Designing a centralised model to value balance between aircraft uptime and downtime from a integral airline perspective

A case study at KLM E&M

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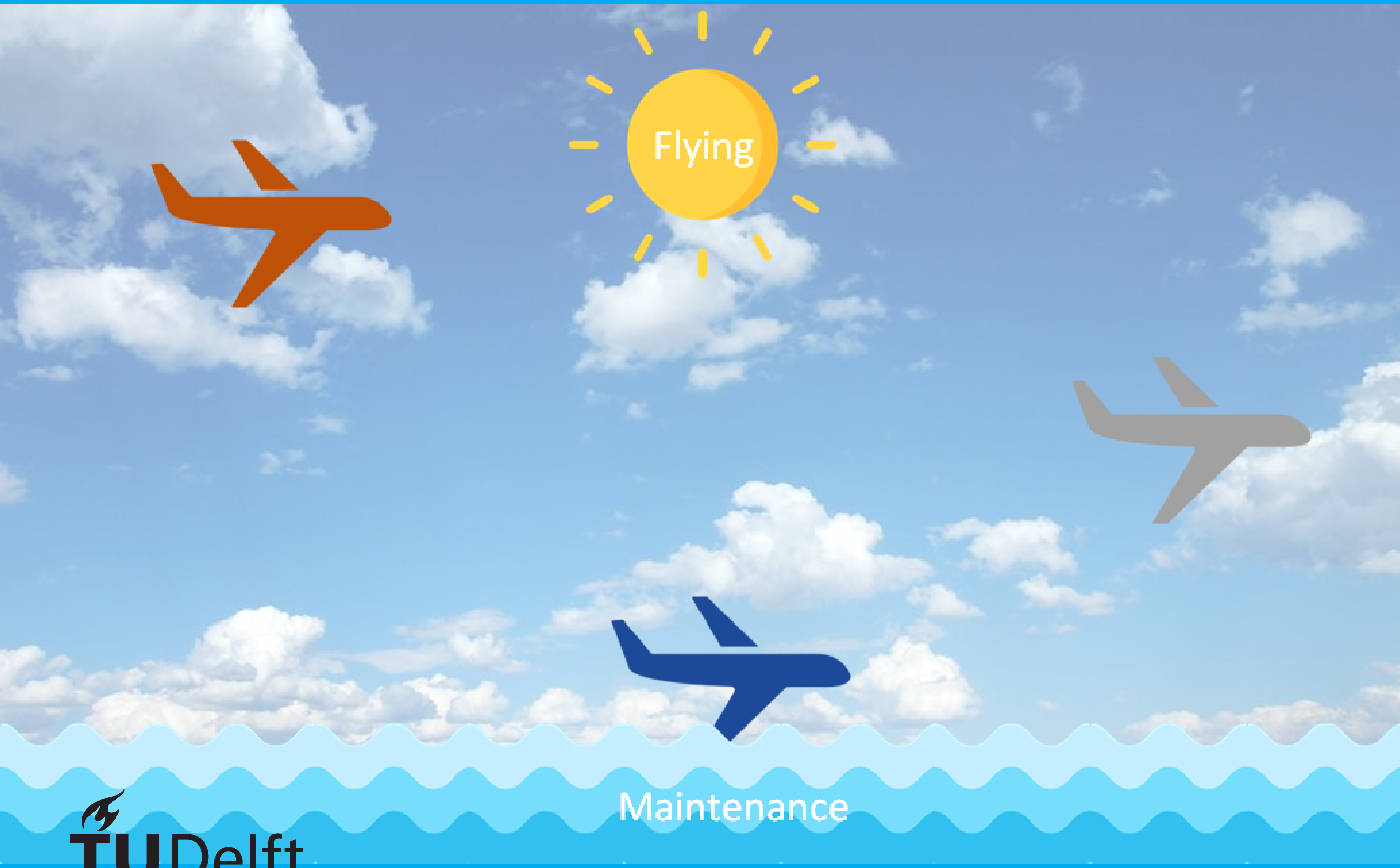
2023.MME.8850



