Linköping University — Department of Management and Engineering
Master's thesis, 30 ECTS credits — Operations Management
Spring 2020 — LIU-IEI-TEK-A–20/03871—SE

Reducing Delays for Unplanned Maintenance of Service Parts in MRO Workshops

- A case study at an aerospace and defence company

Mattias Jenvald
Mikael Hovmöller

Supervisor: Ou Tang
Examiner: Fredik Persson

LINKÖPINGS UNIVERSITET

Linköpings universitet
SE-581 83 Linköping
013-28 10 00, www.liu.se

Abstract

Service parts sometimes break down unexpectedly and require maintenance. The irregular nature of the need for this type of maintenance makes forecasting difficult and unreliable. Saab currently experiences problems with long delays when performing unplanned maintenance of service parts used in the two models of Gripen aircraft, Gripen C and Gripen D. These delays are source of monetary waste, as late delivery of maintained service parts results in Saab having to pay penalty fines to the customers. The purpose of this master thesis was to analyze data collected during a case study at Saab in Linköping, and suggest improvements for how to reduce these delays. This study focused on analyzing what caused the delays, and how the information provided by the customers can be used by the operative planners at the Maintenance, Repair & Overhaul (MRO) workshops in order to be more efficient. The data was collected during the case study using semi-structured interviews of 16 people working with the current system, as well as by collecting historical data from an internal database at Saab. This data was analyzed in parallel with a literature study of relevant research related to service parts supply chains, MRO workshops, and unplanned maintenance operations.

The analysis showed that there were four types of interruptions of maintenance; Internal stock-out of spare parts, internal stock-out of sub-units, external delays at the Original Equipment Manufacturer (OEM), and internal equipment breakdowns. A root cause analysis found that the four root causes of delays were:

- Saab does not have any contracts that incentivizes their OEM's to deliver on time.
- The data from the technical report is not used to provide the operative planners with information about incoming orders.
- The MRO workshops do not have a standardized system for prioritizing maintenance of service parts.
- The MRO workshops currently lacks a method for predicting certain types of machine breakdowns.

Acknowledgement

This master thesis marks the end of our master's degree and is the embodiment of all the theory and knowledge we have acquired during our five years of education at Linköping University. During the 20 weeks that we have worked on this master thesis, we have taken the opportunity to learn valuable practical skills that complement the theoretical knowledge acquired at Linköping University. It has been a rewarding experience that we will benefit from in our future careers. We would like to express our sincere appreciation to the following people, without whom the completion of this master thesis would not have been possible.

- Martin Larsson, our supervisor at Saab, for providing us with excellent support and discussions throughout the whole master thesis.
- Lars Mattsson, Head of Logistics Engineering at Saab, for giving us the resources we needed to complete this master thesis and welcoming us to his department.
- Dino Besic, MRO planner at Saab, for happily answering our never-ending questions.
- Ou Tang, our supervisor at Linköpings University, for his invaluable advice and for always believing in us.
- Fredrik Persson, our examiner at Linköpings University, for an objective and professional audit of our master thesis.
- Our opponents, Christoffer Lind and Jonas Lilja, for interesting discussions and valuable feedback.

In addition to these people, we would like to thank all the people at Saab whom we interviewed during our case study.

Contents

List of Figures

Nomenclature

Acronyms

MRO	Maintenance, Repair and Overhaul
OEM	Original Equipment Manufacturer
BER	Beyond Economical Repair
FIFO	First-In-First-Out
RL	Reverse Logistics
MPC	Manufacturing Planning and Control
ERP	Enterprise Resource Planning
MPS	Master Production Scheduling
S&S	Support and Services
PM	Planned Maintenance
UPM	Unplanned Maintenance
AOG	Aircraft on Ground
LRU	Line Replacement Unit
ICT	Information and communication technology
HR	Human Resources

Terms

Service Parts	Defective components or parts that are replaced
Availability	The degree to which a system is operable
Gripen C/D	Denotation for the single seat Gripen C and two-seat Gripen D

Chapter 1

Introduction

This chapter consists of a description of the underlying theoretical background as well as a description of the case company. This is followed by a problem description, the purpose of this master thesis and the research questions that will be answered.

Keywords: Maintenance, Repair, Overhaul, MRO, Service, Saab, Service Part, Supply Chain, Data, Information, Utilization, Information Logistics, Information System, Strategy, Optimization, Traceability.

1.1 Theoretical Background

The globalization of markets has enabled improvements in transportation and communication possibilities. Global companies are able to sell the same standardized products and services all over the world (Levitt 1993). A globalized market enables global supply chains which provide companies with more options when it comes to suppliers. Global supply chains are a source of competitive advantage through access to benefits such as more financing options, cheaper labor, and cheaper raw materials (Manuj & Mentzer 2008). All manufacturing companies must choose what parts of their products to produce by themselves and what to buy from suppliers. The supplier might sell materials, components, sub-assemblies, or final assemblies to the manufacturing company. These strategic decisions have a substantial impact on supply chains and are important for all modern companies (Hill & Hill 2009).

A conventional supply chain is illustrated in figure 1.1 where the flow of material is represented by the solid black arrows and the flow of information by the dashed arrows with a data sheet. A supply chain consists of different tiers of practitioners. Mentzer et al. (2001) defines a supply chain as *"A set of three or more companies directly linked by one or more of the upstream and downstream flows of products, services, finance, and information from a source to a customer."* This definition is shared by Carter et al. (2015), who defines a supply chain as *"... A network of firms where information, financial resources, and material flows"*.

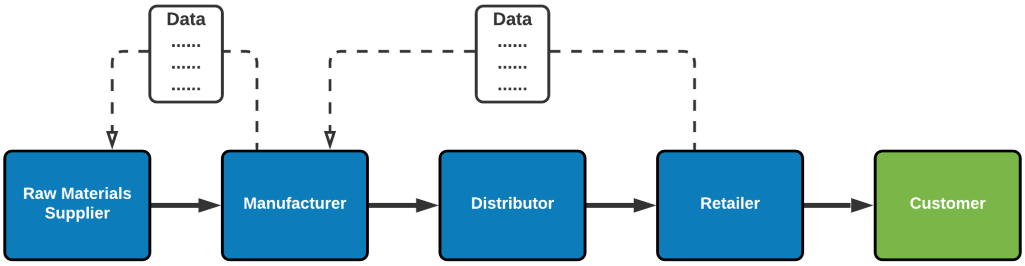

Figure 1.1: Conventional Supply Chain (Mentzer et al. 2001)

A service part supply chain is a supply chain that handles the flow of information and material when providing maintenance and repair of products already sold to customers. Muckstadt (2004) defines Service Parts as the replacements parts used to replace defective parts or components when equipment is repaired. In the aviation industry, components in need of maintenance are removed from the aircraft and immediately replaced with a functional one. The broken component is then sent to a Maintenance, Repair, and Overhaul (MRO) facility where it is repaired. A typical service parts supply chain is illustrated in figure 1.2 where the flow of material is represented by the solid black arrows and the flow of information by the dashed arrows with a data sheet.

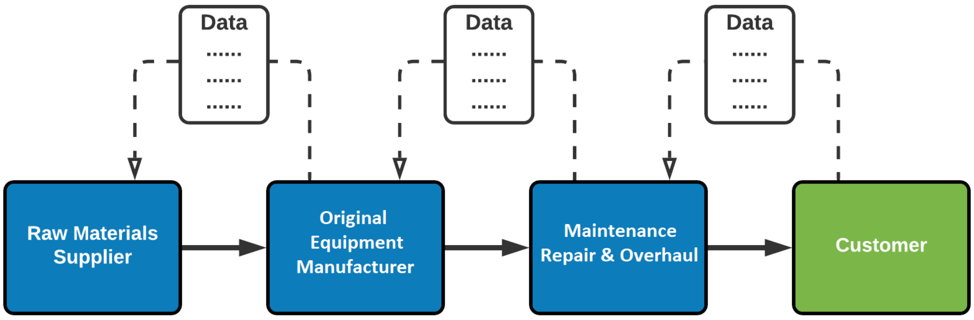

Figure 1.2: Service Parts Supply Chain (Muckstadt 2004)

A critical factor for manufacturing companies to succeed is to efficiently manage information about the customer's demand, the companies internal production capabilities, and supplier's ability to deliver goods and services. A common trend for manufacturing companies is to use information technology to establish interconnected supply chains that utilize connectivity and coordination. By sharing information within the supply chain, the companies involved will be able to cooperate and improve forecasting and reduce uncertainties and delays in manufacturing operations (Benhabib 2003). Being able to collect data, convert it to useful information, and distribute this information within a supply chain is crucial when aiming to improve the overall performance of a business organization. The efficient use of data regarding the current needs and capacities from all parts of the supply chain can help an organization reach a competitive advantage compared to its competitors (Ganesh et al. 2014).

The theory of Ganesh et al. (2014) can be used in the context of a service parts supply chain where it is important that an MRO workshop can utilize information regarding incoming orders, supplier capabilities, and its current internal situation in order to synchronize its operations with the capacity of its suppliers and demand from its customers. This allows for better planning and shorter maintenance lead times as the ability of the MRO to act proactively to the physical arrival of components in need of maintenance will increase significantly.

1.2 Company Background

Saab was founded in 1937 in Linköping, Sweden, and is currently a developer and manufacturer of highly technological products and services in the aerospace and defense industry. As of 2018, 17 096 people were employed by Saab, and Saab had a turnover of 33 billion SEK. Saab's products are sold in over 100 countries and the company operates in 35 countries. Research and development is concentrated in Sweden, where more than 14000 of Saab's employees live and work. The majority of Saab's employees are located in Europe, South Africa, the U.S, Australia, and Brazil (SAAB 2018). Saab's biggest competitors are:

- Lockheed Martin
- Boeing Defence
- Dassault Aviation
- Eurofighter Fighter aircraft GmbH

A map showing the countries where Saab operates is shown in figure 1.3.

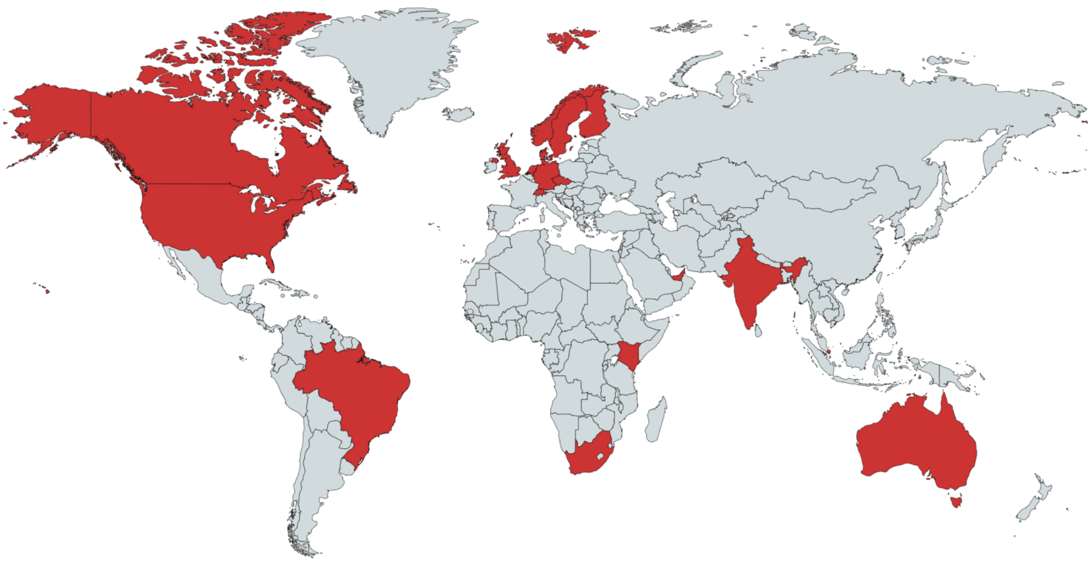

Figure 1.3: Countries where Saab operates (SAAB 2018)

Operations at Saab are divided into the following six business areas, the organizational structure of Saab is shown in figure, where the green box represents *Support & Services*, where this master thesis took place 1.4.

- **Aeronautics** manufactures of military aviation systems and developer of military aviation technology. Saab Aeronautics handles the Gripen fighter and Saab's share of the T-X training aircraft.
- **Dynamics** develops ground combat weapons, missile systems, torpedoes, unmanned underwater vehicles, training systems, and signature management systems.
- **Surveillance** provides solutions for surveillance and decision support used for threat detection, location, and protection through airborne, ground-based and naval radar, electronic warfare, combat-and command-and-control systems.
- **Support and Services** offers service and support for all of Saab's markets. This includes technical maintenance, logistics, and support solutions for both military and civilian missions.
- **Industrial Production Services** focuses on civilian customers and offer services in Aerostructures, Avionics, Traffic Management, and consulting business Combitech.
- **Kockums** designs, delivers, and maintains world-class solutions of naval environments such as submarines, surface combatants, mine hunting systems, and autonomous vessels.

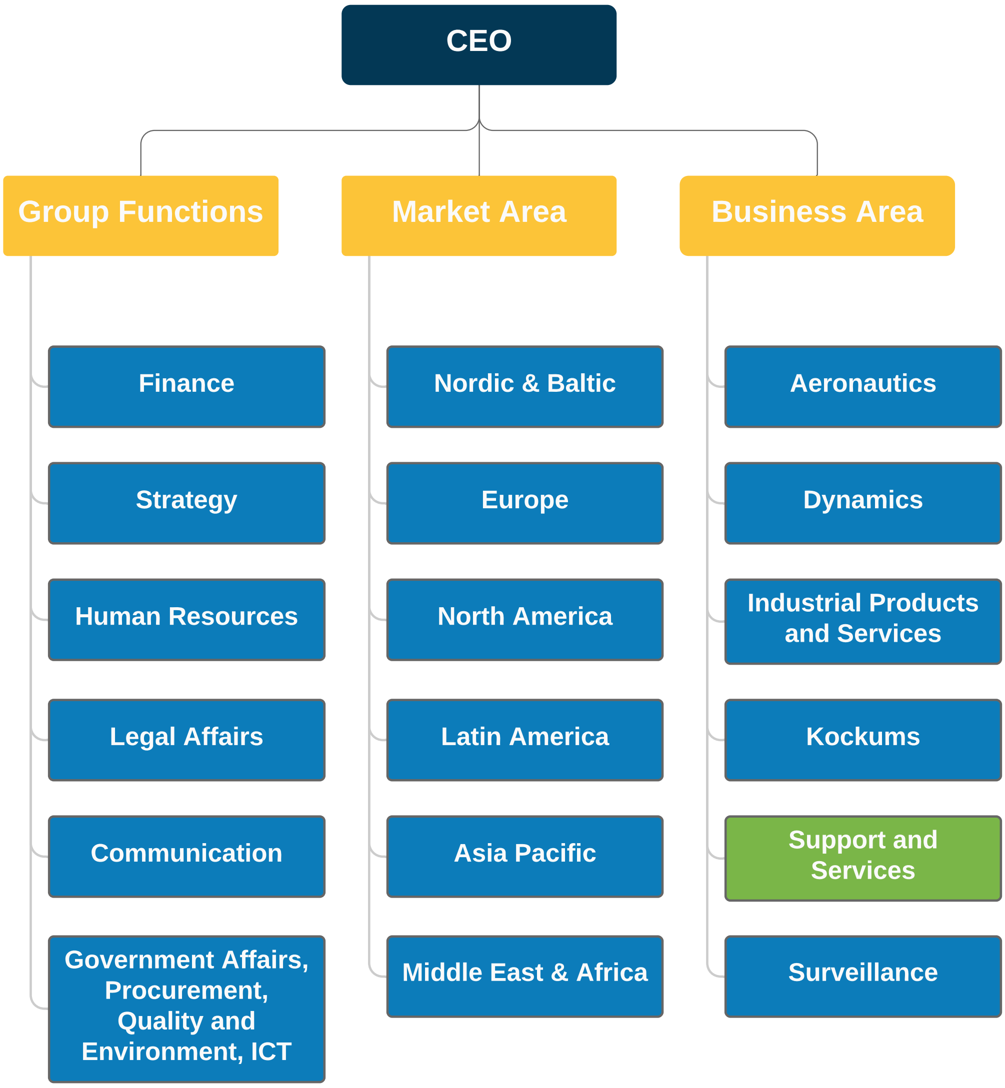

Figure 1.4: Organizational structure of Saab (SAAB 2018)

1.2.1 Gripen Support

This master thesis conducted a case study of Gripen Support which is a part of Saab Support & Services in Linköping, Sweden. In 2018 Gripen Support employed a total number of 493 people distributed over 21 sites around Sweden, the majority of which are located in Linköping. Saab Support & Services provides Saab's customers with maintenance and support of their aircraft that are currently in use. Support & Services also provide new customers with suggestions for maintenance and logistical solutions. The organizational structure of Saab Support & Services is shown in figure 1.5.

Figure 1.5: Organizational structure of Saab Support and Services (SAAB 2018)

1.3 Gripen C/D

In 1979, the Swedish government began a study calling for a versatile platform capable of *JAS* - Jakt, Attack, Spaning, which is Swedish for air-to-air, air-to-surface, and reconnaissance missions, that could fulfill multiple roles during the same mission. A new phase of studies for a Swedish solution to the multi-role aircraft requirement began at Saab in March 1979. In 1988, the first prototype of the Gripen 39A made its 51-minute maiden flight. 39 Gripen A was the first aircraft of a new generation of multi-purpose aircraft. Since that day both development and production have occurred in parallel with the delivery of aircraft to Saabs customers.

The model currently in use is Gripen C/D. Gripen C is the single-seat version of the aircraft and Gripen D is the two-seat version of the aircraft. Both Gripen C and Gripen D retains full operational capability, and Gripen D can be used for both pilot training and combat missions. These two different versions are shown in figure 1.6 and figure 1.7. The figures were collected from *Saab Group* (2020).

In addition to developing and manufacturing the next generation of fighter aircraft, Saab ensures the availability of their aircraft by offering maintenance and repair services of more than 600 service parts used in Gripen C/D to their customers. A comprehensive supply chain for service parts is provided by Saab Support & Services to ensure Saab's customers that they have a steady flow of functional spare parts.

Figure 1.6: Gripen C

Figure 1.7: Gripen D

1.3.1 Aircraft Maintenance

When a customer purchases Gripen C/D, they do not simply buy the aircraft, but the functionality of the Gripen System. This means that Saab is responsible for the maintenance, repair, and upgrades of the Gripen aircraft. These service contracts are made for several years at a time and usually lasts for the entire lifetime of a Gripen aircraft, which can be up to several decades[1]. This means that Saab will be a part of the aircraft during its entire life cycle. The amount of maintenance needed on a Gripen aircraft changes over time. The aircraft needs more maintenance in the early stages of its life cycle due to '*Infant Mortality*' failures. The need for maintenance of the aircraft reaches its lowest point during the middle of its life cycle but increases again at the end of the life cycle when the aircraft starts getting old and the failures are caused by wear[1]. This phenomenon is known as the *Bathtub Curve* (Wilkins 2002), and is shown in figure 1.8.

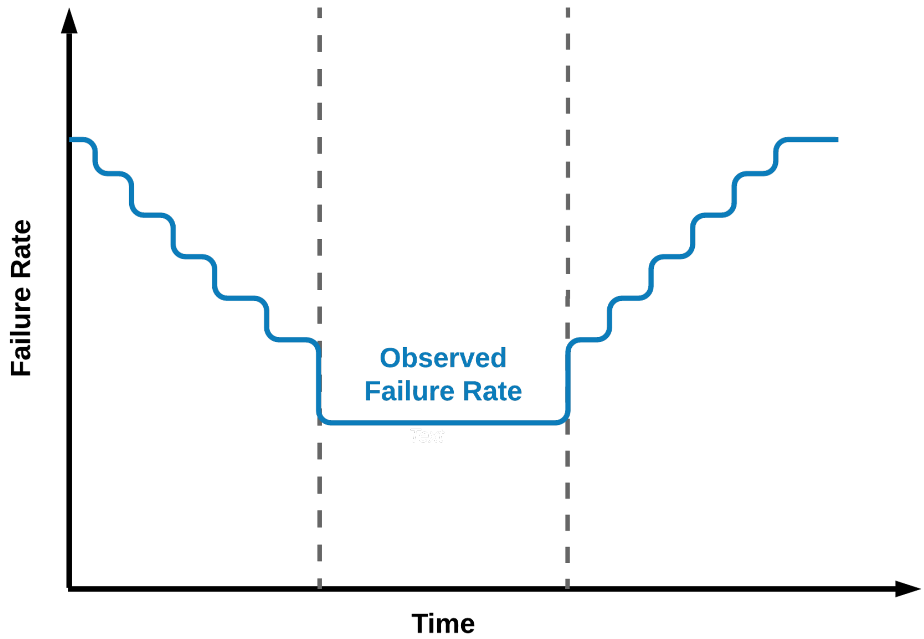

Figure 1.8: The bathtub curve (Wilkins 2002)

Figure 1.9 illustrates the service parts supply chain at Saab Support and Services. This service part supply chain starts from the operating customer, the process of repairing a component is initialized when the component that Saab is responsible for maintaining is removed from the aircraft. There are two reasons for removing a component from an aircraft; planned maintenance, and unplanned maintenance[2]. The green MRO represents the workshops that are operated by Saab. There are three different types of OEM suppliers that support the MRO workshops, and these are illustrated as three different nodes in figure **??**. One type supports the MRO by doing all maintenance for certain components. For these components, the MRO can be seen as a middleman that sends the service part to the right OEM. The second type supports the MRO by doing parts of the maintenance, in this type, the MRO is responsible for maintaining part of the components and sending the other part to the correct OEM. The third type of OEM supports the MRO by producing and delivering disposable replacement parts, while the MRO performs all of the maintenance. It is important to note that there are several hundred different suppliers in each category of OEM. The lines between the different entities in figure 1.9 illustrates

[1]Martin Larsson, Logistics Analytics, Support & Services, 2020-01-20
[2]Martin Brantemo & Marcus Karlsson, Flight Monitoring, Support & Services, 2020-02-10

the information flow between the different components in the supply chain. The direction of the arrows represents the flow of physical material and information flow within the system.

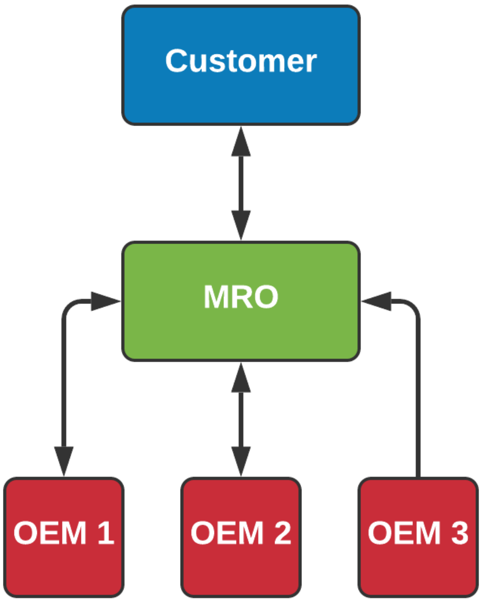

Figure 1.9: A simplified figure of the service part supply chain for Gripen C/D

Planned maintenance is performed according to certain criteria specified by the manufacturer. There are three different kinds of criteria; Calendar Time, Flight Hours, and Cycles. Calendar time is the number of days that have passed since the service part was manufactured, regardless of how the aircraft is used. This is for example used for components made of rubber or the gunpowder used in the ejection seat. The number of flight hours is used for components that only experience wear when the aircraft is used, for example, hydraulic cylinders. Cycles are used for components that take wear according to how many times they are used, regardless of the number of flight hours, such as the landing gear.

Unplanned maintenance is needed whenever something unexpected happens, such as when a component malfunctions or breaks. The only type of planning that Saab does for unplanned maintenance is using historical data. The historical data is used to predict how many service parts will arrive at the workshops in the future. Despite this type of planning approach, service parts in need of unplanned maintenance are often delayed. As the aircraft gets older, so do the service parts, which causes them to break down more frequently. This causes a higher flow of service parts than expected, which leads to long delays and puts pressure on the MRO workshops.

1.4 Problem Description

When Saab sells Gripen aircraft to a customer, the deal usually includes maintenance of certain service parts used in the aircraft. When a service part needs maintenance, it is removed from the aircraft and sent to Saab for maintenance. The faulty service part is immediately replaced with a functional one by the customer to ensure that the aircraft can be used. The customer has a limited number of spare parts stored at their airbases. To ensure a certain level of availability of the aircraft, and that the customer never runs out of service parts, each service part has a specified maintenance lead time. Saab is responsible for completing the maintenance of each service part within this specified lead time. In cases where the maintenance is delayed, Saab has to pay a penalty fine to the customer to compensate for the delay.

There are two types of maintenance, planned and unplanned. Planned maintenance is done according to pre-determined conditions and is expected. Unplanned maintenance is done when a service part malfunctions or breaks unexpectedly without warning. Saab is currently experiencing difficulties in completing unplanned maintenance on time as they are unable to accurately predict future demand for unplanned maintenance. The MRO workshops need different resources depending on the type of service part and why the service part needs maintenance. As this is currently unknown to the MRO workshop before the service part has physically arrived and been inspected, planning how to use the resources available to the MRO workshops becomes difficult. As a result of this uncertainty, many service parts in need of unplanned maintenance are delayed which leads to heavy penalty fines for Saab.

This problem is important to solve as the delays impose large and unnecessary costs to Saab which are expected to increase in the future due to the effects of the bathtub curve if nothing is done to improve the situation[3].

1.5 Purpose

The purpose of this master thesis is to identify and analyze the cause of delays for unplanned maintenance of service parts in an MRO workshop, and to recommend improvements that can reduce these delays. This is important for Saab as these delays currently cause penalty fines.

1.5.1 Research Questions

1. What service parts have an impact on the penalty fines at Saab and how late are they?
2. Why are these service parts delayed?
3. How can information be utilized by an MRO workshop to synchronize all parts of its service parts supply chain and reduce delays of unplanned maintenance?

1.6 Delimitations

The case study was conducted at a single company, Saab in Linköping. The study considered one part of the service parts supply chain of Gripen C/D, namely the MRO workshops. Although it would have been possible to study the entire service parts supply chain, this study focused on the MRO workshops since this is the part of the service parts

[3] Martin Larsson, Logistics Analytics, Support & Services, 2020-01-20

supply chain that Saab operates and can influence. As such, the study considered all flow of data, information, and material to the MRO workshops from the rest of the service parts supply chain as given variables. The study only collected data to be analyzed regarding the service parts that induced penalty fines in 2019.

1.7 The structure of the report

The following section provides a brief introduction to each chapter of this report and also the structure of this report.

1. **Chapter 1 - Introduction** This chapter gives an introduction to the theoretical background, the company background, the problem description, the purpose of this study together with the research questions. The delimitations that have been made together with the structure of this report is also described in this chapter.
2. **Chapter 2 - Method** This chapter describes the research approach, the data collection methods, information about the literature review, the analysis method, the execution plan, and the validity and reliability of this master thesis.
3. **Chapter 3 - Frame of Reference** In this chapter the theory that is relevant to this master thesis is described. The theory is later used as support for the analysis, and as a foundation for the conclusion and discussions in the later chapters.
4. **Chapter 4 - Current State** The current state of the service parts supply chain used by Saab is described in this chapter.
5. **Chapter 5 - Analysis** In this chapter the analysis based on the frame of reference of collected data is presented.
6. **Chapter 6 - Conclusion** This chapter presents the answers to the research questions, as well as the conclusions. Finally, the recommendations the authors have for the case company are presented. In addition to this, the potential outcomes of the given recommendations as well as the generalization of this study are discussed.

Chapter 2

Methods and Methodology

This chapter presents how the study has been conducted. The chapter includes detailed information about the research approach and the type of strategy used, how the data has been collected and how the method was used during the analysis.

2.1 Research Approach

A descriptive research approach aims to understand the relevance of a certain problem and to describe what caused the problem. A descriptive approach is conducted to give a better understanding of a problem and clarify the purpose of the study, collect and analyze empirical data to obtain deeper knowledge, and provide a solution to the problem. For descriptive research, the study starts with a general idea of the cause of the problem and uses this in the research as a topic to identify issues that can be the focus for future research (Forza 2002). This master thesis used a descriptive research approach because the study started by understanding the service part supply chain for Gripen C/D at Saab and identified the problems. Empirical data were then collected for analysis. This research approach was used during this master thesis to understand the problem and to describe how to implement suggestions in order to eliminate or reduce the effects of the identified problems.

