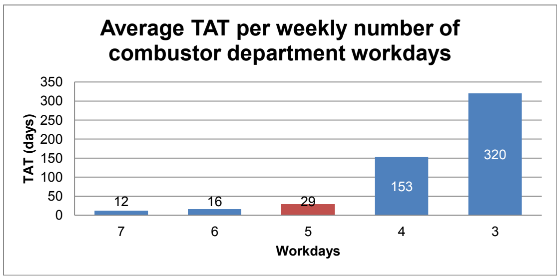


Figure I.8: Average model output TAT for combustor department workdays

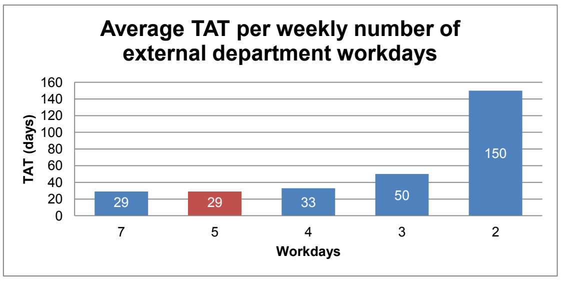


Figure I.9: Average model output TAT for external department workdays

Figure I.10 shows how changes to the external capacity influence TAT. The starting point is a capacity of 1, and increasing the capacity has a maximum influence of 5%, which is achieved at a capacity of 6 mechanics and up. The findings regarding the external capacity are relevant as they show that the influence of the external department as modelled are relatively small. This means that process performance as modelled is mostly dependent on variables within the combustor department. For the purpose of the model this is a positive outcome, as this means that it has been correct to focus on the activities within the combustor department regarding process improvement. However, to see if the influence of the external departments is actually as limited as found from this model the model could be expanded to better represent the external departments and activities.

To see how influential mechanic capacity is this has been tested in the model using multi-skilled mechanics that are capable of performing all required capabilities. Figure I.11 shows the results. It should be noted that the red bar is set at a capacity of 4 mechanics, as in the base. However, in the base model the mechanics do not have all capabilities, and as such generate a different TAT. It is interesting to note that for 4 multi-skilled mechanics the average TAT is 31 days, whereas this is 28.5 days for the base, a difference of 9%. This indicates that limiting the available capabilities has a positive influence on TAT. This will be further investigated later.

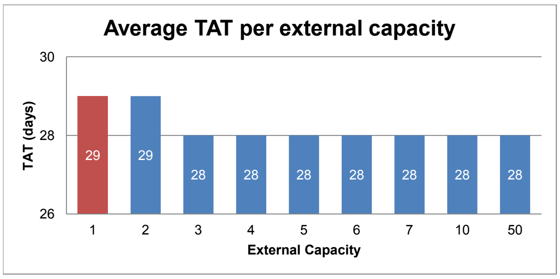


Figure I.10: Average model output TAT for external department capacity

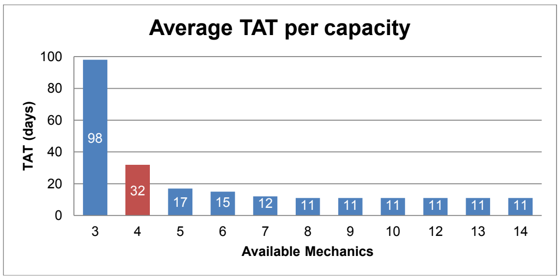


Figure I.11: Average model output TAT for capacity of multi-skilled mechanics

As can be seen the capacity shows a variable TAT between 3 and 8 available mechanics per day. Introducing more than 8 mechanics has very limited effect on TAT. Between 8 and 14 mechanics there is a different value for the average TAT, but this difference is negligible (about half an hour). The difference in averages might be caused by the sensitivity to which mechanic is available when, and who is closest to the server requesting a worker. The total TAT differences are an increase of 214% for a reduction of 1 mechanic, whereas from 8 mechanics onward the TAT reduction is 65%. As such the mechanic capacity has quite a large influence on TAT.

Considering these averages it could be concluded that the combustor department requires at least 5 multi-skilled mechanics to generate an on-time performance of 100%. The TAT for this scenario will be further investigated in order to determine if this is the case. As the base TAT is lower than the TAT for 4 multi-skilled mechanics it is interesting to investigate how changing the available capabilities and 'focus' might further reduce TAT whilst using a capacity of 4 mechanics. It is possible that this might also generate a 100% on-time performance.

I.5.2. Capabilities

As the capabilities have been defined as value drivers, their influence on TAT must be investigated. The research has focussed on Q034, Q683 and Q702. As the first two required capabilities are limited the effect of their availability should be tested. First the separate influence of each of these factors will be investigated, after which combinations will be analysed.

Using a constant capacity of 4 multi-skilled mechanics as a base for comparison something interesting can be seen to happen in Figure I.12. In these scenarios the mechanics are not dedicated to carrying out Q034 tasks, in other words: mechanics that perform inspections also have to perform other tasks. Having all mechanics capable of performing Q034 tasks results in a higher TAT than having 2 or 3 mechanics perform Q034 tasks. Both show a TAT reduction of 10% whereas having only 1 mechanic capable of Q034 results in an increase of 246%. The high influence for only 1 capable Q034 mechanic is expected. The reduced TAT for 2 and 3 mechanics is not. An explanation might be that when reducing the pool of mechanics that can perform Q034 tasks the capacity to perform other capabilities becomes larger, and thus allows the other tasks to be carried out more efficiently. The average TAT for 2 mechanics is a bit lower than for 3 mechanics which seems to fit in with this argument. However the difference is almost negligible and therefore further research into the available and required Q034 capabilities is suggested.

As the previous scenarios tested mechanics that performed tasks of all capabilities the effects of having dedicated Q034 mechanics have been investigated. A dedicated mechanic as used in this context is a mechanic that can only perform Q034 tasks. By doing so, as can be seen in Figure I.13, the TAT increases as the number of dedicated mechanics increases, first with 77% and then 282%. This is easily explained by the fact that Q034 tasks are not always available, and that whilst optimising the performance for Q034 tasks the capacity for other tasks is vastly reduced. The model shows that it is very sensitive to these changes, but these test results also show that it is completely unrealistic to have Q034 mechanics focus solely on inspections (as would be the case if it were up to the inspectors).

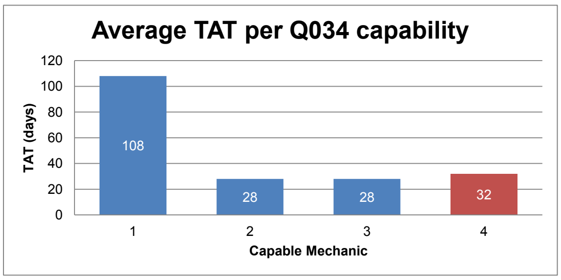


Figure I.12: Average model output TAT for Q034 capabilities

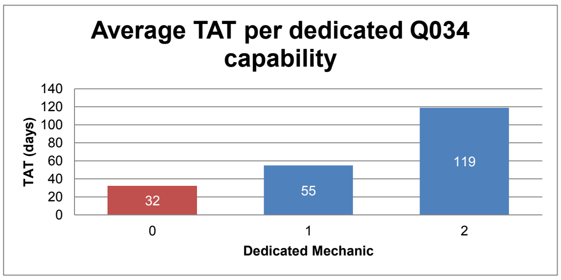


Figure I.13: Average model output TAT for dedicated Q034 capabilities

As having dedicated inspectors has a negative effect on TAT, and having all mechanics capable of inspections it has been investigated what would happen if Q034 tasks were prioritised over other tasks. It was found that, using the standard simio priority rules, the average TAT increased. It is likely that this is because the rules only apply after a task and/or mechanic becomes available whilst it should be possible to anticipate on Q034 tasks and for mechanics to refuse requests for other capabilities in order to optimise TAT. However, as it is the prioritisation of Q034 tasks is considered a limitation to the model, and is a point that is recommended for further research.

Performing the same analysis for Q683 tasks the TAT and graphs show similar results. Reducing the overall Q683 capabilities also shows a positive effect at first after which a negative effect is seen. However the differences are much smaller, a reduction of 1% for 3 mechanics, 3% for 2 and 21% for 1 mechanic. As such the Q683 capabilities can be considered to be less influential to TAT.

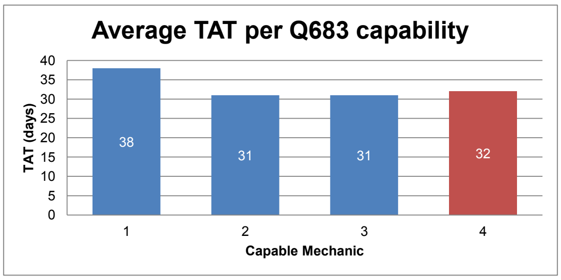


Figure I.14: Average model output TAT for Q683 capabilities

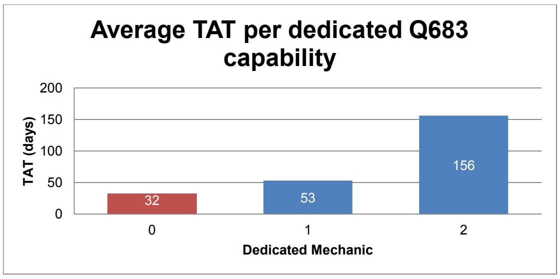


Figure I.15: Average model output TAT for dedicated Q683 capabilities

The influence of dedicating mechanics to Q683 tasks has a relatively large effect on TAT. Dedicating one mechanic causes a 70% increase in TAT whereas dedicating 2 mechanics shows an increase of 402%. This is in line with what has been observed for Q034 mechanics. The larger influence can be explained by the fact that there are fewer Q683 tasks and less time is required for these tasks. As such a larger share of the ‘would be’ available system capacity is wasted.

It can be concluded that from the two required capabilities Q034 has a larger influence on TAT. However, the balance of these available capacities should be investigated. Furthermore, in order to improve TAT mechanics should not be dedicated to one capability alone.

The various combinations of Q034 and Q683 capabilities can be found in the Scenario Information section of Appendix D. As can be seen in Figure I.16 only set P and Q realise a smaller TAT than the base scenario in which, aside from 2 mechanics capble of both Q034 and Q683, for each of the 5 other required capabilities with a limited available capacity there is only one mechanic capable. Scenarios M to O vary between two mechanics capable of Q034 and/or Q683. In set P a third mechanic capable of Q034 is added, for set Q a third Q683 capability is added. As the Q034 capability has been defined as most influential it is logical that set P realises the largest decrease in TAT of 6%. Set N causes the largest increase in TAT with 13%. However, these percentages are larger if the sets were to be compared with multiskilled mechanics. That being said it can be concluded that the exact capability set is not highly influential to TAT as changes to the basic set do not greatly increase or reduce TAT.

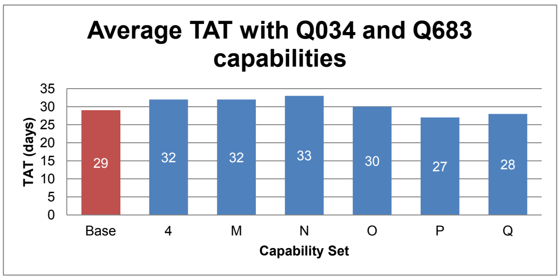


Figure I.16: Average model output TAT for combinations of Q034 and Q683 capabilities

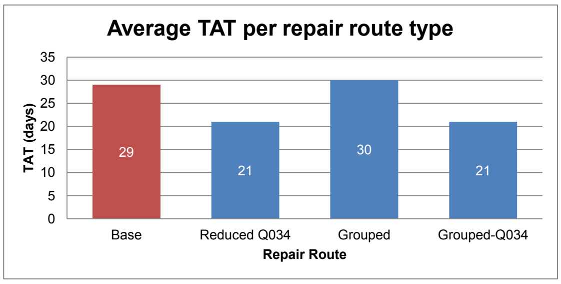


Figure I.17: Average model output TAT for adapted repair routes

I.5.3. Routing

Another factor that was deemed influential to TAT was the repair route, and two suggestions to improve the route have been made. Namely, reducing inspections during the repair route (i.e. removing the inspections that take place during phase Z51, but leaving the inspections during the other phases and at the start and end of Z51), and grouping tasks that require the same capability. It has been found that reducing inspections reduces TAT by 27%, whereas grouping tasks increases TAT by 5%(see Figure I.17. However grouping tasks within the reduced Q034 route seems to show the largest TAT reduction, namely of 29%. It is very logical that reducing Q034 tasks reduces TAT as there are many Q034 tasks, and removing these tasks not only directly reduces the total required maintenance time, but it also reduces pressure on the Q034 required capability. Grouping tasks was believed to reduce TAT as this reduces changeover time between combustor components. However, as the model shows this is not the case. This can be either because the model is more efficient than the actual mechanics in deciding which task to do when and changing over, or because grouping tasks has the long term effect of increasing waiting time for other components. It is very likely that a combination of both is the case, and the cause might be investigated in further research. As the combined grouped and reduced Q034 route does not differ greatly from the reduced Q034 route it is worth investigating the effect both options have on the improved route. It can be concluded that the Q034 changes to the repair route have a significant influence, but grouping tasks does not.

As mentioned during the process analysis, combustors do not arrive at regular intervals. As such it is very likely that the arrival times and rates of combustors will be different in the future. As such it is relevant to know not only how sensitive the model or system is to changes in arrival times, but also to know how if the system could cope with many combustors arriving simultaneously or combustors arriving at regular intervals. The scenarios are mentioned in Table D.11. As Figure I.18 shows the TAT changes for each arrival change. As such it can be said that the model is very sensitive to changes in combustor arrival. Furthermore, the scenarios tested all cause the average TAT to increase between 2% and 37%. It is quite surprising that scenarios B and C cause the highest increase in TAT as these scenarios have the most constant and distributed combustor input. Therefore, it can be concluded that the system is very sensitive to combustor input, and it is recommended that these effects are studied further using more scenarios and looking into how the combustors should be prioritised.

I.5.4. Combined Effects

Finally Figure I.19 shows what happens to TAT if the best performing capability set and changes to the route are combined. As can be seen the reduced Q034 and grouped and reduced Q034 routes are again similar, and the TAT is reduced even further than when each set is tested individually. However, in this case the grouped Q034 route has a 1% larger average TAT. As such it can be concluded that improving TAT by only reducing Q034 tasks suffices. Finally the combination of capability set P and

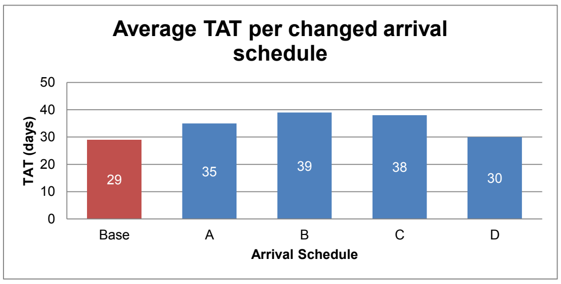


Figure I.18: Average model output TAT for adapted combustor arrival schedules

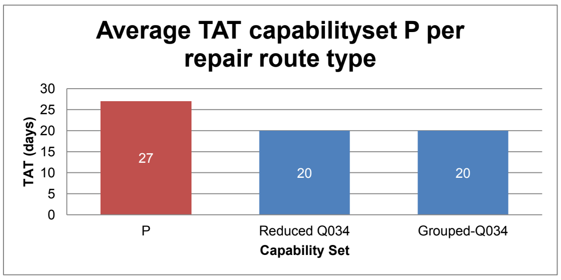


Figure I.19: Average model output TAT for capability set P and adapted repair routes

reducing inspections leads to a TAT reduction of 31% compared to the base scenario. As such this combination might sufficiently improve TAT with the currently available mechanics. This will be further analysed whilst generating an ideal future state.

I.6. Conclusion

In conclusion it has been found that the Base model can correctly represent the current state of the combustor maintenance process at KLM E&M ES. It has been found that a constant capacity of 4 mechanics with a specific set of capabilities better represents the current state than using the mechanics and capabilities that were actually available on a daily basis. This is likely due to the match between supply of tasks and demand for capabilities. Furthermore, by performing a sensitivity analysis the sensitivity of the model to input variables has been tested. It has become clear that the model is very sensitive to changes, as even the slightest change in variables results in a change in the average TAT output. However, this is expected to be the same in reality as well.

Furthermore, it has been found that the department capacity has a large influence on TAT, both regarding the available mechanics and the working days. The latter is especially influential if the working days are reduced, increasing them has a relatively small effect. Furthermore, increasing the available mechanics has very little effect from 8 mechanics onward.

The available capabilities also influence TAT, even though the system is less sensitive to capability changes than to capacity changes. It has been found that having mechanics dedicated to one specific capability has a very large negative influence on TAT, but that reducing the available capacity for a specific capability first reduces TAT after which TAT increases. This effect is larger for Q034 than for Q683. Furthermore, changing the specific capability set has been found to influence TAT even though the difference is not very large.

Routing has also been found to influence TAT, although other route changes should be tested to correctly identfy the influence. It has been found that grouping tasks has a negative influence on TAT, and that reducing Q034 tasks has a positive effect on TAT. The latter effect is mainly due to the reduction of maintenance time, but nonetheless it is a factor to consider whilst looking to improve TAT. The combustor arrivals as such are not directly part of routing, however they do influence the planning of which task should be completed when. It has been found that the system is sensitive to changes regarding combustor arrivals, and that a frequent constant arrival has a negative effect on TAT. However, combustor arrivals should be tested more into depth in order to be able to reach a definitive conclusion on this topic.

Finally combinations of routing improvements and capability set P have been tested. And it has been found that changing the capability set in combination with reducing inspections might sufficiently improve TAT so that it is not necessary to add an additional mechanic.

J

Model Validation Graphs

This appendix contains all the graphs and statistical test outcomes used for the maintenance model validation.

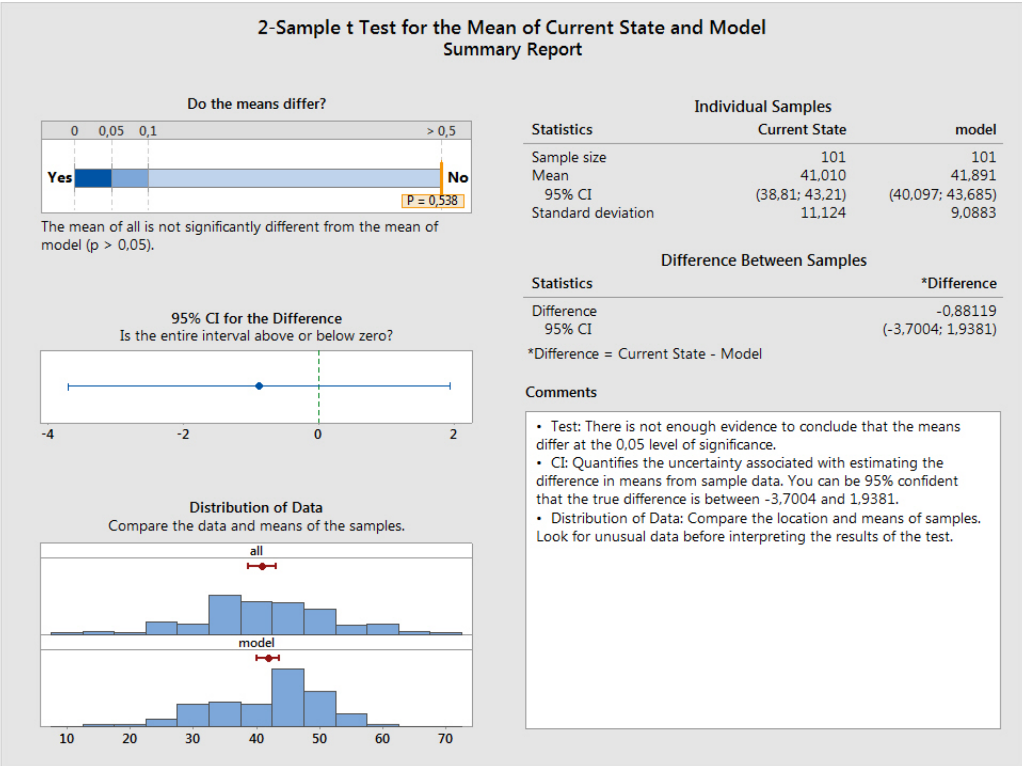


Figure J.1: Sample t-Test Outcome Summary Current State and Model Combustor TAT

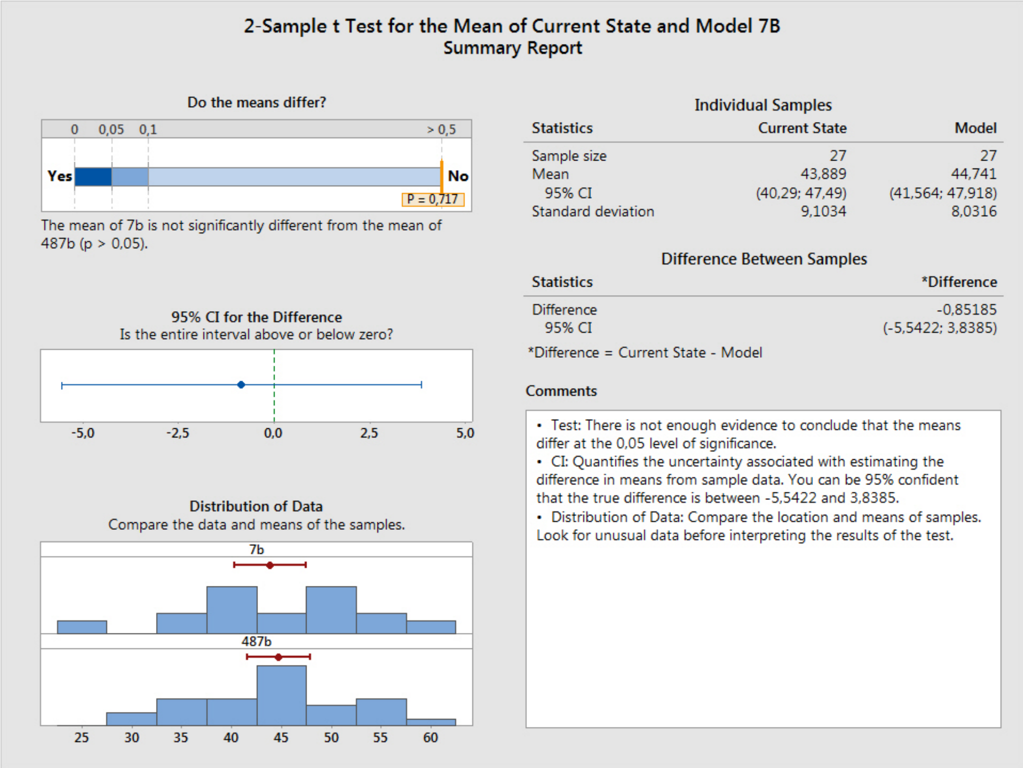


Figure J.2: Sample t-Test Outcome Summary Current State and Model 7B Combustor TAT