Designing a centralised model to value balance between aircraft uptime and downtime from a integral airline perspective

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by

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Msc Mechanical Engineering - Multi-Machine Engineering

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on 03-10-2023

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Project duration:	Feb, 2023 – Sept, 2023	
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Preface

Starting with this research, I knew nothing about aircraft maintenance, but hey, how hard it can be. Before I knew it, I was dragged into the complexity of it all. So many tasks, so many different due dates, so many components, and so many interests. The key challenge for me was to scope it, starting from the perspective of the KLM E&M. I eventually took an airline-wide perspective, so you could think that the scoping wasn't really done properly. However, the challenge of integrating all these stakeholders was what made this research great, as was solving an actual problem that the airline had. This made it great for me, knowing that people were curious about this research's results. And even though many people were hoping for different outcomes and tried to steer it in their directions sometimes, I can say that I also added my personal touch to this research by telling it as a story in Greek mythology. Bringing some of my other interests, such as classical history, together with aircraft maintenance was something I would not think would be possible. However, by balancing between excessive history and excessive airline planning, I tried to make it as fun for me as possible. It may be a strange analogy compared to the story of Icarus, but I think I succeeded.

I am profoundly grateful to the dedicated individuals who have played an instrumental role in guiding me throughout this research journey. I sincerely thank my supervisor at the TU Delft, Dr. Wouter. W.A Beelaerts van Blokland, for his mentorship and guidance. His expertise, encouragement, and patient guidance have been instrumental in shaping this research and my personal development. I really enjoyed our broad talks about aircraft maintenance, aviation and, specifically, our common interest, history. I would also like to thank Prof. Dr. R.R. Negenborn. although we met occasionally, your feedback allowed me to take the research to a higher level.

Next, I would like to express my gratitude to my supervisor at KLM E&M, Paul Crombach, who helped me every day to improve this research. I would also like to thank everybody at the Planning, Scheduling and Fleet Control department at KLM E&M, who, without them, I would have never made it this far. Their expertise was essential for this research, but the times hanging around the coffee machine and making sure we had some fun were of key importance for my experiences these months.

Lastly, I would like to thank my friends and family, especially my twin brother Twan, who helped me immensely throughout this research because he sort of served as my third supervisor on many occasions.

S. Hooijschuur
Amsterdam, September 2023

Abstract

Aviation is one of the most important modes of transport for both passengers and freight. The number of flights and passengers is increasing while the number of fatalities decreased massively over the past decades indicating that aviation is safer than ever. One of the factors that contribute to aircraft safety is Maintenance, Repair and Overhaul (MRO). Maintenance is one of the tasks that needs to be planned by the airline. Planning involves scheduling the flights, operations and maintenance. Currently, the planning of different tasks is handled separately by different operators, leading to misunderstandings, friction and a lack of a shared understanding of definitions and requirements.

This research aim was to design a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between flights and maintenance. The literature on aircraft maintenance, maintenance planning and task clustering was studied and, gaps in these areas were identified. There was a focus on traditional aircraft maintenance in the form of letter checks rather than more dynamic weekly maintenance planning. In addition, literature focusing on optimising maintenance planning was given from a maintenance provider's perspective and did not consider the other essential stakeholders in planning while four key stakeholders can be distinguished: plane, maintenance, service and flight provider. Furthermore, it was shown in the literature that tasks were clustered into large single checks based on Remaining-Useful-Life and cost but not on being critical regarding airworthiness. Thus, a centralised model that takes a multi-stakeholder perspective on airline planning is proposed to solve these problems.

The new equilibrium will enhance the airline's capacity to manage maintenance efficiently and ensure greater uptime. The model addresses the important aspects of airline planning, including maintenance, flight and operation planning. The key importance is that the model considers three stakeholders instead of only one so that the equilibrium between excessive flying and excessive maintenance can be established. In striking such a balance, uptime is assumed to increase.