A quantitative study analyzes numerical data while a qualitative study analyzes non-numerical data (Karlsson 2009). The results are often more precise in a quantitative study than in a qualitative study, as a quantitative study uses large amounts of numerical data. This can allow the researcher to generalize the observations made. The conclusions based on numerical data are often more precise because the data is taken from a real problem, unlike qualitative data, which is often based on theory and existing studies. (Bryman & Bell 2003). However, John & Creswell (2000) claims that the quantitative and qualitative research are two differences on a continuum rather than complete opposites of each other and that the two approaches share several common elements. This leads to the conclusion that a study is never purely qualitative or quantitative. During this master thesis, both qualitative and quantitative data were collected which is preferable for a descriptive research approach. The qualitative data was collected from interviews and observations and quantitative data was collected from historical records. As a result, the research approach used was a combination of qualitative and quantitative research. Bryman & Bell (2003) states that a quantitative study uses a deductive research approach and a qualitative study uses an inductive research approach. John & Creswell (2000) states that deductive research is used when the researcher begins with a theory and then collects data to add to, or contradict, the theory. In contrast, inductive research begins with a broad base of data that can be used to generate a general theory. This master thesis used a combination of quantitative and qualitative data. Consequently, a combination of inductive and deductive research approach was used. Deduction was used when quantitative data was analyzed to find patterns. Induction was used when qualitative data from interviews and observations were analyzed to formulate general solutions and recommendations.

According to Yin (2003), a case study should be used to describe a situation, generate improvements based on the empirical data, and implement these in the real world. During this master thesis, a case study was conducted at Saab to study the service part supply chain for Gripen C/D, and implement the theoretical findings in a real supply chain. A case study can include both single or multiple case companies with different levels of analysis (Yin et al. 1984). This study only considered one company. This decision was made based on the limited amount of time available and because of the unique nature of the supply chain at Saab makes it hard to compare it to another case. According to Voss (2010) the fewer the case studies, the greater the opportunity for depth of observations. By conducting a case study the focus is to understand the dynamics of the problem to get more information (Eisenhardt 1989). An investigation is needed to receive a deeper knowledge of the problem, this is normally carried out through one or more studies within the topic to generate a list of research questions (Voss 2010).

The shift of focus can occur several times during a thesis which contributes to the successive configuration of the thesis's theoretical frame of reference (Melin 2002). Empirical data were collected in parallel with a literature study to ensure that relevant theory was selected. This master thesis contributed to research through the formulation and recommendations of how to reduce delays of unplanned maintenance in an MRO workshop.

2.2 Data Collection

The use of appropriate methods to collect data is crucial in the initial stage of a research process. The outcome of the study is dependent on the choice of methods and how these are connected to the research question, as well as the consideration of time available to apply these methods. A case study is normally based on a combination of different data collection methods, such as surveys, studying archival records, interviews, focus groups, and observations, these methods can include both primary and secondary data. Primary data is collected by the researchers from first-hand sources such as interviews and surveys and is also called raw data. Secondary data is existing data that is available from the library, internet, or the case companies database (Eisenhardt 1989). In the following subsections, the different data collection methods that were used during the case study conducted in this master thesis will be described in detail:

2.2.1 Interviews

The interviews conducted during the planning phase of this master thesis were semi-structured and the aim was to create an understanding of the current problem. A list of the people interviewed during the current state mapping phase of the study is shown in appendix C. According to Gordon & Fleisher (2010) the definition of an interview, is a conversation between two or more people, to gather information. Data collection through interviews allows the collection of primary data required for the research. During an interview, the process must be non-leading, meaning that the person asking the questions should have an objective determination and should not have any inputs to the answers. The interviewer is there to collect useful data. In a structured or semi-structured interview, the interviewer is using a structured question format. According to Gordon & Fleisher (2010), the questionnaire should take approximately 30-60 minutes. A structured interview has all of the questions pre-made and the same set of questions are asked to each and every interviewee. A semi-structured interview also has pre-defined questions but allows for follow-up questions and discussions. A non-structured interview consists of a discussion where questions arise as the discussion progresses and can be called qualitative interviewing (Merriam 1998). A list of the people interviewed during the planning phase of the study is shown in appendix B. The interviews conducted during the current state mapping were a combination of structured and semi-structured and the aim was to map the current state of a specific MRO workshop in the service supply chain.

2.2.2 Historical/Archival Methods

According to Axinn & Pearce (2006), searching for published studies can sometimes be unstructured. When using documents or other secondary sources, the researcher must involve a personal opinion if the content may be valid for the study. A disadvantage for historical data is that the researcher can not decide either a level of structure of the documents or a possibility for later interviewing the person responsible for the historical document (Axinn & Pearce 2006). In this study, historical data was gathered from the company's database. This was done in order to understand which service parts that the case study should focus on.

2.3 Literature Review

A literature review was conducted with the purpose of finding relevant sources of information. UniSearch, Diva, and Google Scholar were used in order to find trustworthy sources. The key-words that were used during the search are shown in Appendix A

The literature was primarily be used in the theoretical background, the method, and the frame of references. The theory collected was then be used further on in analysis to draw conclusions.

2.4 Analysis

What type of analysis method that is suitable for a study depends on the characteristics of the collected data and how that data is structured. The first thing that needs to be done is to structure the collected data. This can be done according to a pre-structured schedule, or it can be defined iteratively as the data is received. When analyzing qualitative data there are no strict rules that have to be followed. The methods that exist are guidelines rather than rules to help to find patterns and structuring the data (Saunders et al. 2007). The following section describes two different analysis methods. The first one describes the time each event a product goes through, from the beginning until it reaches the customer. The second method describes how to categorize the products into three different groups.

2.4.1 Empirical data analysis

The empirical analysis was based on the interviews and the data collected at the case company. The idea was to find patterns in the interviews and historical data. The empirical analysis resulted in the current state chapter which gives an overview of what is happening at the company and find problems to solve.

2.4.2 ABC analysis

ABC analysis is a method where all the products a company deals with are classified into three different categories. The purpose of an ABC analysis is to determine how to allocate the resources available to the company efficiently. The products can be sorted according to different attributes such as value or demand. The products can then be monitored and managed according to their ABC classification. The most important products are included in the A-category which should be thoroughly monitored on an individual level. The A-category usually contains 20% of all products. B-class products are not as important as the ones in the A-category but should still be monitored, only on a less detailed level. The B-class items usually constitute about 30% of all products and are of medium value and are subject to medium demand. The final category is the C-category which consists of the last 50% of all products. These products are usually expensive but in low demand which means that there is no need to keep any in storage or monitor them very frequently. (Flores & Whybark 1986)

According to Sanders et al. (2013), an ABC analysis can be conducted by going through these following steps:

- Determine annual usage or sales for each item.
- Determine the percentage of the total usage or sales by item
- Rank the items from highest to lowest percentage
- Classify the items into groups

As the ABC-analysis conducted in this master thesis was based on each service part's contribution to total penalty fines, the framework presented by Sanders et al. (2013) was used, but adapted slightly to suit better in the context of a service parts supply chain. Instead of usage or sales, the items were sorted according to their contribution to penalty fines paid in 2019.

2.4.3 Lead time analysis

According to Oskarsson et al. (2013), a lead-time analysis involves analyzing information or material flow in a structured way with the aim of reducing the total time in the flow. To carry out a lead time analysis, a map of the flow of material and information is needed.

A lead-time analysis can be used to identify flaws and find alternative solutions to the current situation. Which alternative solutions are appropriate is largely situational, but there are two ways to find good alternatives. One is to base on the general principles found in the literature, the other is to base on practical knowledge. Such knowledge can be found from people in the organization who have ideas on what can be done differently, but it can also be found in other companies. Finding good alternative solutions is one of the major difficulties with lead-time analyzes (Oskarsson et al. 2013).

One of the most common methods in lead-time analysis is when the total time in a process sequence is divided into value-adding and non-value-adding time. Value-adding time is the time when some form of activity is performed assembly or processed. The remaining time, the non-value adding time is when products are waiting in front of a machine or laying in a warehouse. It is mainly the non-value adding time that is interesting to reduce. The passive time adds no value to the product and it is almost always longer than the active one (Oskarsson et al. 2013).

Oskarsson et al. (2013) claims that it is not possible to give clear answers to what should be done to reduce lead times as that depends so much on the specific situation. Instead, they mention the eight principle measures that describe how to work with time reduction in a structured way. The steps described below can be used in any flow or process.

Storhagen (2003) writes that lead time analysis seeks clarity in what the time is used for, and how efficiently it is used. The workflow of a lead-time analysis can be summarized in the following points:

1. Define and determine the total lead time
2. Include both material and information flows
3. Identify all activities that consume time
4. Identify value-added time
5. Identify non-value-added time
6. Question all the time that has no customer value
7. Analyze and propose new solutions
8. Follow up

2.4.4 Process Mapping

Brook (2017) defines process mapping as a way to visually represent how a process actually works, and that it can be used as a foundation for further analysis of the process. Process mapping is a graphic illustration of a process which can be used to identify, document, analyze, and develop a process. It visualizes work processes including activities, the connections between them, and inputs and outputs. A process map can be visualized by a flow chart. Brook (2017) suggests using the most common flowchart symbols which are illustrated in figure 2.1

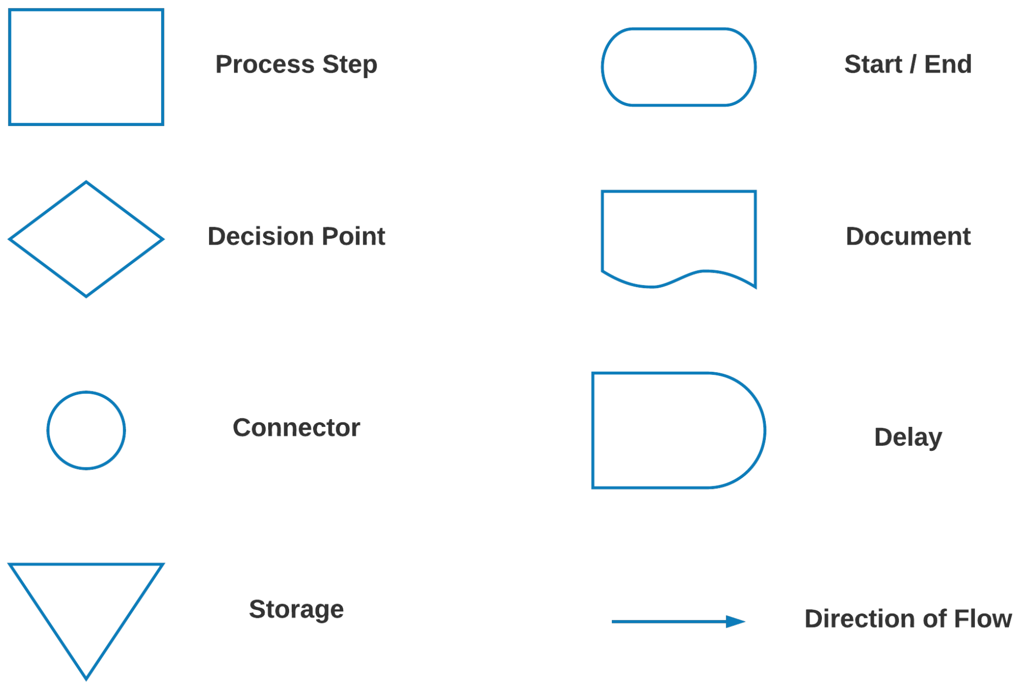

Figure 2.1: Flowchart symbols used to visualize a process map (Brook 2017)

Jacka & Keller (2009) has stated the steps to conduct a process mapping. These steps are:

- **Process Identification**: The process should be identified and the boundaries of the scope should be made clear.
- **Information Gathering**: Information should be gathered from all process activities to get a better understanding of the whole process.
- **Interviewing and Map Generation**: Interviews conducted from this step should come from those who perform each task in the process.
- **Map Analysis and Presentation**: Analysing the process map should be continuously done during the whole mapping, but when the process has been identified and all information has been gathered, all the pieces can be tied together to make a final process map.

Brook (2017) highlights the usefulness of process mapping when dealing with complex systems as it can be used to bring clarity and find what parts of the process can be improved and how. Process mapping can bring information about which steps of the process add value to the customer and which do not when decisions are made what information the decisions are based on. Process mapping can also be used to find rework loops in a process and identify redundant or repeated process steps (Brook 2017).

2.4.5 Root cause analysis

The 5-Why Method

According to Serrat (2017), it does not help to fix the initial state of the problem when trying to eliminate a problem. Instead, by using the 5-why method the root cause problem can be identified and enable the elimination of the root cause of the problem. By conducting the 5-why analysis, a reflection on what caused the initial problem will be answered five times. This method of solving a problem empowers analyzing the problem through questioning, and can be adapted quickly and applied to every problem. The method allows getting down to root-cause problem as it applies the principle of systematic problem-solving. Serrat (2017) has stated five steps to conduct the 5-why method:

1. Start by stating the problem.
2. Ask the first *why* to the previous step: Why is this problem taking place? Record the answer on the worksheet.
3. Ask four more *whys*, repeating the process for each answer and record them on the template. The root cause problem will be identified when asking *why* yields no further useful information. If necessary, continue to ask why beyond the five layers to get to the root cause.
4. Look for systematic causes of the problem by going through the answers from the statement to the last asked *why*. Discuss these and settle on the most likely systemic cause.
5. The next step after finding the root cause problem is to develop an action plan for how to remove it from the system. By using the five why method the initial problem will be removed by removing the root cause problem.

2.5 Execution Plan

The implementation of this master thesis follows the strategy shown in the following list.

1. Map the current state of the service parts supply chain for Gripen C/D at Saab.
2. Conduct ABC-analysis to group the service parts that tribute to penalty fines.
3. Analyse each service part to map the causes of delay.
4. Make a process map for the most critical causes of the delays.
5. Identify the root cause of the delays using the 5-why method.
6. Find out what needs to change at Saab to solve the root causes identified using the 5-why method.
7. Formulate a recommended implementation plan for Saab.

2.6 Validity and Reliability

There are two terms related to strengthening the quality and credibility of this study, which are reliability and validity. The purpose is to minimize the risk of misleading results. This risk can never be completely eliminated, but knowledge of the risk and precautions regarding reliability and validity reduces this risk.

2.6.1 Reliability

Reliability is the term to which the results of this study can be repeated. The use of interviews where the same questions are asked with the same results ensures a higher level of reliability. That was why the *Two question-survey* was used during every interview to ensure that this study would focus on the biggest problem. The researchers' subjectivity can never be eliminated but can be reduced by having open and non-leading questions. There is a risk that the people interviewed might be incorrectly quoted. To reduce this risk, all information collected should be checked again with the interviewed person and compared with hard facts (Patel & Davidson 2003).

2.6.2 Validity

Validity can be divided into two general terms, internal and external validity. Internal validity focuses on checking that there is no support for other factors being responsible for the variation. External validity describes the extent to which the study's results apply to other studies (Patel & Davidson 2003).

To check and ensure the validity of the study, a continuous dialogue has been conducted with supervisors at the case company as well as Linköping university. Since the study was conducted only on one case company and their specific environment, there may be some limitations on external validity. In order to validate that the collected data where correct, an email was sent after each interview to the person to ensure that all information had been written down correctly.

Chapter 3

Frame of References

This chapter contains the theoretical framework used to analyze the findings of the case study and answer the research questions. The theory are then used as a base for analyze the current situation at the case study company. Furthermore, the theory will act as a decision base for conclusion and discussion.

3.1 Service Parts

The replacement of defective components is often needed in order to repair a piece of broken equipment. Components used to repair broken equipment are known as service parts. Service parts are an essential part of all aspects of modern society, from the personal lives of individuals to the commercial and military industry. Domestic appliances, cars, power-plants, and aircraft are examples of common objects that society relies on. These objects rely on the constant availability of services parts in order to function properly. The term service parts encompass a vast array of different types of products, from cheap replaceable parts such as air filters too expensive parts such as jet engines (Muckstadt 2004).

The availability of the service parts secures the utilization of the aircraft by providing spare units to the critical functions of the aircraft. An aircraft is designed so that the most critical parts can easily be removed if required maintenance. The critical parts can then be sent to a workshop for maintenance. These easily replaceable modules of the aircraft are called Line Replaceable Units (LRU). Every time a failed service part is removed from an aircraft, the same one has to be installed before the next flight. The failed service part triggers a demand from the spares supply. A failed service part can take weeks to repair and flight delays are expensive, the airbase manages this by having spare parts in stock and repair the failed units. The availability service, part of the aircraft MRO services, is responsible for providing a supply of those spare units as economically as possible (Mirzahosseinian & Piplani 2011).

3.2 Maintenance, Repair, and Overhaul

Maintenance, repair, and overhaul (MRO) is the term used to describe all activities involved in restoring broken systems, machines, or pieces of equipment to an operable state.

These activities are done as a result of planned or unplanned maintenance and usually involve the disassembly and reassembly of the unit in need of maintenance, the use of service parts as well as functional testing of the unit to ensure that the maintenance has returned the unit to the desired performance level. The MRO industry faces different challenges than the traditional manufacturing industry does. As much of the maintenance done is unplanned, meaning the need arises virtually without any warning, the MRO industry needs to deal with large demand variability, unreliable supplier response times, unpredictable and complex flows of material and customer demand, and limited technical data about the units that need maintenance. Some of these challenges exist in regular manufacturing as well, but not to the same extent. For this reason, managing an MRO process is seen as one of the most complex tasks in modern industry. (Srinivasan et al. 2014)

MRO operations rely on machinery and equipment to test and maintain service parts. According to Epperly et al. (1997), operating equipment until failure can result in heavy financial losses in the form of damaged goods and lost production time as well as human losses as operators are at risk of injury. Being able to predict when a piece of equipment is going to break down allows for preemptive actions to restore the equipment to a safe state before the breakdown occurs. Epperly et al. (1997) states that when using equipment where the condition of the equipment can be indicated by heat patterns, infrared thermography can be used to measure relative heat differences on the surface of the object. Kohli (2017) highlights the importance of preventing malfunctions and breakdowns when possible, and that in situations where big data sets are available, machine learning algorithms can be used to predict equipment failures.

3.2.1 Planned and Unplanned Maintenance

The two main types of maintenance used in industry are planned maintenance and unplanned maintenance. Planned maintenance is scheduled at fixed intervals of a certain number of days, months, quarters, seasons, years, or some other predetermined interval. The intervals are based on how much the service part in question has been used. The two main elements of planned maintenance are discipline and procedure. Discipline refers to the firms' ability to correctly perform all necessary activities in the correct order. The procedure means that the tasks are done correctly. Both of these activities are important and require accurate planning to create an efficient system for planned maintenance (Mobley 2004). The bathtub curve, which is illustrated in figure 1.8 indicates that a new machine has a high probability of failure because of installation problems during the first few weeks of operation. After this initial period, the probability of failure is relatively low for an extended period. After this normal machine life period, the probability of failure increases sharply with elapsed time. In preventive maintenance management, machine repairs or rebuilds are scheduled based on what the manufacturer states for each product (Wilkins 2002).

Unplanned maintenance is any maintenance that is needed unexpectedly. Unplanned maintenance is commonly the result of equipment failure that was not expected (Mobley 2002). When an unplanned event happens, the defective part is replaced with a new one. It is tough to estimate the unplanned maintenance, compared to the planned maintenance. This is because of the complex variety of forecasting when unplanned maintenance will occur (Tracht et al. 2013).

The ratio of stock-outs with the total number of demand is defined as the service level. The amount of service part in stock is normally depending on the service level planned to achieve. A service level of 100 % for a part is only achieved by a very high amount of material in safety stock which leads to high holding costs in the warehouse. But on the other hand, customer satisfaction is reduced with a low service level (Tracht et al. 2013).

The challenge of keeping a high service level is to have the right service parts at the right time. This can be predicted when the service part requires service. It is possible to predict when a service part is being removed for the planned maintenance. According to Kilpi et al. (2009), the service part supply chain can be considered as a closed-loop system. Meissner et al. (2002) states that incomplete information has to be detected or, the user has to be notified about the failure. There are often thousands of parts in the system of an MRO supply chain with each service part having a unique feature and modification. The challenge is to have a proper and structured categorizing of these parts. Inaccurate or incomplete information of the service part can lead to an increased chance of stock-outs or an increase in inventory due to duplication (Khandelwal 2011).

3.2.2 Service Contracts

Morris & Fuller (1989) states that industrial services can be distinguished from industrial products in several significant ways.

- Services are intangible
- Services are consumed at the time of purchase and can not be stored in inventory.
- Services must be customized to suit individual users.
- Services tend to be consumed in irregular patterns.

The purchasing of services is often integrated into the whole company. Buying services is often handled without any participation from the purchasing specialist. Tonks & Flanagan (1994) states that the purchasing of service is a large expense, because of a major part of these costs are maintenance costs.

3.2.3 Lead time

Lead time is the total time that elapses from the time when an order has been made to the time when the ordered material arrives at the recipient (Storhagen 2003). Lead time is now a common concept in many companies and there are several reasons why a company measures lead times. Short lead times lead to faster deliveries and is often seen as a competitive advantage in the hope of winning an order (Storhagen 2003). Lead time is a term that is given different meanings in different contexts. Olhager & Wikner (2000) defines it "*Lead time refers to the time that elapses from the need for an activity or group of activities to arise until one has knowledge that the activity or activities have been performed*". There are several different types of lead time, product development lead time, and delivery lead time. Product development lead time is the time from the discovery of the need for a new product until the product is launched in production mode. Delivery lead time is the time from order to delivery of the order (Olhager & Wikner 2000).

3.2.4 Big Data Analytics and Predictive Maintenance

According to Russom et al. (2011) big data analytics is a method to perform advanced analytical techniques on big data sets, and has three major attributes known as the three Vs;

- **V**olume, because of the sheer amount of data.
- **V**ariety, because the data can be organized in structured sets, semi-structured sets, unstructured sets, or any combination of the three.
- **V**elocity, because of the speed of the data as it can be collected in real-time.

Ashton et al. (2009) defines the Internet of Things as a system where computers are able to collect data without human interaction. According to Xia et al. (2012), the Internet of Things is a network of interconnected objects with the ability to communicate with other objects and human beings.

Big data analytics is an important method of uncovering hidden patterns in big data sets. These patterns can bring valuable knowledge and useful information to managers and help them make information-based decisions by capturing and utilizing data using sensors, the Internet of Things, and big data analytics in all stages of the product life cycle (Ren et al. 2019).

Zhang et al. (2017) states that big data analytics can be used in combination with the Internet of Things to uncover hidden trends in large amounts of data collected from an item when it is used. If this data can successfully be collected and analyzed, customer satisfaction can be increased by allowing for predictive maintenance services. By combining historical maintenance data with real-time data, the interrelationship between different parts of the product life cycle can be identified and the breakdown of a product can be predicted which allows for maintenance actions to be taken in order to prevent the breakdown before it actually occurs.

3.3 Supply Chain

Mentzer et al. (2001) defines a supply chain as a set of several different units that together contribute to the flow of products, services, finances, and information from its source to the customer, this flows in both directions, forward and reverse, along the supply chain. Rogers & Tibben-Lembke (2001) claims that the focus of forward logistics is moving the material from the original manufacturer to the customer, and reverse logistics is the opposite. Rogers et al. (1999) defines reverse logistics as the activities that involve the returned products from a customer. The materials that are related to reverse logistics are often products or spare parts that require service. There are many activities to which both reverse logistics and forward logistics can be equally applied. For example, it is equally important to forecast how many products will arrive as how many products the consumer will be purchasing (Rogers & Tibben-Lembke 2001). According to Sandberg (2015), the supply chain has an important role in a competitive market, and the core product becomes less important but services such as logistics and support become more important.

The service parts supply chain can be considered as a closed-loop system consisting of a repair facility and warehouse, to support the customer. A service part supply chain consists of several major repairable service parts that circulate back and forth between the customers and the MRO warehouses. One type of replenishment policy that is used in the warehouse is called the one-for-one base stock. The definition of the policy is when a service part is removed from the aircraft and sent to the workshop, the service part is immediately replaced by one ready-to-use. The failed service part that requires maintenance will be repaired to normal condition. A back-order takes place when a warehouse is out of stock. The warehouse triggers a replenishment order immediately and the information lead time is assumed to be zero (Mirzahosseinian & Piplani 2011).

3.3.1 Inventory Management

Inventory management is a list of activities that are linked to receive, store, and distribute the incoming inflow and information. To all of these activities includes transportation, arrival control, material handling, storage, inventory control, and reverse logistic (Van Weele & Arbin 2019).

According to Vidal & Goetschalckx (1997) there are three strategical approaches to optimize for a manufacturer. Service level, cost, and quality. The service level should be as high as possible not to be short on any orders, but the hardest part of having a high service part is still to keep the inventory levels as close to zero because having very high inventory levels binds to high inventory costs. Last but not least, having the best quality on the market which will increase the cost. It is always a struggle to balance and optimize these three different parameters. Most often it is a trade-off that the company considers since it is almost impossible to be an order winner on all three. Therefore, various companies try to be the best in their field. Some companies will have a very high service level, but the customer will have to purchase that service for a higher price, while other companies will be able to deliver for longer lead times but the price will be significantly lower.

The key objectives are deciding what level of service to provide for different products and customers, taking into consideration demand variability, available supply, resource constraints, and working capital constraints and revenue objectives. A key part of the process is deciding how much risk to take in positioning supply against uncertain future demand (Vidal & Goetschalckx 1997).

3.3.2 Supply Chain Configuration

Companies and suppliers in a supply chain network are connected through information and material flow (Dwivedi & Butcher 2008). There are a variety of different collaboration strategies in a supply chain network, which encourages the collaborative network to openly share information and knowledge (Dyer & Nobeoka 2000). The common goal for these strategies is to increase transparency and synchronization across the entire supply chain (Holweg et al. 2005).

3.3.3 Information Flow

A system must be in place in order for information to flow through a company. This system must consist of several separate components, so that information can flow from one component to another. Such a system is known as a *distributed system* (Barwise

& Seligman 1997). Information and communication technology (ICT) plays a key role in managing today's logistics operations. For example, data availability has become a principal element to the responsiveness of an organization. Therefore the supply chain and its associated logistics operations have become 100 percent dependent on ICT, both at the intra-organizational and inter-organizational levels. ICT has become a visible element of the required infrastructure of companies, regions, and countries (Dwivedi & Butcher 2008).

Zhao et al. (2013) states that the information system of service parts supply should be constructed based on the supply chain. Supply chain management is an effective method to organize the supplier, manufacturer, storehouse, distribution center, and supply channel. Zhao et al. (2013) also states that some companies focus on improving the supply chain, while others have a specific focus on improving the information sharing among supply chain partners. Khandelwal (2011) states that the MRO supply chain can be one of the best opportunities to reduce cost, this is because of the MRO has traditionally been seen as having low value and have been not received focus and investments in new systems, which has resulted in the MRO supply chain as not as important. Zhao et al. (2013) highlights the effective benefits of having an information system that is linked with the supplier, the demand, the distribution personnel, and the store-keeper. This should be done by collecting, transmitting, analyzing, changing, and processing the data so that all parts of the supply chain can be more efficient. The information system should include two parts. The first part is a common information platform of every spare part and the second is a data-collecting platform of spare parts. The first one is used as a guide to understand each spare part and the second one should be used to collect all the necessary information. The processed information can be uploaded to a common information platform and shared with those partners that require it (Zhao et al. 2013).

Zhao et al. (2013) describes that the goal of constructing an information system is to provide information to personnel or organization through more effective information flow. Khandelwal (2011) also states that the most crucial and important activity in an MRO supply chain is data management. The data management acts as the foundation stone for the success of the planning and execution functions. Since an MRO supply chain has many different service parts and each part differs in feature and characteristics, makes the warehouse extremely complex and challenging to plan Khandelwal (2011).

3.3.4 Material Flow

According to Goldsby & Martichenko (2005), the planning of the material flow must be managed continuously over time, which means that the flow must be constantly planned, measured, and improved regularly. The products that are delivered to meet customer requirements are the material included in the flow. This flow should be investigated to find an improvement that can be implemented for a more efficient flow of material. Goldsby & Martichenko (2005) also states that it is common that businesses know the demand for their products. The fact is that all demand follows some kind patterns that can be documented, described, and understood. By understanding the pattern of business demand, the material flow can be observed to determine accurate cycle times, ordering points, and efficient storage and transport systems.