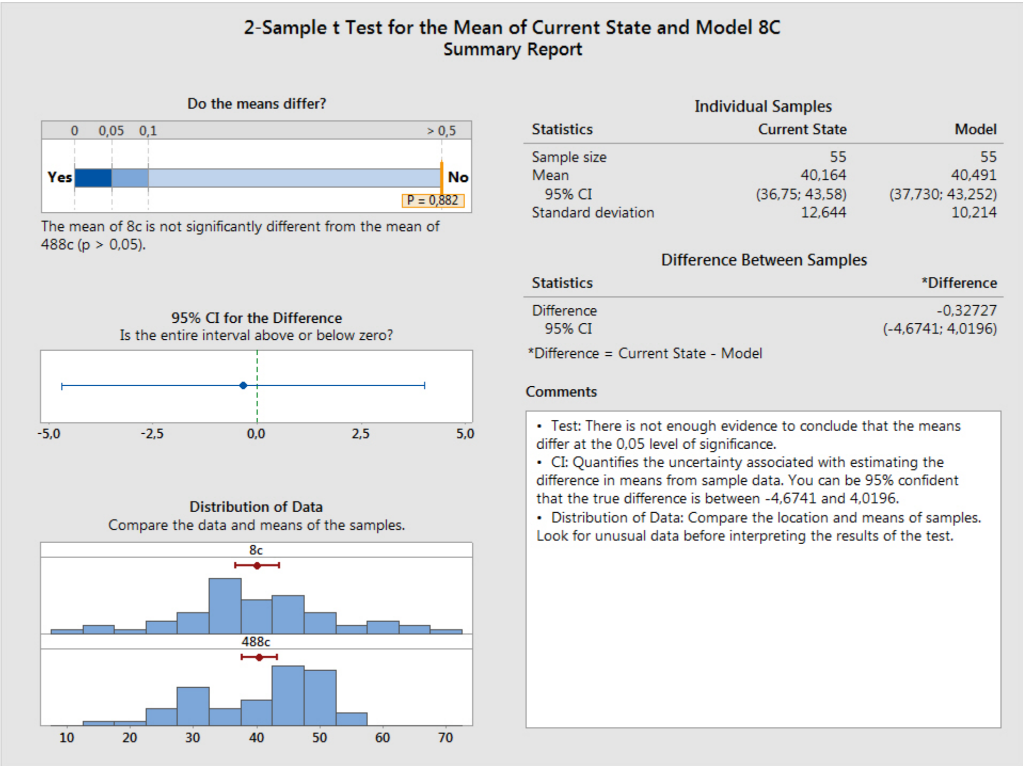


Figure J.3: Sample t-Test Outcome Summary Current State and Model 8C Combustor TAT

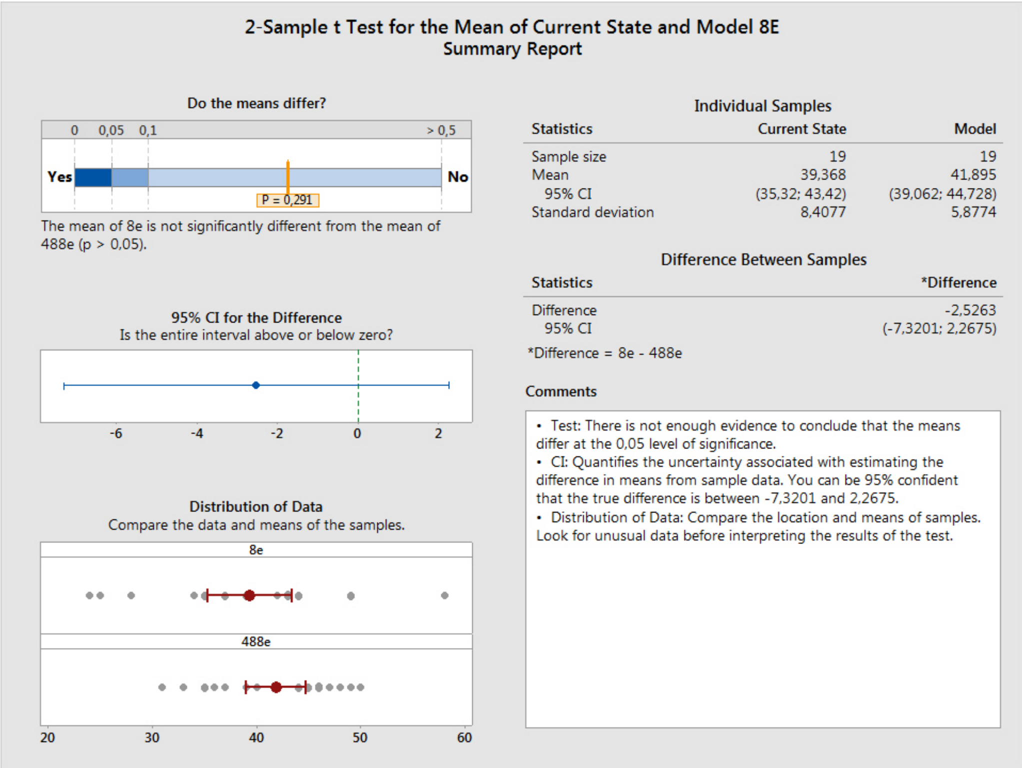


Figure J.4: Sample t-Test Outcome Summary Current State and Model 8E Combustor TAT

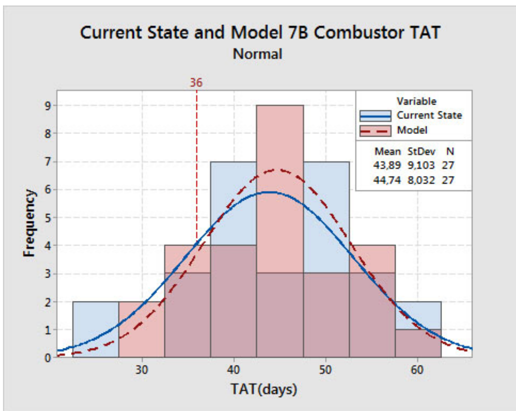


Figure J.5: Histogram of Current State and Model 7B Combustor TAT

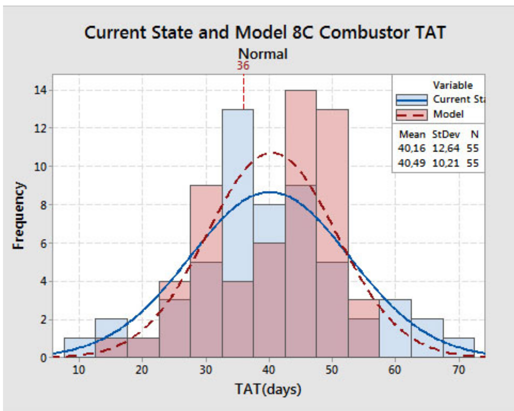


Figure J.6: Histogram of Current State and Model 8C Combustor TAT

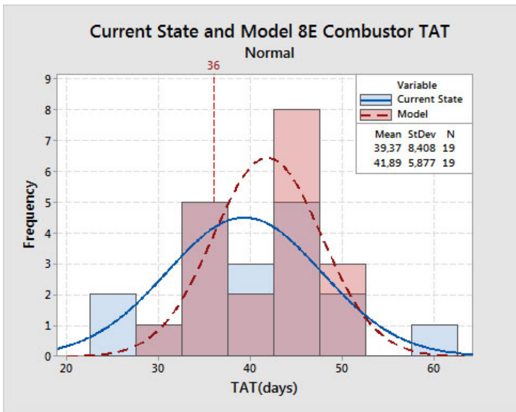


Figure J.7: Histogram of Current State and Model 8E Combustor TAT

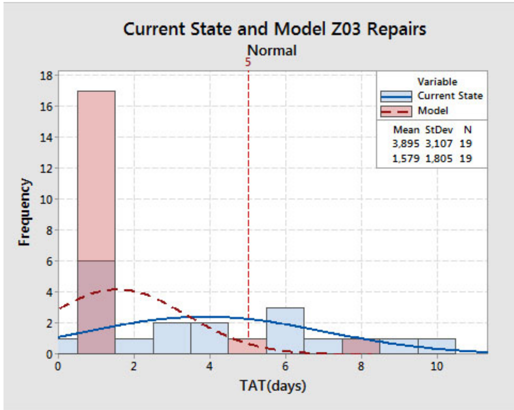


Figure J.8: Histogram of Current State and Model HPC Stator TAT

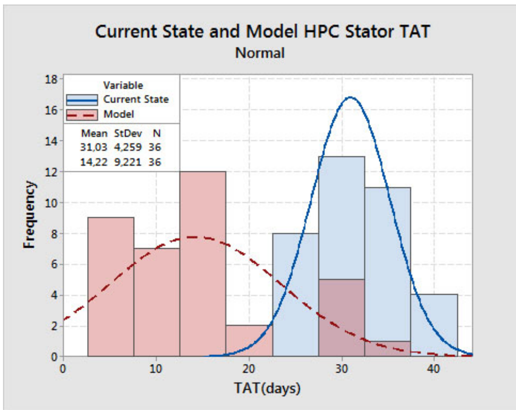


Figure J.9: Histogram of Current State and Model HPC Stator TAT

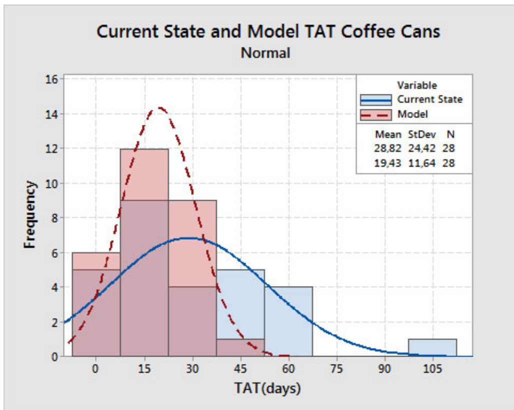


Figure J.10: Histogram of Current State and Model Coffee-can TAT

K

Sensitivity Analysis Output

This Appendix lists the TAT per combustor for each of the scenarios tested during the sensitivity analysis.

Table K.1: Model TAT output (days) per scenario 1a

Comb	Base	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
7B-169363	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-169366	47	47	45	45	45	45	45	47	54	65	59	31	31	31	5	5	5	44	19
7B-171379	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-171814	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-172459	34	31	31	31	31	31	31	35	38	43	59	45	45	45	6	6	8	29	21
7B-172469	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-172922	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-173055	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-173332	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-174790	42	43	41	41	41	41	41	42	43	51	59	43	42	42	7	7	7	38	20
7B-175333	47	47	43	43	43	43	43	44	47	58	57	34	34	34	7	7	7	40	19
7B-176124	47	46	47	47	47	47	47	50	51	65	58	26	26	29	5	5	5	44	18
41933078	30	29	29	29	29	29	29	29	24	19	45	19	18	19	1	1	1	33	11
7B-176503	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-176822	5	1	1	1	1	1	1	4	1	4	1	1	1	1	1	1	1	1	1
7B-176828	52	50	52	52	52	52	52	54	58	65	58	25	25	25	5	5	5	46	18
7B-176861	1	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1	1	1	1
41953805	22	29	31	31	31	31	31	23	24	46	24	3	2	2	1	1	1	29	2
7B-177542	8	5	5	5	5	5	5	2	4	1	1	1	1	1	1	1	1	1	1
7B-178403	51	50	49	49	49	49	49	54	58	79	54	21	21	21	7	7	7	49	19
7B-178048	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-180314	57	57	53	53	53	53	53	58	60	80	47	9	9	9	5	5	5	50	16
7B-180318	54	52	54	54	54	54	54	57	60	79	47	9	9	9	5	5	5	51	17
42021093	31	32	31	37	37	37	37	17	38	59	10	2	1	1	1	1	1	36	9
7B-181062	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-181541	46	45	46	46	46	46	46	47	51	67	36	8	5	5	5	5	5	43	8
7B-182310	43	47	46	43	43	43	43	47	48	63	33	11	8	8	6	6	6	42	15
7B-182576	46	46	45	44	44	44	44	46	50	73	32	11	10	10	5	5	5	43	17
7B-182864	36	37	36	36	36	36	36	39	39	60	25	8	8	8	7	7	7	32	9
7B-184359	40	40	40	40	40	40	40	44	47	67	24	8	8	8	5	5	5	39	10
7B-184522	43	44	45	47	47	47	47	44	52	73	18	9	8	8	5	5	5	43	18
7B-184762	44	44	43	40	40	40	40	46	47	72	24	8	8	8	5	5	5	43	11
7B-185456	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-186117	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41990024	10	11	12	17	17	17	17	16	17	37	2	1	1	1	1	1	1	15	1
7B-186811	32	28	33	32	32	32	32	34	39	54	11	7	7	7	7	7	7	28	8

Table K.2: Model TAT output (days) per scenario 1a continued

7B-187335	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-187348	35	36	36	37	37	37	37	36	42	62	14	9	8	8	7	7	7	34	13
42022391	40	35	34	40	40	40	40	42	36	63	21	8	8	8	1	1	1	49	19
7B-187640	51	51	54	54	54	54	54	55	55	78	27	15	14	14	6	6	6	54	26
7B-188048	38	39	38	39	39	39	39	39	46	66	17	11	10	10	5	5	5	36	16
7B-188112	37	37	36	37	37	37	37	38	43	60	15	9	8	8	3	3	3	37	16
7B-188641	39	40	43	43	43	43	43	43	50	67	18	12	10	10	5	5	5	39	18
42016949	32	28	28	14	14	14	14	20	43	68	19	8	8	8	1	1	1	42	18
42016957	32	28	28	14	14	14	14	21	43	68	19	8	8	8	1	1	1	42	18
42016958	33	28	28	15	15	15	15	21	43	69	19	11	8	8	1	1	1	42	18
7B-189699	56	56	57	56	56	56	56	58	60	87	23	8	8	8	4	4	4	59	23
42038682	10	4	23	8	8	8	8	16	26	79	3	5	8	8	1	1	1	37	4
42038683	9	4	23	8	8	8	8	16	26	79	3	8	8	8	1	1	1	32	4
42038685	10	4	23	8	8	8	8	16	26	72	3	2	5	5	1	1	1	32	2
8C-165302	23	23	22	22	22	22	22	23	23	27	57	43	43	43	1	1	1	28	15
8C-171235	14	14	14	14	14	14	14	15	16	33	50	41	41	41	2	2	7	15	9
8C-171590	24	23	22	22	22	22	22	24	24	38	53	40	40	40	3	3	5	19	12
8C-171591	46	46	46	46	46	46	46	51	51	59	51	17	18	18	5	5	5	43	15
8C-172061	30	33	30	30	30	30	30	30	34	41	57	44	44	44	5	5	5	28	19
41898510	4	1	1	1	1	1	1	3	11	22	46	39	42	39	1	2	8	11	9
41898647	4	1	1	1	1	1	1	3	7	21	17	39	39	39	1	2	8	3	8
41898653	5	2	1	1	1	1	1	4	12	22	47	40	40	40	1	2	9	11	9
8C-172574	30	30	34	34	34	34	34	29	34	43	58	44	44	44	3	3	6	29	17
8C-172987	24	22	24	24	24	24	24	24	26	37	54	44	44	43	4	4	8	22	15
8C-173014	25	26	25	25	25	25	25	25	29	38	57	43	44	43	4	4	8	23	16
8C-173019	22	21	19	19	19	19	19	21	26	34	54	43	43	43	5	5	9	19	13
8C-174051	43	42	42	42	42	42	42	43	45	49	62	43	42	42	6	6	6	37	22
8C-174108	46	43	46	46	46	46	46	46	47	59	50	18	18	18	4	4	4	43	15
8C-174372	38	39	37	37	37	37	37	38	39	44	59	43	42	42	3	3	3	36	18
41915297	16	2	3	3	3	3	3	3	5	29	47	37	37	37	1	1	1	17	12
41915299	15	1	2	2	2	2	2	3	2	30	46	37	37	37	1	1	1	17	5
41915300	16	1	3	3	3	3	3	3	5	30	47	37	37	37	1	1	1	17	12
8C-174734	43	42	43	43	43	43	43	44	47	55	61	42	40	40	6	6	6	37	21
8C-175191	41	37	37	37	37	37	37	41	40	48	54	29	29	29	6	6	6	34	14
8C-175964	35	35	35	35	35	35	35	36	36	42	49	25	25	25	5	5	5	32	11
8C-175965	44	46	40	40	40	40	40	44	47	52	54	25	24	24	5	5	5	38	16
8C-176317	44	45	45	45	45	45	45	45	49	52	58	29	28	28	3	3	3	42	17
8C-177163	50	50	51	51	51	51	51	54	56	63	58	26	26	26	6	6	6	47	20
8C-177464	50	47	47	47	47	47	47	51	57	58	57	22	22	22	5	5	5	45	16
8C-177979	41	41	40	40	40	40	40	42	47	56	46	18	18	18	7	7	7	40	11
8C-178449	47	47	48	48	48	48	48	48	51	73	48	16	16	16	4	4	4	45	13
41949081	14	2	2	2	2	2	2	2	22	56	39	14	14	14	1	1	1	37	7
41949083	14	2	3	3	3	3	3	3	22	57	39	11	14	14	1	1	1	37	9
41949084	14	2	3	3	3	3	3	3	22	51	42	14	14	14	1	1	1	37	8
8C-178772	50	49	49	49	49	49	49	51	56	64	54	20	20	20	7	7	7	47	16
8C-178744	47	45	50	50	50	50	50	47	50	67	45	10	9	9	3	3	3	43	11
8C-180312	51	49	50	50	50	50	50	50	56	73	45	8	7	7	7	7	7	46	15
8C-181214	48	44	45	45	45	45	45	48	49	63	42	6	6	6	6	6	6	44	10
8C-181567	30	30	33	33	33	33	33	33	36	51	21	6	6	6	5	5	5	29	7
8C-181657	46	46	46	46	46	46	46	50	53	66	42	7	4	4	4	4	4	44	9
8C-183126	35	35	36	36	36	36	36	35	41	56	26	7	7	7	6	6	6	33	11
8C-184041	2	7	8	8	8	8	8	3	4	2	1	1	1	1	1	1	1	1	1
8C-184113	43	43	43	40	40	40	40	45	44	60	26	4	4	4	4	4	4	38	11
8C-184727	38	38	39	38	38	38	38	39	42	59	23	7	4	4	3	3	3	37	9
8C-185193	41	43	42	37	37	37	37	41	44	66	21	7	7	7	7	7	7	38	9
8C-185875	29	30	29	29	29	29	29	28	34	51	9	6	6	6	5	5	5	28	7
8C-185988	9	11	5	9	9	9	9	10	10	1	1	1	1	1	1	1	1	1	1
7B-186272	30	31	30	30	30	30	30	31	36	52	10	8	5	5	3	3	3	30	9
8C-186495	38	37	38	38	38	38	38	43	39	60	15	10	9	9	4	4	4	36	14
8C-186522	45	48	48	48	48	48	48	48	52	70	23	13	13	13	6	6	6	45	22
41994765	17	16	15	18	18	18	18	17	16	39	1	1	1	1	1	1	1	15	1
8C-186679	29	26	29	29	29	29	29	30	33	52	5	4	4	4	4	4	4	25	5
8C-187638	7	10	1	10	10	10	10	2	10	3	1	1	1	1	1	1	1	1	1