Three stakeholders (maintenance, service, and flight providers) provided their inputs into the planning and are supposed to function together in a triangle. To optimise the interaction between different stakeholders a centralised model called the Cyrus model is designed. Based on the analysis of the results of the Cyrus model, a future state can be designed that benefits all stakeholders by creating new airline planning.

In Conclusion, based on the analysis of the check frequency, distribution, length and turntime, weekly minimum maintenance requirements, multiple future plans were proposed. These plans contained a 10-week schedule with different varieties of checks and occurrences. After validation of the plans by a capability analysis, it is concluded that the proposed plans provide a more stable plan than the current state. Thus, it is found that a balance between flying and maintenance is supposed to perform better than the current state and lead to a higher uptime.

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Introduction

In this chapter, an introduction will be presented on aircraft maintenance.

1.1. Research context

In 2022, over 3700 million people took to the skies [25]. During COVID-19, passengers dropped from 4500 million in 2019 to 2100 million in 2021 which means it is back on the rise again. More than 33.8 million flights and only six fatal aircraft incidents occurred in 2022 [10], which leads to an average of 1 fatal accident every 5.63 million flights. The number of fatalities decreased massively over the past decades [3] while the number of flights and passengers increased in those decades [25]. This means that aviation is safer than ever. One of the significant contributors to aircraft safety is Maintenance, Repair and Overhaul (MRO). With aircraft renewing and ever-increasing competition in the aviation industry, aircraft maintenance is under tremendous pressure to reduce cost and increase aircraft utilisation.

Aircraft MRO, which ensures airworthiness and describes the aircraft's maintenance activities, is bound to strict rules and regulations. The European Aviation Safety Agency (EASA) created the European rules and regulations to ensure aviation safety. These rules and regulations are compiled in part 145, Maintenance Organisation Approvals. Part 145 is the European standard for approving organisations that perform maintenance on aircraft and aircraft components registered in EASA Member States [47].

Because of the strict rules, aircraft MRO is seen by most parties as a costly affair. The global market size of aircraft MRO in 2022 is estimated to be around $90 billion [21] and is expected to increase to around $130 billion in 2030. However, despite this increase, maintenance providers face huge competition and have to improve their processes continuously [31].

To better understand aircraft maintenance, maintenance structures and strategies will be clarified in this thesis and to explain the maintenance structure of airlines, the maintenance structure of KLM will be elaborated as an example to understand further what a maintenance provider looks like. Aircraft MRO at KLM E&M comprises different segments named Components, Engine and Airframe services [48]. Each of the segments focuses on specific parts of the aircraft. Component services focuses on separate aircraft components that need inspection, repair and testing. Engine services focuses on the aircraft engines, and Airframe services focuses on all the tasks of the aircraft itself. Airframe services can be divided into three sub-segments: Modifications, hangar checks and Line maintenance (see Figure 1.1). Modifications are tasks that change the aircraft configuration; an example of a modification is changing seats and or seating arrangements. Modifications are big projects and require long grounding times for the aircraft, meaning that modifications are primarily performed in the hangar and, sometimes, in combination with a hangar check. For a hangar check, aeroplanes are moved to a hangar for an extensive MRO and will be grounded for at least 12 hours to 2-3 weeks, depending on the check type and season. The last segment of Airframe services is Line maintenance, which consists of all the maintenance that can be done at the gate or near the gate on the platform. This includes pre- and post-flight checks as well as smaller maintenance tasks. Some airlines have Line and Base maintenance outsourced to maintenance providers [37].