3.3.5 Forecasting

A forecast is a prediction of the future. In the industry, forecasting is often associated with predicting customer demand, but other parts of a business organization must be predicted as well; such as the availability of goods from suppliers, which markets their products and services will be successful in, and the affect future political situations might have on the company. Since all other business decisions are based on the results of a forecast of the future, accurate forecasting is an important part of business operations for all companies (Sanders 2016). According to Wallace et al. (1927), every business actor regardless of industry must forecast in order to be successful, and these forecasts must be based on statistics. Forecasts are used in a large number of decisions, ranging from long term strategic decisions such as where to construct a new factory based on business trends and the general state of the economy, to short term operational decisions such as production scheduling and procurement of supplies. Information regarding current, as well as future customer demand is necessary in order to produce accurate forecasts. According to Marx-Gómez et al. (2002) the high level of uncertainty for unplanned maintenance makes the traditional forecasting methods impossible.

3.3.6 Decision Support

According to Liberatore (2012), strategic, tactical, and operational managerial decisions made in a supply chain can be supported by a decision support system. By collecting and analyzing data, the decision support system can improve the decision making process in a supply chain by allowing fast information-based decision making on an operative level as well as faster responses to changing circumstances. Decision support systems for supply chains include a wide range of methodologies and tools such as mathematical optimization algorithms and information technology tools. Liberatore (2012) claims that in order to successfully use a decision support system in a supply chain there are two fundamental requirements:

1. Comprehensive data regarding historical information about logistics activities must be available
2. A planning system that can analyze the data must be available

Liberatore (2012) provides a list of standardized tools that can be used to improve managerial decisions at an operative level in a supply chain:

- A customer logistics scorecard.
- An order cycle monitoring tool.
- An on-time delivery monitoring tool.
- An inventory level and turns monitoring tool.
- An overage, shortage, and damages monitoring tool.
- A detention and delivery unload monitoring tool.
- Daily alerts to transportation load planners on schedule improvement opportunities.
- Daily alerts to the planner on on-time delivery performance results.
- Daily alerts to customers detailing any back-orders that occurred.

3.3.7 Prioritization

Hatton (2007) describes a simple ranking system technique in software development which ranks tasks from 1 to n, where n is an integer value. Items ranked as 1 are of the highest priority, and the priority decreases as the ranking number decreases. This can be used to systematically prioritize tasks in a limited resource environment.

3.4 Manufacturing Planning and Control

Manufacturing Planning and Control (MPC) encompasses decisions regarding the acquisition, utilization, and allocation of resources, and the flow of material and information available to an organization. The goal is to provide customers with value in the most efficient way. For this reason, MPC operations can be seen as an optimization problem, where the goal is to maximize certain outputs from the organization. Examples of MPC activities include the allocation of resources such as equipment, personnel, and resources, as well as decisions regarding lot sizes, inventory levels, and sequence planning in a production system. (Graves 1999)

An MPC system can be used to support managers by providing them with the information they need in order to make effective decisions. An MPC system is not meant to replace human managers, but rather to assist these managers in their efforts to manage the firm's resources in an efficient way to improve their ability to respond to changes in customer requirements. An MPC system is able to do this through the utilization of the manufacturing company's internal capacity in combination with the capacity of its suppliers and customers. In a supply chain environment, an MPC system should aim to coordinate the planning and control of the entire supply chain. This can be done by using internet-based systems that have the ability to support the coordination of several companies. The goal is to reduce inventory levels and lead times between the different parts of the supply chain and replace them with a rapid exchange of information. The ability to acquire and utilize information regarding customer needs as well as to provide customers with information regarding the current status and expected delivery date for current orders is one of the strengths of an MPC system. An efficient MPC system can bring great value to a company if used right, but it also brings costs as it requires skilled professionals and supporting resources in order to operate. An MPC system should be adapted in order to support the strategy chosen by the firm in which it is implemented. An MPC system should also be able to change over time to stay up to date with the firm's current tactics to increase customer value. Whether this is through increasing the speed of delivery, availability, delivery reliability, product flexibility, or other competing priorities such as a reduction of product prices or response times to changes in the market, the MPC system will have to be designed and operated accordingly. If implemented correctly, the use of an MPC system can contribute to an increase in the competitive performance of the company. (Jacobs et al. 2018)

3.4.1 Enterprise Resource Planning

Enterprise Resource Planning (ERP) is used to integrate all of the different functions and departments of a firm into a unified system through the use of a common database. By using the same database, information sharing, and communication within the firm will be improved. If an ERP system is implemented correctly it can have a great positive effect for the firm by improving its efficiency. (Parthasarthy 2007)

An ERP system enables integrated planning and execution of operations across all the different functional areas of a company. These functional areas include sales and marketing, human resources, finance, and more. An ERP system can in many cases be used to support the coordination of planning and execution of operations across different departments in a company or different companies within a supply chain. From the viewpoint of management, ERP can be seen as a tool used to support managers with decision making when planning and controlling operations performed by the company by integrating the different aspects of the company into a single system with a shared database. One of the benefits of using a centralized database is that humans no longer need to manually reenter data in each step of the production process which reduces work and the risk for errors. The use of a shared database requires the company to use consistent definitions of how to collect and classify data across its different functional areas. For example, the definition of how to measure sales can have a great impact on the applicability of an ERP system. A sale could be recognized by the company when the customer places the order when the order arrives at the company, payment is collected, when manufacturing starts, when the product physically leaves the finished goods inventory, or when the product or service is delivered to the customer, or in some other way. If the company uses consistent definitions of key measurements such as sales, demand, and inventory levels, the efficiency of the company can be increased through the use of an ERP system. If these key measurements differ between the different departments of the company, however, confusion and mistakes will inevitably occur and bring unnecessary expenses to the company. Establishing consistency is important when implementing an ERP system. (Jacobs et al. 2018)

An ERP system gives a company direct benefits such as improved information integration and communication which allows for better and faster decision making and responses to customer orders to improve the efficiency of the company. The ERP system can also bring indirect benefits such as better customer relations, and an improved corporate image. By integrating disconnected business units in a company to a single system, ERP allows for rapid decisions based on real-time information. ERP also increases the flexibility of the company, as large amounts of data regarding languages, accounting standards, currencies, or other measurements are all stored in the same centralized system. This is especially important for large, global companies. (Parthasarthy 2007) A company using an ERP system can save money through the use of a centralized information system and common definitions for informed decision making. The quick access to centralized data from different parts of the company allows for new synergies to be formed. This is true especially for large global organizations where different business units are located in several different locations around the world. In addition to these benefits, an ERP system will increase the company's ability to respond quickly to changes in customer expectations as real-time updates to the information in the centralized database allows for fast decision making based on up to date information. (Jacobs et al. 2018)

An ERP system usually consists of several modules representing different business units that are integrated into a common data system. Figure 3.1 illustrates how an ERP system integrates disconnected business units in a company to a common database.

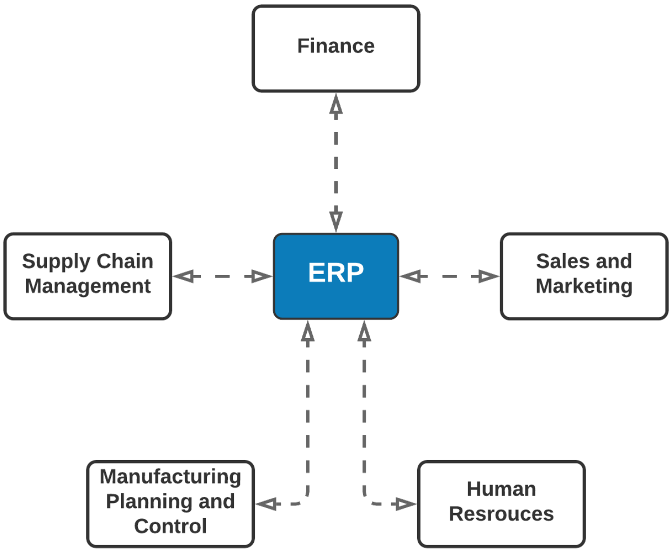

Figure 3.1: ERP connecting business units to a common database (Jacobs et al. 2018)

ERP in Finance

The centralized database provided by the ERP system will collect financial data in real-time automatically. For example, the ERP system enables customer orders to be used not only to trigger manufacturing but also to trigger orders to its suppliers and update the financial statements of accounts payable. When the customer pays, the financial statements for accounts receivable can be automatically updated as well. (Jacobs et al. 2018)

ERP in Supply Chain Management

When managing a supply chain, a large number of activities needs to be overseen. These activities include manufacturing, materials management, sales and marketing, logistics, warehousing, distribution, transportation, and coordination of supply chain members. Decisions regarding these activities need to be made and take into account things such as the volume and weight of the products and material flowing in the supply chain. The implementation of an ERP system assists managers when dealing with all of these things in a complex network by centralizing and standardizing data which allows for decision making based on up to date information. (Jacobs et al. 2018)

ERP in Manufacturing

An ERP system can help generate purchase orders to suppliers and assist manufacturing managers with the planning of maintenance and repairs of factory equipment, product quality assurance, and control, production planning, inventory management, capacity leveling, material requirements planning, product costing and bill of material processing by enabling information-based decision support. (Jacobs et al. 2018)

ERP in Sales and Marketing

This part of the ERP system is used to support the management of sales orders, customer relations, forecasting, marketing, delivery, credit checking, export controls, customs, billing, and invoicing. The use of a common, centralized database allows for quick responses to customer orders, for example; if a customer in Asia places an order for an item that is not available locally, the ERP system will update the database and allow managers to procure this item from internal warehouses in other parts of the world and ship the requested item to the customer. (Jacobs et al. 2018)

The sales and marketing module of an ERP system assists managers with pricing strategies, selling, customer order management, shipping, and billing of products to customers. The data available in the centralized database will allow for efficient marketing campaigns, accurate pricing strategies, and better forecasts of future demand (Parthasarthy 2007).

ERP in Human Resources

The Human Resources (HR) module of an ERP system supports the management of employees regarding scheduling work hours, travel expense accounting, wages, benefits and payment administration, training existing employees and hiring new ones (Jacobs et al. 2018).

In large organizations with thousands of employees, the benefits of the HR module of an ERP system are evident. By automating many of the activities performed by the human resources department the company can improve the management of the employees of the company by making faster and more accurate decisions. Since human behavior varies among each individual, the HR department can focus their attention on special cases, while the HR module of the ERP system handles large amounts of standardized data (Parthasarthy 2007).

3.4.2 Demand Management

Demand Management is the act of integrating information from customers to the manufacturing planning and control system. All potential customer demand is collected and coordinated by the firm. This can be done by taking existing customer orders and determining delivery dates and balance supply with demand. This ensures that promises about delivery dates to customers can be held. As demand management is used to connect the information from customers to the MPC system, demand management can be seen as the link between the firm and the market, as well as the firm and its partners in its supply chain which is illustrated in figure 3.2 where the arrows depict the flow information between the customers and the MRP system, as well as within the MRP system. The arrow between demand management and customers is double-headed to illustrate the importance of two-way communication with customers in addition to pure information gathering. Demand management provides Sales and Operations Planning with information regarding customer demand which is used to plan sales and manufacturing operations on a high aggregation level, usually about one year ahead in time. Demand management also provides Master Production Scheduling (MPS) with forecasts and information about actual customer demand which is used by the MPS for short-term manufacturing planning for specific products. (Jacobs et al. 2018)

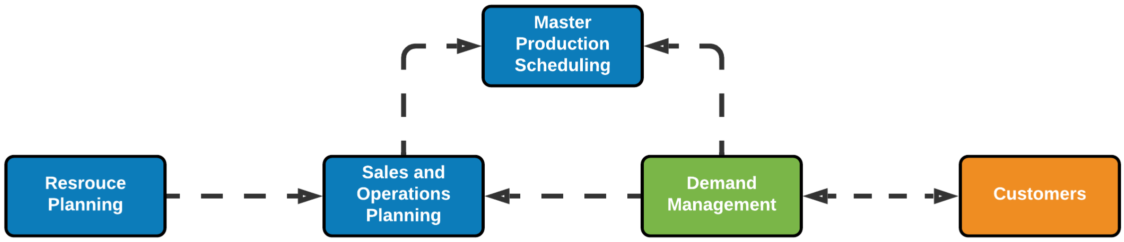

Figure 3.2: The role of Demand Management in MRP (Jacobs et al. 2018).

Chapter 4

Current State

This chapter presents the current state of the Gripen C/D service parts supply chain at Gripen Support, Saab Support & Services in Linköping. All the information in this chapter is based on interviews, documents and historical data from SAAB.

4.1 Gripen C/D Customers

In 2019 there were 167 Gripen C/D aircraft in use by six different customers who are illustrated in figure 4.1. 100 of these aircraft were used by the Swedish Royal Air Force, 14 aircraft by the Hungarian Air Force, as well as the Czech Air Force. 26 aircraft were used by the South African Air Force, and 12 aircraft by the Royal Thai Air Force. In addition to these five air forces, one Gripen C was used by The Empire Test Pilots' School, which is a British school for flight test engineers and test pilots. Saab handles the maintenance of these aircraft except for the one used by Empire Test Pilot's School. The customer owns the aircraft as well as all of the service parts[1].

When a service part is in need of maintenance it is removed from the aircraft and replaced with a new one from the customer's inventory. When the service part has been removed from the aircraft the personnel at the airbase writes a technical report. This technical report is a large set of detailed data that among other things describes why the service part was removed and contains information about the historical usage of the service part. The removed service part is sent to Saab for maintenance. The transportation time depends on where the customer is located. A service part sent from an airbase in Sweden usually arrives within a few days, whereas a service part sent from overseas might take several weeks[2].

[1]Martin Larsson, Logistics Analytics, Support & Services, 2020-04-09
[2]Martin Larsson, Logistics Analytics, Support & Services, 2020-01-24

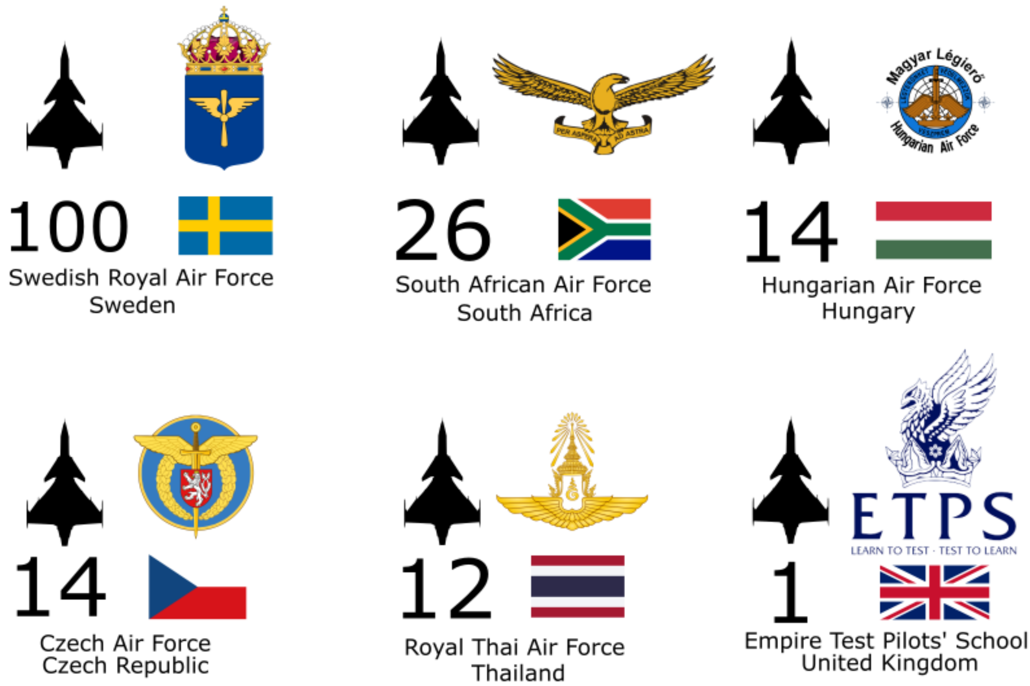

Figure 4.1: Number of Gripen C/D aircraft used by each customer (*Saab Group* 2020)

Saab divides all maintenance into two different categories; planned and unplanned maintenance. Planned maintenance is performed according to certain criteria specified by the manufacturer. There are three different kinds of criteria; Calendar Time, Flight Hours, and Cycles. Calendar time is the number of days that have passed since the service part was manufactured, regardless of how the aircraft is used. This is for example used for service parts made of rubber or the gunpowder used in the ejection seat. The number of flight hours is used for service parts that only experience wear when the aircraft is used, for example, hydraulic cylinders. The number of cycles is used for service parts that are worn down in relation to how many times they are used, regardless of the number of flight hours, such as the landing gear.

Every year the customer plans how much and when the aircraft will be used. With this information, the customer predicts when each service part will need maintenance. This calculation is based on the usage of the aircraft combined with the maximum amount of hours a service part is allowed to be used before maintenance. This type of maintenance is called planned maintenance. The customer is required to send the information to Saab[3].

Unplanned maintenance is needed whenever something unexpected happens, such as when a service part malfunctions or breaks. The only type of planning that Saab does for unplanned maintenance is using historical data. The historical data is used to predict how many service parts will arrive at the workshops in the future. Despite this type of planning approach, service parts in need of unplanned maintenance are often delayed.

[3]Kristian Lundberg, Director of Technology & Innovation, Support & Services, 2020-02-05

4.2 Service Parts

There are about 600 different service parts that can be removed from a Gripen C/D aircraft. All service parts have a specified expected maintenance lead time. The expected maintenance lead time ranges from 25 days to 200 days for different service parts. If Saab is unable to complete the maintenance within the specified maintenance lead time, Saab has to pay a penalty fine based on the value of the service part and the number of days it is delayed.

4.3 Service Parts Supply Chain

In order to provide their customers with maintenance service, Saab Support & Services uses a service parts supply chain, which is illustrated in figure 4.2.

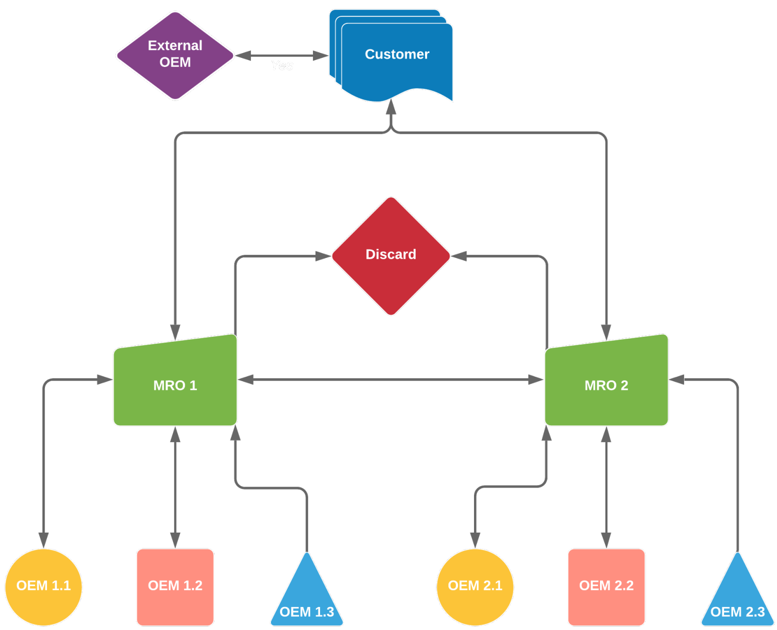

Figure 4.2: Gripen C/D service parts supply chain

Nodes in the service parts supply chain

The following list explains each part of the Gripen C/D service parts supply chain shown in figure 4.2.

- **Customer** - This blue node represents all of Saab's customers who use Gripen C/D and for whom Saab conducts maintenance. This is where the flow of service parts begins.
- **External OEM** - This purple node represents Original Equipment Manufacturers (OEM) that provide service parts directly to the customer. Saab is not involved in this part of the service parts supply chain. The engine is an example of such a service part, as it is wholly handled by its original manufacturer. These external OEM's are excluded from further analysis in this master thesis.

- **MRO 1 & MRO 2** - Saab has two different workshops where they perform Maintenance, Repair, and Overhaul (MRO). The two workshops are located in different locations and handle different types of service parts. MRO 1 handles mechanical parts, and MRO 2 handles avionics. In some instances, the service part is sent to the wrong MRO and has to be transported between MRO 1 and MRO 2[4]
- **Discard** - Saab handles the disposal of old and broken equipment. This is represented by the red square labeled *Discard* in the figure. This part of the service parts supply chain is excluded from further analysis in this master thesis.
- **OEM** - Both MRO 1 and MRO 2 has three different types of Original Equipment Manufacturers (OEM). The difference between the three types is as follows: OEM 1.1 and 2.1 handles all the maintenance of a service part. OEM 1.2 and 2.2 handles part of the maintenance of a service part. OEM 1.3 and 2.3 are not directly involved in the maintenance of service parts but supply the MRO workshops with spare parts. There are several hundred suppliers of each type of OEM in the service parts supply chain.

Each part has an expected lead time for maintenance. If the part is delivered to the customer too late, Saab has to pay a fine based on the value of the service part and the number of days the service part is delayed. The measurement of this lead time begins when the service part arrives at the loading platform of the MRO and ends when the part leaves the MRO again[5].

4.4 MRO workshops

The scope of this master thesis was limited to the MRO workshops at Saab. The boundaries for this system are illustrated in figure 4.3 as the translucent blue boxes marked *Saab Support & Services* and *MRO*. The figure illustrates the flow of information and material within, to, and from the MRO workshop in detail.

[4]Frida Liljenroth, Planning Manager, Support & Services, 2020-02-12
[5]Dino Besic, Production Planner, Support & Services, 2020-02-14

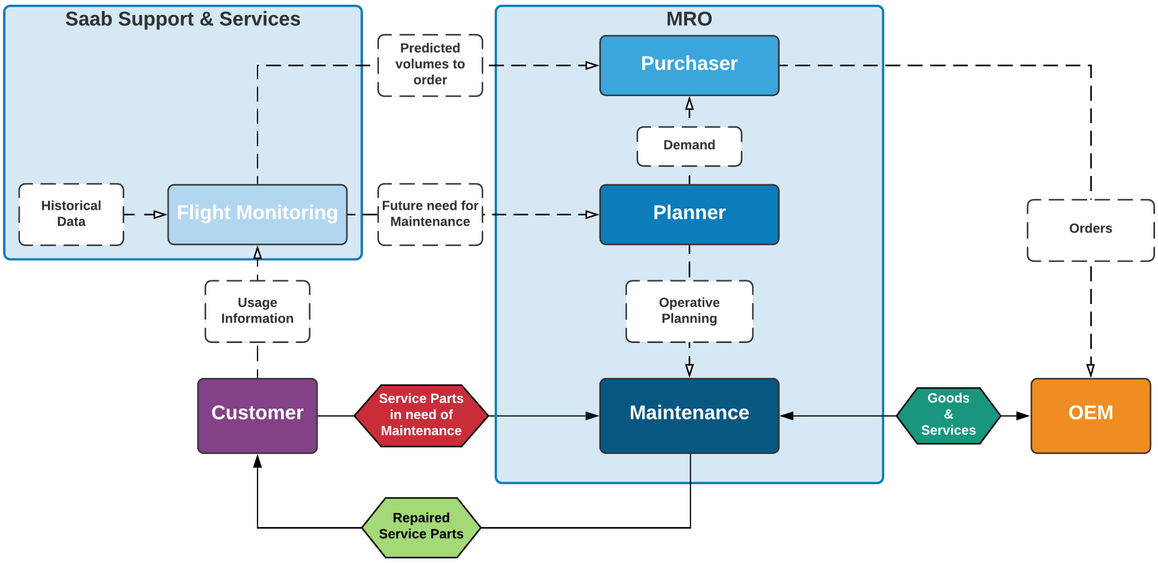

Figure 4.3: MRO in detail

The following text describes figure 4.3. The material and information flow of this supply chain begins at the *Customer*. The *Customer* sends the service parts that require maintenance to the part of the MRO labeled *Maintenance*. Twice a year the customer sends information regarding the service parts that require planned maintenance. This is illustrated in the figure as *Usage Information*. *Flight Monitoring* at Saab uses this information to inform the *Planner* and *Purchaser* at the MRO when maintenance is needed for each service part. The *Planner* uses that information to plan the maintenance and the *Purchaser* orders goods and services from OEM. *Flight Monitoring* receives *Historical Data* from a database that only Saab has access to. This data is used to predict future need for unplanned maintenance. The database is based on *Historical data* from the *Usage Information* from previous years. The *Planner* and *Purchaser* at Saab use *Historical Data* to predict how many unplanned events that will occur. The *OEM* facilitates the *Maintenance* with spare parts, and some service parts are transported directly to the OEM for maintenance. When a service part is repaired and is ready to be installed in an aircraft again, it is sent back to *Customer* from *Maintenance*.

The customer provides Saab with forecasts of future aircraft maintenance. This is the planned maintenance. These forecasts are used as input data to an optimization program that produces statistical data that is used by Saab Support & Services as a basis for purchases from the OEMs for planned maintenance[6]. All operations for unplanned maintenance is planned when these service parts arrive at the MRO[7].

The technical reports written by the customers when a service part is removed from an aircraft are available to Saab digitally. The flow of information from the customers to Saab is illustrated in figure 4.4. The technical reports are written by hand and put into *Computer System 1* manually. The data form the technical report is sent from *Computer System 1* to *Computer System 2* which in turn sends the data to *Computer System 3* at Saab, also automatically. The third computer system provides Saab with

[6]Kristian Lundberg, Director of Technology & Innovation, Support & Services, 2020-02-05
[7]Martin Brantemo & Marcus Karlsson, Flight Monitoring, Support & Services, 2020-02-10

data sheets regarding all the service parts that have been removed. These data sheets often lack certain information that has to be manually retrieved from Computer System 2 by employees at Saab Support & Services[8].

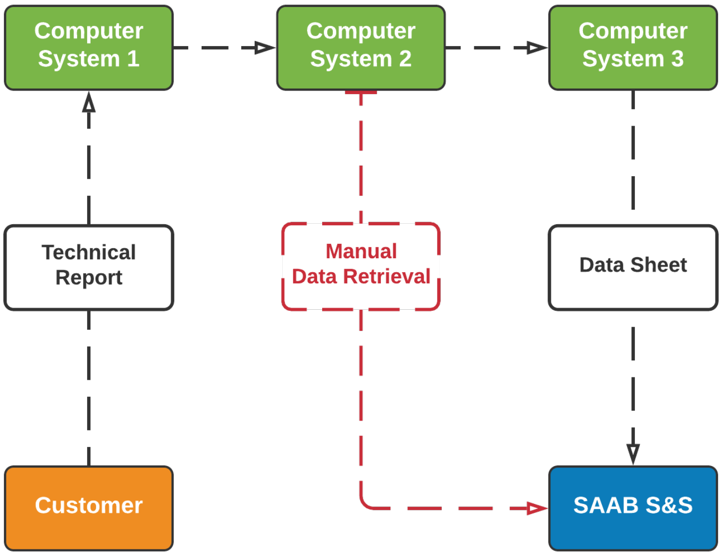

Figure 4.4: Information flow from customers to Saab

When a service part arrives at an MRO workshop it is placed in a First-In-First-Out (FIFO) queue. The personnel can access information about what is wrong with the service part in the technical report. Each service part goes through a process called *arrival inspection* when it enters the MRO workshop for the first time. This test verifies the fault reported in the technical report and finds additional errors that might not have been identified by the customer. After this initial test, the service part goes through maintenance work to restore it to a functional condition. When this is done the service part goes through a final test to make sure that the maintenance has been done correctly and that the service part is safe to use. If the service part should fail this final test, it goes through the entire process again.

The FIFO-queue can be altered by the customer when they want other service parts to be prioritized. This prioritization can be caused when the customer runs out of a certain service part and marks it as Aircraft On Ground (AOG) which means that an aircraft is unable to operate as it can not fly without this particular service part. This can also occur when the customer is running low on a certain service part in their own inventory and risks reaching AOG soon. Whenever these changes in the production queue occur, the measurement of the maintenance lead time is 'paused' for other service parts to avoid fines caused by these delays, as it is not something Saab can control. This is reported as a *clock-stopping* interruption code in the MRO workshop[9].