Table K.3: Model TAT output (days) per scenario 1b

Comb	Base	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
8C-187758	48	48	50	51	51	51	51	51	51	76	23	13	12	12	6	6	6	48	21
41999917	9	15	10	11	11	11	11	15	15	36	1	1	1	1	1	1	1	9	1
8C-188108	43	45	45	46	46	46	46	46	50	70	21	14	10	10	4	4	4	43	21
8C-188109	33	33	36	33	33	33	33	37	40	59	12	9	5	5	3	3	3	32	12
8C-188681	52	53	53	53	53	53	53	53	54	79	24	11	11	11	4	4	4	52	23
8C-189867	51	56	53	51	51	51	51	57	60	86	25	15	14	14	4	4	4	53	24
7B-180753	60	60	60	59	59	59	59	61	66	93	30	16	16	16	5	5	5	60	29
8C-190256	57	57	54	57	57	57	57	58	61	94	25	15	15	15	4	4	4	57	25
8C-191014	52	55	56	55	55	55	55	57	59	86	23	10	9	9	6	6	6	56	22
8C-191114	51	52	54	52	52	52	52	57	58	87	23	9	9	9	4	4	4	53	19
8C-191153	46	47	47	47	47	47	47	51	53	80	16	3	3	3	3	3	3	52	15
8C-191266	46	49	46	49	49	49	49	51	53	85	15	7	4	4	3	3	3	51	14
8C-191712	50	50	44	47	47	47	47	50	50	87	11	10	10	10	4	4	4	50	11
8C-191714	54	55	54	54	54	54	54	55	61	91	16	8	7	7	6	6	6	55	15
8C-193051	50	50	50	51	51	51	51	51	52	88	12	10	9	9	4	4	4	51	12
8E 172863	36	35	35	35	35	35	35	35	37	50	60	46	45	45	4	4	4	32	21
8E 174110	35	35	35	35	35	35	35	34	35	48	61	44	44	44	5	5	5	34	20
8E 174207	33	37	33	33	33	33	33	37	37	50	59	43	43	43	3	3	3	33	18
8E 176409	46	47	46	46	46	46	46	47	48	57	55	26	25	25	6	6	6	42	15
8E 177153	44	45	45	45	45	45	45	45	48	51	55	23	22	22	6	6	6	43	16
8E 178060	44	40	44	44	44	44	44	45	46	53	46	17	17	17	3	3	3	39	11
8E 181089	39	40	40	40	40	40	40	42	43	61	33	6	6	6	5	5	5	36	7
8E 181652	50	52	46	46	46	46	46	51	52	70	43	8	8	8	7	7	7	49	11
8E 183259	45	40	39	39	39	39	39	45	43	59	30	10	9	9	5	5	5	38	12
8E 183555	47	47	49	47	47	47	47	50	50	69	33	12	11	11	7	7	7	43	19
8E 185110	40	41	40	36	36	36	36	40	42	62	21	6	6	6	6	6	6	39	8
8E 185519	37	36	33	31	31	31	31	37	40	61	16	3	3	3	3	3	3	33	4
8E 186468	35	37	38	37	37	37	37	39	37	58	15	8	9	9	4	4	4	36	11
8E 189023	46	45	45	50	50	50	50	53	52	71	22	11	10	10	7	7	7	46	22
8E 189404	49	49	54	54	54	54	54	51	51	76	26	14	13	13	6	6	6	50	23
8E 191289	31	24	27	31	31	31	31	34	29	3	1	1	1	1	1	1	1	1	1
8E 191673	48	49	47	49	49	49	49	50	51	89	14	6	6	6	5	5	5	51	12
8E 191681	45	45	44	44	44	44	44	46	50	84	15	4	4	4	3	3	3	50	14
8E 192087	46	51	46	46	46	46	46	51	53	87	12	10	10	10	4	4	4	47	10
41905579	21	21	20	20	20	20	20	21	25	21	49	42	42	42	1	1	1	21	13
41905582	21	21	20	20	20	20	20	21	25	21	49	42	42	42	1	1	1	21	14
41910974	26	27	28	28	28	28	28	27	28	34	49	36	36	36	1	1	1	22	8
41917639	19	22	20	20	20	20	20	22	22	28	46	27	27	27	1	1	1	18	5
41925160	29	29	23	23	23	23	23	34	34	37	50	21	23	22	1	1	1	34	10
7B-176244	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41948608	25	33	29	29	29	29	29	35	34	55	41	12	12	12	1	1	1	35	7
7B-179318	47	47	47	47	47	47	47	50	52	72	44	9	8	8	5	5	5	45	12
41958592	22	32	30	30	30	30	30	30	30	38	25	1	1	1	1	1	1	24	2
41958594	29	32	29	29	29	29	29	30	30	38	25	1	1	1	1	1	1	24	2
41959389	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959391	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959392	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41962148	21	30	24	24	24	24	24	24	36	43	31	1	1	1	1	1	1	35	1
41991494	22	20	23	22	22	22	22	27	21	37	8	5	5	5	1	1	1	22	7
8C-186077	29	31	29	30	30	30	30	32	38	53	10	5	5	5	4	4	4	29	9
41993716	20	14	17	20	20	20	20	21	21	44	3	1	1	1	1	1	1	20	2
41994769	17	16	15	17	17	17	17	17	17	43	1	1	1	1	1	1	1	18	1
8C-186678	31	31	32	32	32	32	32	36	36	59	5	5	5	5	4	4	4	29	5
8C-187821	29	30	30	31	31	31	31	30	36	52	9	7	4	4	4	4	4	28	9
42004173	7	12	13	13	13	13	13	18	15	39	4	1	1	1	1	1	1	13	1
8C-190415	57	54	54	54	54	54	54	54	58	86	26	12	12	12	4	4	4	54	25
7B-187595	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
42023901	35	30	30	35	35	35	35	37	31	58	16	3	3	3	1	1	1	46	16
42028319	29	34	36	35	35	35	35	34	35	69	8	1	1	1	1	1	1	39	12
42029357	37	37	37	39	39	39	39	39	42	77	11	1	1	1	1	1	1	45	10
42036303	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
42038347	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8C-172214	31	31	31	31	31	31	31	32	33	45	57	44	44	44	3	3	3	29	17
8C-174612	36	36	35	35	35	35	35	36	38	50	51	30	30	29	4	4	4	31	11
41929923	14	15	5	5	5	5	5	6	9	20	48	23	23	23	1	1	1	26	15
41929926	14	13	5	5	5	5	5	2	6	14	48	23	22	23	1	1	1	26	15
41929952	14	15	5	5	5	5	5	6	9	21	48	23	22	22	1	1	1	41	15
41938629	8	11	4	4	4	4	4	7	19	46	42	15	15	15	1	1	1	32	7
41938631	5	11	4	4	4	4	4	7	12	47	41	15	14	15	1	1	1	35	8
41938634	8	11	4	4	4	4	4	7	12	47	41	15	15	15	1	1	1	35	8
8C-179257	51	50	50	50	50	50	50	50	51	73	45	10	10	10	4	4	4	43	12
41977408	5	3	9	9	9	9	9	2	2	45	18	3	3	3	1	1	1	29	5
41977409	8	4	9	9	9	9	9	2	2	51	18	3	3	3	1	1	1	29	5
41977411	5	3	9	9	9	9	9	2	2	45	18	3	3	3	1	1	1	25	5
41993117	14	14	2	3	3	3	3	9	22	44	4	2	2	2	1	1	1	21	3
41993121	14	14	4	3	3	3	3	8	22	44	4	2	2	2	1	1	1	21	3
41993122	14	14	4	4	4	4	4	9	22	44	4	2	2	2	1	1	1	21	3
42016899	32	30	31	17	17	17	17	22	45	65	21	10	10	10	1	1	1	43	11
42016904	32	30	31	17	17	17	17	22	45	70	21	9	9	9	1	1	1	43	11
42016906	32	31	31	18	18	18	18	22	46	70	21	10	10	10	1	1	1	43	18
7B-189684	54	57	58	53	53	53	53	53	61	93	26	15	15	15	5	5	5	53	25
42030975	6	1	5	1	1	1	1	7	36	74	12	4	4	4	1	1	1	40	7
42030985	6	5	5	1	1	1	1	7	36	76	12	4	4	4	1	1	1	40	8
42030988	5	5	5	1	1	1	1	7	35	75	12	4	4	4	1	1	1	40	7
7B-191293	1	2	1	1	1	1	1	2	1	1	1	1	1	1	1	1	1	1	1
42033989	21	15	22	2	2	2	2	10	32	71	9	2	2	2	1	1	1	42	8
42033991	18	16	23	3	3	3	3	11	36	72	9	2	2	2	1	1	1	42	8
42033995	9	16	22	2	2	2	2	10	32	78	8	2	2	2	1	1	1	42	8
Average	28.5	28.1	28.0	27.1	27.1	27.1	27.1	28.6	32.7	49.4	26.6	13.5	13.2	13.2	3.1	3.0	3.3	31.0	10.8
Combustor	113	112	115	112	112	112	112	108	96	46	120	162	162	162	187	187	187	100	187
Late	74	75	72	75	75	75	75	79	91	141	67	25	25	25	0	0	0	87	0
Total	60%	60%	61%	60%	60%	60%	60%	58%	51%	25%	64%	87%	87%	87%	100%	100%	100%	53%	100%
Min	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max	60	60	60	59	59	59	59	61	66	94	62	46	45	45	7	7	9	60	29

Table K.4: Model TAT output (days) per scenario 2a

Comb	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
7B-169363	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-169366	19	19	19	19	22	29	30	85	19	19	19	19	102	44	40	60	44	43	65
7B-171379	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-171814	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-172459	21	21	20	21	21	23	24	51	20	20	20	21	69	30	29	41	29	29	45
7B-172469	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-172922	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-173055	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-173332	1	1	1	1	1	1	1	1	1	1	1	1	15	1	1	1	1	1	1
7B-174790	20	20	21	21	22	27	29	70	21	21	21	21	85	37	36	52	37	37	57
7B-175333	20	20	19	19	20	26	28	76	16	16	16	16	92	41	37	56	40	37	61
7B-176124	18	18	18	18	22	29	30	89	18	18	18	18	113	44	44	64	44	44	68
41933078	10	10	9	5	11	16	17	67	9	9	9	8	96	25	23	3	31	29	45
7B-176503	1	1	1	1	1	1	1	1	1	1	1	1	36	1	1	1	1	1	1
7B-176822	1	1	1	1	1	1	1	1	1	1	1	1	63	1	1	1	1	1	7
7B-176828	19	19	19	19	22	30	32	95	18	18	18	18	115	47	45	66	46	46	72
7B-176861	1	1	1	1	1	1	1	1	1	1	1	1	84	8	2	1	1	2	10
41953805	2	2	3	3	4	11	15	86	3	3	3	3	116	26	17	2	31	32	40
7B-177542	1	1	1	1	1	1	1	1	1	1	1	1	88	2	1	1	1	1	3
7B-178403	19	19	19	20	19	27	29	106	19	19	19	20	135	49	47	68	48	48	77
7B-178048	1	1	1	1	1	1	1	1	1	1	1	1	37	1	1	1	1	1	2
7B-180314	16	16	15	16	17	24	26	117	17	17	17	16	148	51	50	73	47	47	80
7B-180318	17	17	16	17	17	25	29	120	17	17	17	17	145	50	47	73	47	50	80
42021093	10	10	9	10	10	18	15	159	10	10	10	10	208	30	33	5	36	37	75
7B-181062	1	1	1	1	1	1	1	1	1	1	1	1	64	1	1	1	1	1	1
7B-181541	8	8	8	8	9	12	16	115	9	9	9	8	149	40	39	67	40	43	75
7B-182310	15	15	15	15	15	19	18	125	15	15	15	15	160	42	39	70	42	42	76
7B-182576	17	17	17	17	18	19	18	123	17	17	17	17	158	43	39	71	43	43	75
7B-182864	9	9	9	9	9	9	10	108	9	9	9	9	140	31	30	58	31	35	66
7B-184359	10	10	10	10	10	12	12	128	10	10	10	10	162	36	37	67	38	39	75
7B-184522	18	18	17	17	18	19	23	158	18	18	18	18	200	39	38	75	40	43	88
7B-184762	11	11	11	12	11	16	16	134	11	11	11	11	166	39	38	68	40	39	78
7B-185456	1	1	1	1	1	1	1	1	1	1	1	1	99	1	1	1	1	1	1
7B-186117	1	1	1	1	1	1	1	1	1	1	1	1	103	1	1	1	1	1	2
41990024	1	1	1	1	1	1	1	110	1	1	1	1	149	11	10	3	12	17	44
7B-186811	8	8	8	8	11	11	12	137	8	8	8	8	173	26	25	63	27	29	70
7B-187335	1	1	1	1	1	1	1	1	1	1	1	1	102	1	1	1	1	1	1
7B-187348	13	13	13	13	13	14	15	141	13	13	13	13	183	30	29	70	33	34	75
42022391	20	20	20	20	21	20	27	174	20	20	20	20	218	33	44	13	49	49	83
7B-187640	26	26	26	26	27	33	30	174	26	26	26	26	218	50	51	96	51	56	103
7B-188048	16	16	16	16	17	17	18	144	16	16	16	16	186	33	32	72	36	37	75
7B-188112	16	16	16	16	17	16	17	148	16	16	16	16	190	31	32	71	33	36	75
7B-188641	18	18	18	17	19	22	22	152	18	18	18	18	192	37	36	75	38	39	82
42016949	18	18	18	18	19	14	22	161	18	18	18	18	5	32	29	12	42	34	76
42016957	19	19	18	19	19	14	22	160	19	19	19	19	5	32	29	12	42	34	76
42016958	19	19	19	19	19	15	22	160	19	19	19	19	7	33	29	12	43	34	76
7B-189699	24	24	23	23	23	31	31	185	24	24	24	24	239	52	53	99	59	59	108
42038682	2	2	3	2	3	9	8	163	2	2	2	2	4	19	29	9	25	33	66
42038683	4	4	4	4	3	10	11	164	4	4	4	4	3	18	29	11	25	38	67
42038685	2	2	3	3	3	8	8	170	2	2	2	2	4	19	29	8	32	33	66
8C-165302	15	15	16	17	17	20	21	51	17	17	17	15	64	22	23	30	28	24	37
8C-171235	9	9	9	12	9	12	13	30	9	9	9	9	42	15	13	20	14	14	26
8C-171590	12	12	12	12	15	16	17	39	12	12	12	12	52	22	19	25	22	22	36
8C-171591	16	16	16	16	16	24	25	101	15	15	15	16	122	43	40	64	43	44	68
8C-172061	19	19	19	20	20	23	23	51	19	19	19	19	65	30	28	35	29	28	43
41898510	9	9	9	9	9	8	8	8	9	9	9	9	3	9	9	4	9	10	4
41898647	8	8	8	8	9	8	3	8	8	8	8	8	2	3	4	4	3	3	4
41898653	9	9	9	9	9	9	9	8	9	9	9	9	4	9	4	5	10	10	5
8C-172574	17	17	17	17	20	23	24	50	17	17	17	17	63	28	28	35	27	28	44
8C-172987	15	15	15	15	15	17	19	40	15	15	15	15	53	23	23	26	22	22	33
8C-173014	16	16	16	16	16	18	19	43	16	16	16	16	54	24	23	30	24	24	37
8C-173019	13	13	13	13	14	14	15	36	13	13	13	13	44	16	16	23	16	16	30
8C-174051	21	21	22	22	22	28	29	69	21	21	21	22	84	37	36	50	37	37	57
8C-174108	15	15	15	15	16	23	25	99	15	15	15	15	123	40	40	61	44	44	66
8C-174372	18	18	21	21	21	25	28	65	21	21	21	21	78	32	35	45	35	35	51
41915297	9	9	8	9	8	11	11	39	8	8	8	9	5	12	17	4	26	18	26
41915299	9	9	8	8	8	11	18	39	8	8	8	9	5	12	17	4	18	17	26
41915300	8	8	8	8	12	10	18	40	8	8	8	8	4	15	17	4	25	17	26
8C-174734	21	21	21	21	22	27	30	72	21	21	21	21	89	37	37	55	40	37	56
8C-175191	14	14	14	14	15	22	23	70	14	14	14	14	90	35	34	49	34	34	50
8C-175964	11	11	12	12	12	19	20	69	11	11	11	11	85	32	28	43	29	32	47
8C-175965	16	16	16	17	18	24	25	81	15	15	15	16	100	39	37	57	37	37	61
8C-176317	17	17	18	17	18	28	29	86	17	17	17	18	105	43	42	58	39	42	60
8C-177163	19	19	20	20	21	29	33	93	20	20	20	20	119	48	47	64	47	47	72
8C-177464	16	16	16	16	17	29	31	96	15	15	15	16	117	45	45	66	45	46	68
8C-177979	11	11	11	11	12	19	22	91	11	11	11	11	112	36	35	61	40	36	62
8C-178449	12	12	12	16	13	23	25	103	13	13	13	16	129	41	41	65	44	41	69
41949081	8	8	4	9	9	14	18	86	8	8	8	10	2	35	31	7	30	32	57
41949083	8	8	8	9	7	14	16	86	8	8	8	9	2	35	31	8	32	32	57
41949084	9	9	8	9	8	14	16	86	9	9	9	10	2	35	35	8	32	32	57
8C-178772	16	16	16	16	19	27	28	104	16	16	16	15	131	44	44	64	47	48	71
8C-178744	11	11	10	11	12	19	22	102	11	11	11	11	130	40	39	61	40	40	68
8C-180312	14	14	14	15	15	23	25	112	15	15	15	15	141	46	44	72	45	46	77
8C-181214	10	10	10	10	10	20	22	112	14	14	14	13	140	42	41	66	43	43	66
8C-181567	7	7	7	7	7	8	8	105	7	7	7	7	138	27	27	50	29	30	58
8C-181657	9	9	9	10	10	17	21	114	11	11	11	10	143	42	39	67	44	44	73
8C-183126	11	11	11	11	11	12	12	112	11	11	11	11	145	33	29	56	33	34	67
8C-184041	1	1	1	1	1	1	1	1	1	1	1	1	144	10	4	1	1	1	1
8C-184113	11	11	11	11	12	15	15	124	11	11	11	11	158	38	36	66	38	39	72
8C-184727	10	10	9	9	10	14	11	126	10	10	10	10	161	36	35	65	37	37	71
8C-185193	9	9	9	9	9	13	13	128	9	9	9	9	167	36	34	65	36	36	72
8C-185875	7	7	7	7	7	7	7	124	7	7	7	7	161	23	26	56	28	27	64
8C-185988	1	1	1	1	1	1	1	1	1	1	1	1	150	4	4	1	1	1	2
7B-186272	9	9	10	9	8	9	9	127	9	9	9	9	164	25	26	57	29	29	67
8C-186495	14	14	14	14	15	16	16	136	14	14	14	14	176	31	31	66	36	36	72
8C-186522	22	22	23	22	23	27	27	161	22	22	22	22	204	43	41	79	44	45	87
41994765	1	1	1	1	1	1	1	115	1	1	1	1	156	17	16	2	15	18	51
8C-186679	5	5	5	5	5	5	5	129	5	5	5	5	170	23	22	59	25	25	64
8C-187638	1	1	1	1	1	1	1	1	1	1	1	1	157	7	6	51	2	1	6

Table K.5: Model TAT output (days) per scenario 2b

Comb	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
8C-187758	21	21	21	21	21	26	27	167	21	21	21	21	211	43	42	91	47	47	92
41999917	1	1	1	1	1	1	1	115	1	1	1	1	150	11	14	1	14	14	39
8C-188108	21	21	21	21	21	22	23	156	21	21	21	21	200	39	38	79	42	43	86
8C-188109	12	12	12	12	15	16	16	144	12	12	12	12	187	29	30	71	32	33	73
8C-188681	23	23	23	23	24	29	31	172	23	23	23	23	221	47	46	94	52	52	96
8C-189867	24	24	25	25	25	30	31	176	24	24	24	24	225	50	50	95	52	53	101
7B-180753	29	29	29	29	30	36	38	186	29	29	29	29	236	57	57	103	60	61	109
8C-190256	25	25	24	25	26	32	32	179	25	25	25	25	234	51	51	96	54	59	103
8C-191014	23	23	23	23	23	29	30	182	23	23	23	23	237	49	51	98	55	57	101
8C-191114	22	22	23	22	22	26	30	180	22	22	22	22	235	51	50	95	53	54	102
8C-191153	17	17	17	16	17	24	24	178	17	17	17	17	235	44	46	92	51	50	96
8C-191266	14	14	15	14	16	22	24	179	14	14	14	14	238	44	45	88	50	51	100
8C-191712	11	11	11	11	11	17	22	183	11	11	11	11	247	45	45	86	50	51	99
8C-191714	16	16	16	15	19	26	28	184	16	16	16	16	246	49	50	92	54	55	107
8C-193051	12	12	15	11	15	19	23	183	12	12	12	12	249	46	46	87	51	53	101
8E 172863	22	22	21	22	22	25	28	58	22	22	22	22	70	30	32	45	32	35	44
8E 174110	21	21	21	21	21	27	27	58	21	21	21	22	72	30	33	43	34	34	44
8E 174207	19	19	18	19	19	25	25	60	19	19	19	19	73	31	31	44	32	32	47
8E 176409	15	15	18	18	18	26	29	89	15	15	15	15	109	43	41	60	42	41	60
8E 177153	16	16	16	15	17	27	28	92	16	16	16	16	114	42	41	62	43	44	63
8E 178060	12	12	12	11	12	19	23	94	11	11	11	11	117	39	39	59	39	39	61
8E 181089	7	7	7	7	7	12	14	110	7	7	7	7	139	35	34	56	36	39	67
8E 181652	11	11	10	10	11	21	23	116	11	11	11	10	144	43	42	70	45	46	74
8E 183259	11	11	12	12	12	15	15	117	11	11	11	11	150	38	36	64	39	39	66
8E 183555	18	18	19	19	18	19	21	127	18	18	18	18	159	42	41	67	43	43	71
8E 185110	11	11	8	11	11	13	13	127	11	11	11	11	161	34	35	62	35	36	69
8E 185519	5	5	4	5	5	9	9	127	5	5	5	5	159	31	30	58	32	33	66
8E 186468	11	11	14	14	14	15	15	135	11	11	11	11	172	32	31	65	37	36	70
8E 189023	22	22	21	21	22	25	25	163	22	22	22	22	205	43	42	79	45	45	86
8E 189404	23	23	23	23	23	28	29	173	23	23	23	23	212	47	47	86	50	50	91
8E 191289	1	1	1	1	1	1	1	3	1	1	1	1	230	30	2	1	1	1	13
8E 191673	13	13	13	13	15	22	22	181	13	13	13	13	243	43	48	86	49	54	98
8E 191681	14	14	14	14	15	21	23	178	14	14	14	14	234	43	44	87	50	51	95
8E 192087	10	10	10	10	15	19	18	184	10	10	10	10	247	43	46	81	46	51	96
41905579	13	13	13	14	12	19	15	46	13	13	13	13	54	21	20	7	20	19	32
41905582	14	14	13	14	12	19	18	46	14	14	14	14	54	21	19	7	21	21	33
41910974	8	8	8	8	8	13	14	49	11	11	11	8	69	26	22	7	21	21	36
41917639	5	5	7	4	5	11	12	54	5	5	5	7	69	14	19	1	19	19	26
41925160	9	9	13	13	7	21	23	76	13	13	13	9	92	28	15	2	31	36	45
7B-176244	1	1	1	1	1	1	1	1	1	1	1	1	16	1	1	1	1	1	1
41948608	7	7	6	7	6	14	18	84	6	6	6	7	113	33	32	5	33	29	55
7B-179318	12	12	12	15	15	22	25	109	15	15	15	12	137	45	43	67	45	45	73
41958592	2	2	2	2	3	8	10	87	2	2	2	4	124	24	23	1	24	25	33
41958594	2	2	3	3	5	8	12	86	3	3	3	3	124	24	23	1	24	25	33
41959389	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959391	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959392	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41962148	3	3	2	2	3	9	13	97	7	7	7	3	133	29	28	9	31	34	55
41991494	7	7	5	7	7	6	9	121	7	7	7	7	162	26	15	9	26	28	50
8C-186077	9	9	9	9	9	9	9	123	9	9	9	9	164	25	25	59	26	29	65
41993716	2	2	3	3	3	3	6	119	2	2	2	2	156	21	17	7	20	23	56
41994769	1	1	1	1	1	1	1	115	1	1	1	1	157	17	16	2	15	18	51
8C-186678	5	5	5	5	8	8	9	131	5	5	5	5	171	26	24	60	29	29	67
8C-187821	9	9	9	9	9	9	9	134	9	9	9	9	177	23	23	63	25	28	66
42004173	1	1	1	1	4	5	5	125	1	1	1	1	154	13	11	1	12	14	36
8C-190415	26	26	25	25	25	31	31	180	26	26	26	26	233	52	50	99	53	54	102
7B-187595	1	1	1	1	1	1	1	1	1	1	1	1	112	1	1	1	1	1	1
42023901	15	15	15	15	16	18	23	169	15	15	15	15	217	28	42	8	44	45	78
42028319	11	11	11	8	13	19	18	167	11	11	11	11	228	35	34	5	46	42	89
42029357	10	10	9	10	14	17	18	172	10	10	10	10	227	38	42	11	43	44	88
42036303	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
42038347	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8C-172214	17	17	18	18	18	23	23	52	17	17	17	17	66	29	29	36	29	29	44
8C-174612	11	11	11	11	11	18	21	65	11	11	11	11	84	30	29	45	30	30	49
41929923	14	14	13	9	9	12	13	65	9	9	9	8	6	12	23	2	27	30	42
41929926	7	7	12	9	9	19	13	68	13	13	13	8	6	12	23	2	27	33	42
41929952	7	7	13	9	16	20	21	68	15	15	15	15	6	12	23	2	27	33	42
41938629	7	7	5	7	8	12	18	81	8	8	8	7	5	8	28	6	34	28	33
41938631	7	7	7	7	11	12	18	81	7	7	7	7	4	8	27	6	34	28	33
41938634	7	7	7	7	8	13	18	84	8	8	8	7	5	11	28	5	34	28	33
8C-179257	11	11	11	12	12	19	24	103	12	12	12	12	134	43	40	66	43	44	71
41977408	5	5	5	5	5	9	8	108	5	5	5	5	4	15	25	11	25	25	47
41977409	5	5	5	5	8	9	8	109	5	5	5	5	4	15	25	10	26	24	47
41977411	5	5	5	5	5	9	5	108	5	5	5	5	4	12	25	10	15	24	47
41993117	3	3	4	4	3	4	4	119	3	3	3	3	2	22	18	7	18	24	49
41993121	3	3	4	3	4	4	7	119	3	3	3	3	2	21	18	8	21	24	49
41993122	3	3	4	4	4	4	7	120	3	3	3	3	2	22	9	8	21	24	57
42016899	17	17	18	21	21	16	23	161	17	17	17	17	4	32	30	14	42	36	78
42016904	17	17	18	21	21	16	23	162	17	17	17	17	4	32	30	11	43	36	78
42016906	21	21	18	18	21	16	23	162	21	21	21	21	4	31	31	14	44	36	74
7B-189684	25	25	26	25	26	30	31	176	25	25	25	25	225	52	51	95	53	53	101
42030975	8	8	7	8	11	14	20	172	8	8	8	8	5	32	34	8	40	41	84
42030985	8	8	7	8	11	14	20	173	8	8	8	8	5	32	35	11	40	41	84
42030988	8	8	7	8	11	14	20	169	8	8	8	8	5	32	35	11	40	41	84
7B-191293	1	1	1	1	1	1	1	1	1	1	1	1	172	1	1	1	1	1	2
42033989	9	9	9	9	8	14	11	164	9	9	9	9	3	29	37	15	37	43	78
42033991	8	8	9	9	10	15	11	164	8	8	8	8	4	30	37	16	37	44	78
42033995	9	9	9	9	10	14	11	163	9	9	9	9	4	30	37	15	37	44	77
Average	10.8	10.8	10.9	10.9	11.6	14.9	16.2	97.4	11.0	11.0	11.0	10.9	107.3	27.8	27.9	37.5	30.3	30.7	55.0
Combustor	187	187	187	187	187	187	186	33	187	187	187	187	50	126	125	95	107	111	48
Late	0	0	0	0	0	0	1	154	0	0	0	0	137	61	62	92	80	76	139
Total	100%	100%	100%	100%	100%	100%	99%	18%	100%	100%	100%	100%	27%	67%	67%	51%	57%	59%	26%
Min	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max	29	29	29	29	30	36	38	186	29	29	29	29	249	57	57	103	60	61	109