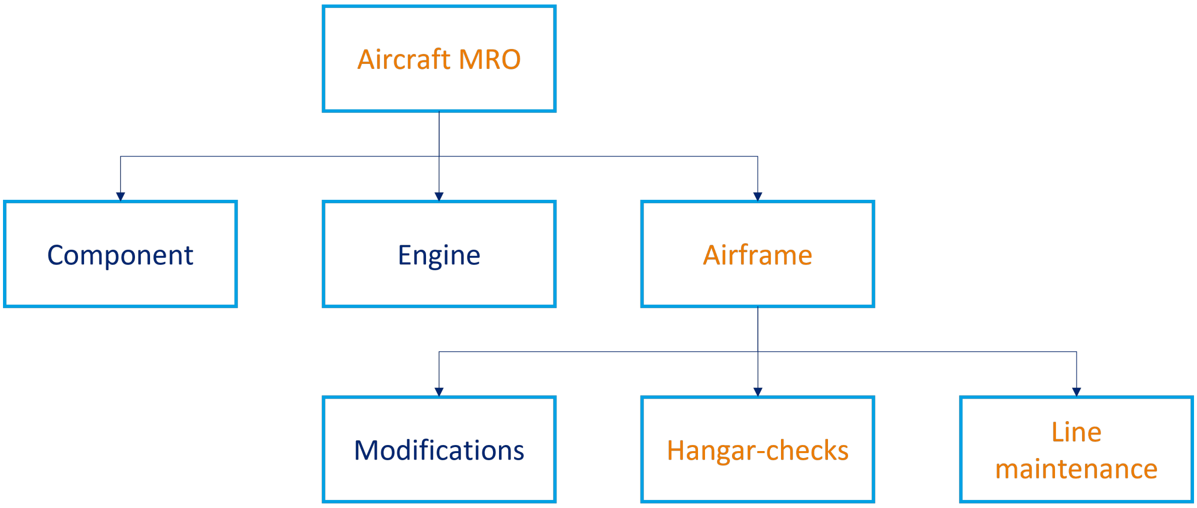

Figure 1.1: Company structure of KLM E&M [48]

1.2. Research field

This research is conducted at the Delft University of Technology as part of the Master of Mechanical Engineering with the Multi-Machine track in collaboration with KLM E&M, specifically the planning, scheduling and fleet control department. Additional stakeholders are Netwerk and the Operation Control Centre (OCC).

A critical and important aspect of the airline is planning. Planning involves scheduling, the flights, maintenance and operation planning. Different stakeholders focus on different areas of the planning. E&M focuses on maintenance planning, Netwerk on flight planning and the OCC on operations planning. The stakeholders must work together to provide the best operations performance. This research focuses on maintenance, flight and operations planning to develop an improved airline planning. To this end, different plans will be combined to create a complete overview of aircraft operations. This is crucial for the determination of maintenance requirements. Having the minimum maintenance requirements clear, overall planning can be improved.

1.2.1. Maintenance planning

Maintenance planning is essential for the airline's operation. Maintenance planning is an effect of a maintenance strategy, and most airlines currently perform two types of maintenance strategies: corrective and preventive maintenance [4]. Corrective Maintenance (CM) is a reactive strategy that involves replacing or repairing components after failure. CM tasks are in most organisations prioritised because failure often results in an Aircraft On Ground (AOG). An AOG is a situation wherein the aircraft is not allowed to fly due to critical failures or does not comply with the rules and regulations, such as the Minimum Equipment List (MEL). The MEL is a list of minimal components for an aircraft, allowing it to fly.

Corrective maintenance is costly due to the unpredictability of failure

CM is considered cheap because it can be done with few resources and a small maintenance infrastructure. However, CM is also an inefficient maintenance strategy, and in the long run, it results in expensive equipment failure and more accidents [13]. The expensive equipment failure manifests in more component damage and longer repair times, which means that the Mean Time To Repair (MTTR) is long. Also, because it is a reactive strategy, there is no analysis of the causes of the failure as the failure comes unexpectedly. Thus, if the cause of failure is unknown, it can happen again shortly, which means that the Mean Time Between Failures will be low. Another aspect of CM is the cost due to the unpredictability of failure. Because of the unpredictability, the occupation of hangar space and the required workforce differ. However, the hangar space and workforce must be available at any time, which makes it costly[4].