In addition to the clock-stopping interruption code, there are regular interruption codes. These codes are used to classify and log interruptions that may occur in the maintenance work. These interruptions can occur when the MRO workshop runs out of spare parts,

[8]Marcus Karlsson, Flight Monitoring, Support & Services, 2020-02-20
[9]Dino Besic, Production Planner, Support & Services, 2020-02-14

or when a service part has been delayed at an OEM. Saab uses 47 unique interruptions codes to log the different disturbances that may occur during maintenance.

Saab is responsible to calculate the cost to repair the service parts that they maintain. Each service part has a certain percentage level of its purchasing cost which is called Beyond Economical Repair (BER). Saab contacts the customer if the calculation exceeds the limit of the BER to decide if maintenance of the service part should continue or a new service part should be purchased. Some times maintenance continues despite the cost as it is usually faster than waiting for a new service part. This decision is made by the customer as they own the service parts[10].

Since many spare parts used to maintain the service parts are expensive, and some spare parts have a limited lifetime, the MRO workshops avoid purchasing anything until they know for sure what they need. Often when there is a service part that requires planned maintenance, the MRO has a good idea of what type of service is required. It could be a standardized service after a certain amount of hours, and a spare part that always has to be changed. This allows the MRO workshops to complete planned maintenance on time more often. These things are much harder to know for unplanned maintenance as the type of maintenance needed is unknown before an operator has tested what type of problem that needs to be fixed. To handle the complexity of not knowing what type of fault that a service part has, Saab uses historical data to predict what spare parts that are needed to be purchased each year. The problem with using historical data is that the aircraft and the service parts are getting older. This means that relying on historical data only shows what demand has looked like in the past. The operators have seen an increase in service parts arriving at the MRO throughout the years. This is illustrated in figure 1.8, which illustrates as the service part gets older the maintenance is required more often. As a result, much of the unplanned maintenance suffers from severe delays[10].

4.5 OEM

There are two purchasing units at Saab. Firstly the strategic procurement department at Saab Support & Services handles strategic purchases and deal with long term contracts and supplier relationships with OEM. Secondly, the operative planners at MRO handle operative purchasing where orders of goods and services are actually placed to the OEM's according to the contracts set up by the strategic purchasers. The flow of information to OEM in the Gripen C/D service parts supply chain regarding unplanned maintenance is illustrated in figure 4.5 which is described below. The flow begins with the node labeled *Aeronautics* which designs the Gripen aircraft and provides the *Strategic Procurement* with product specifications for all service parts. *Strategic Procurement* then uses this information to find and select OEM companies that can provide Saab with goods and services that meet the product specification. The strategic purchasers at *Strategic Procurement* make long term contracts and establishes a relationship with these companies. The *Operative Planning* at the MRO workshops handles operative purchasing. For unplanned maintenance, decisions regarding operative purchasing are based partly on *Forecasts based on historical data.* These forecasts are not 100% accurate which means that service parts arrive unexpectedly from time to time. This is represented in figure 4.5 by the node labeled *Service Part Arrive at MRO.* The operative planners place orders to

[10]Dino Besic, Production Planner, Support & Services 2020-02-14

the OEM according to the contracts made by the strategic purchasers based on a combination of the forecasts and the requirements of the service parts that are present in the MRO workshop.

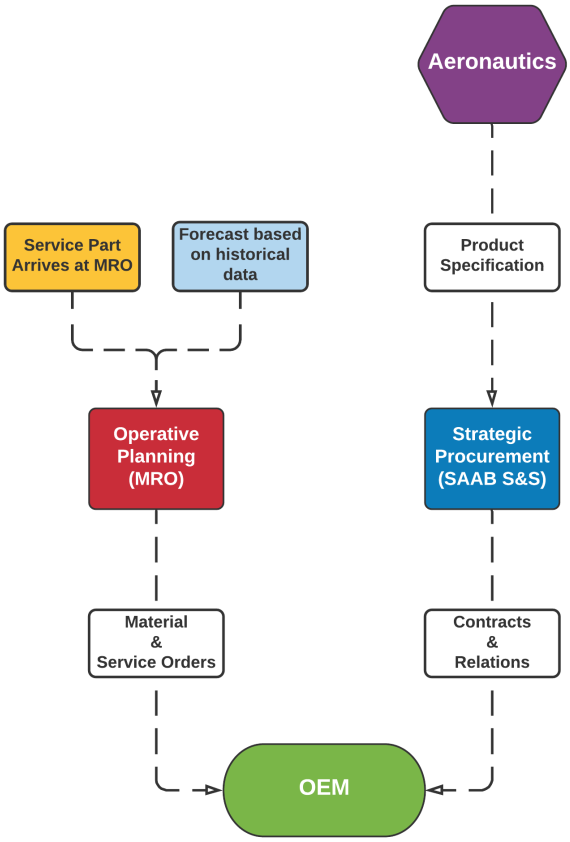

Figure 4.5: Information flow to OEM

Saab uses three different types of OEM. What distinguishes them from each other is the way they are used to support the MRO as shown in figure 4.6, where the black arrows illustrate the flow of material. The first type of OEM handles all the maintenance of a service part, and Saab's MRO workshop is not involved in the work. This is illustrated as *Scenario 1* in figure 4.6. The second type of OEM helps by performing some of the maintenance, while Saab's MRO workshop performs the rest, illustrated as *Scenario 2* in figure 4.6. The third and final type only provides Saab's MRO workshop with disposable items such as spare parts or lubricants, illustrated by *Scenario 3* in figure 4.6. Saab uses several hundred different OEMs of each type to support and supply their MRO workshops with the correct material and services[11].

[11]Timmy Svensson & Johan Haraldsson, Purchaser, Support & Services, 2020-02-17

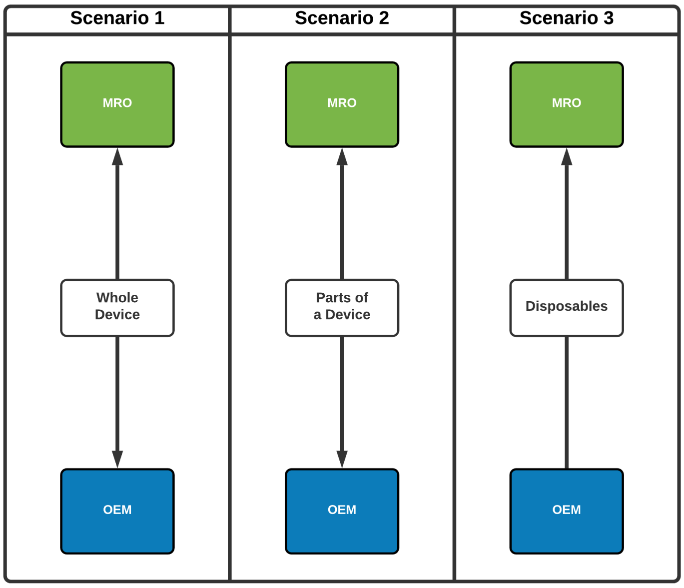

Figure 4.6: The three types of OEM

Chapter 5

Analysis

This chapter analyzes the data found at Saab and connects it with the theoretical framework. The analysis is divided into four major sections. The first section is an ABC-analysis where the service parts that contribute the most to penalty fines are identified. The second part is a process map analysis which analyzes the activities that make up the maintenance process in the MRO workshops. The third section is a lead time analysis where the lead time of the each activity in the maintenance process is analysed for all units of the A-category service parts identified in the ABC-analysis, and identifies interruptions in the maintenance process. The final section is a root cause analysis which exposes the reasons behind the interruptions and delays of the maintenance process.

5.1 Service Parts

The names and identification numbers for the service parts are classified. As a result of this, the service parts have been given new names in this report. They are all referred to as *Service part* followed by a number. The amount of penalty fines paid is also classified. Instead of presenting a number, each service part will be presented with its share of the total penalty fines paid in 2019.

In 2019, 4277 units of service parts were maintained by Saab's MRO workshops. Out of these units, 895 units of 82 different types of service parts were delayed and induced penalty fines. Information about these 82 service parts is presented in table D.2 in appendix D together with their contribution to the total sum of penalty fines paid in 2019.

5.2 ABC - Analysis

An ABC analysis was conducted in order to determine which service parts contributed the most to the penalty fines paid by Saab in 2019. This ABC analysis was based on the service parts' contribution to the total amount of money paid in fines in 2019. The 82 service parts that contributed to penalty fines in 2019 are shown in table D.2 in appendix D. These service parts were sorted according to their share of the total penalty fines paid in 2019. The ABC-analysis divided them into three categories; A, B, and C. The top 20 % of the units on the list were assigned to the A-category. The next 30% of the service parts were assigned to the B-category, and the final 50% were assigned to the C-category according to the theory presented by Flores & Whybark (1986) in chapter 2. The result of the ABC analysis is shown in table 5.1. The units in the A-category amounts to 86% of the total penalty fines paid in 2019. The 16 service parts in the A-category were selected for further analysis.

Category	**Proportion of Service Parts**	**Share of total fines 2019**
A	20 %	86 %
B	30 %	12 %
C	50 %	2 %

Table 5.1: ABC analysis of service parts contribution to penalty fines 2019

5.3 A-class Items

Figure E.1 to figure E.16 in appendix E illustrates bar charts showing the difference between actual maintenance lead time and planned maintenance lead time for each individual unit of the service parts. An example is shown for service part 1 in figure 5.1. The length of the bars illustrates the difference between actual maintenance lead time and planned lead time in workdays for each unit. That is, positive bars represent late completion of maintenance, and the negative bars represent early completion of maintenance. If a unit is delivered right on time, the length of the bar will be zero. The blue bars represent unplanned maintenance, and the orange bars represent planned maintenance.

27 individual units of service part 1 were maintained by Saab's MRO workshops in 2019. 8 of these units underwent planned maintenance, and 19 units underwent unplanned maintenance. Figure 5.1 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 6, which was completed 250 days later than expected, with a total lead time of 280 days.

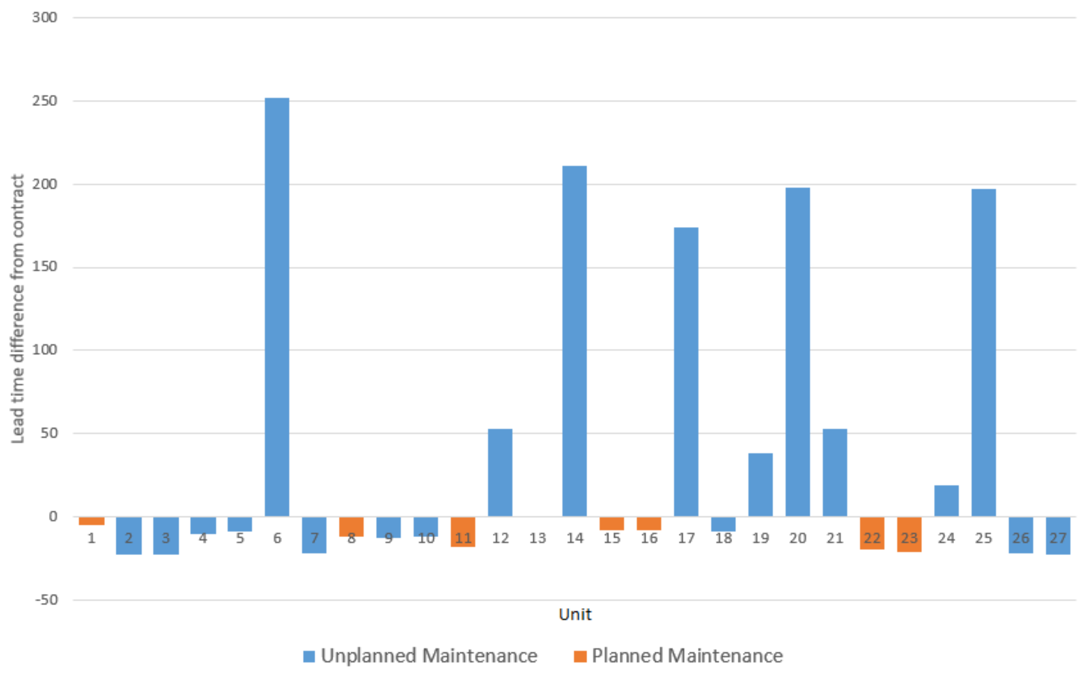

Figure 5.1: Service Part 1

In total 486 individual units of the 16 A-category service parts were maintained and delivered in 2019. 71% of these 486 units required unplanned maintenance, and the remaining 29% required planned maintenance. 86% of all penalty fines paid in 2019 were caused by delays in unplanned maintenance. The relationship between volume and penalty fines 2019 is illustrated in figures 5.2 and 5.3. In total, there were 190 units of the 16 service parts in the A-category that required unplanned maintenance and were delayed.

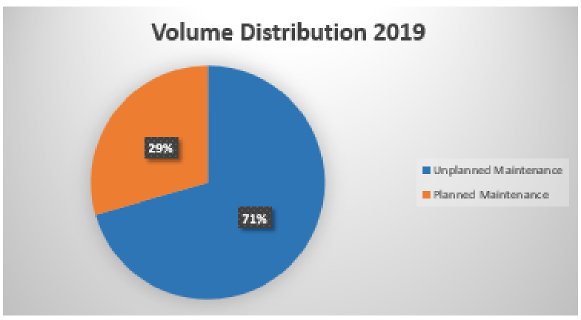

Figure 5.2: Volume Distribution

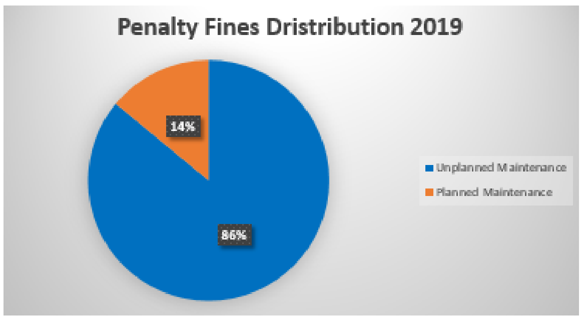

Figure 5.3: Penalty Fines Distribution

As a result of this information, only unplanned maintenance was analyzed from this point onward.

5.4 Process Map Analysis

A process map was conducted in order to visualize all the activities and to identify what information the decisions are based on. This process map analysis is based on the theory of Brook (2017) and Jacka & Keller (2009) which is described in detail in Chapter 2.

The process begins when a service part is removed from an aircraft due to a need for unplanned maintenance. The next step is that the service part is transported to an MRO workshop for maintenance. The process map illustrated in figure 5.4 shows what happens during maintenance in greater detail. After maintenance is completed, the service part is transported back to the customer.

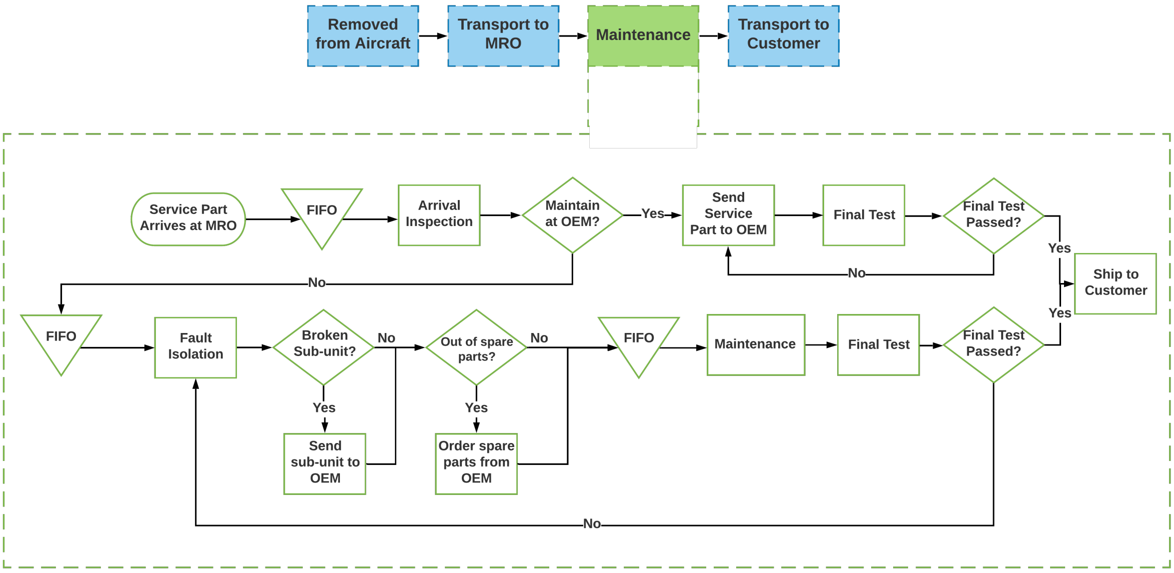

Figure 5.4: Process map of Unplanned Maintenance

The maintenance process begins when a service part arrives at the MRO workshop and is placed in a FIFO-queue. The operators at the MRO workshop then perform an arrival inspection where the service part is examined and the information in the technical is verified. After the arrival inspection has been completed, the operators document in Saab's database that the service part has been received and that arrival inspection has been completed. Whether or not the service part should be maintained in the MRO workshop or at its OEM is pre-determined for each type of service part, As illustrated in figure 4.6 in chapter 4.

If the service part should be maintained by the OEM, the operative MRO planner informs the operative purchasers who in turn order maintenance from the OEM and sends the service part to its OEM for maintenance. When the service part returns from the OEM it is tested by the operators at the MRO workshop to make sure that the service part is safe to use in an aircraft. If the service part fails this test it is sent back to the OEM, but if it passes the final test it is shipped back to the customer, and maintenance of the service part is deemed as completed. This is illustrated as Scenario 1 in figure 4.6 in chapter 4.

If the service part should be maintained in the MRO workshop, it is instead sent into a FIFO storage at the MRO workshop. The service part then goes through a series of tests called *Fault Isolation* where the operators at the MRO workshop identify what type of maintenance is required to restore the service part to a working condition. These tests vary between different types of service parts.

If the service part uses sub-units, and the fault isolation identifies broken sub-units, these sub-units are removed from the service part and sent to the OEM to be repaired. New sub-units are put into the service part. This is illustrated as Scenario 2 in figure 4.6 in chapter 4.

If the fault isolation identifies that a type of maintenance that requires spare parts is needed, the inventory of spare parts at the MRO workshop is checked. If the MRO workshop does not have enough spare parts to perform the maintenance, new spare parts are ordered from the OEM. This is illustrated as Scenario 3 in figure 4.6 in chapter 4.

If the MRO workshop does not have enough sub-units or spare parts in stock to maintain the service part, the service part is put in storage until the MRO workshop has access to all sub-units and spare parts necessary to maintain the service part. Maintenance of the service part begins when the MRO workshop has access to all necessary resources.

The final step of the maintenance process at the MRO workshop is the final test of the service part. During this test, the operators make sure that the service part reaches pre-determined levels of performance and is safe to use in an aircraft. If the service part fails the final test, it is sent back to fault isolation and goes through the entire maintenance process again. If the service part passes the final test, it is shipped back to the customer, and maintenance of the service part is completed.

5.5 Lead Time Analysis

A lead time analysis was conducted for all 190 units of the 16 service parts classified into the A-category that needed unplanned maintenance and were delayed in 2019. The lead time analysis analyzed the steps and interruptions that occurred during maintenance of the service part as described by Oskarsson et al. (2013) in chapter 2.

As described in chapter 4, Saab uses codes to log when maintenance is stopped due to an interruption in a database. When investigating the data regarding maintenance for all of the 190 units of the 16 service parts in category A in need of unplanned maintenance that were delayed in 2019, these interruption codes were used to identify the cause of each event that happened during maintenance. This data was available in an extensive database at Saab. For each of these 190 units, data from the database was analyzed to understand what transpired during the time from the removal of the unit from the aircraft until maintenance was completed. The database contains information about when the unit was removed from the aircraft, when it arrived at the MRO workshop, the maintenance activities that were performed in the MRO workshop, and how long they took to complete. Data regarding the interruptions of the maintenance were available together with the time needed to resolve the interruption. The database also contained information about when maintenance was completed.

Data was collected regarding what type of interruptions occurred and how long it took to resolve the issue for each unit. This data was then aggregated for each service part to make sure that data from all cases were included in the extensive lead time analysis presented below. This data for all 16 service parts is available in appendix F.

The analysis from the 190 units showed that four types of interruptions caused delays, as shown in table 5.2.

Type of Interruption	Share of Interruptions	Share of Time
External Delay at OEM	38 %	57 %
Internal stock-out (sub-units)	22 %	24 %
Internal stock-out (spare parts)	25 %	18 %
Internal machinery breakdown	15 %	1 %

Table 5.2: Summary of the different interruptions that occurred the A-category items 2019

The first column in table 5.2 shows the interruption that caused a delay as it was reported in the database at Saab. The second column shows what proportion of the number of occurrences each type of interruption was responsible for. For example, 25% of all interruptions were caused by an internal stock-out of spare parts. The third and final column shows what proportion of the total time needed to resolve the issues each interruption has caused. For example, the time needed to resolve the interruptions caused by internal faulty equipment amounted to 1% of the total time needed to resolve all the interruptions. The four causes of delays identified were; internal stock-out of spare parts, internal stock-out of sub-units, external delay at OEM, and internal faulty equipment.

Cause of delay	Average Interruption Time
Internal stock-out (spare parts)	120 days
Internal stock-out (sub-units)	171 days
External delay at OEM	242 days
Internal faulty equipment	15 days

Table 5.3: Average number of days needed to resolve each cause of delay

Timelines are illustrated in figures 5.5, 5.6, 5.7, 5.8 in the following sub-sections. The bars and numbers in the timelines are color coded as follows:

- **Blue:** Transportation time from customer to MRO workshop.
- **Yellow:** Time spent by the service part in inventory at the MRO workshop.
- **Green:** Time spent doing maintenance work.
- **Red:** Time spent waiting for an interruption be resolved.
- **Purple:** The expected due-date or deadline of the maintenance.

5.5.1 Internal stock-out (spare parts)

An interruption reported as an internal stock-out of spare parts means that maintenance had been interrupted as the MRO workshop did not have enough spare parts and disposable material, such as screws, O-rings, or lubricant on hand. The issue is resolved when a delivery of new spare parts or disposable material is received at the MRO workshop. This is a one-way flow of spare parts and material from OEM to the MRO workshops.

In order to illustrate this interruption, the aggregated timeline shown in figure 5.5 was created using data from all 48 units that were delayed of an internal stock-out of spare parts. A larger time-line is illustrated in Appendix G.

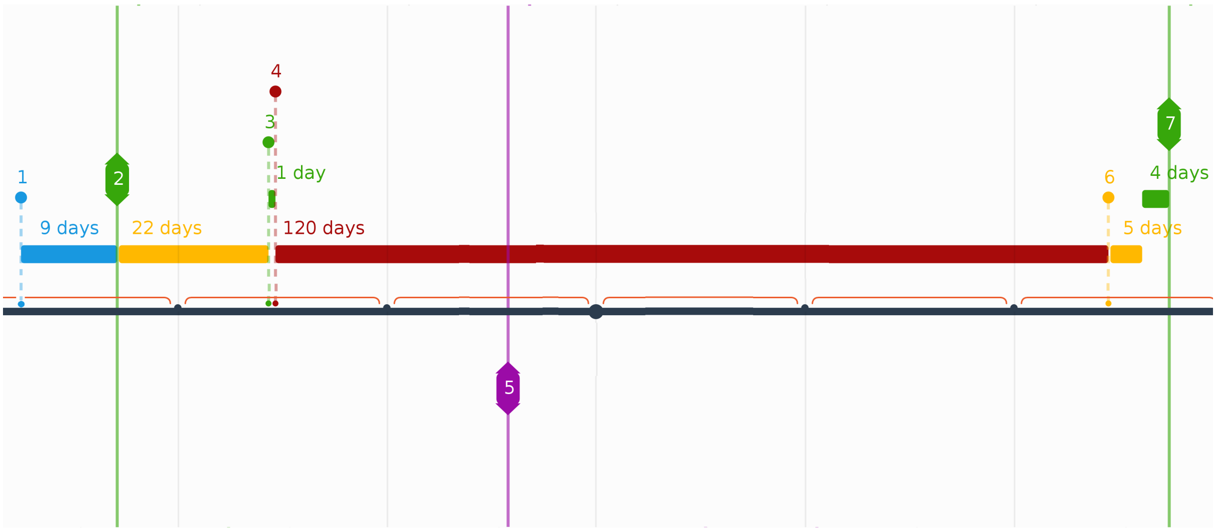

Figure 5.5: Aggregated time line for internal stock-out (spare parts)

The numbers in the timeline correlate to the events described by the same numbers in the following list. The maintenance process is illustrated in the process map in figure 5.4.

1. The service part was removed from the aircraft by mechanics at the airbase. A technical report was written and submitted to a database. The information in the technical report is available to Saab, but it is not used.
2. The service part arrived at the MRO workshop after being transported for **9** days. The service part went through arrival inspection and put in storage where it waited for fault isolation.
3. The service part went through fault isolation after **22** days in storage. During the fault isolation, the operators at the MRO workshop identified that the service part required maintenance that needed spare parts. The operators at the MRO workshop checked the inventory and discovered a lack of the specific spare parts needed to maintain the service part. The operative planner informed the operative purchasers that new spare parts are needed.
4. **1** day later, the operative purchasers placed an order for new spare parts to the OEM.
5. Deadline. Maintenance of the service part should be finished by now.
6. New spare parts arrived at the MRO workshop **120** days after the order was placed by the operative purchasers. There is no expected delivery lead time from the OEM. The service part was still in storage for another **5** days before maintenance began.
7. **4** days later, maintenance was complete and the service part passed the final inspection and was shipped back to the customer.

The expected maintenance lead time was on average 56 calendar days. As shown in figure 5.5, the average actual maintenance lead time was 152 calendar days. On average, the delay was 96 calendar days.

As figure 5.5 shows, the maintenance was on average interrupted for 120 days because the MRO workshop was waiting for new spare parts from the OEM. This time was longer than the expected maintenance lead time which means that the service part could not have been delivered on time. As the first yellow bar and the green number 3 shows, it took 22 days on average from the arrival of the service part until the fault isolation was made. This means that the MRO planner discovered the need for new spare parts after 22 days. During these 22 days nothing happened to the service part and this time should be considered waste as it did not add any value to the customer. If the fault isolation would have been conducted together with the arrival inspection, new spare parts could have been ordered on average 22 days earlier. This leads to the third source of delay, which is that the service part spends too much time in inventory at the MRO workshop. This refers to the 22 days spent in inventory after the arrival inspection, but also to the 5 days spent in inventory between the arrival of new spare parts and the actual maintenance work begun.

The following three sources of the delay were found:

- The OEM delivers spare parts too slowly.
- New spare parts are ordered too late.
- The service part spends too much time in inventory.

5.5.2 Internal stock-out (sub-units)

Interruptions reported as caused by an internal stock-out of sub-units are similar to the last source of delay, but instead of lacking spare parts or disposable material, the MRO workshop has run out of a certain sub-part of the service part, such as a central processing unit. Another difference is that these sub-units circulate in a closed-loop system. The issue is resolved when the MRO workshop gets access to a functional sub-unit that can be put in the service part.

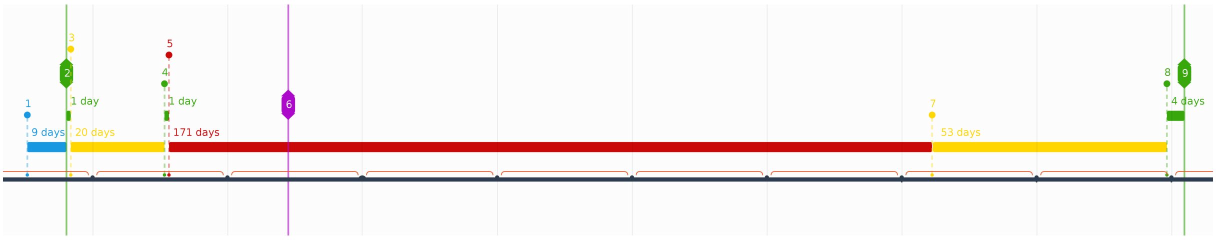

Figure 5.6: Aggregated time line for internal stock-out (sub-units)

The numbers in the timeline correlate to the events described by the same numbers in the following list. The maintenance process is illustrated in the process map in figure 5.4.