Table K.6: Model TAT output (days) per scenario 3a

Comb	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
7B-169363	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-169366	94	60	122	43	43	43	43	44	39	46	39	66	44	40	46	46	46	122	36
7B-171379	1	1	2	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-171814	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-172459	57	38	73	29	29	29	29	29	27	31	27	34	25	27	34	29	31	83	28
7B-172469	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-172922	1	1	1	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-173055	1	1	1	1	1	1	1	1	1	1	1	4	2	1	1	1	1	1	1
7B-173332	1	1	16	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-174790	78	51	98	37	37	37	36	37	31	41	31	63	20	23	50	41	41	105	32
7B-175333	85	54	110	37	37	37	37	41	35	44	35	51	33	34	46	44	42	111	34
7B-176124	100	60	124	45	45	45	44	45	37	47	37	44	41	41	45	45	47	115	33
41933078	94	38	106	32	32	32	32	37	25	26	24	38	25	19	22	30	25	108	8
7B-176503	1	1	35	1	1	1	1	1	1	1	1	1	2	1	1	1	1	1	1
7B-176822	1	1	74	1	1	1	1	1	1	5	1	12	2	3	1	1	1	1	1
7B-176828	107	66	136	45	45	45	47	47	39	52	39	54	52	49	54	46	47	128	34
7B-176861	1	2	83	1	1	1	1	1	3	2	1	15	4	1	1	1	1	6	1
41953805	113	36	141	31	31	31	31	19	19	31	17	20	40	31	12	30	30	137	5
7B-177542	1	1	95	2	2	2	1	1	1	8	2	4	4	4	2	8	1	5	1
7B-178403	124	68	159	47	47	47	47	49	37	50	36	62	46	48	47	49	50	168	29
7B-178048	1	1	37	1	1	1	1	1	1	1	1	3	2	2	1	1	1	5	1
7B-180314	135	73	172	47	47	47	47	54	38	54	37	61	54	58	59	53	51	177	24
7B-180318	135	72	176	47	47	47	47	50	38	52	38	56	54	54	58	51	51	171	25
42021093	199	73	260	33	43	43	38	47	16	39	15	31	66	69	37	33	36	241	12
7B-181062	1	1	72	1	1	1	1	1	1	1	1	1	5	1	1	1	1	1	1
7B-181541	137	71	178	40	40	40	40	44	29	45	30	49	52	52	47	45	46	177	16
7B-182310	151	70	196	40	40	40	41	43	27	46	26	43	72	66	41	43	46	180	19
7B-182576	148	73	192	39	39	39	40	44	29	46	29	71	68	68	54	45	45	178	20
7B-182864	130	60	172	32	32	32	32	36	21	38	17	56	59	60	50	36	35	170	11
7B-184359	150	67	198	38	38	38	37	40	23	43	23	56	68	69	41	43	43	191	17
7B-184522	190	82	250	43	40	40	40	46	29	45	25	61	93	91	62	43	43	234	24
7B-184762	157	73	204	40	40	40	40	45	25	44	23	68	69	73	48	44	43	198	18
7B-185456	1	1	85	1	1	1	1	1	1	1	1	1	5	6	1	1	1	1	1
7B-186117	1	1	114	1	1	1	1	1	1	1	1	1	10	7	1	1	1	1	1
41990024	138	40	179	9	9	9	11	23	2	15	1	37	61	57	18	12	15	171	1
7B-186811	160	63	215	27	27	27	28	34	13	34	13	43	79	76	30	32	32	201	13
7B-187335	1	1	121	1	1	1	1	1	1	1	1	1	6	1	1	1	1	1	1
7B-187348	169	70	224	30	30	30	30	36	20	43	20	57	81	82	44	37	36	208	17
42022391	211	86	272	47	48	48	42	61	29	42	29	32	59	59	39	35	35	266	21
7B-187640	205	97	273	54	55	55	54	61	36	55	35	71	101	97	71	54	55	251	34
7B-188048	173	73	232	33	36	36	36	39	22	44	22	62	88	85	51	38	38	213	19
7B-188112	176	74	239	33	36	36	38	39	19	38	19	35	80	80	38	39	37	213	18
7B-188641	183	79	242	38	39	39	40	45	24	44	25	40	86	83	44	43	40	226	25
42016949	200	74	257	34	34	34	34	40	18	33	15	12	3	2	10	28	18	249	15
42016957	200	71	260	34	34	34	35	40	18	33	18	11	4	3	10	28	18	249	15
42016958	200	74	263	34	34	34	34	40	18	34	18	11	4	3	10	28	18	249	15
7B-189699	224	105	298	58	59	59	58	66	37	58	36	74	86	83	60	57	57	282	29
42038682	205	82	289	32	30	30	32	44	11	16	5	17	11	10	9	12	15	281	4
42038683	211	78	278	37	38	38	37	45	11	15	9	21	10	10	9	16	15	295	4
42038685	205	75	288	32	38	38	32	45	10	15	8	21	10	6	9	15	15	288	3
8C-165302	57	35	71	27	27	27	28	27	23	22	21	32	11	10	19	23	24	78	17
8C-171235	36	20	50	14	14	14	14	14	13	14	14	12	11	11	13	14	14	55	13
8C-171590	46	30	64	19	19	19	19	22	19	22	17	22	19	17	23	19	22	72	18
8C-171591	115	60	144	45	45	45	43	46	38	45	36	49	45	48	48	45	46	149	25
8C-172061	58	36	76	28	28	28	28	28	28	33	27	35	18	19	35	30	33	77	24
41898510	31	4	11	9	9	9	10	10	8	4	8	14	3	6	9	1	1	50	8
41898647	31	4	2	4	4	4	3	3	8	3	3	14	3	9	9	1	1	50	8
41898653	32	5	12	5	5	5	10	11	9	5	9	14	3	2	9	1	1	51	9
8C-172574	57	35	72	28	28	28	28	28	28	30	29	34	24	23	33	30	31	77	27
8C-172987	46	29	61	22	22	22	22	19	19	24	22	22	20	20	26	24	24	73	20
8C-173014	47	31	65	24	24	24	23	24	23	24	24	27	18	19	27	24	25	73	23
8C-173019	40	27	55	16	16	16	16	19	19	20	20	15	16	16	16	20	21	68	16
8C-174051	76	50	94	37	37	37	37	38	37	42	36	60	30	28	44	41	42	105	32
8C-174108	113	60	143	44	44	44	40	44	36	45	33	47	45	47	46	45	47	148	25
8C-174372	71	49	88	32	32	32	35	35	35	38	32	53	24	26	40	38	37	86	31
41915297	64	24	8	16	16	16	16	29	16	2	15	5	3	4	6	12	3	79	10
41915299	65	24	8	16	16	16	16	29	16	11	12	4	3	4	5	11	1	79	10
41915300	65	24	10	17	17	17	16	29	16	15	15	4	3	1	6	11	3	79	10
8C-174734	82	50	100	37	37	37	37	40	36	43	35	67	24	26	55	42	43	106	35
8C-175191	79	43	103	33	33	33	33	36	30	40	29	46	26	24	41	36	36	99	27
8C-175964	78	43	103	32	32	32	29	33	26	35	27	50	25	25	32	34	35	96	22
8C-175965	89	53	115	37	37	37	39	39	33	46	37	60	38	34	41	43	43	101	27
8C-176317	98	56	122	42	42	42	42	43	36	43	37	64	40	37	43	43	45	106	32
8C-177163	110	64	138	47	47	47	43	50	41	51	41	58	47	48	57	50	48	124	34
8C-177464	109	61	141	45	45	45	45	46	38	50	38	66	47	48	51	50	46	128	30
8C-177979	105	57	133	36	36	36	39	39	32	42	33	40	46	42	36	41	40	138	21
8C-178449	118	62	156	44	44	44	41	46	34	47	33	61	46	41	48	47	47	157	24
41949081	108	49	15	31	31	31	32	36	10	2	9	6	6	3	5	2	2	134	10
41949083	108	49	2	31	31	31	32	36	14	2	9	5	4	3	5	2	2	140	11
41949084	108	51	2	31	31	31	31	37	15	2	16	6	6	14	5	2	3	140	10
8C-178772	119	68	152	48	48	48	47	48	37	51	40	55	52	51	53	50	51	155	28
8C-178744	121	64	156	39	39	39	40	44	32	47	37	68	46	46	53	47	46	156	23
8C-180312	128	66	168	44	44	44	44	46	35	53	37	49	51	49	46	50	49	169	23
8C-181214	132	65	170	43	43	43	43	45	35	48	30	60	46	45	46	44	44	161	21
8C-181567	127	51	169	27	27	27	28	33	16	30	15	51	54	52	35	30	29	160	9
8C-181657	134	66	175	44	44	44	43	45	35	50	31	68	51	47	53	46	46	169	21
8C-183126	134	57	174	33	33	33	33	35	20	36	20	58	53	53	40	35	33	172	13
8C-184041	1	1	140	1	1	1	2	1	1	15	1	20	31	28	4	10	15	1	1
8C-184113	149	68	193	38	38	38	38	40	24	44	24	48	69	69	48	43	43	178	17
8C-184727	151	66	196	36	36	36	36	39	21	38	23	55	67	64	40	37	38	183	15
8C-185193	156	66	202	36	36	36	37	42	21	43	22	41	79	73	41	38	41	203	14
8C-185875	152	61	196	26	26	26	29	30	14	33	13	45	73	75	47	28	29	187	8
8C-185988	1	1	157	1	1	1	1	1	1	9	1	13	51	51	26	11	8	1	1
7B-186272	156	60	204	29	29	29	29	32	12	31	11	48	79	76	35	30	30	191	11
8C-186495	164	67	213	35	35	35	35	38	21	42	18	58	80	82	48	38	36	205	17
8C-186522	191	87	252	45	45	45	45	51	31	49	30	49	86	83	51	48	45	237	25
41994765	141	50	194	17	17	17	19	23	3	17	3	15	58	52	17	16	15	183	2
8C-186679	157	64	207	24	24	24	25	30	10	31	11	38	79	73	24	29	26	193	9
8C-187638	1	2	170	1	1	1	1	2	2	17	1	27	54	54	15	15	1	2	1

Table K.7: Model TAT output (days) per scenario 3b

Comb	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
8C-187758	201	92	265	48	50	50	47	58	34	54	35	68	95	93	55	49	50	245	29
41999917	150	38	185	14	14	14	14	17	1	15	1	29	65	61	14	11	11	177	1
8C-188108	185	80	248	42	43	43	42	46	25	46	28	46	81	82	48	46	45	226	24
8C-188109	176	68	233	32	32	32	32	40	18	38	18	35	76	73	37	37	36	212	19
8C-188681	206	95	271	51	52	52	52	59	36	53	38	76	95	92	62	53	52	254	32
8C-189867	212	99	281	53	53	53	53	60	37	58	37	53	83	80	52	57	51	268	32
7B-180753	221	108	295	60	61	61	60	68	40	64	40	66	89	89	65	60	60	289	39
8C-190256	218	102	289	54	58	58	57	61	37	59	37	61	86	80	60	57	57	283	34
8C-191014	219	100	290	55	56	56	55	64	37	59	36	67	79	79	53	56	56	280	30
8C-191114	219	100	292	54	54	54	53	61	33	57	33	72	81	78	57	54	53	288	30
8C-191153	215	94	291	52	51	51	51	58	30	52	29	43	76	73	45	50	46	276	24
8C-191266	219	99	296	50	51	51	50	58	30	53	31	50	68	69	52	50	50	288	22
8C-191712	225	96	306	50	50	50	47	57	30	51	30	71	59	59	58	47	45	303	18
8C-191714	224	103	302	54	56	56	54	63	35	57	35	58	72	69	59	54	55	294	24
8C-193051	226	99	309	50	52	52	51	57	30	53	30	73	60	59	58	51	47	309	23
8E 172863	67	44	80	32	32	32	31	32	35	35	30	43	19	23	29	32	31	91	28
8E 174110	68	44	83	33	33	33	34	34	30	35	33	46	23	21	29	34	33	90	28
8E 174207	67	45	86	32	32	32	32	33	32	32	31	48	19	20	34	36	36	92	25
8E 176409	99	56	126	42	42	42	42	43	40	47	35	46	45	42	46	43	46	112	30
8E 177153	106	58	134	43	43	43	42	45	37	43	35	58	44	38	44	48	44	125	25
8E 178060	110	57	142	39	39	39	40	40	36	44	31	42	45	43	41	43	43	136	22
8E 181089	132	61	173	36	36	36	36	40	25	41	26	38	47	45	39	36	39	161	12
8E 181652	141	70	178	45	45	45	45	50	37	51	32	73	48	48	53	49	50	169	23
8E 183259	144	65	185	37	37	37	37	43	26	43	24	64	62	63	49	44	39	169	16
8E 183555	153	70	196	43	43	43	42	47	32	47	28	42	62	65	42	49	46	186	21
8E 185110	154	67	201	34	34	34	36	40	22	40	20	34	72	67	33	39	39	187	14
8E 185519	155	64	199	33	33	33	33	38	19	37	18	40	75	76	41	36	33	191	9
8E 186468	164	71	212	35	35	35	36	39	21	38	21	55	80	77	46	37	39	191	16
8E 189023	193	87	256	44	45	45	45	50	32	51	31	57	93	95	66	49	49	242	26
8E 189404	204	93	266	50	51	51	51	61	36	51	33	71	90	89	55	51	51	250	29
8E 191289	1	1	219	1	2	2	1	1	7	35	6	50	48	60	40	27	30	3	2
8E 191673	223	97	302	50	51	51	50	61	30	49	29	59	66	66	47	49	49	292	21
8E 191681	218	95	294	49	51	51	50	57	30	51	30	50	68	64	51	46	49	287	21
8E 192087	225	95	305	46	51	51	50	57	32	47	29	69	52	58	59	50	46	296	20
41905579	50	25	64	18	18	18	22	21	15	20	13	25	9	10	22	19	20	68	14
41905582	50	27	64	19	19	19	22	22	14	20	13	25	10	8	22	19	20	68	15
41910974	63	28	78	21	21	21	22	29	19	27	21	42	16	16	30	25	26	76	20
41917639	68	18	76	19	19	19	25	21	12	20	14	18	11	7	13	22	18	76	13
41925160	87	44	108	35	35	35	27	35	23	28	28	52	18	16	32	30	21	77	21
7B-176244	1	1	25	1	1	1	1	1	1	1	1	1	2	2	1	1	1	1	1
41948608	105	50	137	29	29	29	29	35	22	29	22	42	27	25	28	32	29	145	8
7B-179318	127	66	164	45	45	45	44	46	32	47	31	47	47	45	45	47	46	163	22
41958592	115	47	145	23	23	23	23	25	18	29	16	41	34	34	30	26	26	135	6
41958594	120	47	151	23	23	23	23	25	18	29	16	41	34	34	38	26	29	135	6
41959389	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959391	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959392	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41962148	119	49	161	31	31	31	34	35	22	37	17	56	32	23	30	29	34	160	10
41991494	148	58	196	26	26	26	27	29	12	28	7	39	66	63	29	23	23	170	6
8C-186077	151	64	201	26	26	26	29	32	15	32	15	51	72	72	36	31	30	197	11
41993716	146	55	199	22	22	22	24	28	8	22	8	15	59	56	14	17	17	188	4
41994769	144	50	197	17	17	17	19	23	3	17	4	15	55	52	17	17	15	183	1
8C-186678	159	66	211	26	26	26	29	32	15	33	12	35	73	72	36	32	32	199	10
8C-187821	163	60	214	25	25	25	25	31	15	32	14	45	80	78	32	30	31	191	12
42004173	151	36	202	13	14	14	15	19	5	19	5	8	52	61	9	14	11	180	6
8C-190415	218	100	289	53	54	54	54	64	38	60	38	59	86	78	57	54	54	275	31
7B-187595	1	1	127	1	1	1	1	1	1	1	1	1	2	1	1	1	1	7	1
42023901	207	84	276	44	43	43	37	56	24	37	24	32	59	56	25	30	31	261	17
42028319	209	88	284	47	46	46	41	47	21	36	25	54	66	65	43	39	36	258	5
42029357	213	85	284	44	44	44	43	51	22	39	24	35	61	61	37	39	37	273	12
42036303	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
42038347	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8C-172214	59	38	78	26	26	26	30	29	25	31	25	36	23	22	37	30	31	80	26
8C-174612	73	43	94	29	29	29	30	31	28	37	29	39	20	24	34	36	32	100	25
41929923	98	41	9	26	26	26	22	37	21	23	23	3	12	9	4	1	1	111	9
41929926	91	34	14	26	26	26	22	23	23	23	23	3	11	6	4	1	1	111	9
41929952	93	34	9	26	26	26	30	26	21	21	22	3	12	6	4	1	1	111	9
41938629	95	48	4	27	27	27	33	32	25	13	25	5	6	5	5	6	11	123	4
41938631	97	48	1	27	27	27	33	35	21	14	25	5	9	4	5	6	11	123	13
41938634	99	48	4	27	27	27	33	35	25	14	25	5	9	2	5	6	11	123	14
8C-179257	122	64	158	40	40	40	40	45	33	51	38	70	46	44	55	46	47	163	23
41977408	137	46	50	26	26	26	26	30	15	2	15	6	23	2	4	3	4	170	8
41977409	136	46	128	26	26	26	26	30	15	3	15	6	24	2	4	9	5	170	8
41977411	136	46	169	26	26	26	30	30	15	4	15	6	16	16	19	3	4	169	8
41993117	147	56	199	23	23	23	25	23	9	7	3	6	9	9	4	3	4	183	4
41993121	147	56	190	22	22	22	23	29	9	9	8	6	9	10	4	3	4	183	4
41993122	147	56	199	23	23	23	25	29	9	8	9	6	10	7	4	4	4	183	4
42016899	196	74	245	36	36	36	36	42	8	23	18	8	5	6	6	3	21	246	16
42016904	196	74	245	36	36	36	36	42	18	36	17	8	5	3	6	3	21	245	17
42016906	199	74	260	36	36	36	36	42	18	23	18	8	5	2	7	3	21	239	17
7B-189684	208	100	277	53	54	54	52	60	39	57	36	54	82	82	51	54	54	267	32
42030975	211	83	277	40	41	41	40	50	19	6	22	10	32	32	5	6	1	271	13
42030985	211	83	285	40	41	41	42	50	20	6	25	13	32	29	4	6	4	277	12
42030988	211	82	285	40	41	41	41	48	19	6	22	13	25	25	5	6	1	277	12
7B-191293	1	1	165	1	1	1	1	1	1	1	1	2	2	2	1	1	1	1	1
42033989	214	86	291	39	42	42	44	50	21	24	14	16	20	20	8	23	22	281	10
42033991	214	87	277	39	43	43	44	53	21	25	16	16	20	16	8	25	25	281	11
42033995	214	87	291	42	43	43	43	52	21	25	16	16	13	13	5	25	23	281	10
Average	118.3	52.7	155.7	29.8	30.1	30.	30.2	33.9	20.7	29.8	20.2	34.4	39.0	37.7	29.0	27.7	27.3	149.8	15.4
Combustor	32	50	29	115	113	113	112	92	166	105	169	90	92	94	104	113	116	28	186
Late	155	137	158	72	74	74	75	95	21	82	18	97	95	93	83	74	71	159	1
Total	17%	27%	16%	61%	60%	60%	60%	49%	89%	56%	90%	48%	49%	50%	56%	60%	62%	15%	99%
Min	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max	226	108	309	60	61	61	60	68	41	64	41	76	101	97	71	60	60	309	39