Preventive maintenance is only cost-efficient if maintenance is done at optimal times

Preventive Maintenance (PM) involves replacing, repairing and inspecting components before failure and can be seen as an active strategy. The objective of this maintenance strategy is to avoid or mitigate the consequences of component failure [27]. Most PM includes relatively simple tasks such as lubrication and cleaning, Etc. PM results in improved reliability and decreased costs of replacement and downtime. However, PM is only cost-efficient if it is done at optimal times. Unnecessary PM might increase reliability in the early stages but will be very expensive in the long run. The balancing of CM and PM is crucial for the performance of a maintenance provider [7].

1.3. Research problems

Maintenance, flight and operations planning are handled separately by different operators. The maintenance operator focuses on optimising the maintenance planning, the flight operator focuses on optimising the number of flights, and the general operator focuses on the overall planning. This complicates overall planning because they all have different objectives that collide and obstruct each other. In general, maintenance planning is focused on maintenance spread over large checks at fixed intervals. These checks are so-called 'letter checks' and have an interval from several months to several years. Letter checks are the traditional form of aircraft maintenance set up by aircraft manufacturers decades ago. However, maintenance is a continuous requirement and should be done at intervals between the letter checks. It is a problem that it is impossible to determine the ground time requirements even though they are crucial to make maintenance more plannable and prevent corrective maintenance.

At the airline, they say: "An aircraft needs six hours of maintenance per week" [4]

Another problem is miscommunication between stakeholders, who have different definitions regarding maintenance planning. The airline invented terms to code specific maintenance jobs. However, this coding has no clear priority distinction and categorisation, which makes it unclear what codes are used for plannable maintenance and what for unplanned maintenance. This ambiguity is shown in the quote above: "An aircraft needs six hours of maintenance per week". However, it is unclear what kind of maintenance must be done within these six hours and how they should be divided weekly. Thus, clear categorisation and definition combined with determining the weekly maintenance requirements is crucial for the airline's operation and achieving a value balance between flights and maintenance.

The third problem is a misunderstanding of the activities that occur between flights. Current planning tools show an empty gap in the schedule, indicating free time. Thus, a misconception arises for several stakeholders that maintenance activities can be performed in that time. A categorisation of these activities can help understand what is currently occurring in this 'free time' and, if there is any free time, how it could actually be used.

1.4. Research scope

This research focuses on maintenance planning as part of the overall planning of the airline. Bottlenecks in maintenance, such as material deliveries and capacity shortages, are not considered to decrease complexity due to a lack of valuable data. Thus, a full capacity is assumed with material deliveries on time for planned maintenance. For the case study, a specific part of the airline fleet is selected, namely the Intercontinental fleet, consisting of the Boeing 747, 777, 787 and the Airbus A330. These aircraft are called Wide-body (WB) aircraft. This is the opposite of Narrow-body (NB) aircraft, which focus more on continental flights. The intercontinental fleet is particularly interesting because of its flight schedule, which consists of long intercontinental flights and short stops at the home base, which could be used for maintenance.

Also, some aspects are not considered in the scope, including financial assessment, due to the inconsistency of profits and costs related to flights and maintenance. Workforce is another aspect not considered in this scope due to the irregularity of tasks requiring different mechanic skill levels. Thus, workforce capacity planning is a whole discussion on its own.

1.5. Research objective

This project aims to create a model that can estimate weekly ground time requirements based on historical use to create a value balance between aircraft uptime and downtime from a holistic perspective. This holistic perspective takes the perspective of all the stakeholders instead of only one to create a combined maintenance plan.