1. The service part was removed from an aircraft. A technical report was written and submitted to the database. The information in the technical report is available to Saab, but it is not used.
2. The service part arrived at the MRO workshop after **9** days. The measurement of actual maintenance lead time began. The service part went through the first step of the maintenance process which was arrival inspection.

3. **1** day later the service part was placed in a FIFO inventory for **20** days.
4. Fault isolation showed that the service part needed new sub-units. The inventory of sub-units at the MRO workshop was empty. The operative planner informed the operative purchasers.
5. The broken sub-units removed from the service part were sent to the OEM to be repaired by the operative purchasers.
6. Deadline. Maintenance of the service part should be finished by now.
7. Repaired sub-units arrived at the MRO from the OEM after **171** days. The service part stays in the FIFO inventory. for another **53** days before maintenance continues.
8. **53** days later, the service part went through the final stages of maintenance for **4** days.
9. The service part passed the final test and was shipped to the customer.

The expected lead time was on average 50 calendar days. As shown in figure 5.6 the average actual lead time was 250 calendar days. On average, the delay was 200 calendar days for the service parts that were interrupted by an internal stock-out of sub-units. A larger time-line is illustrated in Appendix G.

As shown in figure 5.6, this type of interruption is related to the same sources of delays as the service parts that were interrupted by a stock-out of spare parts. The OEM took on average 171 days to deliver new sub-units, which was more time than the expected maintenance lead time of the service part. New sub-units were not ordered until the fault isolation process was conducted, which on average was done after 20 days. Finally, the service part spent an unnecessary amount of time in inventory at the MRO workshop during the 20 days before fault isolation, but also during the 53 days between the arrival of new sub-units and the final maintenance work was done.

The following three sources were found:

- The OEM delivers sub-units too slowly.
- Old sub-units are sent to the OEM too late.
- The service part spends too much time in inventory.

5.5.3 External work at OEM

As described in chapter 4, the maintenance of some service parts is completely handled by the OEM, and Saab's MRO workshops only send the service parts to the correct OEM. If these service parts are delayed at the OEM, the interruption is reported as external delay at OEM. The issue is reported as resolved when the service part has returned to the MRO workshop.

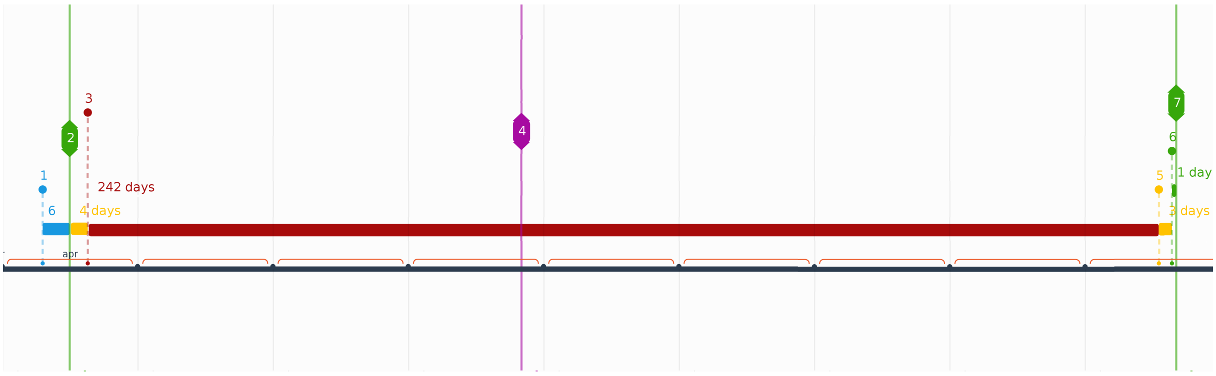

Figure 5.7: Aggregated time line for external delay at OEM

The numbers in the timeline correlate to the events described by the same numbers in the following list. The maintenance process is illustrated in the process map in figure 5.4. A larger time-line is illustrated in Appendix G.

1. The service part was removed from an aircraft. A technical report was written and submitted to the computer system. Saab has access to the information, but it is not used.
2. The service part arrived at the MRO workshop **6** days after being removed from the aircraft. An arrival inspection was made when the service part arrived at the MRO workshop. The service part should be maintained entirely by the OEM. The operative planner informs the operative purchasers that the service part should be sent to its OEM for maintenance.
3. **4** days after the service parts' arrival to the MRO workshop, the operative purchasers place the order and ship the service part to the OEM.
4. Deadline. Maintenance of the service part should according to the contract be finished by now.
5. The service part returns from the OEM to the MRO workshop **242** days after the order was sent to the purchasers at Saab.
6. The service part went through the final test **3** days after arriving at the MRO workshop to make sure that the service part was correctly maintained by the OEM.
7. The service part was shipped back to the customer **1** day after beginning the final test. Measurement of actual maintenance lead time was stopped.

The expected maintenance lead time was on average 112 calendar days. As shown in figure 5.7, the average actual maintenance lead time was 250 calendar days. On average, the delay was 138 calendar days.

As shown in figure 5.7, the service part was sent to the OEM for maintenance almost as soon as it arrived at the MRO workshop. The service part then spent on average 242 days at the OEM, which was longer than the expected maintenance lead time for the service part.

The following source of delays was found:

- The OEM takes too long time to maintain the service part

In this case, sending the service part to the OEM is supposed to happen. For some reason, the service part was delayed, but since that happened at another company it is out of the scope of this master thesis.

5.5.4 Internal faulty equipment

An interruption reported as internal faulty equipment means that maintenance had to stop because necessary tools or machinery was not functional at the time. The issue is resolved when the appropriate tools or machinery has been repaired.

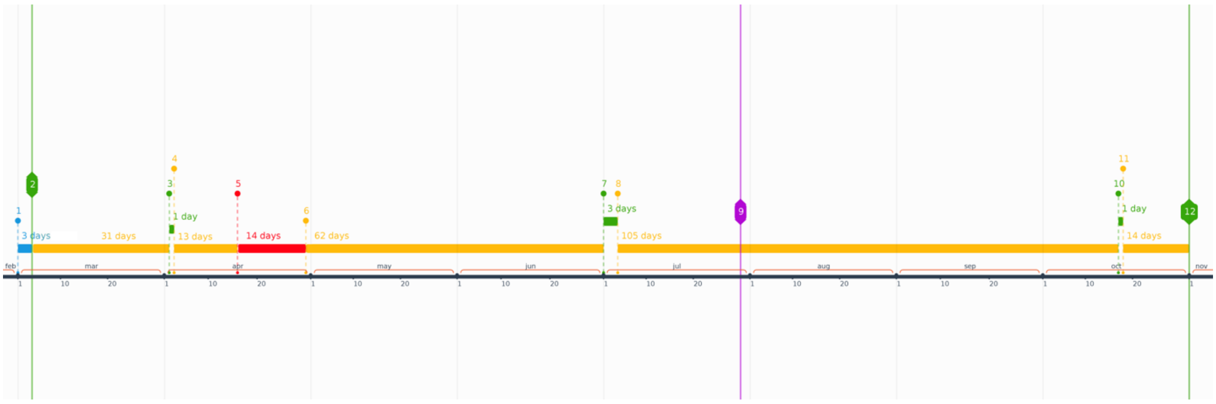

Figure 5.8: Aggregated time line for internal faulty equipment

In order to illustrate this interruption, the aggregated timeline shown in figure 5.8 was created using data from all 48 units that were delayed of an internal stock-out of spare parts. A larger timeline is illustrated in Appendix G.

1. The service part was removed from an aircraft. A technical report was written and submitted to the computer system. Saab has access to the information, but it is not used.
2. The service part arrives at the MRO workshop after **3** days. An arrival inspection was made when the service part arrived at the MRO workshop.
3. After **31** days a fault isolation was conducted. The MRO workshop does not have to order any sub-units or spare parts.
4. **1** day after the fault isolation the service part was put into storage.
5. After **13** days in storage, maintenance of the service part was supposed to begin but it was interrupted when a piece of machinery broke down.
6. The equipment was restored and maintenance could continue after **14** days, but the service part remains in storage for another **62** days.
7. The service part was maintained during **3** days.
8. After the maintenance was completed the service part was put in storage for **105** days.
9. Deadline. Maintenance of the service part should according to the contract be finished by now.

10. The service part went through the final inspection and the test was successfully completed.
11. One day after the final test began the service part was put in storage for another **14** days.
12. The service part was shipped to the customer, the maintenance was completed.

The expected lead time was on average 98 calendar days. As shown in figure 5.8 the average actual lead time was 244 calendar days. On average, the delay was 200 calendar days for the service parts that were interrupted by an internal stock-out of sub-units.

As shown in figure 5.8, the service part spent on average 31 days in inventory before the fault isolation was conducted. The service part was then stored in inventory for another 13 days before maintenance work was supposed to begin, but then the maintenance was interrupted due to machinery breakdown. On average, it took 14 days to repair the broken machinery, and the service part spends another 43 days in inventory before the service part was successfully maintained for 3 days. The service part then spent on average 105 days in storage before going through the final test. Finally, the service part spent 14 days in inventory before being shipped back to the customer.

The following two sources of delays were found:

- The service part spends too much time in inventory
- The machinery broke down

5.6 Root Cause Analysis

The lead time analysis of the aggregated timelines exposed seven different causes of delays related to the interruptions of maintenance of service parts. The causes were divided into two categories; the ones that were caused by the OEM, and the ones that were caused by the MRO.

Delays caused by OEM

1. The OEM delivers spare parts too late.
2. The OEM delivers sub-units too late.
3. The OEM takes too long to maintain service parts.

Even though the three causes related to OEM are specific to different types of interruptions, all three can be aggregated into one cause of delay. The three types of interruption have one thing in common, which was the fact that they provide the MRO workshops with some kind of service, and this service was not always provided in time. Therefore the three causes were aggregated to the following cause of delay: *The OEM takes too long to deliver its service to the MRO workshop.*

Delays caused by MRO

1. Spare parts are ordered too late.
2. Broken sub-units are sent to OEM too late.

3. Service parts spend too much time in inventory.
4. Machines brake down.

The two first causes of delays related to the MRO workshop can be aggregated as well. The two types of causes are related to different types of interruptions but stem from the same problem which was: *The MRO workshop places orders to the OEM too late.*

The third cause of delay was related to *service parts spend too much time in inventory* at the MRO workshop. This type of delay was not related to a particular type of interruption as it has been observed together with several types of interruptions.

The final cause of delay at the MRO workshop was *machinery broke down* which happened when maintenance was interrupted as a result of machinery necessary to perform maintenance malfunctions.

5.6.1 5-Why analysis

The 5-Why method was used to identify the root causes of the reasons for interruptions of maintenance, according to the theory presented by Serrat (2017) in chapter 2.

The following four types of causes of delays were investigated using the 5-why method.

1. The OEM takes too long to deliver its service to the MRO workshop.
2. The MRO workshop places orders to the OEM too late.
3. Service parts spend too much time in inventory.
4. Machines brake down.

The OEM takes too long to deliver its service to the MRO workshop

The lead time analysis showed that the OEM takes too much time to deliver its service to the MRO workshops. As the aggregated timelines illustrated in figures 5.5, figure 5.6, and figure 5.7, the OEM takes more time to deliver their service to the MRO workshop than the time allocated for Saab to complete the maintenance of the service part. This makes it impossible for the MRO workshops to deliver maintained service parts on time. Together with the lead time analysis and interviews of operative planners and purchasers at Saab Support & Services the 5-why method was conducted. The complete 5-why analysis is shown in table 5.4 and began with the question: *Why does it take too long for OEM to deliver its service to the MRO workshops?*

Question	**Answer**
Why?	Because there is no incentive for OEM to deliver on time
Why?	The OEM does not loose anything if they do not deliver on time
Why?	Saab does not have any contracts that states that the OEM's have to deliver on time

Table 5.4: Root cause analysis - Late deliveries from OEM

The lead time analysis showed that late deliveries from OEM was the single largest source of delays of unplanned maintenance in 2019. As shown in table 5.2, external delay at OEM is responsible for 57% of the downtime caused by interruptions. The lead time analysis showed that the interruptions caused by stock-outs also led to delays largely due to the fact that OEM's are delivering their services to the MRO workshops too late.

The root cause analysis showed that the reason that services from the OEM are delayed is that Saab does not currently have strictly written contracts with their OEM's to ensure that they deliver within a specified time frame. If contracts were used, Saab could ensure that the MRO workshops are able to complete the maintenance of service parts in time. Interviews with strategic purchasers at Saab Support & Services revealed that Saab is using contracts that specify the expected lead time for some of their OEM's. However, these expected lead times do not match the expected maintenance lead times in the MRO workshops. For example, service part 2 has an expected maintenance lead time of 30 working days, but the OEM who provides maintenance of sub-units is allowed 90 working days to repair the sub-units. In addition to this, Saab never issues penalty fines to their OEM's if they are late. Holweg et al. (2005) discusses the importance of synchronizing the different parts of a supply chain. To synchronize the OEM's with the MRO workshops, Saab needs to use contracts that specify the expected lead time for the service that the OEM provides the MRO workshops with. It is important that these expected lead times from the OEM's match the expected maintenance lead times in the MRO workshop in order to synchronize the different parts of the service parts supply chain, as this would ensure that Saab has the capability to deliver maintained service parts to their customers in time. In addition to synchronizing the expected lead times, Saab should start issuing penalty fines based on delays to their OEM's. While this will not directly reduce the delay of service part maintenance, it will incentives the OEMs to deliver on time, and balance out the penalty fine Saab needs to pay to their customers, effectively eliminating the negative effect of these delays from Saab's financial perspective.

The MRO workshop places orders to the OEM too late

The lead time analysis of the aggregated timelines of service parts that were delayed by internal stock-outs of spare parts and sub-units shown in figure 5.5 and figure 5.6 revealed that one type of waste was that orders to OEM were placed too late. Both types had an average waiting time between arrival inspection and fault isolation of about 3 weeks. The operative planners currently only place orders for OEM services after the completion of fault isolation as this process shows what type of maintenance is required to restore the service part to a normal condition. The 5-why analysis is shown in table 5.5.

Question	Answer
Why?	Because the operative planner at the MRO workshop was not aware of the need of OEM services in time.
Why?	Because fault isolation was conducted too late.
Why?	Because the MRO workshop had not planned for the arrival of service parts in need of unplanned maintenance.
Why?	The operative planner at the MRO workshop was not aware of the need of unplanned maintenance before the service part physically arrived at the MRO workshop.
Why?	The operative planner at the MRO workshop did not receive any information about incoming service parts in need of unplanned maintenance.
Why?	The data from the technical report was not used to provide the operative planner with information about incoming orders.

Table 5.5: Root cause analysis - Late orders to OEM

The challenges with unplanned maintenance are to predict which type of maintenance will be needed for each unit of different service parts, and what type of spare parts that will be required to perform this maintenance. This makes planning the procurement of spare parts and other resources difficult for the operative planners at the MRO workshops. Meissner et al. (2002) states that the operative planners at the MRO workshops have to be notified about the need for maintenance of a service part as soon as possible to plan the resources needed to perform maintenance. Tracht et al. (2013) states that it is very hard to estimate unplanned maintenance, compared to the planned maintenance. This is because of the complexity and variety of demand for unplanned maintenance which makes forecasting when unplanned maintenance will be needed difficult. If incomplete or no information is given to the operative planners, this can lead to an increased risk of stock-outs, or the other way around, too much inventory due to over-purchasing (Khandelwal 2011).

According to Sandberg (2015), having a well-functioning supply chain is important in a competitive market, and services such as support and logistics are in some situations even more important than the actual core product. Dyer & Nobeoka (2000) states that collaborative planning and information sharing is possible in a connected network if the right collaboration strategy is used. Holweg et al. (2005) explains that the goal of such strategies is, among other things, to increase synchronization between the different actors in a supply chain.

There is no information given to inform the operative planners that a service part in need of unplanned maintenance is on its way to the MRO workshop. The technical report contains information about the date on which a service part was removed from the aircraft. The blue bars in the aggregated timelines illustrated in figures 5.5, 5.6, 5.7, and 5.8 illustrates the time between the removal of the service part and its arrival to the MRO workshop. The fault description that is included in the technical report is a description of what problems that the pilot or mechanics at the airbase have found. This fault description could give the operative planners an indication of what type of maintenance is required. This information could be useful to the operative planners as it would allow them to make informed decisions about planning for the maintenance of incoming service parts before they physically arrive at the MRO workshop. This would allow the operative planners to better plan the operations for unplanned maintenance at the MRO workshop and reduce the waiting time between the arrival of the service part and the fault isolation process.

In addition to sooner fault isolation, the utilization of the information in the technical report could be used to order certain OEM services before the service part arrives at the MRO workshop. By analyzing historical maintenance data patterns of what type of maintenance is typically needed for each service part might be found. By combining this information with the technical report the operative planners at the MRO workshops will be able to order OEM services as soon as the service part is removed from the aircraft. For example, if a certain service part has needed one type of maintenance that required spare parts in the past, it is likely to need those spare parts in the future as well. If the operative planner notices that the MRO workshop has run out of these spare parts, the operative planner can order new spare parts as soon as the service part is removed from the aircraft if they use the fault description in the technical report. This would lead to the transportation of the service part to the MRO workshop would occur at the same time as the spare parts are delivered to the MRO workshop. Sometimes the estimation of the required maintenance will be wrong, which will lead to over-purchasing certain spare parts as described by Khandelwal (2011).

Service parts spend too much time in inventory

The problem with service parts spending to much time in inventory has already been discussed during the analysis of late orders, however the service parts spend too much time in inventory after the fault isolation as well. This is particularly clear in the aggregated timeline for internal faulty equipment illustrated in figure 5.8. The database at Saab only contains information about interruptions and maintenance, as a result of this there was no information about the long waiting time in inventory. To complete the analysis interviews with operative planners were conducted instead. The 5-why analysis is shown in table 5.6.

Question	Answer
Why?	Maintenance of the service part was put on hold for long periods of time.
Why?	Maintenance of other service parts with shorter expected maintenance lead times were prioritized for too long.
Why?	Prioritization of maintenance is done haphazardly with focus on the currently most urgent service parts.
Why?	The MRO workshops do not have a standardised system for prioritizing maintenance of service parts.

Table 5.6: Root cause analysis - Long waiting times in inventory

The root cause analysis showed that the reason that service parts spend so much time in storage at the MRO workshops is that the MRO workshops lack a standardized planning system for prioritizing maintenance of different service parts. On paper, the MRO workshops use a FIFO queue system. This queue system is often altered by the customer, and also by the operative planners. When the customer orders a change in the queue to prioritize a certain service part, Saab needs to comply. The measurement of maintenance lead time is paused for other service parts to make sure that Saab does not have to pay penalty fines as a result of the customers request. But the customer is not alone in altering the maintenance queue at the MRO workshop, as this is frequently done by the operative planners as well. The sequence of service parts that shall be maintained is altered regularly which leads to inefficient work and the fact that service parts spend too much time in storage between maintenance processes. The prioritization technique described by Hatton (2007) could be used in an MRO workshop environment to ensure that a systematic approach is used to select which service parts to maintain first in a changing MRO environment. The use of a systematic approach when planning maintenance of service parts would ensure that fewer service parts were delayed as a result of spending too much time in storage. Saab could rank the different service parts according to their due date, lead times of maintenance processes, and possible penalty fines induced should the service part be delayed. This would help the operative planners to make informed and structured decisions when planning with the purpose of reducing penalty fines. In cases where a delay is inevitable, the service part that would induce the highest penalty fine should be prioritized.

Machines brake down

The lead time analysis of the aggregated timeline of the service parts that were interrupted by machinery break down illustrated in figure 5.8 showed that the broken machinery was repaired relatively quickly and that this was actually not the major cause of the delay. This is shown in table 5.2 which shows that interruptions caused by internal faulty machinery represent 15% of all interruptions, but only 1% of the downtime caused by that interruption. The problem was not that the machines broke down, as the service parts would on average have been delayed nonetheless due to long times in inventory. Despite the fact that machine breakdowns are not causing very long delays, it is worth investigating how they can be reduced. In order to find out why machines broke down during maintenance in the MRO workshop, MRO planners and operators were interviewed. The 5-why analysis is shown in table 5.7.

Question	Answer
Why?	Because the machinery is used until it breaks down.
Why?	Because the operators at the MRO workshops are currently unable to predict these types of breakdowns.
Why?	Because they do currently not have a method for predicting breakdowns of machinery.

Table 5.7: Root cause analysis - Machinery broke down

As these break-downs affect the efficiency of the MRO workshops in a negative way, it is recommended to predict machinery break-downs in the future, such as through machine learning as proposed by Kohli (2017) or infrared thermography as suggested by Epperly et al. (1997). The method of machine learning suggested by Kohli (2017) is a highly technological solution that requires a large amount of sensors and a system that can handle big data. Data collected from the machines using the sensors would allow the operators at the MRO workshop to predict breakdowns before they occur. The method suggested by Epperly et al. (1997) is a more practical solution that involves measuring the surface temperature of the machines in order to detect heat patterns that might reveal a cause of a breakdown before it happens. This method is only viable where the wear of the machine can be correlated to the surface temperature of the machine when it is used. These are two different approaches to predicting breakdowns and the need for maintenance before the breakdown occurs.

Summary of the root cause analysis

The root cause analysis identified the four following root causes for delays of unplanned maintenance.

- Saab did not have any contracts that states that the OEM's have to deliver on time.
- The data from the technical reports were not used to provide the operative planners at the MRO workshops with information about incoming orders.
- The MRO workshops did not have a standardized system for prioritizing maintenance of service parts.
- The MRO workshops did not use methods to predict breakdowns of certain machines.

Chapter 6

Conclusions

This part of the report presents a discussion of the chosen methods used during this master thesis, as well as ethics, and sustainability related to the study. This chapter also includes the conclusions of the study and the answers to the research questions. A generalization of the findings from the study is also presented.

This master thesis was conducted at one case company, by only investigating one company there will be limitations regarded how the conclusions and recommendations have been generalized. This master thesis can be seen as an inspiration for how this case study has been conducted.

The need of collecting data is recommended to be able to make decisions based on information. By using standardization information, decisions can be made faster which will reduce lead times. However, collecting this amount of data will cause companies to invest in software and educate their personal to get all the information. So, even if this study was conducted at just one case company, the methods used to find the root causes for delays of unplanned maintenance in an MRO workshop can be used by other companies as well. Furthermore, the recommendations presented in this master thesis, though specifically formulated for Saab, can be implemented by other companies who sell service contracts to their customers. For example, using contracts to synchronize lead times and penalty fines within a service parts supply chain is not a solution that is unique to Saab. Another recommendation is that Saab should use the information in the technical report to plan operations at their MRO workshop. This recommendation builds on the principle that information should be shared within a system and used to plan for future activities, and can thus be implemented in any organization with minor situational adjustments to provide all parts of the organization with useful information. Any company will have an easier time making decisions if they use a standardized prioritization system, and any company that uses machinery to provide their customers with value can benefit from predicting and preventing breakdowns before they occur. For this reason, the recommendations presented in this master thesis are applicable to companies that use MRO workshops to provide their customers with maintenance services.

The suggestions that have been given to Saab are improvements related to reducing the late deliveries of service parts from the MRO. These implementations will need to be implemented from the management of the division within Support & Services. These implementations will reduce delays, which will lead to reduced penalty fines.

The biggest challenge during the thesis was initially when the problem was given to the researchers, the problem description was that data was not utilized. The Logistics Engineering Department of Gripen Support highlighted that there were some problems with the service supply chain, but not specifically what. The first task was to map the current state to identify where the problem occurred and to get a deeper understanding of the scope. This required a lot of time and 16 people were interviewed to get a wider picture of the scope. This caused the thesis to jump from one direction one week, to another one the next.

This could have been eliminated by understanding the boundaries of the problem, as this would have helped to gain an overall understanding of which people were involved and to understand whom to interview. Another thing that could have been done differently, would have been to make the trip to MRO1 much earlier and also tried to visit MRO2. During this thesis, only three trips were made to MRO1, and the first one was made after a few weeks. This could have helped to understand the material and information flow in an MRO workshop. Last but not least, the software used to find all the data should have been installed much earlier, because when it was needed it caused some problem and took some time to sort it out.

During the planning phase, the researchers decided to delimit all the data collection from MRO2, because of the limit of time but also from interviews from Saab employees that stated the highest volume and highest penalty fines were from MRO1. When the phase went over to collecting and analyzing data, the researchers found out that Service Part 1 and 2 that stood for most of the penalty fines came from MRO2. This changed the focus of the scope and the researchers decided to include both MRO1 and MRO2 in the analysis. This states that it is very important to not only trust the information given from interviews but to also clarify it with secondary data, if possible.

The literature in the area of unplanned maintenance of service parts in an MRO workshop is very scarce. This master thesis has contributed to research within the area of using existing methods to analyze the service part supply chain in the MRO workshop to reduce lead times using one company as a case study.

Initially, the researches planned to visit the MRO workshops, and at least one airbase at a customer. However, these visits were canceled due to the out-brake of the Covid-19 virus. This caused problems as the researchers were unable to make observations at the MRO workshops, and because some interviews could not be conducted in person. If the situation would have been different, a more detailed analysis of the information flow within the MRO workshops would have been possible.

In detail, this master thesis aimed to understand how maintenance lead times for service parts in need of unplanned maintenance could be reduced, and in particular, how the information flow in the MRO supply chain could be utilized to improve the current system at Saab.

The purpose of this master thesis was to develop improvement suggestions for how to reduce delays of unplanned maintenance for service parts in an MRO workshop, these recommendations are presented in section 6.2.

Delays of unplanned maintenance is an important issue for Saab to solve for several reasons; most obviously as the current delays result in substantial financial losses in the form of penalty fines. Saab will benefit in other ways in addition to saving money. By improving Saab's ability to provide maintenance in time, customer relations and the company's reputation can improve. This improvement should increase the probability of doing profitable business in the future as well.

6.1 Answers to research questions

6.1.1 Research Question 1

What service parts have an impact on the penalty fines at Saab and how late are they?

Out of all the 600 service parts that can be removed in Gripen C/D, 82 of them had an impact on the penalty fines Saab paid in 2019. These 82 service parts are shown in Appendix D along with their contribution to penalty fines in 2019. It is not possible to answer in a general manner how late the service parts are due to the large variety in delays between different units and service parts. The delays vary between a few days to over a year. An ABC analysis showed that 16 of the service parts were the source of 86 % of the total penalty fines in 2019. The delay of each unit from the 16 service parts is shown in appendix E.

6.1.2 Research Question 2

Why are these service parts delayed?

The lead time analysis in chapter 5 showed that there were four types of interruptions.

- Internal stock-out of spare parts
- Internal stock-out of sub-units
- Internal faulty machinery
- External delay at OEM

Each type of interruption was related to at least one cause of delay, which were analyzed in a root cause analysis using the 5-why method. The root cause analysis showed that the delays were caused by the following problems:

- Saab does not have any contracts that forces the OEM's to deliver on time.
- The data available in the technical report is not used to provide the operative planners with information about incoming orders.
- The MRO workshops do not have a standardized. system for prioritizing maintenance of service parts.
- The MRO workshops do not have a method for predicting breakdowns of machinery.

6.1.3 Research Question 3

How can information be utilized by an MRO workshop to synchronize all parts of its service parts supply chain and reduce delays for unplanned maintenance?

If the data that is given by the customer in the technical report when a service part is removed from an aircraft is used to provide the operative planners at the MRO workshops with information about incoming service parts in need of unplanned maintenance, the delays of unplanned maintenance should be reduced. The operative planners at the MRO workshops should be given information about the identification number of the incoming service part, when the service part was shipped and when it is expected to arrive at the MRO workshop, the fault description that gives information about why the service part needs maintenance, the maintenance deadline, and the priority rank of the service part. This information will allow the MRO workshop to be more proactive when maintaining service parts in need of unplanned maintenance.

6.2 Recommendations to SAAB

Since the study was initiated by Saab Support & Services to gain a greater understanding of how to reduce the long delays for unplanned maintenance of service parts, the following recommendations have been formulated. The recommendations are actions that can be implemented by Saab Support & Services to reduce the delays of service parts in need of unplanned maintenance and reduce penalty fines.

The following recommendations should be implemented for the 16 service parts in category A from the ABC-analysis in chapter 5. Since these service parts were the source of 86 % of the penalty fines paid in 2019, they should be the focus of improvements. When the recommendations have been implemented for the A-class service parts, Saab can continue doing this for other service parts according to their ranking shown in appendix D.