Table K.8: Model TAT output (days) per scenario 4a

Comb	57	58	59	60	61	62	63	64	65	66	67	68	69	70
7B-169363	1	5	6	1	1	1	1	1	1	1	1	1	1	1
7B-169366	25	149	275	31	37	37	33	50	45	45	44	44	36	33
7B-171379	1	5	12	1	1	1	1	1	1	1	1	1	1	1
7B-171814	1	5	6	1	1	1	1	1	1	1	1	1	1	1
7B-172459	24	90	167	45	27	27	27	31	30	29	30	29	28	27
7B-172469	1	1	1	1	1	1	1	1	1	1	1	1	1	1
7B-172922	1	1	8	1	1	1	1	1	1	1	1	1	1	1
7B-173055	1	4	18	1	1	1	1	1	1	1	1	1	1	1
7B-173332	1	30	93	1	1	1	1	1	1	1	1	1	1	1
7B-174790	23	118	223	42	34	31	31	41	38	37	37	37	31	31
7B-175333	22	133	250	34	34	30	34	42	40	40	40	41	30	33
7B-176124	20	149	282	29	37	37	37	51	46	46	45	45	37	38
41933078	5	128	253	19	30	29	17	31	25	24	23	25	22	23
7B-176503	1	47	159	1	1	1	1	1	1	1	1	1	1	1
7B-176822	1	95	228	1	1	1	1	1	1	1	1	1	1	1
7B-176828	24	163	303	25	39	39	39	53	50	47	47	47	37	38
7B-176861	1	106	244	1	1	1	1	14	1	1	1	9	1	1
41953805	2	157	338	2	25	24	23	30	31	18	30	29	23	24
7B-177542	1	121	274	1	1	1	1	8	2	1	1	4	1	1
7B-178403	20	189	362	21	40	37	37	55	50	49	47	49	36	37
7B-178048	1	38	183	1	1	1	1	1	1	1	1	1	1	1
7B-180314	17	211	408	9	38	37	38	58	52	51	46	50	36	38
7B-180318	17	206	401	9	39	39	37	58	52	50	50	50	37	37
42021093	8	302	632	1	23	19	26	44	31	43	23	33	23	16
7B-181062	1	96	258	1	1	1	1	1	1	1	1	1	1	1
7B-181541	11	213	428	5	31	31	29	51	44	43	39	43	26	30
7B-182310	16	228	460	8	29	28	27	50	43	41	41	42	26	26
7B-182576	19	227	463	10	30	29	26	52	45	43	40	43	25	26
7B-182864	15	211	428	8	21	21	21	42	36	32	30	32	21	21
7B-184359	13	234	485	8	25	25	23	47	40	38	36	38	23	23
7B-184522	18	295	631	8	26	24	22	51	45	40	37	40	23	19
7B-184762	16	240	498	8	30	25	25	51	45	40	38	40	23	23
7B-185456	1	134	405	1	1	1	1	1	1	1	1	1	1	1
7B-186117	1	150	421	1	1	1	1	1	1	1	1	1	1	1
41990024	1	205	463	1	3	3	2	24	12	15	8	12	2	2
7B-186811	13	256	543	7	13	12	11	40	33	29	26	28	11	11
7B-187335	1	170	435	1	1	1	1	1	1	1	1	1	1	1
7B-187348	20	271	572	8	20	16	14	43	37	34	29	34	15	14
42022391	13	300	643	8	33	27	33	47	51	48	37	35	29	30
7B-187640	24	315	656	14	37	36	34	64	58	55	50	51	35	35
7B-188048	18	276	583	10	22	18	18	47	39	36	32	37	18	17
7B-188112	13	275	596	8	19	17	16	46	37	37	32	36	16	16
7B-188641	20	283	603	10	24	22	22	51	44	39	36	39	23	19
42016949	14	5	13	8	32	27	15	15	39	34	28	36	18	14
42016957	14	5	13	8	32	26	15	14	39	34	28	35	15	13
42016958	14	5	13	8	32	26	18	15	39	34	28	36	18	15
7B-189699	19	338	708	8	42	37	37	65	60	58	51	52	36	35
42038682	3	12	12	8	19	18	15	25	31	30	22	11	15	8
42038683	3	12	11	8	22	15	17	24	30	32	22	12	11	11
42038685	2	12	11	5	18	18	15	24	40	32	26	11	11	15
8C-165302	12	77	160	43	24	27	24	27	27	23	23	22	22	24
8C-171235	12	61	117	41	14	13	12	14	15	14	14	14	14	13
8C-171590	13	71	135	40	18	18	18	22	22	22	22	18	18	19
8C-171591	15	171	344	18	39	38	36	47	44	44	43	43	36	33
8C-172061	22	90	160	44	27	27	27	30	29	28	29	29	26	27
41898510	9	11	9	39	9	8	8	8	9	9	9	9	9	9
41898647	8	2	10	39	3	3	9	8	4	3	3	3	9	9
41898653	9	12	10	40	10	9	9	9	5	9	10	4	10	9
8C-172574	22	84	160	44	27	24	24	29	29	28	29	28	27	24
8C-172987	16	73	142	43	19	18	22	23	22	23	22	23	19	22
8C-173014	19	78	148	43	22	22	22	24	24	23	24	24	22	22
8C-173019	15	68	125	43	16	16	16	16	19	16	19	16	16	19
8C-174051	28	118	210	42	34	34	31	41	38	37	37	37	34	35
8C-174108	16	170	331	18	37	37	33	47	44	43	40	40	32	33
8C-174372	23	107	196	42	30	30	31	38	36	35	35	35	30	31
41915297	9	3	10	37	24	15	25	3	26	8	15	16	15	16
41915299	9	3	10	37	24	15	24	2	26	5	15	16	12	16
41915300	9	3	10	37	24	15	23	3	26	8	12	16	15	16
8C-174734	25	124	229	40	34	33	34	43	41	37	37	40	33	35
8C-175191	20	126	236	29	28	27	27	41	34	34	34	34	28	27
8C-175964	14	125	242	25	27	26	26	35	33	32	33	33	25	26
8C-175965	21	141	267	24	32	30	32	44	38	37	39	38	30	32
8C-176317	19	142	273	28	36	36	35	49	43	43	42	42	35	36
8C-177163	22	166	314	26	41	40	40	54	49	49	47	48	37	40
8C-177464	18	169	323	22	38	38	37	51	47	45	45	44	38	37
8C-177979	13	165	313	18	29	29	28	43	41	39	36	36	29	32
8C-178449	14	177	359	16	34	33	34	51	46	41	44	45	32	34
41949081	4	2	8	14	28	25	28	4	37	32	32	10	23	28
41949083	4	2	8	14	28	25	25	4	32	32	30	11	23	25
41949084	4	2	8	14	28	25	28	4	37	32	32	11	23	28
8C-178772	17	181	349	20	40	37	37	51	48	48	44	47	36	37
8C-178744	16	183	365	9	32	32	32	50	43	43	38	44	31	32
8C-180312	15	197	392	7	36	36	36	52	49	46	45	49	35	35
8C-181214	14	197	398	6	34	34	30	49	45	43	41	43	31	31
8C-181567	7	201	412	6	19	19	16	35	30	28	26	28	15	16
8C-181657	11	210	413	4	32	31	31	51	44	44	38	45	31	32
8C-183126	14	208	431	7	22	21	20	41	36	33	29	33	19	21
8C-184041	1	162	379	1	1	1	1	23	1	1	8	10	1	1
8C-184113	16	227	464	4	26	25	24	46	40	38	37	38	23	25
8C-184727	15	231	477	4	25	24	23	44	38	36	32	36	21	22
8C-185193	14	245	496	7	24	22	21	45	42	37	34	37	20	20
8C-185875	8	231	496	6	15	13	12	35	30	28	23	27	9	13
8C-185988	1	198	450	1	1	1	1	22	2	1	1	11	2	1
7B-186272	11	239	506	5	17	15	12	37	32	30	25	29	11	11
8C-186495	16	253	532	9	23	21	21	46	38	35	31	37	17	18
8C-186522	23	294	615	13	30	29	29	56	49	45	42	44	27	27
41994765	1	226	484	1	8	4	4	25	18	18	11	17	3	3
8C-186679	10	247	534	4	11	10	8	37	29	25	19	25	8	8
8C-187638	1	210	482	1	1	1	1	22	1	7	3	15	1	1

Table K.9: Model TAT output (days) per scenario 4b

Comb	57	58	59	60	61	62	63	64	65	66	67	68	69	70
8C-187758	20	307	649	12	34	34	35	62	54	48	42	47	30	34
41999917	1	225	490	1	2	2	1	22	17	8	8	14	1	1
8C-188108	22	289	610	10	28	25	24	52	45	43	38	43	23	23
8C-188109	18	274	589	5	19	18	18	45	37	33	29	33	17	16
8C-188681	24	317	660	11	36	33	33	61	57	53	47	50	33	33
8C-189867	25	329	680	14	39	37	36	65	58	53	49	53	32	35
7B-180753	31	339	701	16	44	40	39	74	66	61	54	59	39	39
8C-190256	25	331	688	15	39	38	38	71	60	54	50	53	36	36
8C-191014	21	335	700	9	38	36	36	65	59	56	49	51	35	34
8C-191114	20	337	702	9	38	33	33	65	59	54	47	51	32	31
8C-191153	12	332	701	3	32	31	26	60	53	52	44	46	29	29
8C-191266	14	338	714	4	32	31	30	59	57	50	44	46	29	29
8C-191712	13	351	737	10	32	30	25	61	53	47	40	46	29	23
8C-191714	16	350	726	7	37	35	34	64	58	55	48	51	33	34
8C-193051	17	358	737	9	32	31	29	64	54	50	43	50	29	25
8E 172863	23	93	175	45	30	30	30	32	32	30	30	31	30	31
8E 174110	23	97	180	44	29	29	29	34	34	33	30	33	30	30
8E 174207	22	100	197	43	30	31	30	33	33	31	32	31	30	30
8E 176409	20	152	291	25	36	35	36	49	43	42	42	42	35	39
8E 177153	15	160	301	22	37	37	35	49	48	43	42	42	36	35
8E 178060	13	170	331	17	33	33	31	45	40	40	39	39	32	31
8E 181089	9	200	404	6	27	27	26	46	39	39	33	39	25	26
8E 181652	11	205	420	8	35	35	35	51	46	46	42	46	35	35
8E 183259	15	220	450	9	26	26	25	44	40	37	33	36	22	25
8E 183555	20	235	466	11	33	33	29	50	47	43	40	41	28	29
8E 185110	14	237	481	6	26	22	20	46	40	39	33	34	20	22
8E 185519	8	240	491	3	22	19	18	43	38	33	30	31	17	17
8E 186468	17	252	533	9	24	22	18	45	38	35	31	36	18	18
8E 189023	23	308	638	10	30	28	29	57	50	46	39	45	28	28
8E 189404	23	314	650	13	35	33	33	57	56	50	47	49	33	30
8E 191289	5	300	657	1	1	1	1	52	2	2	16	31	1	1
8E 191673	12	349	720	6	35	33	29	62	55	54	43	49	30	28
8E 191681	11	336	707	4	32	30	29	58	53	49	43	45	29	28
8E 192087	13	352	736	10	32	29	29	59	53	50	43	46	29	26
41905579	13	75	144	42	21	21	21	21	20	19	20	20	19	20
41905582	13	75	137	42	21	21	21	22	22	19	20	20	19	20
41910974	13	90	172	36	26	21	20	28	26	26	25	27	19	19
41917639	5	88	180	27	21	21	18	27	20	18	19	19	14	21
41925160	9	120	238	22	30	28	29	31	29	15	17	29	28	28
7B-176244	1	38	86	1	1	1	1	1	1	1	1	1	1	1
41948608	6	152	326	12	27	22	26	36	35	29	32	28	20	26
7B-179318	15	191	379	8	36	36	32	50	46	45	44	45	33	31
41958592	2	169	352	1	22	16	23	37	25	24	19	25	12	22
41958594	2	169	352	1	24	16	25	37	25	25	23	25	15	22
41959389	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959391	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41959392	1	1	1	1	1	1	1	1	1	1	1	1	1	1
41962148	4	169	370	1	24	22	22	31	35	34	16	35	22	23
41991494	3	223	495	5	13	14	12	36	27	21	14	23	5	9
8C-186077	10	239	506	5	16	12	15	38	31	26	25	26	12	12
41993716	4	231	489	1	13	9	8	30	23	23	10	17	8	7
41994769	1	226	485	1	8	4	3	25	19	19	11	19	3	3
8C-186678	10	253	534	5	16	12	11	39	31	29	24	30	11	11
8C-187821	11	259	553	4	14	10	9	38	30	28	23	28	10	10
42004173	6	242	529	1	4	5	6	22	11	14	11	15	5	5
8C-190415	24	325	681	12	39	37	36	66	58	54	50	53	37	37
7B-187595	1	175	467	1	1	1	1	1	1	1	1	1	1	1
42023901	8	295	638	3	28	29	28	42	46	43	37	31	24	25
42028319	8	307	677	1	26	25	25	50	46	39	35	39	21	21
42029357	8	323	680	1	25	28	24	53	49	44	36	42	22	24
42036303	1	1	1	1	1	1	1	1	1	1	1	1	1	1
42038347	1	1	1	1	1	1	1	1	1	1	1	1	1	1
8C-172214	20	92	170	44	25	24	25	30	31	29	29	29	24	24
8C-174612	17	119	224	29	25	24	24	36	31	31	30	30	24	25
41929923	9	6	8	23	27	35	19	5	27	27	23	13	23	20
41929926	9	6	8	23	27	26	16	5	21	26	21	13	19	16
41929952	9	6	8	22	36	26	16	5	21	27	22	13	19	19
41938629	7	8	20	15	22	22	22	4	33	28	11	11	20	22
41938631	7	8	13	15	22	22	25	4	34	29	14	8	21	26
41938634	7	8	19	15	25	22	25	4	34	29	14	11	21	26
8C-179257	16	190	373	10	33	33	33	50	44	44	40	44	31	33
41977408	9	5	3	3	18	16	3	3	18	16	12	8	12	15
41977409	9	5	2	3	17	16	15	3	18	16	22	9	12	16
41977411	9	8	2	3	18	17	3	3	18	15	22	3	12	15
41993117	4	22	8	2	14	10	9	14	24	24	10	4	9	3
41993121	4	22	43	2	14	10	8	15	24	23	11	4	9	8
41993122	7	22	37	2	14	10	9	15	24	24	11	4	8	8
42016899	15	3	3	10	32	17	18	1	39	35	30	35	17	16
42016904	15	2	3	9	32	18	17	3	39	36	30	35	17	16
42016906	15	3	3	10	32	28	17	3	39	36	30	35	17	16
7B-189684	27	325	681	15	40	36	33	65	60	53	47	53	32	33
42030975	7	6	12	4	25	25	22	8	46	40	32	7	18	21
42030985	7	6	12	4	25	26	25	13	48	40	33	8	20	22
42030988	7	6	12	4	28	26	25	8	48	40	33	8	20	21
7B-191293	1	210	519	1	1	1	1	1	1	1	1	1	1	1
42033989	2	3	22	2	30	18	17	3	42	39	31	22	22	14
42033991	2	3	22	2	29	18	17	4	39	42	31	23	22	16
42033995	2	3	22	2	30	18	16	7	39	39	30	23	22	14
Average	11.7	152.8	319.0	13.2	23.0	21.2	20.4	31.7	32.1	29.9	26.9	27.5	19.6	19.9
Combustor	187	48	45	162	165	170	176	96	95	110	127	121	180	176
Late	0	139	142	25	22	17	11	91	92	77	60	66	7	11
Total	100%	26%	24%	87%	88%	91%	94%	51%	51%	59%	68%	65%	96%	94%
Min	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Max	31	358	737	45	44	40	40	74	66	61	54	59	39	40

L

Future State Analysis

L.0.1. Constant Capacity of 4 Multiskilled Mechanics

This section contains the graphs of the model output using a constant capacity of 4 multiskilled mechanics per day. The following graphs show histograms and probability plots of the combustor TAT for all combustors together and for each combustor type.

All Combustors

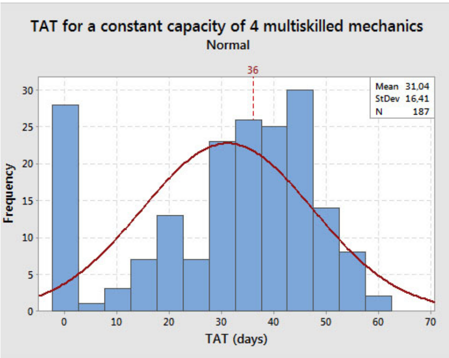


Figure L.1: Combustor TAT for a constant capacity of 4 multiskilled mechanics

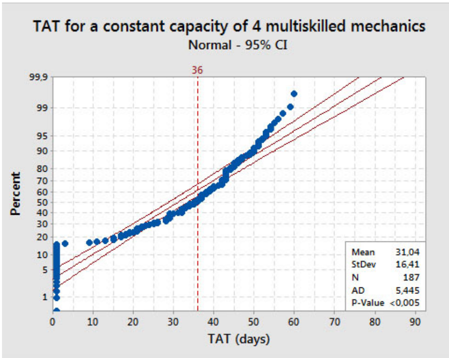


Figure L.2: Combustor TAT for a constant capacity of 4 multiskilled mechanics

7B Combustors

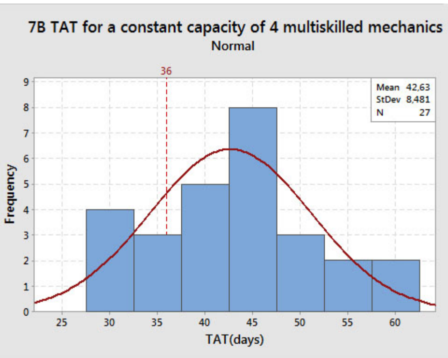


Figure L.3: 7B Combustor TAT for a constant capacity of 4 multiskilled mechanics

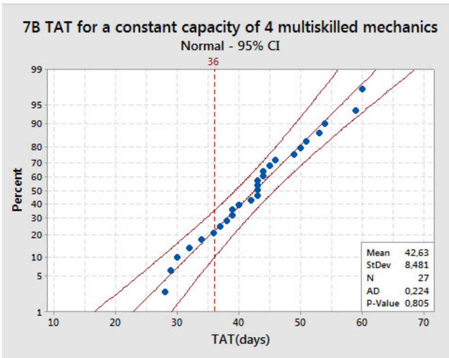


Figure L.4: 7B Combustor TAT for a constant capacity of 4 multiskilled mechanics

8C Combustors

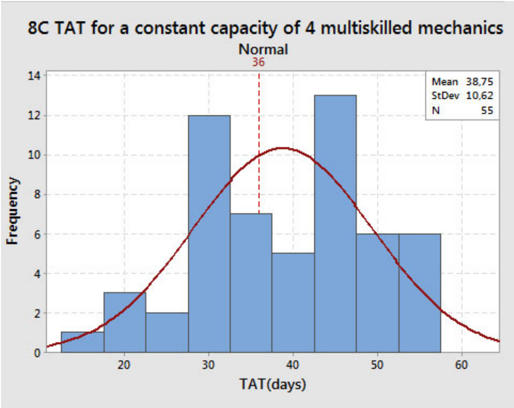


Figure L.5: 8C Combustor TAT for a constant capacity of 4 multiskilled mechanics

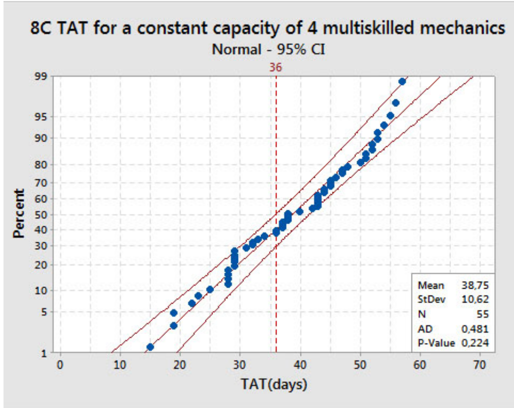


Figure L.6: 8C Combustor TAT for a constant capacity of 4 multiskilled mechanics

8E Combustors

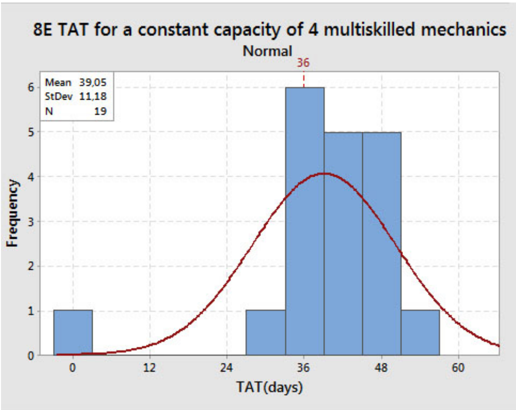


Figure L.7: 8E Combustor TAT for a constant capacity of 4 multiskilled mechanics

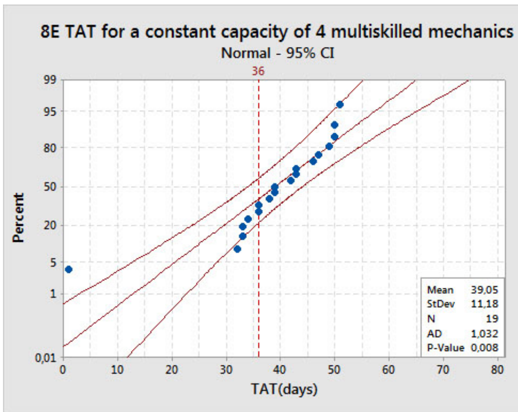


Figure L.8: 8E Combustor TAT for a constant capacity of 4 multiskilled mechanics

L.0.2. Constant Capacity of 5 Multiskilled Mechanics

This section contains the graphs of the model output using a constant capacity of 5 multiskilled mechanics per day. The following graphs show histograms and probability plots of the combustor TAT for all combustors together and for each combustor type.