> **Aim: Create a balance between uptime and downtime with the help of a data model that can be used to estimate weekly minimum maintenance requirements based on historical flight and maintenance data.**

Finding the balance between flights and maintenance is like the story in the Greek mythology of Icarus. Icarus was the son of the inventor Daedalus. Daedalus was in service of the Minoan King Minos and was the architect of the famous labyrinth beneath the palace that held the mythical creature the Minotaur. After Theseus, King of Athens, slew the Minotaur and escaped, King Minos suspected Daedalus to have given the price of the labyrinth's secrets. He thus was imprisoned in a tower overlooking the sea. Daedalus constructed wings for himself and Icarus from all the materials he could find to escape imprisonment. Before taking the leap, he warned Icarus to fly neither too high nor too low, lest the sea's dampness clogs his wings or the sun's heat melt them. Icarus ignored Daedalus and flew too close to the sun, causing his wings to melt. Icarus thus fell from the sky into the sea, where he drowned. It gave rise to the saying: "Do not fly too close to the sun". Now, why tell all this? An airline has a similar problem when it comes to flights and maintenance.

Some stakeholders within the airline would fly as much as possible because it generates revenue. However, too much flying without maintenance leads to a dangerous situation with no more control of the planning and a decrease in stability. Too much flying is like flying too close to the sun. Too much ambition to achieve the highest profits with more flying without the proper maintenance planning. in contrast, flying far from the sun resembles setting up an ample maintenance plan. It might seem safe because there is more than enough ground time for maintenance. However, flying too low and close to the sea is also dangerous. Too much maintenance, in combination with little flying, leads to low profits. Thus, this can cause an airline to 'drown' in their high expenses and low returns. Thus, a balance needs to be found between them.

1.6. Research deliverables

This research is conducted for the Delft University of Technology with the cooperation of KLM E&M. The deliverables will be of value to both parties. The main deliverable will be a value balance between uptime and downtime (read flights vs. maintenance). This main deliverable is achieved with the help of other deliverables, which are mentioned below:

- Model to assess historical maintenance, flights, fleet count and turn times
- Priority categorisation of maintenance tasks and maintenance slots
- Defining of value for maintenance
- Analysis of maintenance requirements
- Analysis of turn time
- Plan for maintenance ground time distribution and slot length

1.7. Research questions

How to value the balance between aircraft up and downtime from a holistic airline perspective?

- What is Aircraft MRO?
- What is the state of the art in maintenance planning?
- What is the state of the art in task clustering?
- What are theories that could be used to improve the planning?
- What is the current state of planning at the airline?
- What are the stakeholders in planning?
- How do the stakeholders cooperate?
- How can the planning improve?
- How can the maintenance ground time be determined?
- What are important factors to consider for determining ground time requirements?
- How would a model look that could value balance from an integral airline perspective?
- Can the maintenance requirements be categorised, and how would this look?
- Can waste in waiting time be identified and categorised?
- What would be a future state of planning that considers all stakeholders?
- How can the proposed model be verified?
- How can the proposed model be validated

1.8. Methodology

This research is conducted as a case study of the airline and follows a clear methodology. The methodology is taken from Dul J [15] and distinguishes two types of research: practice- and theory-orientated research. To make this distinction is essential for the effect of the research.

> "Practice-oriented research is research where the objective is to contribute to the knowledge of one or more specified practitioners." [15]
>
> "Theory-oriented research is research where the objective is to contribute to theory development. Ultimately, the theory may be useful for the practice in general." [15]

This research is more theory-orientated but closely related to the practice and focuses on theories around maintenance requirements and planning. Because it is theory-orientated, a specific step by step guide will be retained. The first phase is the theory-exploring phase, which explores theories such as planning and Lean. This step aims to identify the practical problems and define the research questions, followed by an overview of the literature. This results in a research problem and a scope already presented in this chapter. The second phase is theory-building, where an analysis of the current situation will be drawn that helps in the next step in this phase: model development. In this step, the model design will be detailed. The third phase is theory-assessing, which includes model analysis, a future state design and finally, model verification and validation.

2

Theory analysis

In this chapter, an overview of the literature study will be discussed. First, traditional maintenance will be explained in more detail in section 2.1, which makes it possible to understand the development of maintenance planning and how it originates. Maintenance planning is crucial in this thesis and overall airline planning, so in section 2.2, the development of maintenance planning will be investigated and analysed. Task clustering will be discussed in section 2.3. Task clustering is important because it becomes important to know how to use this time optimally after establishing the ground time requirements for maintenance. In section 2.4, other important underlying theories that will be used to develop the model further will be discussed.