6.2.1 Contracts

In order to better synchronize the activities within the service parts supply chain with each other, the OEM contracts should be updated. The expected lead time for the OEM must be synchronized with the expected lead time at the MRO workshops to ensure that service parts can be delivered on time. In addition to this, Saab should include penalty fines in the contracts with the OEM's to ensure that they deliver their services on time. If a service part is delayed and Saab needs to pay a penalty fine to the customer as a result of a delay at the OEM, this fine should be directly transferred to the OEM.

6.2.2 Service Part Prioritization

There will be times when the MRO workshops can not deliver all service parts on time. In such times difficult choices must be made regarding which service parts to prioritize. If Saab were to formulate a prioritization strategy these choices would become mere routines. Such a strategy could rank the service parts based on attributes such as their deadlines, expected maintenance lead time, and related penalty fines if the service part should be delayed. In a scenario where two service parts need maintenance, but the MRO workshop can only deliver one of them on time, the service priority number will determine which of the two service parts gets maintained first, and which gets delayed.

6.2.3 Utilizing the Data

Saab receives large amounts of data regarding service parts from their customers in technical reports whenever a service part is removed from an aircraft. These technical reports should be used to provide the operative planners at the MRO workshop with the information they need to plan for the arrival of service parts in need of unplanned maintenance. The information in the technical report can be combined with historical data regarding what type of maintenance a certain service part usually needs. This would allow the operative planners to prepare the arrival inspection and fault isolation processes, as well as notify the operative purchasers that certain OEM services will be needed when the service part arrives, and sometimes ordered before the physical arrival of the service part. This would allow the MRO workshop to be more proactive rather than reactive to unplanned maintenance. This will lead to reduced waste as service parts in need of unplanned maintenance will spend less time in storage, waiting for these processes to be available.

The MRO workshops should be notified with the following information when a service part is removed from an aircraft in order to prepare for the arrival of service parts as described above:

1. **The identification number of the service part** - This information can be used to check if the service part should be maintained at the MRO workshop or sent to its OEM, as well as what type of maintenance the MRO workshop can expect to do.

2. **When the service part will be shipped and when it is expected to arrive** - This information can be used to make operational plans at the MRO workshop and make sure that sufficient capacity is available.

3. **Fault description that gives information about why the service part needs maintenance** - This information can be used by the MRO workshop to be better prepared for what needs to be done to restore the service part to a functional condition. Historical maintenance data can be used in combination with this data to check if there are patterns in the type of maintenance required. This would allow the operative purchasers to place orders for OEM services that have been needed in the past and are likely to be needed when the service part arrives at the MRO workshop.

4. **Maintenance Deadline** - The latest day maintenance of the service part must be completed.

5. **Service priority** - A prioritization of each service part should be included in order to use a systematic approach to select which service part to maintain first.

6.2.4 Predicting Machine Breakdowns

Zhang et al. (2017) states that by combining historical maintenance data with real-time data, the interrelationship between different parts of the product life cycle can be identified and the breakdown of a machine can be predicted which allows for maintenance actions to be taken in order to prevent the breakdown before it actually occurs. This combination is important of uncovering hidden patterns and determine the current state of a machine. This will bring valuable knowledge and useful information to managers and help them make information-based decisions. To be able to capture this type of real-time data, Ren et al. (2019) claims that sensors, internet of things and big data analytics in all stages of the product life cycle have to be fully utilized. This could turn unplanned maintenance into planned maintenance.

6.2.5 Recommendation prioritization

The four different types of interruptions are shown in table 6.1 below. As shown, the interruption that caused the longest delays was external delays at OEM. The root cause analysis showed that the only root cause to this type of delay was that Saab lacks contracts that states that the OEM's have to deliver their services on time. Implementing contracts for each OEM that specifies an expected lead time and penalty fine will reduce the number of delays at OEM's. This recommendation will also benefit two internal stock-outs, as these the lead time analysis showed that these interruptions were also related to late deliveries from Saab's OEM's. As a result of this, it is recommended that the contracts are implemented first. This recommendation would not be easy to implement as it requires a lot of work regarding writing unique contract with each individual OEM, but it would reduce the delays greatly, as the majority of the delays are caused by late deliveries from the OEM's.

The second most important recommendation is the utilization of the data available in the technical report. As shown in the lead time analysis, this improvement would benefit the MRO workshops in all situations, both in terms of planning and execution. This recommendation would be easy to implement as all the data is available in the current system and just needs to be utilized.

The third most important recommendation to implement is the prioritization system for service parts. This recommendation would reduce the amount of time service parts spends idle in inventory at the MRO workshops when maintenance work could be performed. This recommendation is estimated to be both cheap and easy to implement, as it only requires a small change in how operative planning is done at the MRO workshops.

The least important recommendation to implement is to predict machine breakdowns, as this interruption is only responsible for 1 % of the delays caused by interruptions. This recommendations is also estimated to be both expensive and difficult to implement.

Type of Interruption	**Share of Interruptions**	**Share of Time**
External Delay at OEM	38 %	57 %
Internal stock-out (sub-units)	22 %	24 %
Internal stock-out (spare parts)	25 %	18 %
Internal machinery breakdown	15 %	1 %

Table 6.1: Types of interruptions

- Contracts
- Utilizing the Data
- Service Part Prioritization
- Predicting Machine Breakdowns

6.3 Ethics and Sustainability

6.3.1 Ethics

It is important that the management of the company understands the ethical implications when implementing the recommendations presented in this master thesis. The ethical implications of working in the defense industry are many, and are worth considering. Saab considers it a human right to feel safe, and claims that their products and services protects society and makes people feel safe. Saab works vigorously with export control to make sure that their products do not end up in "the wrong hands".

6.3.2 Sustainability

Sustainability plays an important role in modern society and companies must take it into consideration when conducting their business. According to Assembly (2005), there are three main goals in terms of sustainable development. These three are social, economical, and environmental sustainability. All aspects need to be fulfilled simultaneously if a company wishes to be considered to be a fully sustainable company. Long term thinking is needed to achieve sustainable development, which is something that Saab does naturally, as most of their projects span several decades.

Economic Sustainability

The main purpose of this study was to analyze delays of unplanned maintenance and suggest improvements that would reduce the delays of unplanned maintenance of service parts. This is very important for Saab as these improvements can reduce the penalty fines induced by the delays in their MRO workshops. Since the company is working with very expensive products and the service contracts that they sell to customers often last for 20-30 years, these implementations will have a positive impact on the economy in the long run. The implementations will help the company to reduce the delays of unplanned maintenance will not only benefit the company but also their customers. By implementing the improvements the company will be able to reduce delays of unplanned maintenance as well as reduce the occurrence of errors in the MRO workshops and for the OEM from which the company will benefit financially in the future.

Social Sustainability

Some of the improvements may cause some negative impact on the employees due to changed and added work tasks. This will require effort from the management to make sure that the implementations are not causing too much stress on the staff. The management has to make sure that they encourage and educate all their employees so that they are prepared for the implementation of new routines. By working in this manner the company will be able to work with cooperative employees that are comfortable with the change working. The positive aspect of educating their employees, is that the management can create meaningful work for the employees and make the employees proud of their work.

Environmental Sustainability

Saab works with three main areas regarding environmental sustainability. Reducing their contributions to greenhouse gas emissions, phase out the use of hazardous substances, and improving their resource efficiency (SAAB 2018). It is difficult to tell if the improvements suggested in this master thesis will contribute to a change in Saab's environmental sustainability, but hopefully Saab's resource efficiency will improve as a result of these improvements.

6.4 Future Work

This master thesis has addressed how to reduce delays of unplanned maintenance in an MRO workshop in the context of a service parts supply chain through the utilization of data. The nature of unplanned maintenance is just that, unplanned. The solutions presented in this master thesis can help companies become more proactive, but the method is still reactive in a certain way. The next step is to find a way to eliminate the need for unplanned maintenance. For this reason, we recommend future research on how to predict breakdowns using the internet of things and big data analytic. This would give companies information about the current state of all service parts in real-time and allow them to remove service parts just in time before a breakdown occurs. Big data analytics and machine learning could also be used to predict breakdowns of machinery and equipment inside MRO workshops.

This master thesis excluded the internal operative planning at the MRO, this should be looked into further to optimize the work flow of the MRO workshop. A recommendation would be to make a Value Stream Mapping of the work flow to reduce time that is considered non-value adding in the MRO workshop.

This master thesis aimed to synchronize the activities in the different parts of the service parts supply chain through efficient information sharing from the perspective of the MRO workshops. If Saab were to optimize the supply chain on a higher level to truly reach a global optimum rather than a set of local optimal solutions, the efficiency of the service parts supply chain would increase further.

Bibliography

Ashton, K. et al. (2009), 'That 'internet of things' thing', *RFID journal* **22**(7), 97–114.

Assembly, U. N. G. (2005), '2005 world summit outcome, resolution a/60/1, adopted by the general assembly on 15 september 2005.'.

Axinn, W. G. & Pearce, L. D. (2006), *Mixed method data collection strategies*, Cambridge University Press.

Barwise, J. & Seligman, J. (1997), *Information flow: the logic of distributed systems*, Vol. 44, Cambridge University Press.

Benhabib, B. (2003), *Manufacturing: design, production, automation, and integration*, CRC Press.

Brook, Q. (2017), *Lean Six Sigma & Minitab: The complete toolbox guide for business improvement*, OPEX Resources Limited.

Bryman, A. & Bell, E. (2003), 'Breaking down the quantitative/qualitative divide', *Business Research Methods* **2**(1), 465–478.

Carter, C. R., Rogers, D. S. & Choi, T. Y. (2015), 'Toward the theory of the supply chain', *Journal of Supply Chain Management* **51**(2), 89–97.

Dwivedi, A. & Butcher, T. (2008), *Supply chain management and knowledge management*, Springer. (pages 8-9).

Dyer, J. H. & Nobeoka, K. (2000), 'Creating and managing a high-performance knowledge-sharing network: the toyota case', *Strategic management journal* **21**(3), 345–367.

Eisenhardt, K. M. (1989), 'Building theories from case study research', *Academy of management review* **14**(4), 532–550.

Epperly, R. A., Heberlein, G. E. & Eads, L. G. (1997), A tool for reliability and safety: predict and prevent equipment failures with thermography, *in* 'Record of Conference Papers. IEEE Industry Applications Society 44th Annual Petroleum and Chemical Industry Conference', IEEE, pp. 59–68.

Flores, B. E. & Whybark, D. C. (1986), 'Multiple criteria abc analysis', *International Journal of Operations & Production Management* .

Forza, C. (2002), 'Survey research in operations management: a process-based perspective', *International journal of operations & production management* .

Ganesh, K., Mohapatra, S., Anbuudayasankar, S. & Sivakumar, P. (2014), *Enterprise resource planning: fundamentals of design and implementation*, Springer. (pages 1-4).

Goldsby, T. J. & Martichenko, R. (2005), *Lean six sigma logistics: Strategic development to operational success*, J. Ross Publishing.

Gordon, N. J. & Fleisher, W. L. (2010), *Effective interviewing and interrogation techniques*, Academic Press.

Graves, S. C. (1999), 'Manufacturing planning and control', *Massachusetts institute of technology* pp. 1–26.

Hatton, S. (2007), Early prioritisation of goals, *in* 'International Conference on Conceptual Modeling', Springer, pp. 235–244.

Hill, A. & Hill, T. (2009), *Manufacturing operations strategy*, Palgrave Macmillan.

Holweg, M., Disney, S., Holmström, J. & Småros, J. (2005), 'Supply chain collaboration:: Making sense of the strategy continuum', *European management journal* **23**(2), 170–181.

Jacka, J. M. & Keller, P. J. (2009), *Business Process Mapping: Workbook*, Wiley Online Library.

Jacobs, F. R., Berry, W. L., Whybark, D. C., Vollmann, T. E. & Vollmann, T. (2018), *Manufacturing planning and control for supply chain management, The CPIM Reference, Second Edition*, McGraw-Hill Education.

John, W. & Creswell, P. C. (2000), Designing and conducting mixed methods research, SAG.

Karlsson, C. (2009), *Researching Operations Management*, Routledge, United Kingdom, pp. 6–41. Trykt i løbenummer: 092160.

Khandelwal, L. (2011), 'Mro supply chain optimization in manufacturing and utility industries'.

Kilpi, J., Töyli, J. & Vepsäläinen, A. (2009), 'Cooperative strategies for the availability service of repairable aircraft components', *International Journal of Production Economics* **117**(2), 360–370.

Kohli, M. (2017), 'Using machine learning algorithms on data residing in sap erp application to predict equipment failures', *International Journal of Engineering & Technology* **7**(2.28), 312–319.

Levitt, T. (1993), 'The globalization of markets', *Readings in international business: a decision approach* **249**. (pages 249-252).

Liberatore, M. J. (2012), *Supply chain planning: practical frameworks for superior performance*, Business Expert Press.

Manuj, I. & Mentzer, J. T. (2008), 'Global supply chain risk management strategies', *International Journal of Physical Distribution & Logistics Management* .

Marx-Gómez, J., Rautenstrauch, C., Nürnberger, A. & Kruse, R. (2002), 'Neuro-fuzzy approach to forecast returns of scrapped products to recycling and remanufacturing', *Knowledge-Based Systems* **15**(1-2), 119–128.

Meissner, A., Luckenbach, T., Risse, T., Kirste, T. & Kirchner, H. (2002), Design challenges for an integrated disaster management communication and information system, *in* 'The First IEEE Workshop on Disaster Recovery Networks (DIREN 2002)', Vol. 24, pp. 1–7.

Melin, U. (2002), Koordination och informationssystem i företag och nätverk, PhD thesis, Linköping University Electronic Press.

Mentzer, J. T., DeWitt, W., Keebler, J. S., Min, S., Nix, N. W., Smith, C. D. & Zacharia, Z. G. (2001), 'Defining supply chain management', *Journal of Business logistics* **22**(2), 1–25.

Merriam, S. B. (1998), *Qualitative Research and Case Study Applications in Education. Revised and Expanded from" Case Study Research in Education."*., ERIC.

Mirzahosseinian, H. & Piplani, R. (2011), 'A study of repairable parts inventory system operating under performance-based contract', *European Journal of Operational Research* **214**(2), 256–261.

Mobley, R. K. (2002), *An introduction to predictive maintenance*, Elsevier.

Mobley, R. K. (2004), *Maintenance fundamentals*, Elsevier.

Morris, M. H. & Fuller, D. A. (1989), 'Pricing an industrial service', *Industrial Marketing Management* **18**(2), 139–146.

Muckstadt, J. A. (2004), *Analysis and algorithms for service parts supply chains*, Springer Science & Business Media.

Olhager, J. & Wikner, J. (2000), 'Production planning and control tools', *Production Planning & Control* **11**(3), 210–222.

Oskarsson, B., Aronsson, H. & Ekdahl, B. (2013), *Modern logistik: för ökad lönsamhet*, Liber.

Parthasarthy, S. (2007), *Enterprise resource planning: a managerial & Technical perspective*, New Age International.

Patel, R. & Davidson, B. (2003), *Forskningsmetodikens grunder. Att planera, genomföra och rapportera en undersökning.*, Studentlitteratur.

Ren, S., Zhang, Y., Liu, Y., Sakao, T., Huisingh, D. & Almeida, C. M. (2019), 'A comprehensive review of big data analytics throughout product lifecycle to support sustainable smart manufacturing: A framework, challenges and future research directions', *Journal of cleaner production* **210**, 1343–1365.

Rogers, D. S. & Tibben-Lembke, R. (2001), 'An examination of reverse logistics practices', *Journal of business logistics* **22**(2), 129–148.

Rogers, D. S., Tibben-Lembke, R. S. et al. (1999), *Going backwards: reverse logistics trends and practices*, Vol. 2, Reverse Logistics Executive Council Pittsburgh, PA.

Russom, P. et al. (2011), 'Big data analytics', *TDWI best practices report, fourth quarter* **19**(4), 1–34.

SAAB (2018), *Annual and sustainability report 2018*, SAAB.

Saab Group (2020), `https://saabgroup.com`.

Sandberg, E. (2015), *Logistik och strategi - För lönsamhet och tillväxt*, Studenlitteratur AB, Lund.

Sanders, N. (2016), *Forecasting fundamentals*, Business Expert Press.

Sanders, N. R. et al. (2013), *The Definitive Guide to Manufacturing and Service Operations: Master the Strategies and Tactics for Planning, Organizing, and Managing how Products and Services are Produced*, Pearson Education.

Saunders, M., Lewis, P. & Thornhill, A. (2007), 'Research methods', *Business Students 4th edition Pearson Education Limited, England* .

Serrat, O. (2017), The five whys technique, *in* 'Knowledge solutions', Springer, pp. 307–310.

Srinivasan, M. M., Bowers, M. R. & Gilbert, K. C. (2014), *Lean Maintenance Repair and Overhaul: Changing the Way You Do Business*, McGraw Hill Professional.

Storhagen, N. G. (2003), *Logistik: grunder och möjligheter*, Liber ekonomi.

Tonks, P. & Flanagan, H. (1994), 'Positioning the human resource business using service level agreements', *Health manpower management* **20**(1), 13–17.

Tracht, K., Niestegge, A. & Schuh, P. (2013), 'Demand planning based on performance measurement systems in closed loop supply chains', *Procedia CIRP* **12**, 324–329.

Van Weele, A. & Arbin, K. (2019), *Inköp och supply chain management: analys, strategi, planering och praktik*, Studentlitteratur AB.

Vidal, C. J. & Goetschalckx, M. (1997), 'Strategic production-distribution models: A critical review with emphasis on global supply chain models', *European journal of operational research* **98**(1), 1–18.

Voss, C. (2010), Case research in operations management, *in* 'Researching operations management', Routledge, pp. 176–209.

Wallace, W. et al. (1927), 'Business forecasting and its practical application'.

Wilkins, D. J. (2002), 'The bathtub curve and product failure behavior part one - the bathtub curve, infant mortality and burn-in', *Reliability Hot Wire* **21**.

Xia, F., Yang, L. T., Wang, L. & Vinel, A. (2012), 'Internet of things', *International journal of communication systems* **25**(9), 1101.

Yin, R. K. (2003), ‘Case study research design and methods third edition’, *Applied social research methods series* **5**.

Yin, R. et al. (1984), ‘case study research. beverly hills’.

Zhang, Y., Ren, S., Liu, Y. & Si, S. (2017), ‘A big data analytics architecture for cleaner manufacturing and maintenance processes of complex products’, *Journal of Cleaner Production* **142**, 626–641.

Zhao, W. K., Zhang, C. & Zhao, X. (2013), Information system construction of spare parts supply based on supply chain, *in* ‘Advanced Materials Research’, Vol. 765, Trans Tech Publ, pp. 3245–3248.

Appendices

Appendix A

Keywords

The following keywords were used during the master thesis in order to find relevant literature.

- *Saab*
- *Maintenance*
- *Servicification in Manufacturing*
- *Planned Maintenance*
- *Unplanned Maintenance*
- *Corrective Maintenance*
- *Availability*
- *Service Parts Supply Chain*
- *Service Part*
- *Supply Chain Management*
- *Maintenance, Repair and Overhaul*
- *Lean MRO*
- *Reverse Logistics*
- *Manufacturing Planning and Control*
- *Enterprise Resource Planning*
- *Information Flow*
- *Forecasting*
- *Decision Support*
- *Predicting equipment failure*

Appendix B

Interview Subjects - Planning

The following people were interviewed during the planning phase of the study.

- Lars Mattsson, Head of Logistics Engineering, Support & Services
- Martin Larsson, Logistics analytics, Support & Services
- Frida Liljenroth, Planning Manager, Support & Services

Appendix C

Interview Subjects - Current State

The following people were interviewed during the current state mapping process of the study.

- Kristian Lundberg, Director of Technology & Innovation, Saab Support & Services
- Martin Brantemo, Flight Monitoring, Saab Support & Services
- Marcus Karlsson, Fligth Monitoring, Saab Support & Services
- Martin Larsson, Logistics analytics, Saab Support & Services
- Dino Besic, MRO Production Planner, Saab Support & Services
- Peter Serrander, MRO Production Planner, Saab Support & Services
- Johan Haraldsson, Purchaser, Saab Support & Services
- Timmy Svensson, Purchaser, Saab Support & Services
- Frida Liljenroth, Planning Manager, Saab Support & Services
- Thomas Carlsson, Planning Manager, Saab Support & Services
- Lucas Ljungberg, Strategic Purchaser, Saab Support & Services
- Kristina Biewendt, Senior Strategic Sourcing Manager, Saab Aeronautics
- Kent Johansson, Strategic Purchaser, Saab Support & Services
- Håkan Stake, Contract Manager, Saab Support & Services
- Johnny Bergqvist, MRO production planner, Saab Support & Services

Appendix D

Service parts that contributed to penalty fines 2019

Service Part	% of cost	Service Part	% of cost
Service Part 1	16,21%	Service Part 21	1,13%
Service Part 2	14,01%	Service Part 22	1,12%
Service Part 3	8,36%	Service Part 23	0,93%
Service Part 4	8,11%	Service Part 24	0,81%
Service Part 5	6,06%	Service Part 25	0,59%
Service Part 6	4,78%	Service Part 26	0,57%
Service Part 7	4,16%	Service Part 27	0,54%
Service Part 8	3,53%	Service Part 28	0,51%
Service Part 9	3,05%	Service Part 29	0,49%
Service Part 10	2,85%	Service Part 30	0,47%
Service Part 11	2,74%	Service Part 31	0,44%
Service Part 12	1,96%	Service Part 32	0,44%
Service Part 13	1,64%	Service Part 33	0,42%
Service Part 14	1,51%	Service Part 34	0,41%
Service Part 15	1,51%	Service Part 35	0,37%
Service Part 16	1,43%	Service Part 36	0,28%
Service Part 17	1,40%	Service Part 37	0,25%
Service Part 18	1,37%	Service Part 38	0,20%
Service Part 19	1,25%	Service Part 39	0,18%
Service Part 20	1,22%	Service Part 40	0,18%

Table D.1: Each service parts contribution to the total penalty fines 2019

Service Part	% of cost	Service Part	% of cost
Service Part 41	0,16%	Service Part 62	0,02%
Service Part 42	0,16%	Service Part 63	0,02%
Service Part 43	0,16%	Service Part 64	0,02%
Service Part 44	0,16%	Service Part 65	0,02%
Service Part 45	0,14%	Service Part 66	0,02%
Service Part 46	0,13%	Service Part 67	0,02%
Service Part 47	0,13%	Service Part 68	0,02%
Service Part 48	0,12%	Service Part 69	0,02%
Service Part 49	0,09%	Service Part 70	0,02%
Service Part 50	0,08%	Service Part 71	0,01%
Service Part 51	0,07%	Service Part 72	0,01%
Service Part 52	0,06%	Service Part 73	0,0048%
Service Part 53	0,06%	Service Part 74	0,0044%
Service Part 54	0,05%	Service Part 75	0,0043%
Service Part 55	0,04%	Service Part 76	0,0041%
Service Part 56	0,04%	Service Part 77	0,0028%
Service Part 57	0,04%	Service Part 78	0,0011%
Service Part 58	0,04%	Service Part 79	0,0005%
Service Part 59	0,03%	Service Part 80	0,0002%
Service Part 60	0,03%	Service Part 81	0,0002%
Service Part 61	0,02%	Service Part 82	0,0002%

Table D.2: Each service parts contribution to the total penalty fines 2019

Appendix E

A-class service parts

Service Part 1

27 individual units of service part 1 were maintained by Saab's MRO workshops in 2019. 8 of these units underwent planned maintenance, and 19 units underwent unplanned maintenance. Figure E.1 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 6, which was completed 250 days later than expected, with a total lead time of 280 days.

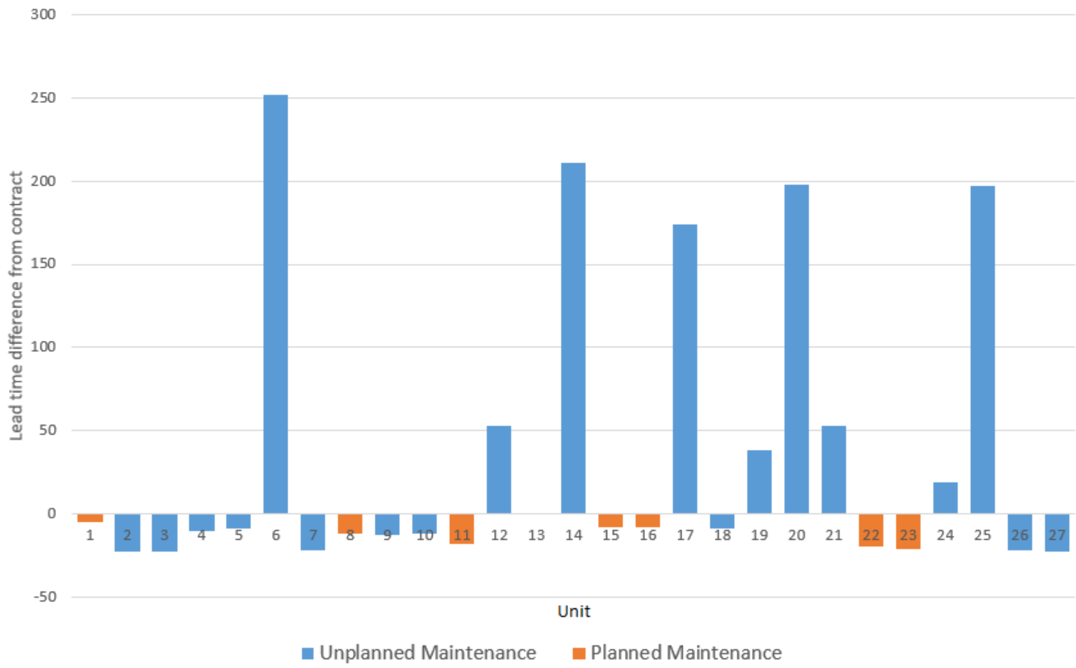

Figure E.1: Service Part 1

Unit	**Type**	**Difference**
1	PM	-5
2	UPM	-23
3	UPM	-23
4	UPM	-10
5	UPM	-9
6	UPM	252
7	UPM	-22
8	PM	-12
9	UPM	-13
10	UPM	-12
11	PM	-18
12	UPM	53
13	PM	0
14	UPM	211
15	PM	-8
16	PM	-8
17	UPM	174
18	UPM	-9
19	UPM	38
20	UPM	198
21	UPM	53
22	PM	-20
23	PM	-21
24	UPM	19
25	UPM	197
26	UPM	-22
27	UPM	-23

Table E.1: Raw data for service part 1

Service Part 2

42 individual units of service part 2 were maintained by Saab's MRO workshops in 2019. All 42 of these units underwent unplanned maintenance, and no units underwent planned maintenance. Figure E.2 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 37, which was completed 258 days later than expected, with a total lead time of 295 days.