All Combustors

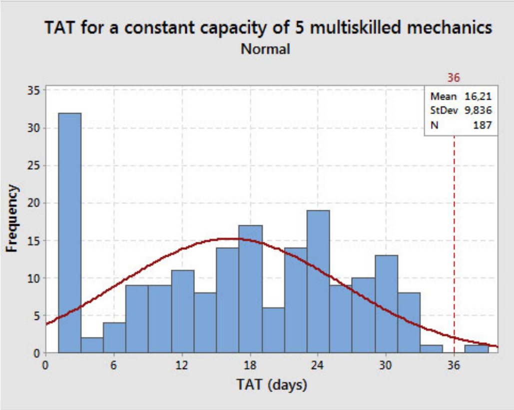


Figure L.9: Combustor TAT for a constant capacity of 5 multiskilled mechanics

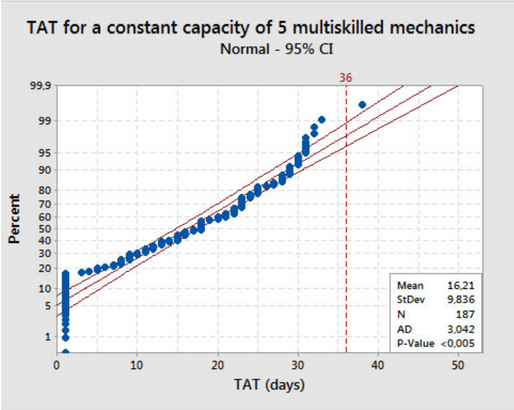


Figure L.10: Combustor TAT for a constant capacity of 5 multiskilled mechanics

7B Combustors

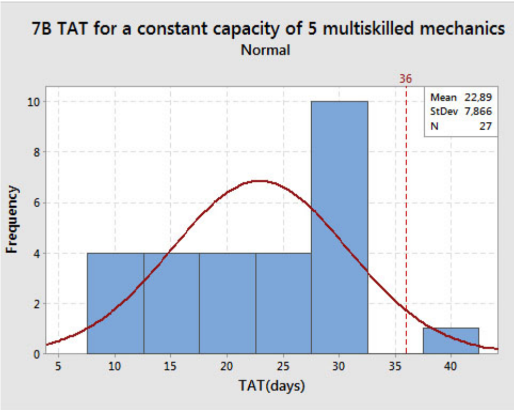


Figure L.11: 7B Combustor TAT for a constant capacity of 5 multiskilled mechanics

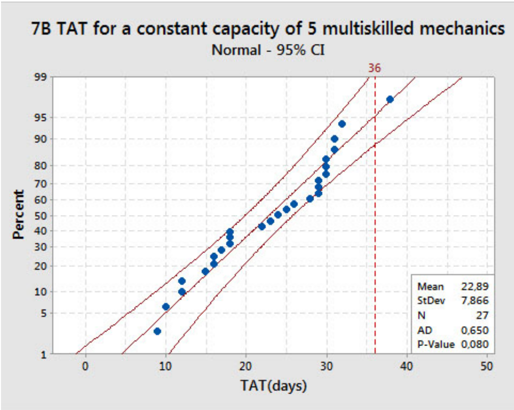


Figure L.12: 7B Combustor TAT for a constant capacity of 5 multiskilled mechanics

8C Combustors

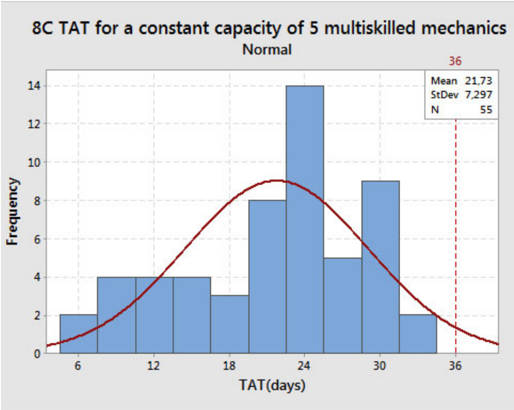


Figure L.13: 8C Combustor TAT for a constant capacity of 5 multiskilled mechanics

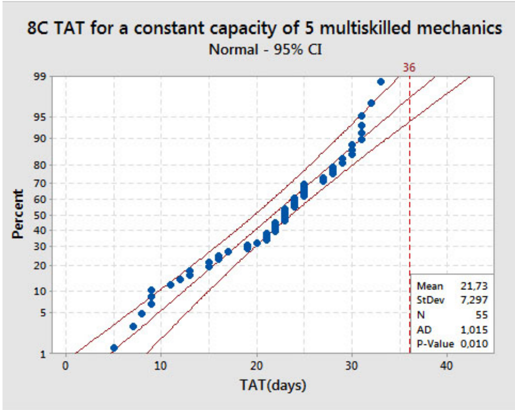


Figure L.14: 8C Combustor TAT for a constant capacity of 5 multiskilled mechanics

8E Combustors

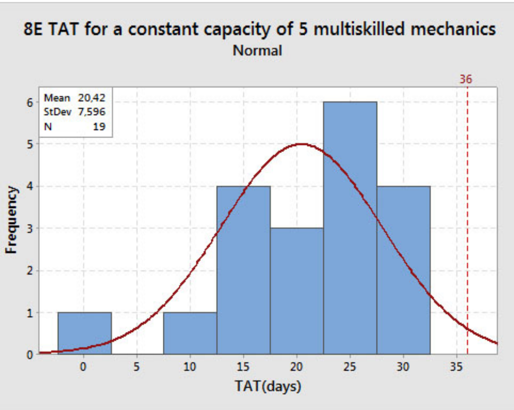


Figure L.15: 8E Combustor TAT for a constant capacity of 5 multiskilled mechanics

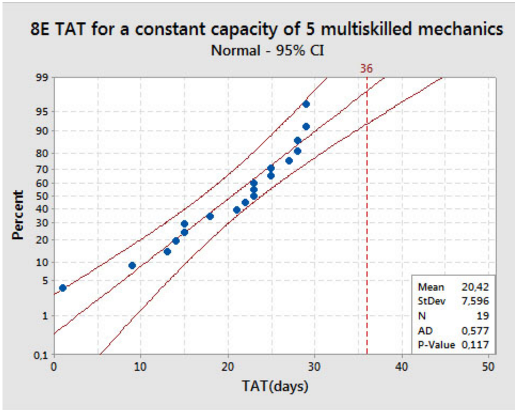


Figure L.16: 8E Combustor TAT for a constant capacity of 5 multiskilled mechanics

L.0.3. Constant Capacity of 6 Multiskilled Mechanics

This section contains the graphs of the model output using a constant capacity of 6 multiskilled mechanics per day. The following graphs show histograms and probability plots of the combustor TAT for all combustors together and for each combustor type.

All Combustors

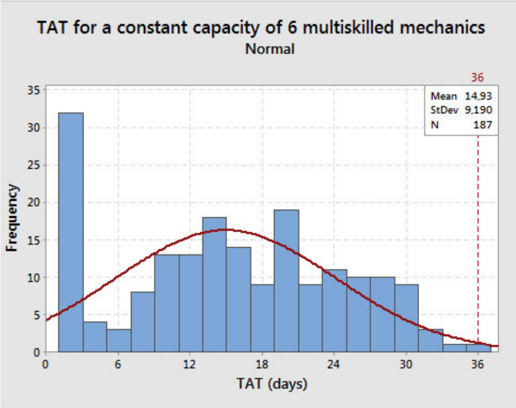


Figure L.17: Combustor TAT for a constant capacity of 6 multiskilled mechanics

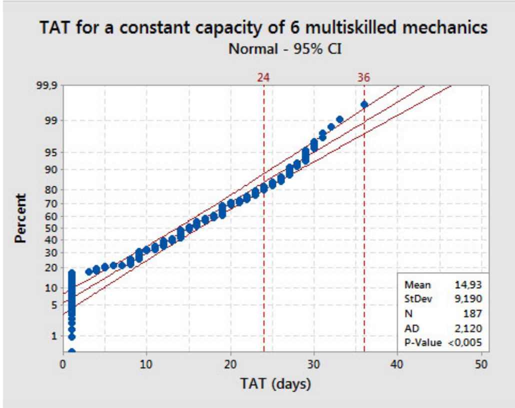


Figure L.18: Combustor TAT for a constant capacity of 6 multiskilled mechanics

7B Combustors

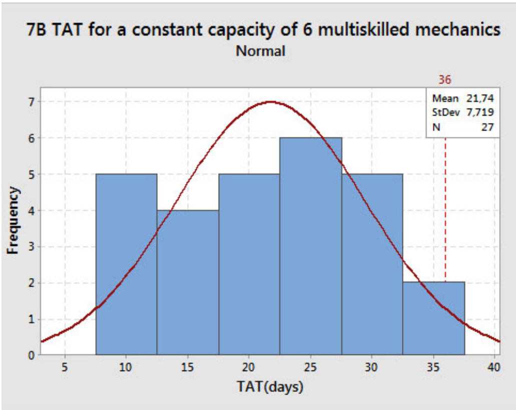


Figure L.19: 7B Combustor TAT for a constant capacity of 6 multiskilled mechanics

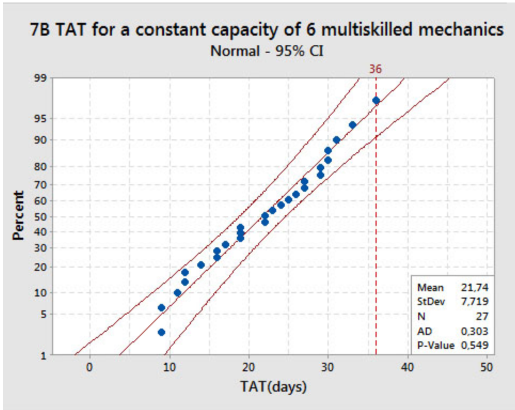


Figure L.20: 7B Combustor TAT for a constant capacity of 6 multiskilled mechanics

8C Combustors

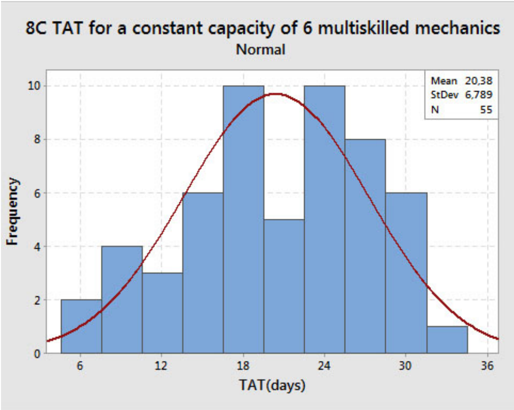


Figure L.21: 8C Combustor TAT for a constant capacity of 6 multiskilled mechanics

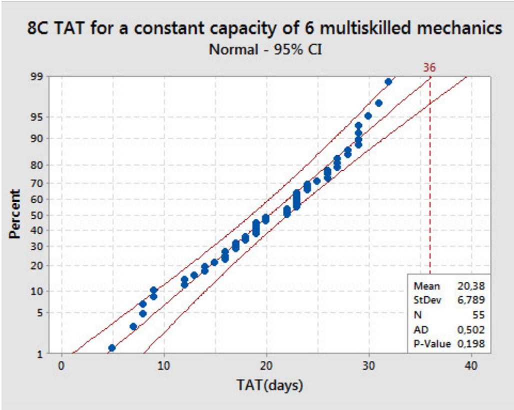


Figure L.22: 8C Combustor TAT for a constant capacity of 6 multiskilled mechanics

8E Combustors

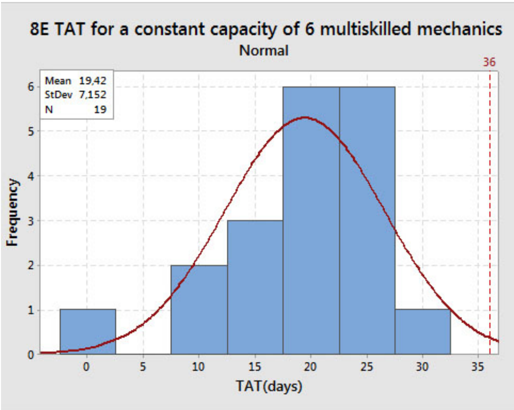


Figure L.23: 8E Combustor TAT for a constant capacity of 6 multiskilled mechanics

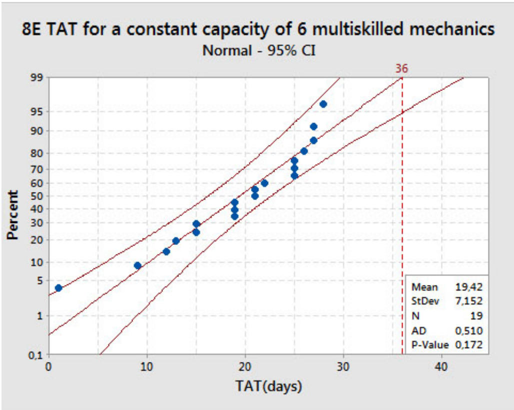


Figure L.24: 8C Combustor TAT for a constant capacity of 6 multiskilled mechanics

L.0.4. Constant Capacity of 7 Multiskilled Mechanics

This section contains the graphs of the model output using a constant capacity of 7 multiskilled mechanics per day. The following graphs show histograms and probability plots of the combustor TAT for all combustors together and for each combustor type.

All Combustors

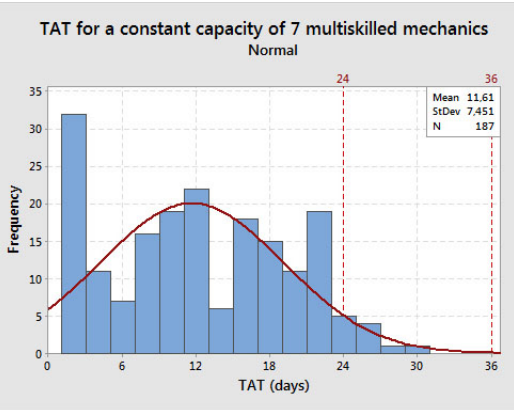


Figure L.25: Combustor TAT for a constant capacity of 7 multiskilled mechanics

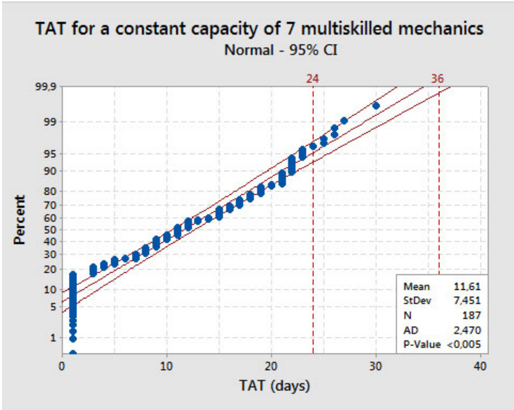


Figure L.26: Combustor TAT for a constant capacity of 7 multiskilled mechanics

7B Combustors

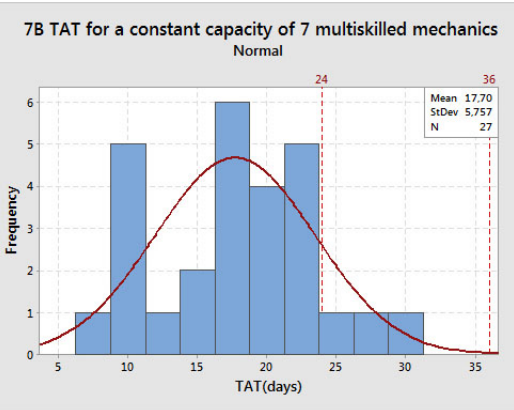


Figure L.27: 7B Combustor TAT for a constant capacity of 7 multiskilled mechanics

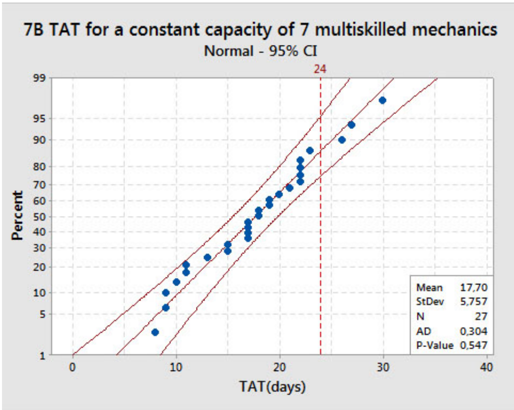


Figure L.28: 7B Combustor TAT for a constant capacity of 7 multiskilled mechanics

8C Combustors

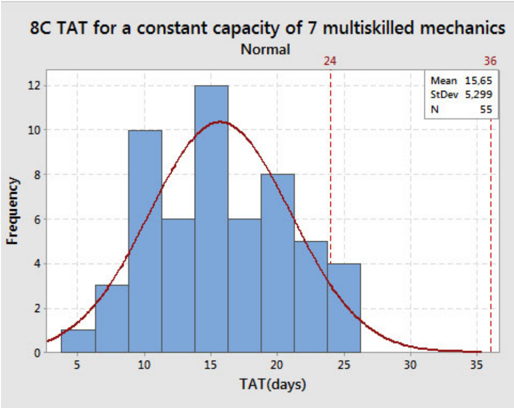


Figure L.29: 8C Combustor TAT for a constant capacity of 7 multiskilled mechanics

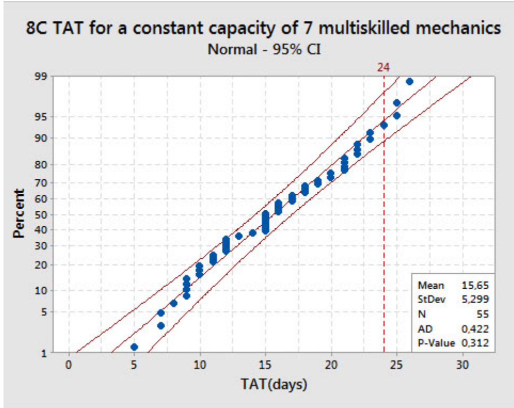


Figure L.30: 8C Combustor TAT for a constant capacity of 7 multiskilled mechanics

8E Combustors

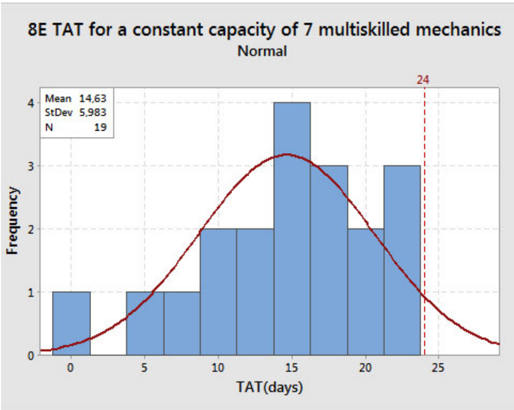


Figure L.31: 8E Combustor TAT for a constant capacity of 7 multiskilled mechanics

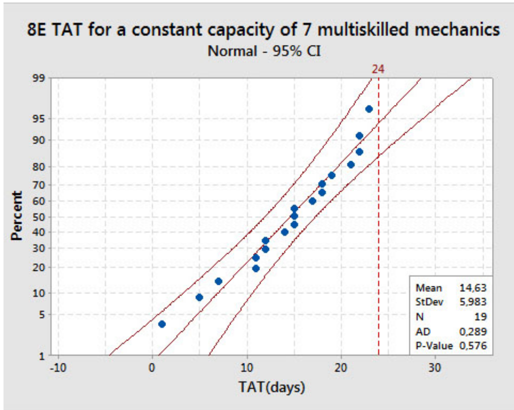


Figure L.32: 8C Combustor TAT for a constant capacity of 7 multiskilled mechanics

L.0.5. Constant Capacity of 4 Mechanics with limited capabilities

This section contains the graphs of the model output using a constant capacity of 4 mechanics with limited capabilities per day. The following graphs show histograms and probability plots of the combustor TAT for all combustors together and for each combustor type.

All Combustors

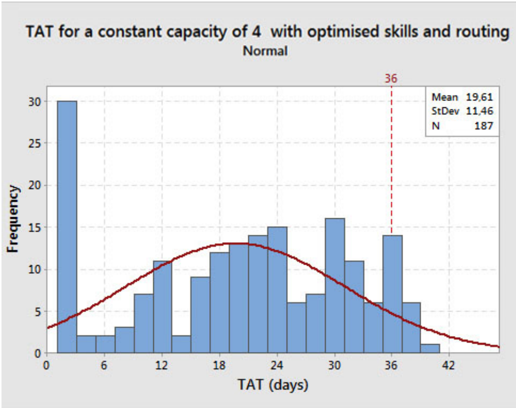


Figure L.33: Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

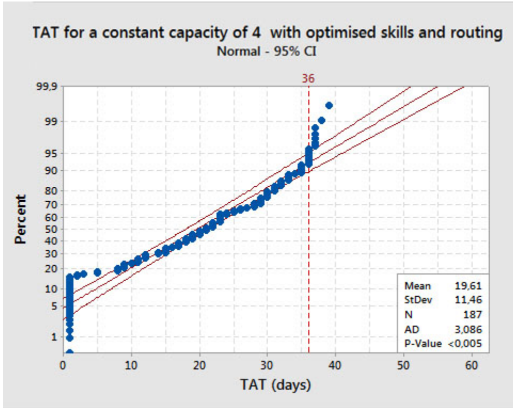


Figure L.34: Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

7B Combustors

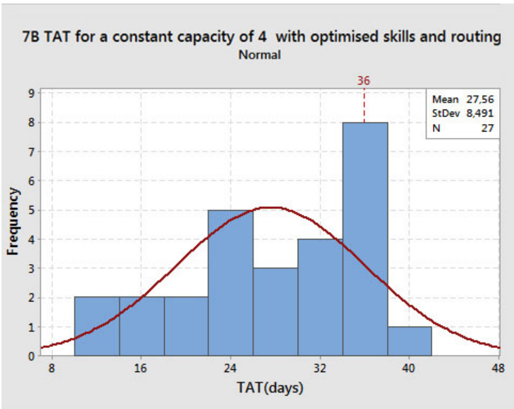


Figure L.35: 7B Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

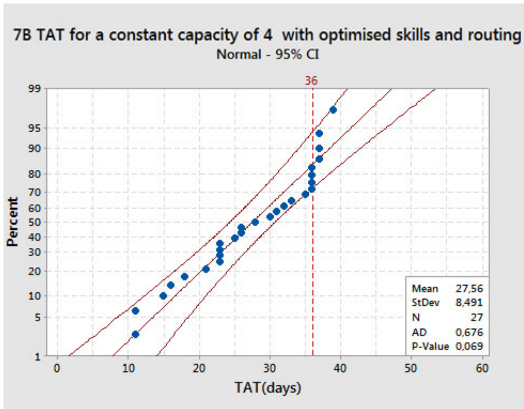
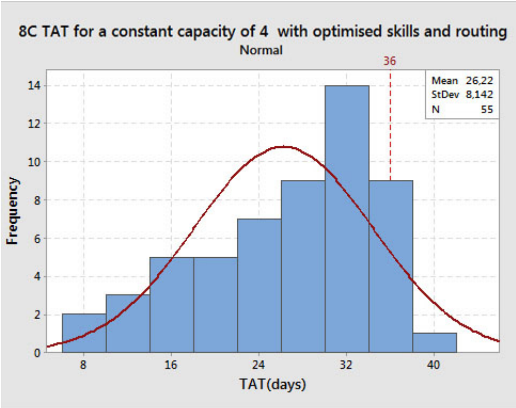


Figure L.36: 7B Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

8C Combustors



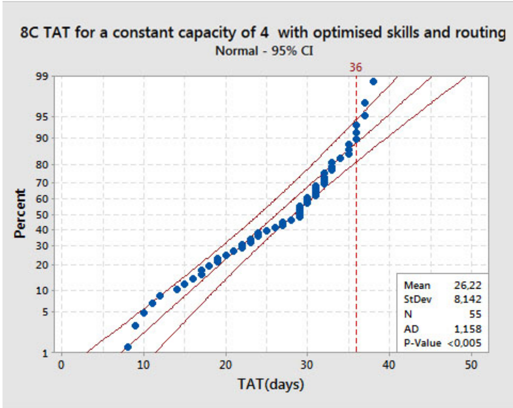
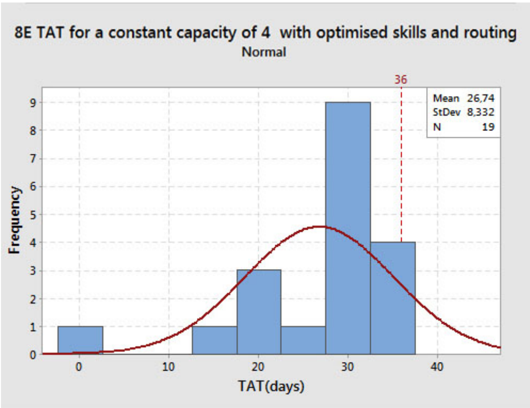


Figure L.37: 8C Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

Figure L.38: 8C Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

8E Combustors



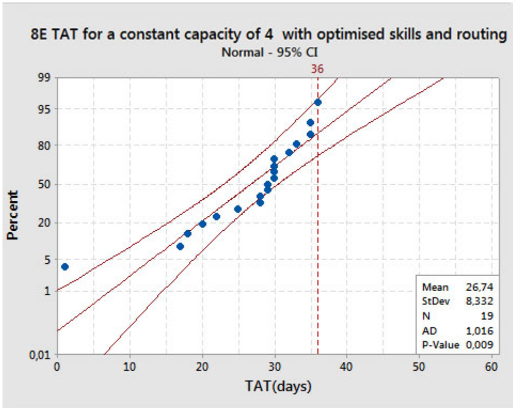


Figure L.39: 8E Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

Figure L.40: 8C Combustor TAT for a constant capacity of 4 mechanics with limited capabilities

M

Simulation Results Future State

This appendix contains the simulation results regarding the optimised future state scenarios. For each scenario the TAT per combustor, utilised capacity per available mechanic, utilised capacity for Q034, Q683, Q702 and the external server are determined along with the average and maximum components in a queue for these servers and the average waiting time in the queue. These findings are shown in a table for each scenario. Furthermore, for each scenario the utilisation rates of mechanics and servers can be found in a table.

Table M.1: Model output TAT (in days) per mechanic capacity scenario for 8E combustors

Combustor	**Start**	**TAT**	**4**	**5**	**6**	**7**	**4+**
8E 172863	14-1-2014	24	32	28	25	22	30
8E 174110	16-1-2014	25	34	27	27	21	30
8E 174207	20-1-2014	44	33	25	25	19	30
8E 176409	7-3-2014	49	42	29	26	18	35
8E 177153	19-3-2014	43	43	28	27	17	36
8E 178060	7-4-2014	37	39	23	19	12	32
8E 181089	6-6-2014	34	36	14	12	7	25
8E 181652	27-5-2014	37	49	23	21	11	35
8E 183259	30-6-2014	44	38	15	15	12	22
8E 183555	4-7-2014	39	43	21	19	18	28
8E 185110	1-8-2014	35	39	13	13	11	20
8E 185519	11-8-2014	28	33	9	9	5	17
8E 186468	26-8-2014	42	36	15	15	14	18
8E 189023	21-10-2014	58	46	25	25	22	28
8E 189404	23-10-2014	43	50	29	28	23	33
8E 191289	26-11-2014	43	1	1	1	1	1
8E 191673	18-12-2014	39	51	22	22	15	30
8E 191681	9-12-2014	35	50	23	21	15	29
8E 192087	29-12-2014	49	47	18	19	15	29
Average		39.37	39.05	20.42	19.42	14.63	26.74
On-time		6	7	19	19	19	19
Late		13	12	0	0	0	0
Total		19	19	19	19	19	19
% on-time		47%	100%	100%	100%	100%	
Min		24	1	1	1	1	1
Max		58	51	29	28	23	36

Table M.2: Model output TAT (in days) per mechanic capacity scenario for 7B combustors

Combustor	Start	Current	4	5	6	7	4+
7B-169366	24-2-2014	54	44	30	29	22	36
7B-172459	8-1-2014	23	29	24	23	21	28
7B-174790	29-1-2014	39	38	29	27	22	31
7B-175333	13-2-2014	42	40	28	26	20	30
7B-176124	3-3-2014	56	44	30	29	22	37
7B-176828	10-3-2014	50	46	32	30	22	37
7B-178403	17-4-2014	48	49	29	27	19	36
7B-179318	5-5-2014	25	45	25	22	15	33
7B-180314	12-5-2014	45	50	26	24	17	36
7B-180318	12-5-2014	38	51	29	25	17	37
7B-180753	10-11-2014	50	60	38	36	30	39
7B-181541	9-6-2014	38	43	16	12	9	26
7B-182310	4-7-2014	35	42	18	19	15	26
7B-182576	30-6-2014	37	43	18	19	18	25
7B-182864	24-6-2014	48	32	10	9	9	21
7B-184359	21-7-2014	41	39	12	12	10	23
7B-184522	20-10-2014	58	43	23	19	18	23
7B-184762	28-7-2014	38	43	16	16	11	23
7B-186272	25-8-2014	34	30	9	9	8	11
7B-186811	19-9-2014	45	28	12	11	11	11
7B-187348	25-9-2014	43	34	15	14	13	15
7B-187640	23-10-2014	49	54	30	33	27	35
7B-188048	29-9-2014	55	36	18	17	17	18
7B-188112	6-10-2014	38	37	17	16	17	16
7B-188641	6-10-2014	58	39	22	22	19	23
7B-189684	3-11-2014	50	53	31	30	26	32
7B-189699	25-11-2014	48	59	31	31	23	36
Average		43.89	42.63	22.89	21.74	17.70	27.56
On-Time		6	26	27	27	23	
Late		23	21	1	0	0	4
Total		27	27	27	27	27	27
Total		15%	22%	96%	100%	100%	85%
Min		23	28	9	9	8	11
Max		58	60	38	36	30	39

Table M.3: Model output TAT (in days) per mechanic capacity scenario for 8C combustors

Combustor	Start	Current	4	5	6	7	4+
8C-165302	15-1-2014	27	28	21	20	17	22
8C-171235	2-1-2014	15	15	13	12	9	14
8C-171590	6-1-2014	18	19	17	16	15	18
8C-171591	7-4-2014	52	43	25	24	16	36
8C-172061	9-1-2014	14	28	23	23	20	26
8C-172214	13-1-2014	11	29	23	23	18	24
8C-172574	8-1-2014	27	29	24	23	20	27
8C-172987	6-1-2014	35	22	19	17	15	19
8C-173014	6-1-2014	37	23	19	18	16	22
8C-173019	2-1-2014	34	19	15	14	14	16
8C-174051	22-1-2014	51	37	29	28	22	34
8C-174108	7-4-2014	49	43	25	23	16	32
8C-174372	21-1-2014	41	36	28	25	21	30
8C-174612	11-2-2014	36	31	21	18	11	24
8C-174734	30-1-2014	34	37	30	27	22	33
8C-175191	13-2-2014	42	34	23	22	15	28
8C-175964	21-2-2014	45	32	20	19	12	25
8C-175965	24-2-2014	60	38	25	24	18	30
8C-176317	25-2-2014	38	42	29	28	18	35
8C-177163	13-3-2014	47	47	33	29	21	37
8C-177464	24-3-2014	52	45	31	29	17	38
8C-177979	4-4-2014	42	40	22	19	12	29
8C-178449	20-4-2014	36	45	25	23	13	32
8C-178744	28-4-2014	42	43	22	19	12	31
8C-178772	10-4-2014	61	47	28	27	19	36
8C-179257	28-4-2014	45	43	24	19	12	31
8C-180312	6-5-2014	64	46	25	23	15	35
8C-181214	21-5-2014	37	44	22	20	10	31
8C-181567	26-6-2014	34	29	8	8	7	15
8C-181657	27-5-2014	44	44	21	17	10	31
8C-183126	27-6-2014	38	33	12	12	11	19
8C-184113	14-7-2014	36	38	15	15	12	23
8C-184727	22-7-2014	35	37	11	14	10	21
8C-185193	6-8-2014	35	38	13	13	9	20
8C-185875	21-8-2014	32	28	7	7	7	9
8C-186077	25-8-2014	28	29	9	9	9	12
8C-186495	26-8-2014	28	36	16	16	15	17
8C-186522	8-10-2014	57	45	27	27	23	27
8C-186678	8-9-2014	43	29	9	8	8	11
8C-186679	15-9-2014	37	25	5	5	5	8
8C-187758	23-10-2014	28	48	27	26	21	30
8C-187821	23-9-2014	63	28	9	9	9	10
8C-188108	7-10-2014	69	43	23	22	21	23
8C-188109	6-10-2014	43	32	16	16	15	17
8C-188681	27-10-2014	57	52	31	29	24	33
8C-189867	4-11-2014	41	53	31	30	25	32
8C-190256	10-11-2014	43	57	32	32	26	36
8C-190415	10-11-2014	58	54	31	31	25	37
8C-191014	19-11-2014	28	56	30	29	23	35
8C-191114	24-11-2014	50	53	30	26	22	32
8C-191153	1-12-2014	42	52	24	24	17	29
8C-191266	9-12-2014	43	51	24	22	16	29
8C-191712	29-12-2014	24	50	22	17	11	29
8C-191714	11-12-2014	46	55	28	26	19	33
8C-193051	29-12-2014	35	51	23	19	15	29
Average		42.91	41.80	21.98	20.52	15.43	26.91
On-time		14	13	44	44	44	41
Late		30	31	0	0	0	3
Total		44	44	44	44	44	44
% on-time		32%	30%	100%	100%	100%	93%
min		11	15	5	5	5	8
max		69	57	33	32	26	38

Table M.4: Mechanic utilisation rates per scenario

Worker	**4**	**4+**	**5**
A	98%	93%	81%
B	96%	94%	80%
C	97%	93%	101%
D	96%	87%	87%
E	-	-	69%
Average	97%	92%	84%

Table M.5: Server utilisation rates per scenario

Server	**4**	**4+**	**5**
#	5%	5%	4%
Ext	61%	64%	65%
Q029	0%	0%	0%
Q033	0%	0%	0%
Q034	80%	65%	68%
Q071	13%	13%	13%
Q100	1%	1%	1%
Q114	9%	9%	7%
Q116	4%	4%	3%
Q224	1%	1%	1%
Q244	2%	2%	2%
Q254	1%	1%	1%
Q434	0%	0%	0%
Q502	7%	7%	7%
Q516	0%	0%	0%
Q682	1%	1%	0%
Q683	49%	62%	44%
Q685	1%	1%	1%
Q702	100%	98%	94%
Q800	0%	0%	0%
Q801	0%	0%	0%
Average	16%	16%	15%

Table M.6: Scenario 4 server queue information

Server	**Utilization**	**Avg in queue**	**Avg Waiting time (hrs)**	**Max in queue**
Q034	80%	2.45	3.57	19
Q683	49%	0.42	1.57	6
Q702	100%	22.29	27.11	53
Q502	7%	0.01	0.35	2
Ext	61%	1.67	2.77	14

Table M.7: Scenario 4+ server queue information

Server	**Utilization**	**Avg in queue**	**Avg Waiting time (hrs)**	**Max in queue**
Q034	65%	1.57	4.37	15
Q683	62%	0.96	3.42	8
Q702	98%	13.11	16.41	33
Q502	7%	0.03	0.70	2
Ext	64%	2.12	3.30	22

Table M.8: Scenario 5 server queue information

Server	**Utilization**	**Avg in queue**	**Avg Waiting time (hrs)**	**Max in queue**
Q034	68%	1.64	2.25	14
Q683	44%	0.49	1.74	6
Q702	94%	10.72	13.40	36
Q502	7%	0.04	0.90	2
Ext	65%	2.10	3.23	15

N

Simio Model Properties

This appendix contains the specifications that have been used to generate the base model. Images are created of the model 'facility' of the add-on processes, the lists and additional statistics that have been used, and the tables that have been made using the current state data. Furthermore the properties for the servers, workers and combiners are shown.