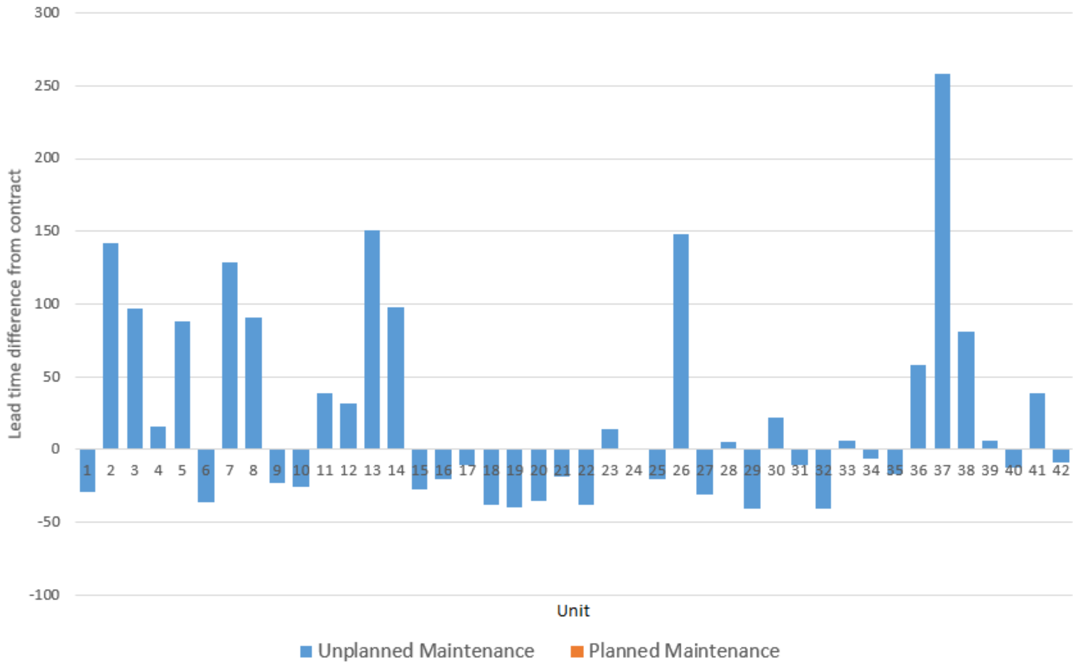

Figure E.2: Service Part 2

Unit	Type	Difference
1	UPM	-29
2	UPM	142
3	UPM	97
4	UPM	16
5	UPM	88
6	UPM	-36
7	UPM	129
8	UPM	91
9	UPM	-23
10	UPM	-26
11	UPM	39
12	UPM	32
13	UPM	151
14	UPM	98
15	UPM	-27
16	UPM	-20
17	UPM	-11
18	UPM	-38
19	UPM	-40
20	UPM	-35
21	UPM	-19
22	UPM	-38
23	UPM	14
24	UPM	1
25	UPM	-20
26	UPM	148
27	UPM	-31
28	UPM	5
29	UPM	-41
30	UPM	22
31	UPM	-11
32	UPM	-41
33	UPM	6
34	UPM	-6
35	UPM	-17
36	UPM	58
37	UPM	258
38	UPM	81
39	UPM	6
40	UPM	-12
41	UPM	39
42	UPM	-9

Table E.2: Raw data for service part 2

Service Part 3

18 individual units of service part 3 were maintained by Saab's MRO workshops in 2019. 2 of these units underwent planned maintenance, and 16 units underwent unplanned maintenance. Figure E.3 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 90 days. The unit with the longest observed delay is unit number 12, which was completed 188 days later than expected, with a total lead time of 278 days.

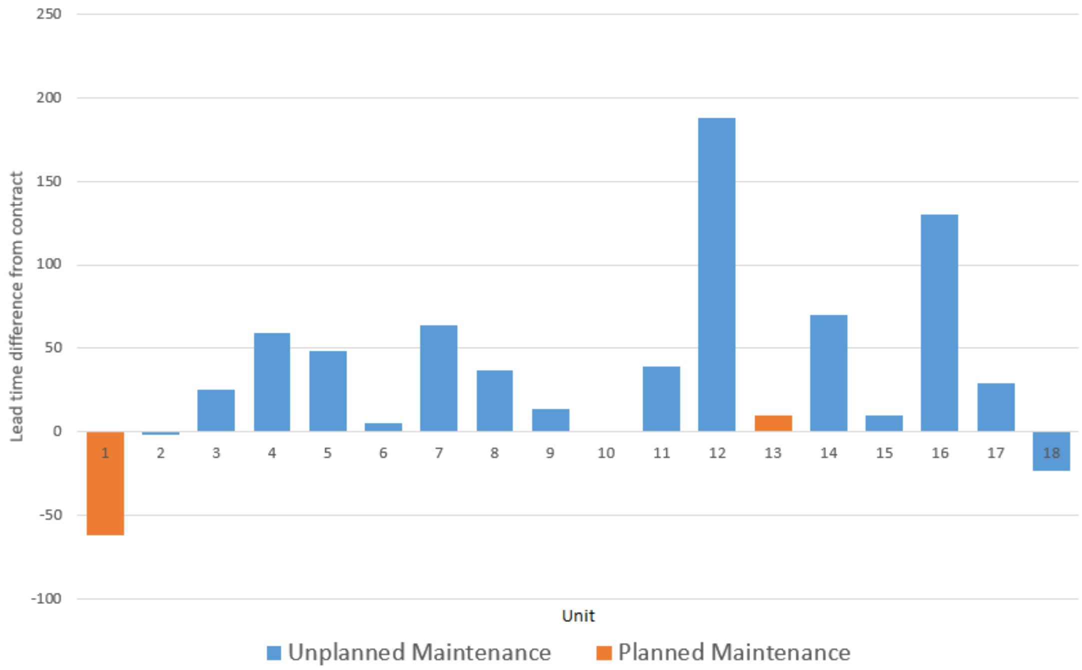

Figure E.3: Service Part 3

Unit	Type	Difference
1	PM	-62
2	UPM	-2
3	UPM	25
4	UPM	59
5	UPM	48
6	UPM	5
7	UPM	64
8	UPM	37
9	UPM	14
10	UPM	0
11	UPM	39
12	UPM	188
13	PM	10
14	UPM	70
15	UPM	10
16	UPM	130
17	UPM	29
18	UPM	-23

Table E.3: Raw data for service part 3

Service Part 4

90 individual units of service part 4 were maintained by Saab's MRO workshops in 2019. 49 of these units underwent planned maintenance, and 41 units underwent unplanned maintenance. Figure E.4 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 105 days. The unit with the longest observed delay is unit number 12, which was completed 426 days later than expected, with a total lead time of 531 days.

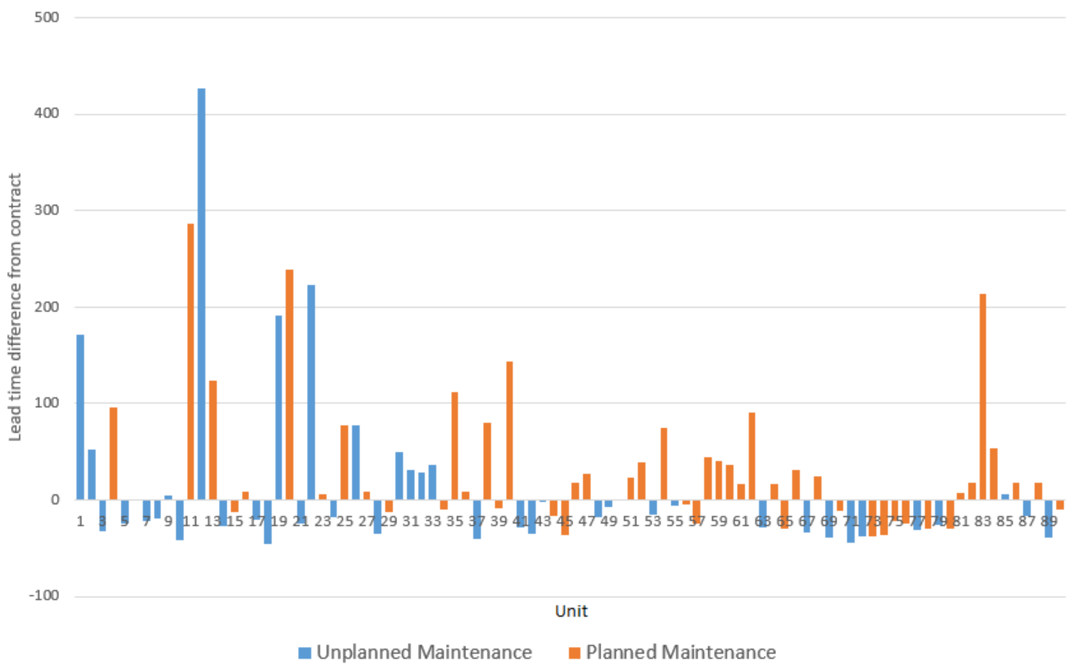

Figure E.4: Service Part 4

Unit	Type	Difference	Unit	Type	Difference
1	UPM	171	46	PM	18
2	UPM	52	47	PM	27
3	UPM	-33	48	UPM	-18
4	PM	96	49	UPM	-7
5	UPM	-24	50	UPM	1
6	PM	0	51	PM	23
7	UPM	-22	52	PM	39
8	UPM	-19	53	UPM	-15
9	UPM	5	54	PM	75
10	UPM	-41	55	UPM	-6
11	PM	287	56	PM	-5
12	UPM	426	57	PM	-24
13	PM	124	58	PM	44
14	UPM	-27	59	PM	41
15	PM	-12	60	PM	37
16	PM	8	61	PM	16
17	UPM	-20	62	PM	90
18	UPM	-45	63	UPM	-29
19	UPM	191	64	PM	16
20	PM	239	65	PM	-30
21	UPM	-24	66	PM	31
22	UPM	223	67	UPM	-34
23	PM	6	68	PM	25
24	UPM	-18	69	UPM	-39
25	PM	78	70	PM	-11
26	UPM	78	71	UPM	-44
27	PM	9	72	UPM	-38
28	UPM	-35	73	PM	-38
29	PM	-12	74	PM	-36
30	UPM	50	75	PM	-22
31	UPM	31	76	PM	-24
32	UPM	28	77	UPM	-31
33	UPM	36	78	PM	-30
34	PM	-10	79	UPM	-26
35	PM	112	80	PM	-30
36	PM	9	81	PM	7
37	UPM	-40	82	PM	18
38	PM	80	83	PM	214
39	PM	-8	84	PM	53
40	PM	143	85	UPM	6
41	UPM	-29	86	PM	18
42	UPM	-35	87	UPM	-16
43	UPM	-2	88	PM	18
44	PM	-17	89	UPM	-39
45	PM	-36	90	PM	-10

Table E.4: Raw data for service part 4

Unit	**Type**	**Difference**
1	UPM	139
2	UPM	52
3	UPM	-24
4	PM	15
5	UPM	-26
6	UPM	57

Table E.5: Raw data for service part 5

Service Part 5

6 individual units of service part 5 were maintained by Saab's MRO workshops in 2019. 1 of these units underwent planned maintenance, and 5 units underwent unplanned maintenance. Figure E.5 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 1, which was completed 139 days later than expected, with a total lead time of 181 days.

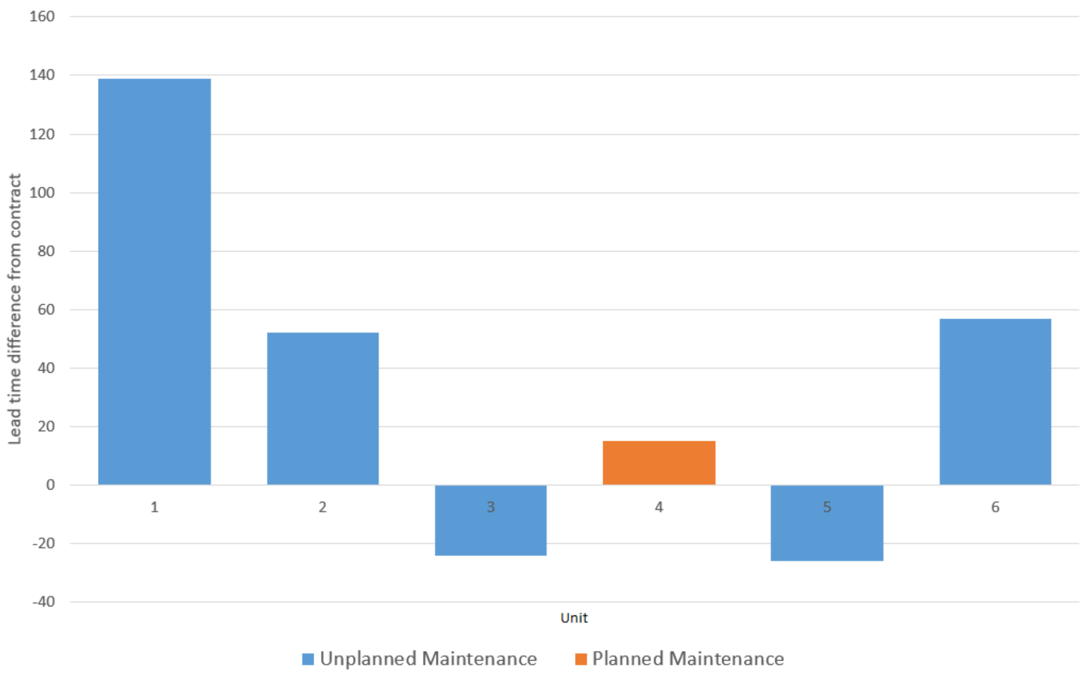

Figure E.5: Service Part 5

Unit	Type	Difference
1	UPM	-12
2	UPM	92
3	UPM	35
4	UPM	-17
5	UPM	106
6	UPM	19
7	UPM	109
8	UPM	12
9	UPM	24
10	UPM	-3
11	UPM	23
12	UPM	57

Table E.6: Raw data for service part 6

Service Part 6

12 individual units of service part 6 were maintained by Saab's MRO workshops in 2019. All 12 of these units underwent unplanned maintenance, and no units underwent planned maintenance. Figure E.6 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 7, which was completed 109 days later than expected, with a total lead time of 151 days.

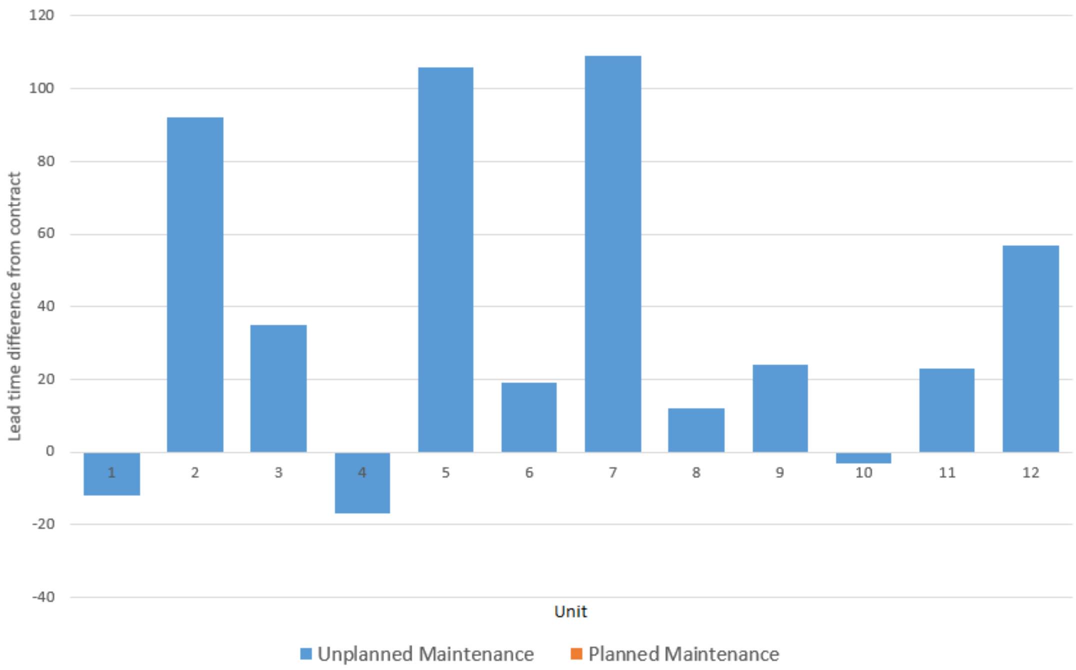

Figure E.6: Service Part 6

Service Part 7

127 individual units of service part 7 were maintained by Saab's MRO workshops in 2019. 62 of these units underwent planned maintenance, and 65 units underwent unplanned maintenance. Figure E.7 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 43, which was completed 243 days later than expected, with a total lead time of 285 days.

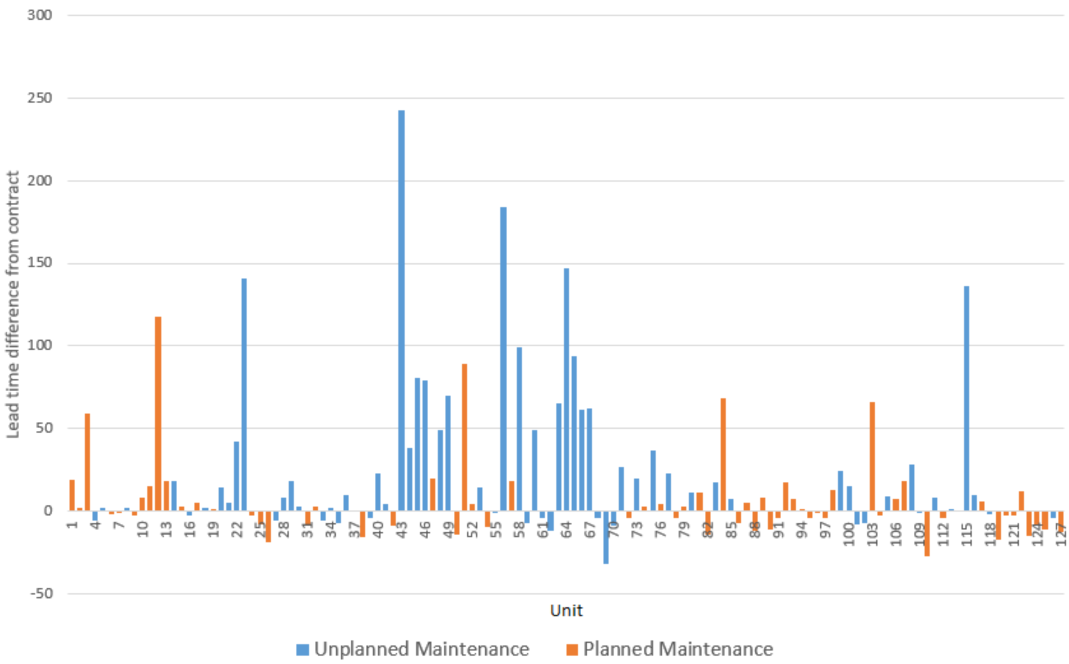

Figure E.7: Service Part 7

Unit	Type	Dif
1	PM	19
2	PM	2
3	PM	59
4	UPM	-6
5	UPM	2
6	PM	-2
7	PM	-1
8	UPM	2
9	PM	-3
10	PM	8
11	PM	15
12	PM	118
13	PM	18
14	UPM	18
15	PM	3
16	UPM	-3
17	PM	5
18	UPM	2
19	PM	1
20	UPM	14
21	UPM	5
22	UPM	42
23	UPM	141
24	PM	-3
25	PM	-8
26	PM	-19
27	UPM	-6
28	UPM	8
29	UPM	18
30	UPM	3
31	PM	-8
32	PM	3
33	UPM	-6
34	UPM	2
35	UPM	-7
36	UPM	10
37	UPM	0
38	PM	-16
39	UPM	-4
40	UPM	23
41	UPM	4
42	PM	-9

Unit	Type	Dif
43	UPM	243
44	UPM	38
45	UPM	81
46	UPM	79
47	PM	20
48	UPM	49
49	UPM	70
50	PM	-14
51	PM	89
52	PM	4
53	UPM	14
54	PM	-10
55	UPM	-1
56	UPM	184
57	PM	18
58	UPM	99
59	UPM	-7
60	UPM	49
61	UPM	-4
62	UPM	-12
63	UPM	65
64	UPM	147
65	UPM	94
66	UPM	61
67	UPM	62
68	UPM	-4
69	UPM	-32
70	UPM	-9
71	UPM	27
72	PM	-4
73	UPM	20
74	PM	3
75	UPM	37
76	PM	4
77	UPM	23
78	PM	-4
79	PM	3
80	UPM	11
81	PM	11
82	PM	-14
83	UPM	17
84	PM	68

Unit	Type	Dif
85	UPM	7
86	PM	-7
87	PM	5
88	PM	-12
89	PM	8
90	PM	-11
91	PM	-4
92	PM	17
93	PM	7
94	PM	1
95	PM	-4
96	PM	-1
97	PM	-4
98	PM	13
99	UPM	24
100	UPM	15
101	UPM	-8
102	UPM	-7
103	PM	66
104	PM	-3
105	UPM	9
106	PM	7
107	PM	18
108	UPM	28
109	UPM	-1
110	PM	-27
111	UPM	8
112	PM	-4
113	UPM	1
114	UPM	0
115	UPM	136
116	UPM	10
117	PM	6
118	UPM	-2
119	PM	-17
120	PM	-3
121	PM	-3
122	PM	12
123	PM	-15
124	PM	-8
125	PM	-11
126	UPM	-4
127	PM	-13

Table E.7: Raw data for service part 7

Service Part 8

30 individual units of service part 8 were maintained by Saab's MRO workshops in 2019. 2 of these units underwent planned maintenance, and 28 units underwent unplanned maintenance. Figure E.8 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 11, which was completed 132 days later than expected, with a total lead time of 162 days.

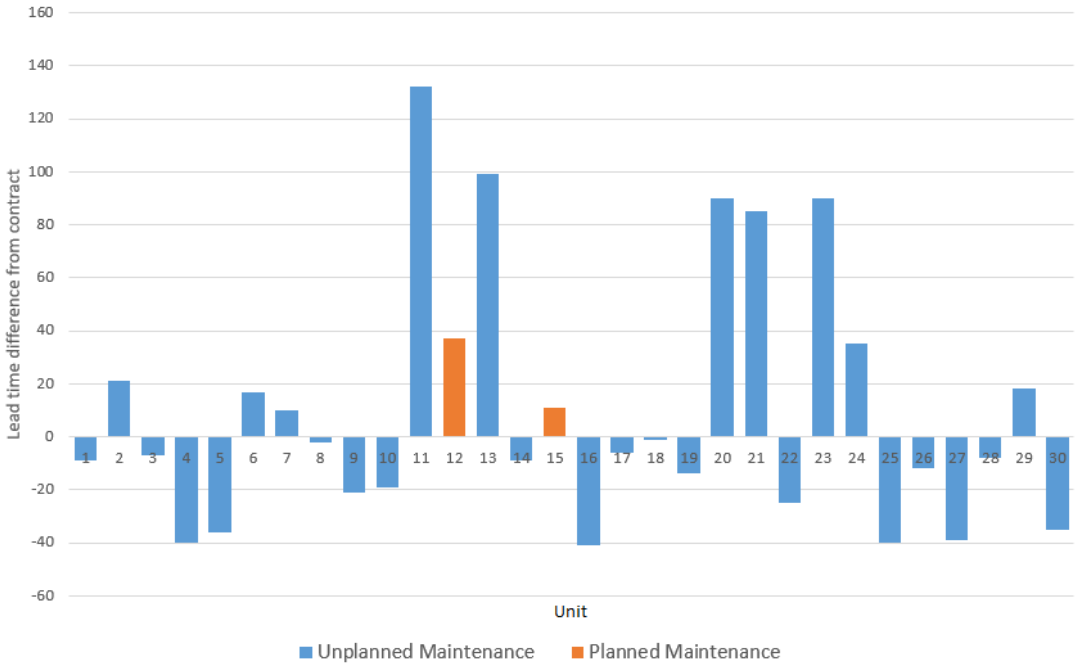

Figure E.8: Service Part 8

Unit	**Type**	**Difference**
1	UPM	-9
2	UPM	21
3	UPM	-7
4	UPM	-40
5	UPM	-36
6	UPM	17
7	UPM	10
8	UPM	-2
9	UPM	-21
10	UPM	-19
11	UPM	132
12	PM	37
13	UPM	99
14	UPM	-9
15	PM	11
16	UPM	-41
17	UPM	-6
18	UPM	-1
19	UPM	-14
20	UPM	90
21	UPM	85
22	UPM	-25
23	UPM	90
24	UPM	35
25	UPM	-40
26	UPM	-12
27	UPM	-39
28	UPM	-8
29	UPM	18
30	UPM	-35

Table E.8: Raw data for service part 8

Service Part 9

19 individual units of service part 9 were maintained by Saab's MRO workshops in 2019. 2 of these units underwent planned maintenance, and 17 units underwent unplanned maintenance. Figure E.9 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 8, which was completed 82 days later than expected, with a total lead time of 124 days.

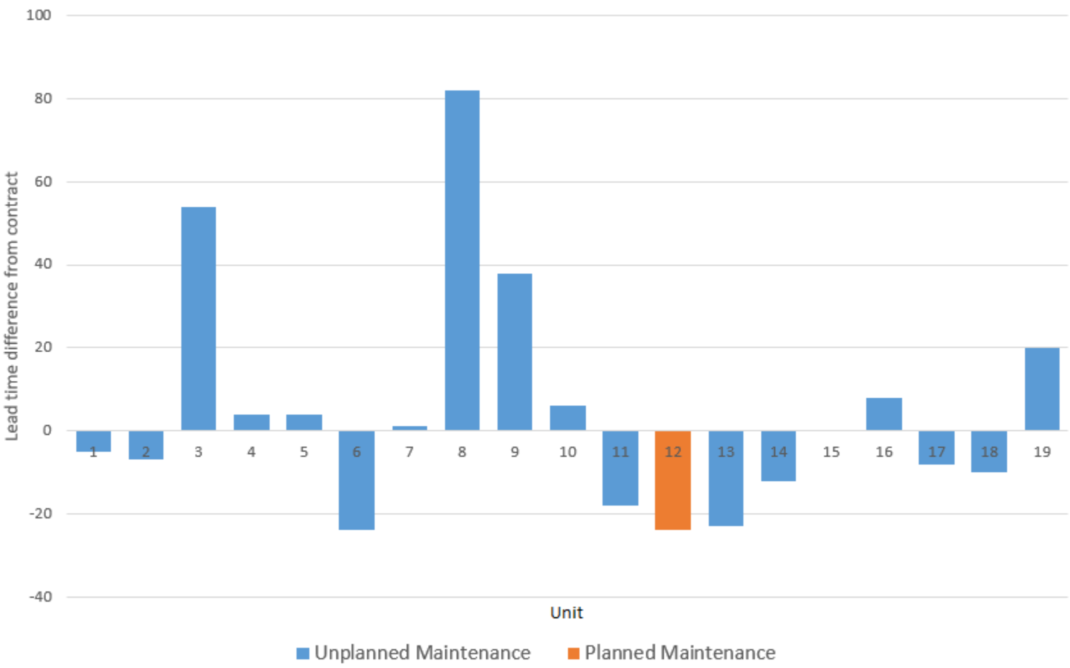

Figure E.9: Service Part 9

Unit	Type	Difference
1	UPM	-5
2	UPM	-7
3	UPM	54
4	UPM	4
5	UPM	4
6	UPM	-24
7	UPM	1
8	UPM	82
9	UPM	38
10	UPM	6
11	UPM	-18
12	PM	-24
13	UPM	-23
14	UPM	-12
15	PM	0
16	UPM	8
17	UPM	-8
18	UPM	-10
19	UPM	20

Table E.9: Raw data for service part 9

Service Part 10

11 individual units of service part 10 were maintained by Saab's MRO workshops in 2019. 1 of these units underwent planned maintenance, and 10 units underwent unplanned maintenance. Figure E.10 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 200 days. The unit with the longest observed delay is unit number 10, which was completed 166 days later than expected, with a total lead time of 366 days.

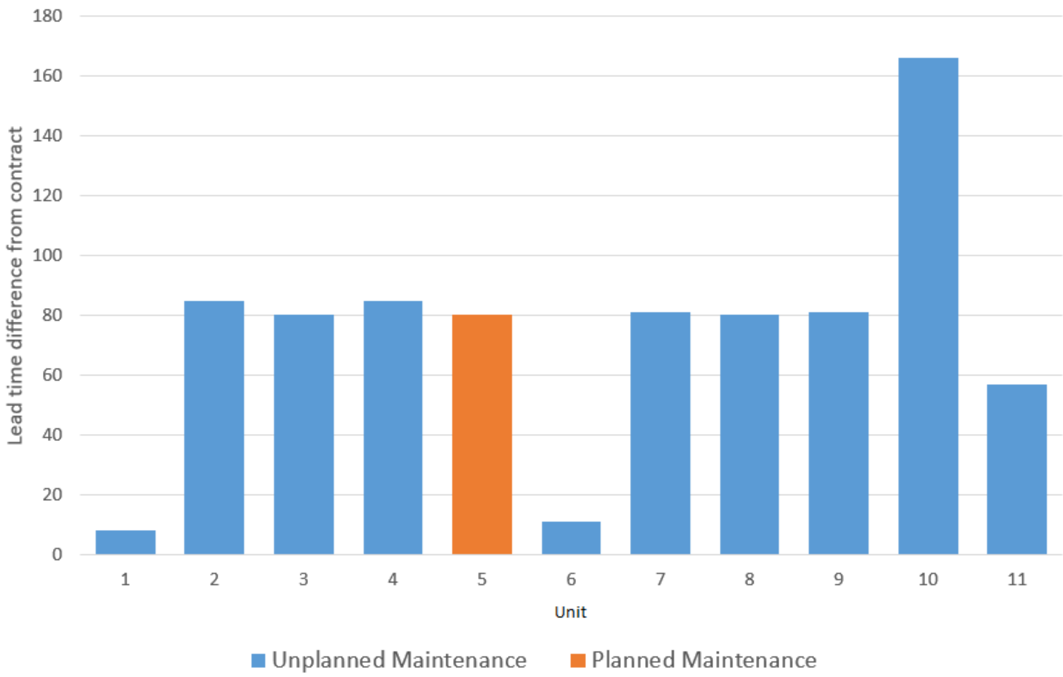

Figure E.10: Service Part 10

Unit	Type	Difference
1	UPM	8
2	UPM	85
3	UPM	80
4	UPM	85
5	PM	80
6	UPM	11
7	UPM	81
8	UPM	80
9	UPM	81
10	UPM	166
11	UPM	57

Table E.10: Raw data for service part 10

Service Part 11

10 individual units of service part 2 were maintained by Saab's MRO workshops in 2019. All 10 of these units underwent unplanned maintenance, and no units underwent planned maintenance. Figure E.11 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 8, which was completed 274 days later than expected, with a total lead time of 304 days.

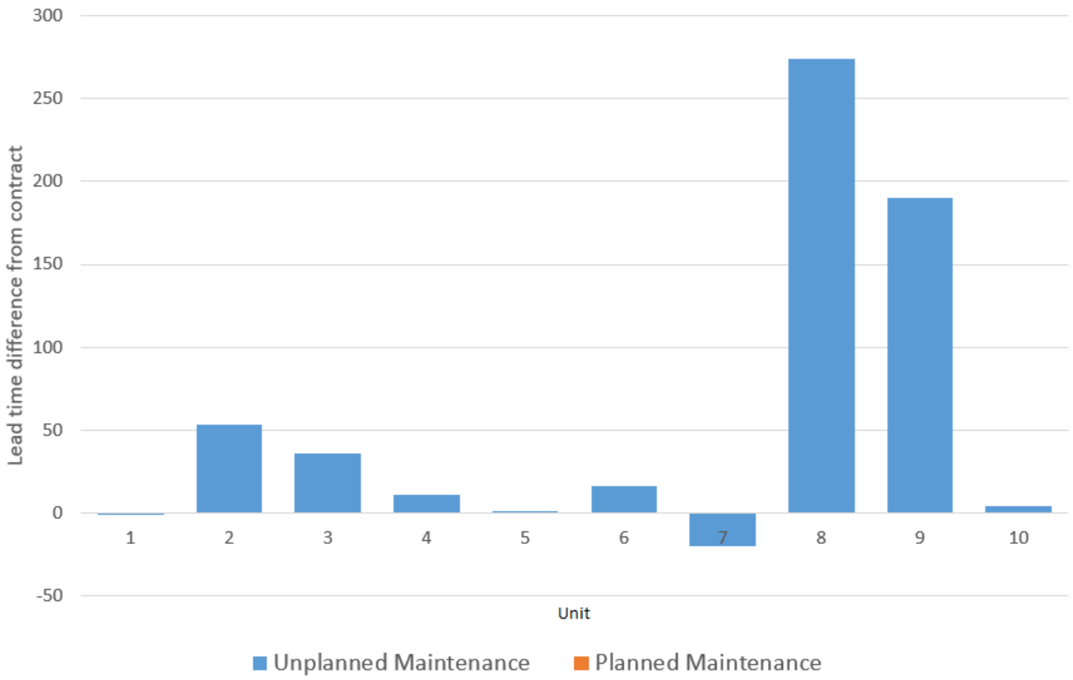

Figure E.11: Service Part 11

Unit	Type	Difference
1	UPM	-1
2	UPM	53
3	UPM	36
4	UPM	11
5	UPM	1
6	UPM	16
7	UPM	-20
8	UPM	274
9	UPM	190
10	UPM	4

Table E.11: Raw data for service part 11

Service Part 12

31 individual units of service part 2 were maintained by Saab's MRO workshops in 2019. All 31 of these units underwent unplanned maintenance, and no units underwent planned maintenance. Figure E.12 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 1, which was completed 193 days later than expected, with a total lead time of 235 days.

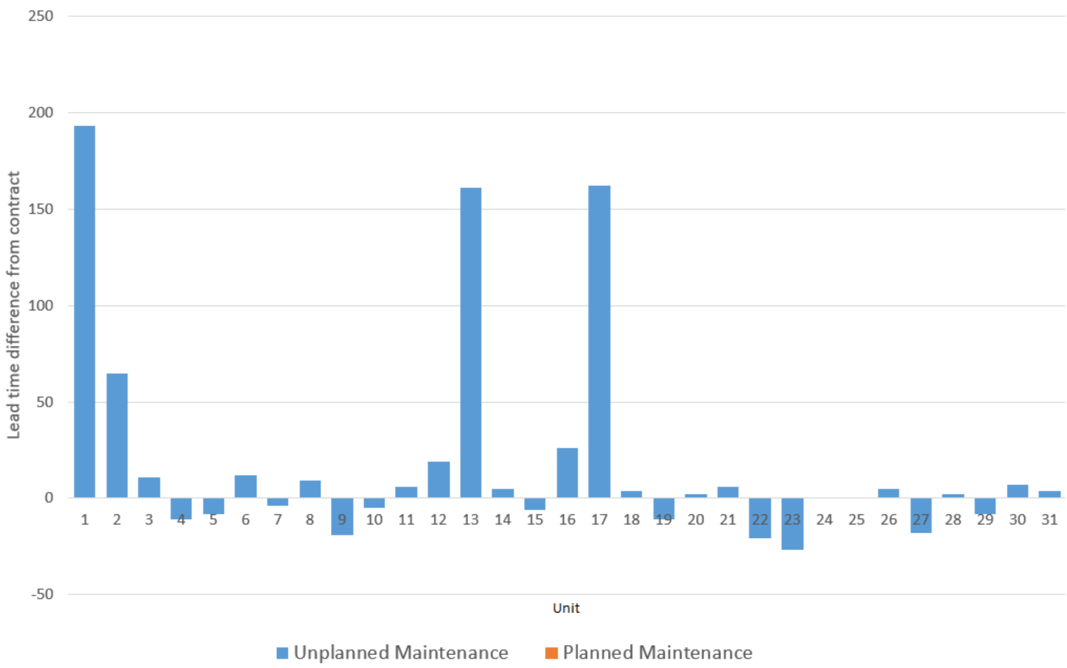

Figure E.12: Service Part 12

Unit	**Type**	**Difference**
1	UPM	193
2	UPM	65
3	UPM	11
4	UPM	-11
5	UPM	-8
6	UPM	12
7	UPM	-4
8	UPM	9
9	UPM	-19
10	UPM	-5
11	UPM	6
12	UPM	19
13	UPM	161
14	UPM	5
15	UPM	-6
16	UPM	26
17	UPM	162
18	UPM	4
19	UPM	-11
20	UPM	2
21	UPM	6
22	UPM	-21
23	UPM	-27
24	UPM	0
25	UPM	0
26	UPM	5
27	UPM	-18
28	UPM	2
29	UPM	-8
30	UPM	7
31	UPM	4

Table E.12: Raw data for service part 12

Service Part 13

25 individual units of service part 13 were maintained by Saab's MRO workshops in 2019. 8 of these units underwent planned maintenance, and 17 units underwent unplanned maintenance. Figure E.13 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 4, which was completed 248 days later than expected, with a total lead time of 290 days.

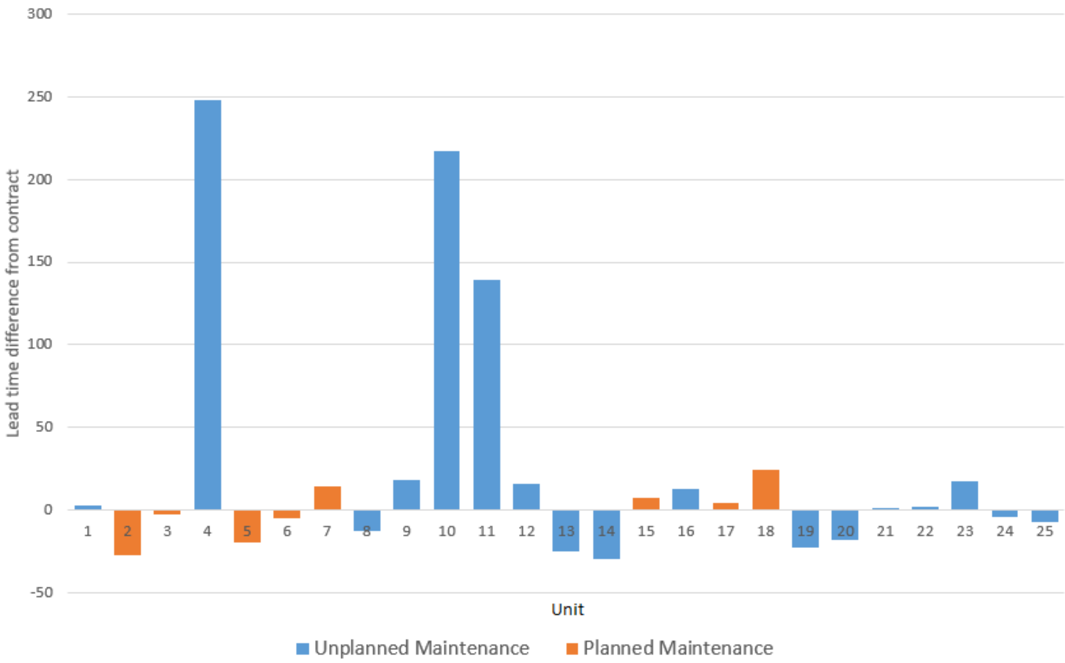

Figure E.13: Service Part 13

Unit	Type	Difference
1	UPM	3
2	PM	-27
3	PM	-3
4	UPM	248
5	PM	-20
6	PM	-5
7	PM	14
8	UPM	-13
9	UPM	18
10	UPM	217
11	UPM	139
12	UPM	16
13	UPM	-25
14	UPM	-30
15	PM	7
16	UPM	13
17	PM	4
18	PM	24
19	UPM	-23
20	UPM	-18
21	UPM	1
22	UPM	2
23	UPM	17
24	UPM	-4
25	UPM	-7

Table E.13: Raw data for service part 13

Service Part 14

2 individual units of service part 2 were maintained by Saab's MRO workshops in 2019. Both of these units underwent unplanned maintenance, and no units underwent planned maintenance. Figure E.14 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 42 days. The unit with the longest observed delay is unit number 2, which was completed 167 days later than expected, with a total lead time of 209 days.

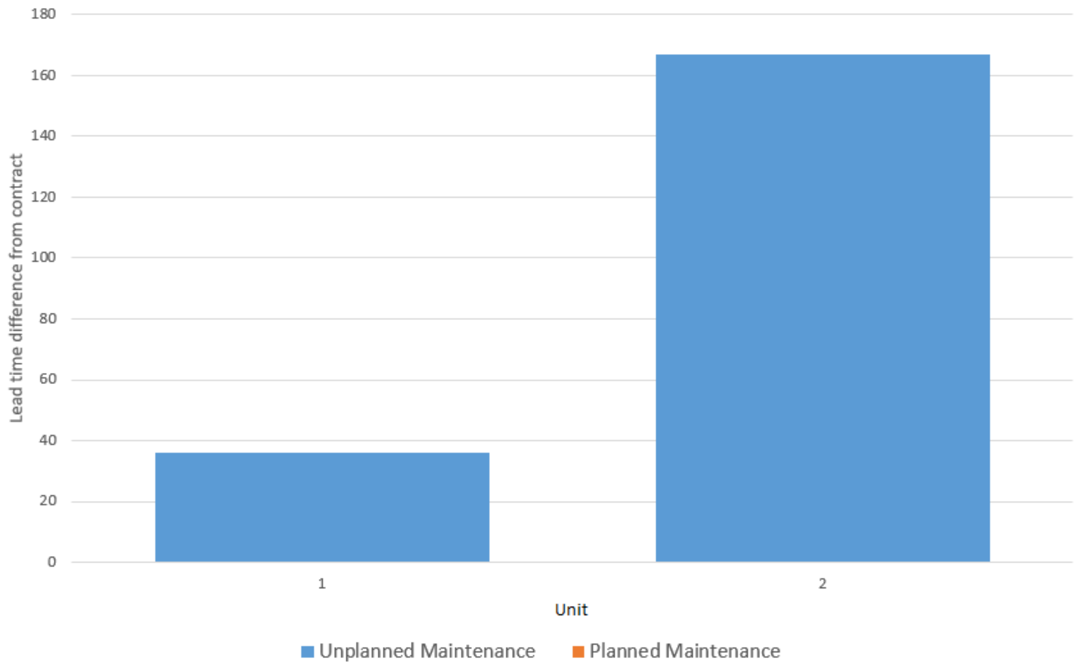

Figure E.14: Service Part 14

Unit	Type	Difference
1	UPM	36
2	UPM	167

Table E.14: Raw data for service part 14

Service Part 15

9 individual units of service part 15 were maintained by Saab's MRO workshops in 2019. 3 of these units underwent planned maintenance, and 6 units underwent unplanned maintenance. Figure E.15 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 9, which was completed 230 days later than expected, with a total lead time of 260 days.

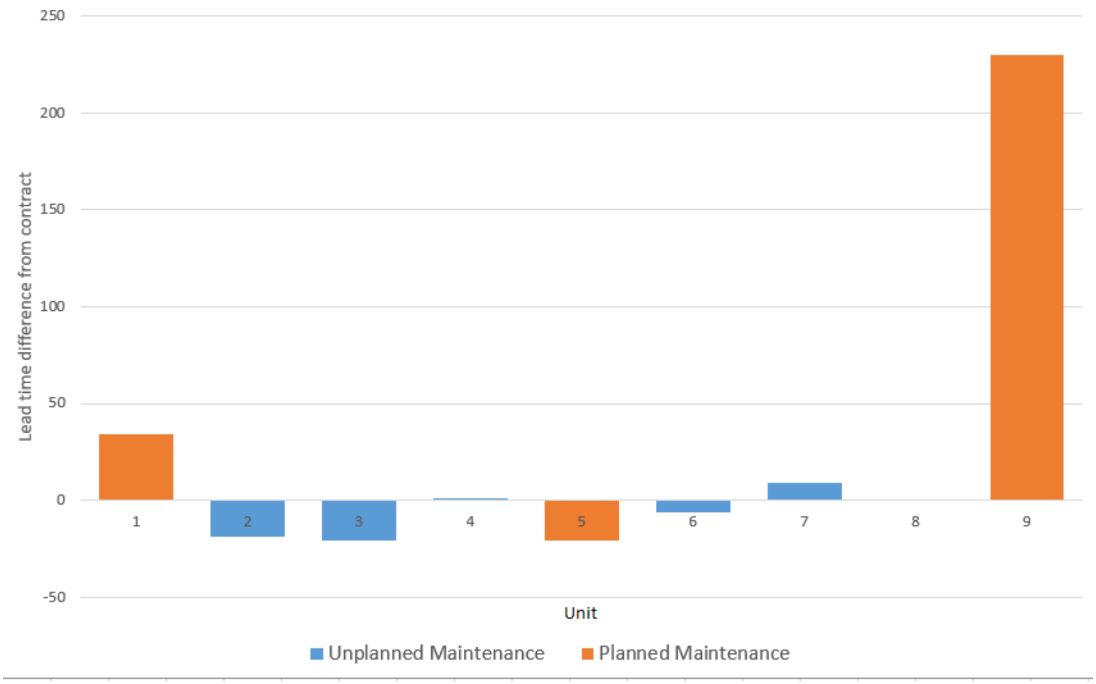

Figure E.15: Service Part 15

SP15	Type	Difference
1	PM	34
2	UPM	-19
3	UPM	-21
4	UPM	1
5	PM	-21
6	UPM	-6
7	UPM	9
8	UPM	0
9	PM	230

Table E.15: Raw data for service part 15

Service Part 16

9 individual units of service part 15 were maintained by Saab's MRO workshops in 2019. 1 of these units underwent planned maintenance, and 8 units underwent unplanned maintenance. Figure E.16 shows the difference between the actual lead time for each individual unit compared to the expected lead time of 30 days. The unit with the longest observed delay is unit number 9, which was completed 133 days later than expected, with a total lead time of 163 days.

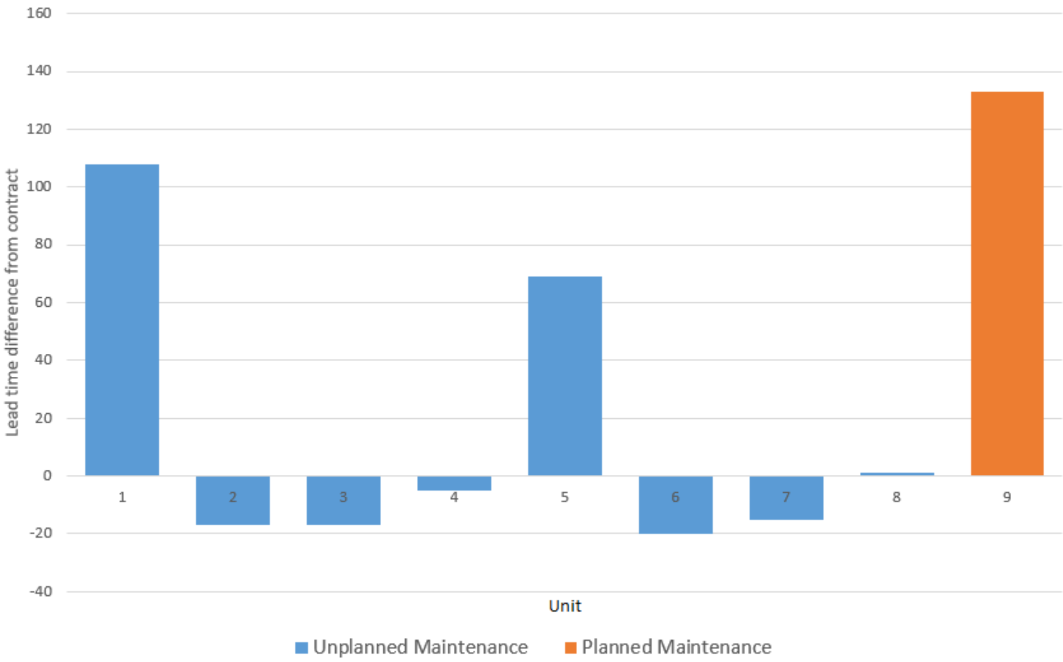

Figure E.16: Service Part 16

SP16	Type	Difference
1	UPM	108
2	UPM	-17
3	UPM	-17
4	UPM	-5
5	UPM	69
6	UPM	-20
7	UPM	-15
8	UPM	1
9	PM	133

Table E.16: Raw data for service part 16

Appendix F

Causes for delays

F.1 Service Part 1

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	7	1606
Internal stock-out (spare parts)	1	307
External Delay at OEM	1	46

Table F.1: Causes for delays - Service part 1

F.2 Service Part 2

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	10	1710
External delay at OEM	1	274

Table F.2: Causes for delays - Service part 2

F.3 Service Part 3

Interruption	Number of occurrences	Total days
External Delay at OEM	5	528
Internal faulty equipment	10	140

Table F.3: Causes for delays - Service part 3

F.4 Service Part 4

Interruption	Number of occurrences	Total days
External delay at OEM	13	3929

Table F.4: Causes for delays - Service part 4

F.5 Service Part 5

Interruption	Number of occurrences	Total days
Internal stock-out (spare parts)	5	555
External delay at OEM	3	40

Table F.5: Causes for delays - Service part 5

F.6 Service Part 6

Interruption	Number of occurrences	Total days
Internal stock-out (spare parts)	17	2077
External delay at OEM	2	202
Internal equipment breakdown	4	61

Table F.6: Causes for delays - Service part 6

F.7 Service Part 7

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	5	564
Internal equipment breakdown	4	64

Table F.7: Causes for delays - Service part 7

F.8 Service Part 8

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	5	564
Internal equipment breakdown	4	64

Table F.8: Causes for delays - Service part 8

F.9 Service Part 9

No interruptions reported.

F.10 Service Part 10

Interruption	Number of occurrences	Total days
External delay at OEM	10	3797

Table F.9: Causes for delays - Service part 10

F.11 Service Part 11

Interruption	Number of occurrences	Total days
Internal stock-out (spare parts)	3	730

Table F.10: Causes for delays - Service part 11

F.12 Service Part 12

Interruption	Number of occurrences	Total days
External delay at OEM	4	943
Internal stock-out (spare parts)	2	72

Table F.11: Causes for delays - Service part 12

F.13 Service Part 13

Interruption	Number of occurrences	Total days
External delay at OEM	5	909
Internal stock-out (spare parts)	2	53

Table F.12: Causes for delays - Service part 13

F.14 Service Part 14

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	1	283

Table F.13: Causes for delays - Service part 14

F.15 Service Part 15

No interruptions reported.

F.16 Service Part 16

Interruption	Number of occurrences	Total days
Internal stock-out (sub-units)	2	220

Table F.14: Causes for delays - Service part 16

Appendix G

Lead time analysis timelines

G.1 Aggregated timeline of internal stock-out (spare parts)

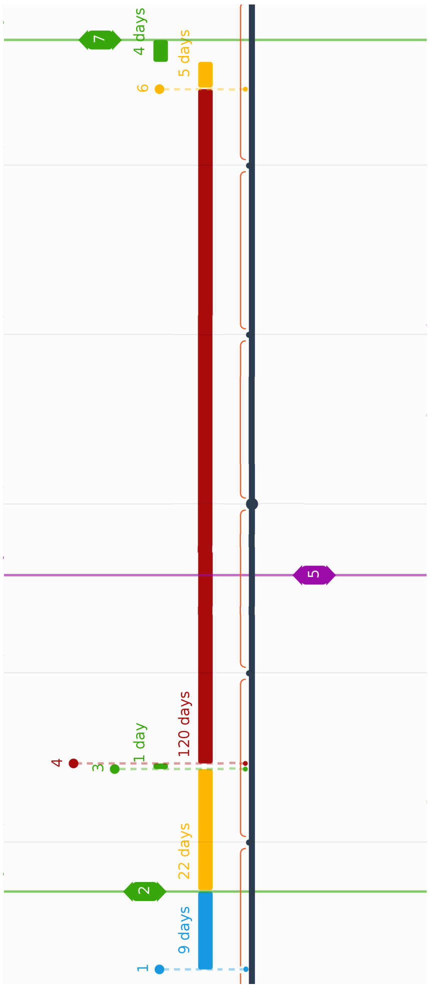

Figure G.1: Aggregated timeline for internal stock-out (spare parts)

G.2 Aggregated timeline of internal stock-out (sub-units)

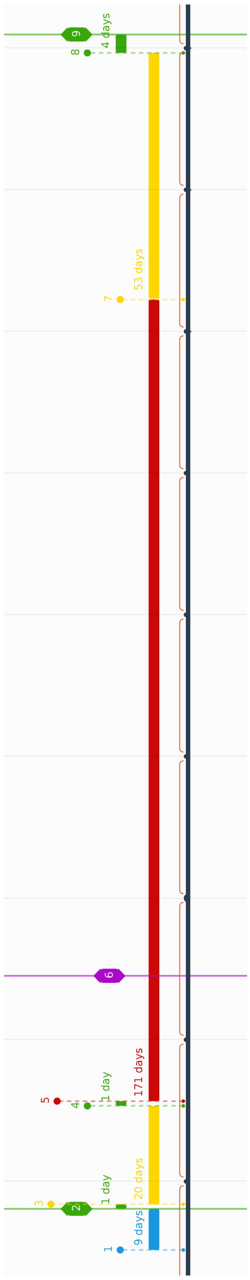

Figure G.2: Aggregated timeline for internal stock-out (sub-units)

G.3 Aggregated timeline of external delay at OEM

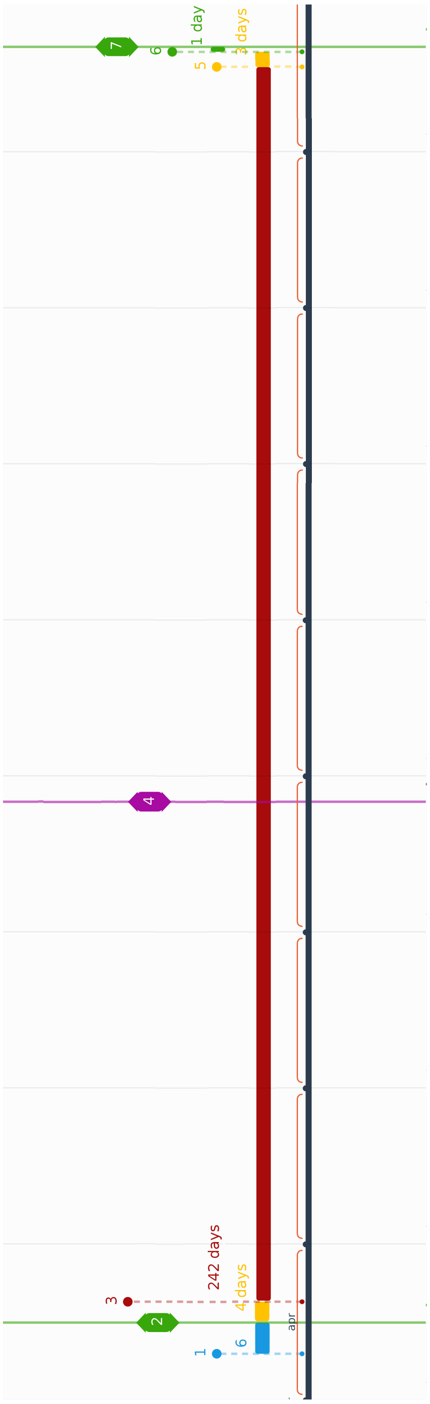

Figure G.3: Aggregated timeline of external delay at OEM)

G.4 Aggregated timeline of internal faulty equipment

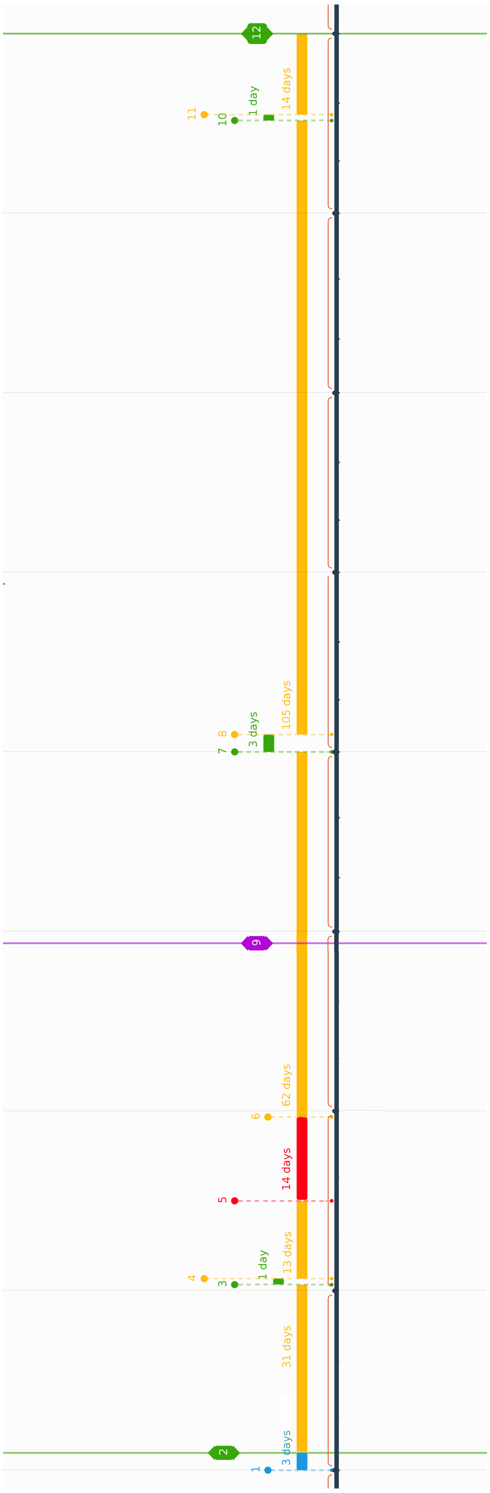

Figure G.4: Aggregated timeline of internal faulty equipment)