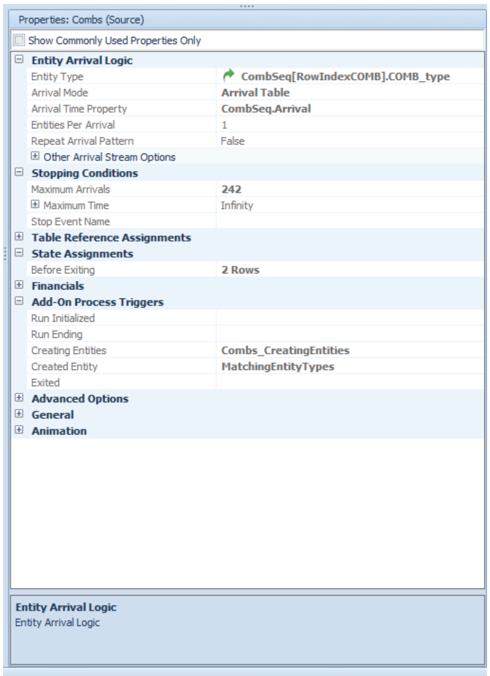


Figure N.1: Source Properties

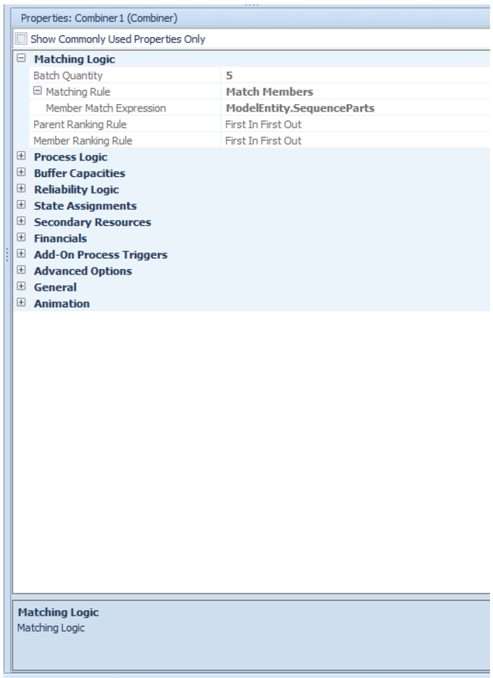


Figure N.2: Combiner Properties

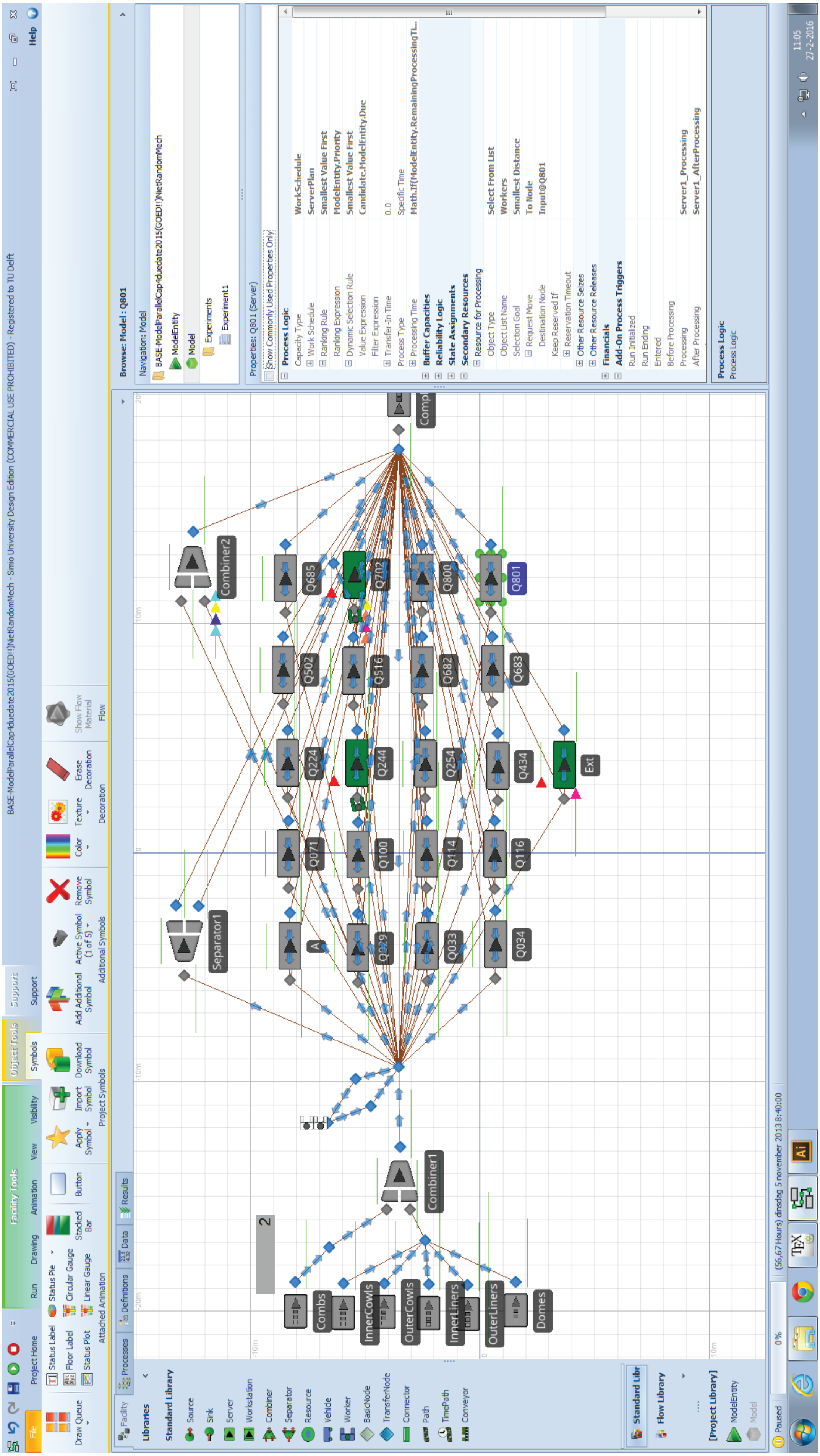


Figure N.3: Model Facility

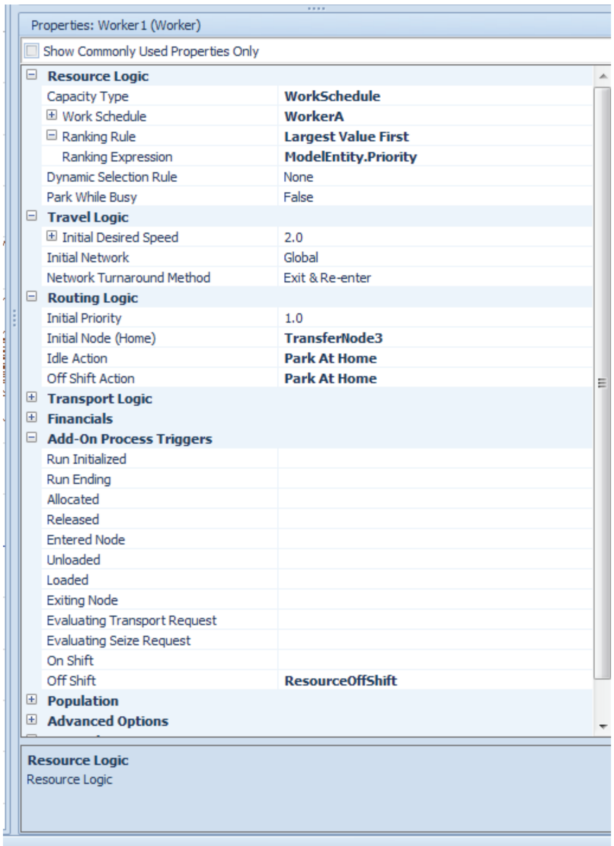


Figure N.4: Worker Properties

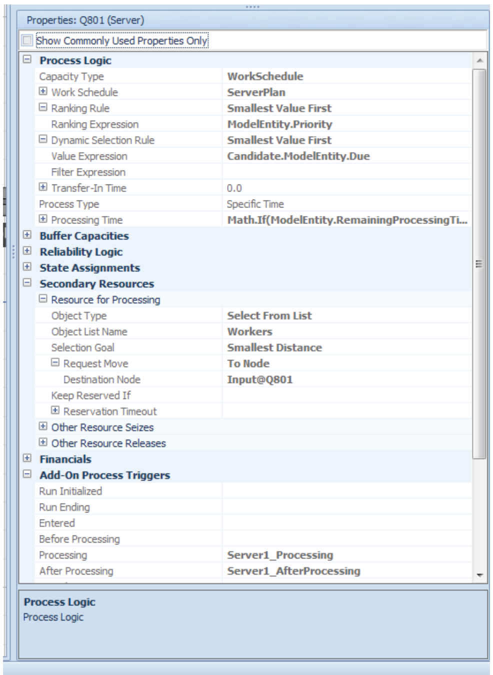


Figure N.5: Server Properties

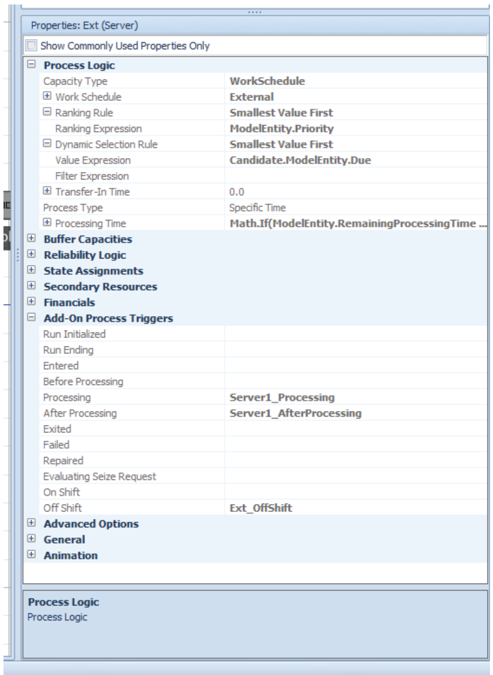


Figure N.6: External Server Properties

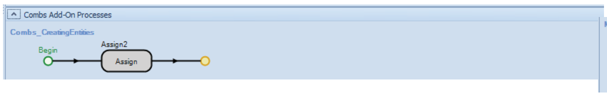


Figure N.7: Add-On Process to allocate the correct sequence to combustors

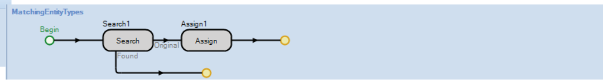


Figure N.8: Add-On Process to correctly match entities

Figure N.9: Add-On Process to correctly allocate sequences

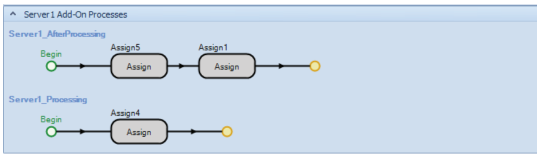


Figure N.10: Add-On Process for server behaviour when off-shift

Figure N.11: Add-On Process to correctly time the combustor completion

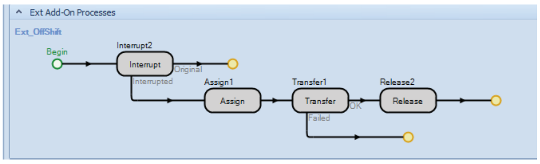


Figure N.12: Add-On Process for the external server behaviour when off-shift

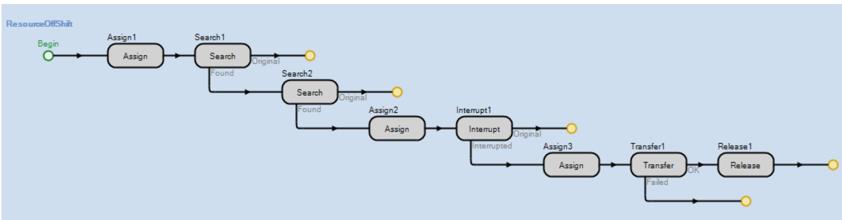


Figure N.13: Add-On Process for resource behaviour when off-shift

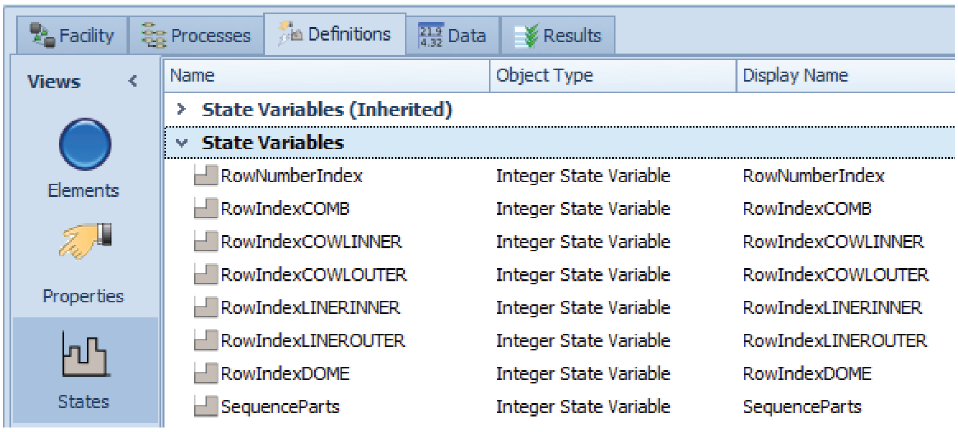


Figure N.14: List of used state variables

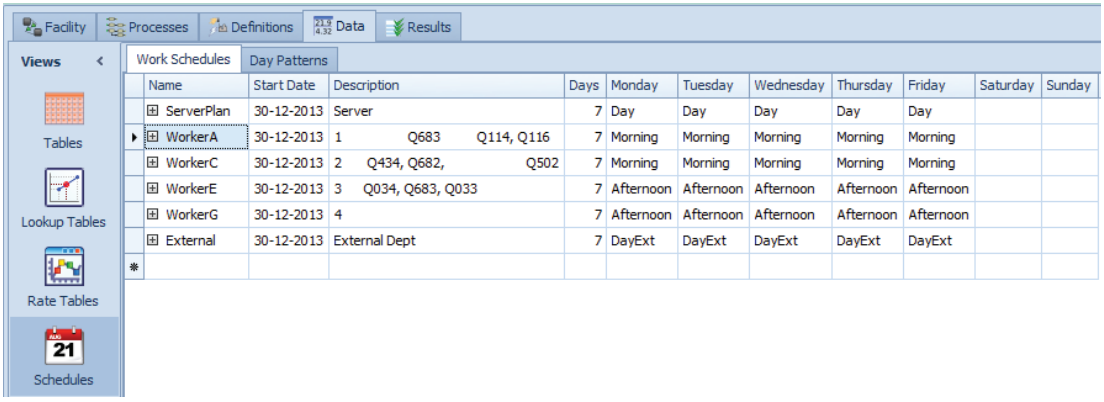


Figure N.15: Work-schedules for mechanics and servers

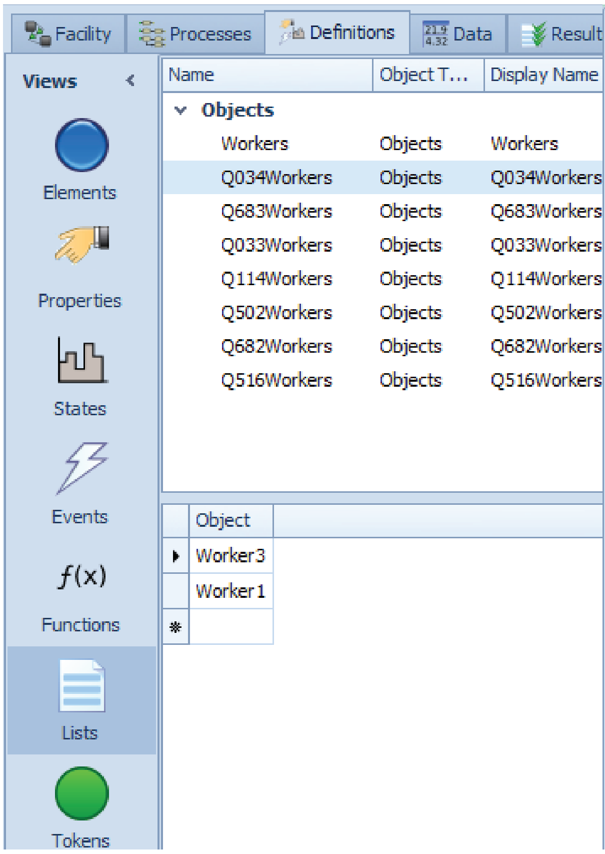


Figure N.16: List of Q034 workers

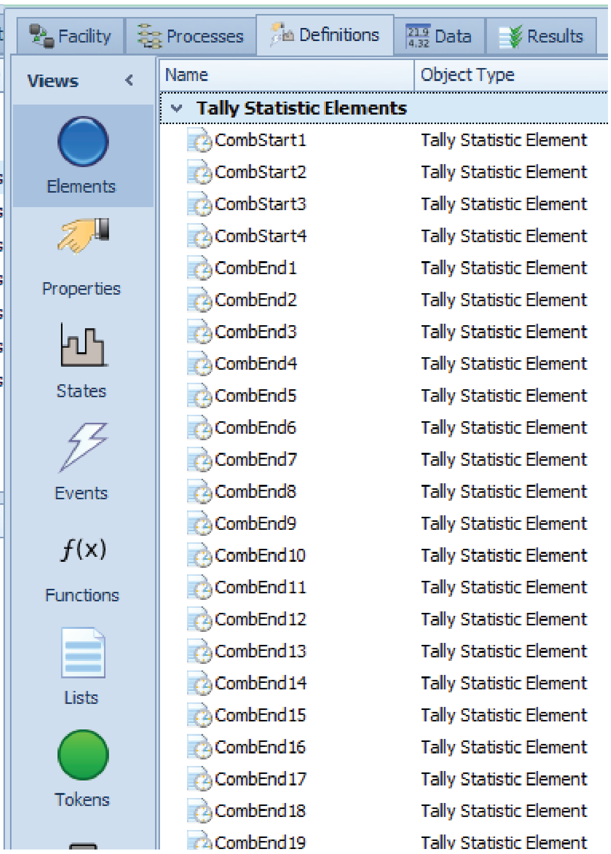
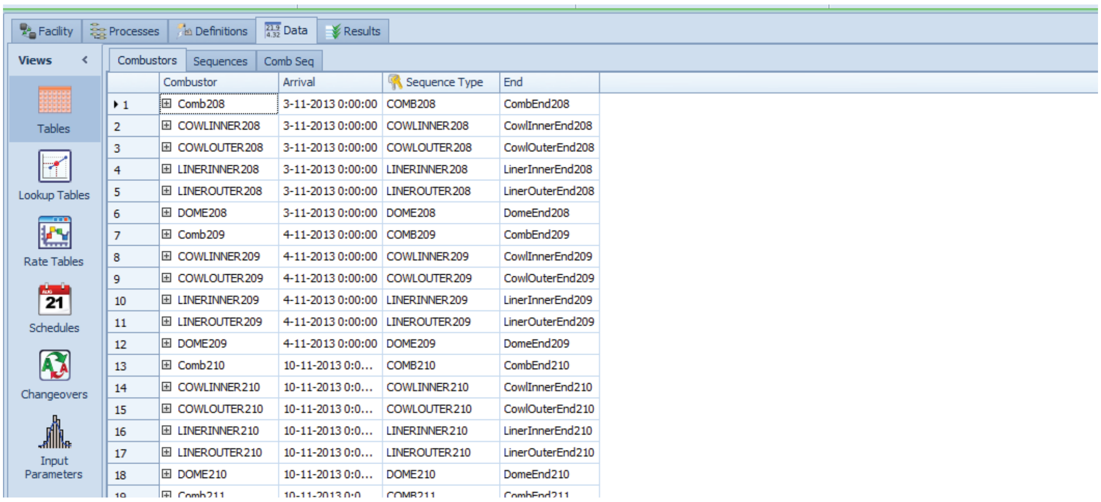
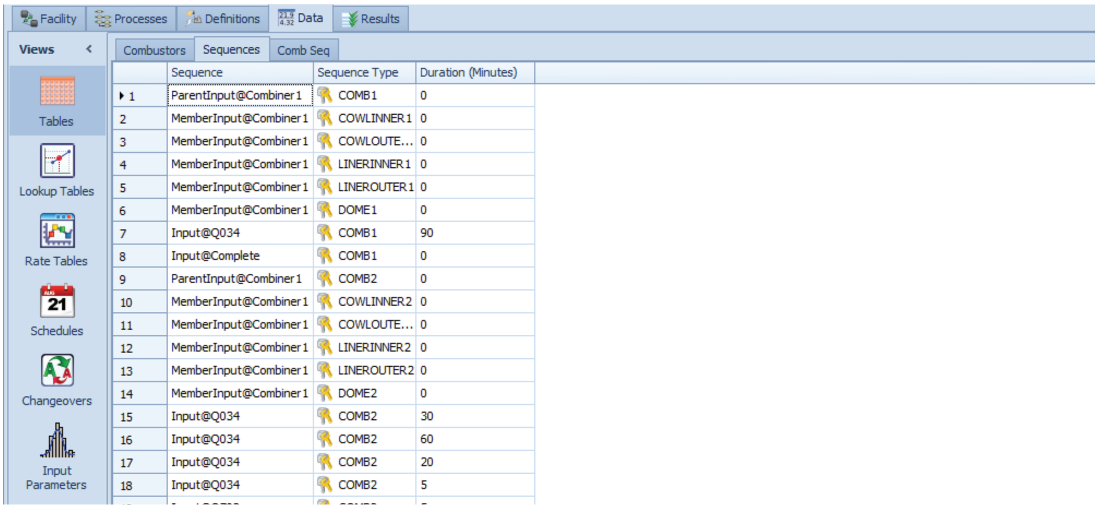


Figure N.17: List of used tally statistics



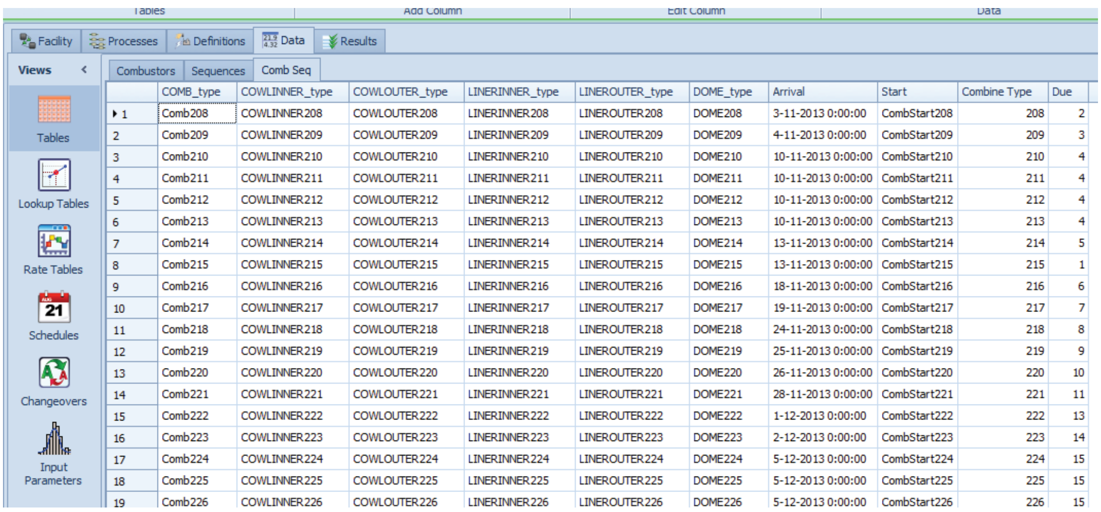
	Combustor	Arrival	Sequence Type	End
1	Comb208	3-11-2013 0:00:00	COMB208	CombEnd208
2	COWLINNER208	3-11-2013 0:00:00	COWLINNER208	CowlInnerEnd208
3	COWLOUTER208	3-11-2013 0:00:00	COWLOUTER208	CowlOuterEnd208
4	LINERINNER208	3-11-2013 0:00:00	LINERINNER208	LinerInnerEnd208
5	LINEROUTER208	3-11-2013 0:00:00	LINEROUTER208	LinerOuterEnd208
6	DOME208	3-11-2013 0:00:00	DOME208	DomeEnd208
7	Comb209	4-11-2013 0:00:00	COMB209	CombEnd209
8	COWLINNER209	4-11-2013 0:00:00	COWLINNER209	CowlInnerEnd209
9	COWLOUTER209	4-11-2013 0:00:00	COWLOUTER209	CowlOuterEnd209
10	LINERINNER209	4-11-2013 0:00:00	LINERINNER209	LinerInnerEnd209
11	LINEROUTER209	4-11-2013 0:00:00	LINEROUTER209	LinerOuterEnd209
12	DOME209	4-11-2013 0:00:00	DOME209	DomeEnd209
13	Comb210	10-11-2013 0:0...	COMB210	CombEnd210
14	COWLINNER210	10-11-2013 0:0...	COWLINNER210	CowlInnerEnd210
15	COWLOUTER210	10-11-2013 0:0...	COWLOUTER210	CowlOuterEnd210
16	LINERINNER210	10-11-2013 0:0...	LINERINNER210	LinerInnerEnd210
17	LINEROUTER210	10-11-2013 0:0...	LINEROUTER210	LinerOuterEnd210
18	DOME210	10-11-2013 0:0...	DOME210	DomeEnd210
19	Comb211	10-11-2013 0:0...	COMB211	CombEnd211

Figure N.18: Table 1 listing combustor arrival and maintenance sequence



	Sequence	Sequence Type	Duration (Minutes)
1	ParentInput@Combiner1	COMB1	0
2	MemberInput@Combiner1	COWLINNER1	0
3	MemberInput@Combiner1	COWLOUTE...	0
4	MemberInput@Combiner1	LINERINNER1	0
5	MemberInput@Combiner1	LINEROUTER1	0
6	MemberInput@Combiner1	DOME1	0
7	Input@Q034	COMB1	90
8	Input@Complete	COMB1	0
9	ParentInput@Combiner1	COMB2	0
10	MemberInput@Combiner1	COWLINNER2	0
11	MemberInput@Combiner1	COWLOUTE...	0
12	MemberInput@Combiner1	LINERINNER2	0
13	MemberInput@Combiner1	LINEROUTER2	0
14	MemberInput@Combiner1	DOME2	0
15	Input@Q034	COMB2	30
16	Input@Q034	COMB2	60
17	Input@Q034	COMB2	20
18	Input@Q034	COMB2	5

Figure N.19: Table 2 listing component maintenance sequences



	COMB_type	COWLINNER_type	COWLOUTER_type	LINERINNER_type	LINEROUTER_type	DOME_type	Arrival	Start	Combine Type	Due
1	Comb208	COWLINNER208	COWLOUTER208	LINERINNER208	LINEROUTER208	DOME208	3-11-2013 0:00:00	CombStart208	208	2
2	Comb209	COWLINNER209	COWLOUTER209	LINERINNER209	LINEROUTER209	DOME209	4-11-2013 0:00:00	CombStart209	209	3
3	Comb210	COWLINNER210	COWLOUTER210	LINERINNER210	LINEROUTER210	DOME210	10-11-2013 0:00:00	CombStart210	210	4
4	Comb211	COWLINNER211	COWLOUTER211	LINERINNER211	LINEROUTER211	DOME211	10-11-2013 0:00:00	CombStart211	211	4
5	Comb212	COWLINNER212	COWLOUTER212	LINERINNER212	LINEROUTER212	DOME212	10-11-2013 0:00:00	CombStart212	212	4
6	Comb213	COWLINNER213	COWLOUTER213	LINERINNER213	LINEROUTER213	DOME213	10-11-2013 0:00:00	CombStart213	213	4
7	Comb214	COWLINNER214	COWLOUTER214	LINERINNER214	LINEROUTER214	DOME214	13-11-2013 0:00:00	CombStart214	214	5
8	Comb215	COWLINNER215	COWLOUTER215	LINERINNER215	LINEROUTER215	DOME215	13-11-2013 0:00:00	CombStart215	215	1
9	Comb216	COWLINNER216	COWLOUTER216	LINERINNER216	LINEROUTER216	DOME216	18-11-2013 0:00:00	CombStart216	216	6
10	Comb217	COWLINNER217	COWLOUTER217	LINERINNER217	LINEROUTER217	DOME217	19-11-2013 0:00:00	CombStart217	217	7
11	Comb218	COWLINNER218	COWLOUTER218	LINERINNER218	LINEROUTER218	DOME218	24-11-2013 0:00:00	CombStart218	218	8
12	Comb219	COWLINNER219	COWLOUTER219	LINERINNER219	LINEROUTER219	DOME219	25-11-2013 0:00:00	CombStart219	219	9
13	Comb220	COWLINNER220	COWLOUTER220	LINERINNER220	LINEROUTER220	DOME220	26-11-2013 0:00:00	CombStart220	220	10
14	Comb221	COWLINNER221	COWLOUTER221	LINERINNER221	LINEROUTER221	DOME221	28-11-2013 0:00:00	CombStart221	221	11
15	Comb222	COWLINNER222	COWLOUTER222	LINERINNER222	LINEROUTER222	DOME222	1-12-2013 0:00:00	CombStart222	222	13
16	Comb223	COWLINNER223	COWLOUTER223	LINERINNER223	LINEROUTER223	DOME223	2-12-2013 0:00:00	CombStart223	223	14
17	Comb224	COWLINNER224	COWLOUTER224	LINERINNER224	LINEROUTER224	DOME224	5-12-2013 0:00:00	CombStart224	224	15
18	Comb225	COWLINNER225	COWLOUTER225	LINERINNER225	LINEROUTER225	DOME225	5-12-2013 0:00:00	CombStart225	225	15
19	Comb226	COWLINNER226	COWLOUTER226	LINERINNER226	LINEROUTER226	DOME226	5-12-2013 0:00:00	CombStart226	226	15

Figure N.20: Table 3 listing which components belong together and when they should be completed

TU Delft

KLM