- What does traditional aircraft maintenance look like?
- What is the state of the art in maintenance planning?
- What is the state of the art in task clustering?
- What are theories that could be used to improve the planning?

2.1. Traditional aircraft maintenance

Traditional aircraft maintenance is maintenance in the form of letter checks executed in a hangar. Traditional aircraft maintenance is a strategy set up by aircraft manufacturers decades ago aiming to ensure that the aircraft is safe to operate. Letter checks are hangar checks wherein several maintenance tasks are clustered into a larger package. In most cases, these maintenance tasks are defined by aircraft manufacturers with the help of operators and authorities. Each task has a suggested interval within which it must be executed. In most cases, this interval is more of an obligation than a suggestion. The interval can be displayed in different ways, such as flight hours, cycles or calendar days. Whatever due date comes first will be maintained. During COVID-19, when most aircraft were grounded, calendar days were the leading way to determine maintenance, while pre-COVID-19, flight hours and flight cycles were the leading ways [4]. Maintenance tasks with similar intervals are clustered in so-called "Letter checks". The letter checks traditionally consisted of four letters: A, B, C and D. In Table 2.1, the letter checks and their traditional Type, Interval and Maintenance Tasks are presented. Most MRO providers no longer use the four letters and have switched to a more efficient system consisting of two letters.

The four-letter system coincides with the objectives of the aircraft manufacturers. That is to maintain the aircraft as extensively as possible; however, extensive maintenance collides with the airline's desire to minimise downtime. Airlines value the uptime of an aircraft highly because it ensures the most profit, while manufacturers have uptime less high as a priority. The question arises if the traditional letter check system is more advantageous for the manufacturers than the airlines. Although airlines switched to a two-letter system, the traditional letter check remains the basis of aircraft maintenance. Designing a maintenance strategy can have multiple demand drivers. These demand drivers can be manufacturers, crew, airline and maintenance providers. Currently, the main driver of the maintenance strategy is the aircraft manufacturer.

Table 2.1: Traditional representation of "Letter checks" [5]

Checks	Maintenance Type	Interval	Maintenance Task
A	Light Maintenance	2-3 months	External visual inspection, filter replacement, lubrication etc.
B	Light Maintenance	Rarely mentioned	Tasks are commonly Incorporated in to successive A-checks
C	Heavy Maintenance	18-24 months	Thorough inspection of the individual systems and components
D	Heavy Maintenance	6-10 years	Thorough inspection of most structurally significant items

Most airlines use a two-letter consisting of the A-check and the C-check [4]. Tasks that belonged to the B-check are incorporated into the A-check, and tasks that belonged to the D-check are incorporated into the C-check. A two-letter check is a system with only a light and heavy maintenance check. Generally, the tasks in each letter check are similar for different aircraft. Letter checks result in very rigid planning, while airlines desired more flexibility because of the unpredictability of maintenance. The two-letter system provides more flexibility than the four-letter system, which is why the latter system is rarely seen anymore.

2.2. State of the art in maintenance planning

Maintenance planning is crucial in overall airline planning. Maintenance planning is always under continuous pressure from the airline and becomes crucial for maintenance providers because of the need to reduce maintenance costs and increase aircraft utilisation [37]. How an airline performs is related to security, quality, efficiency, costs and speed of the maintenance operation [19]. These five factors are directly related to the performance of the maintenance planning department.

> **"Planning the maintenance of an aircraft involves monitoring aircraft or equipment conditions to determine when work is due in the short, medium, and long term" [2]**

Modern maintenance schedules are based on the most recent document produced by the Maintenance Steering Group (MSG-3) of the Air Transport Association (ATA) [38]. The goal of this document was to present a methodology that can be used to develop a maintenance schedule that corresponds with regulatory authorities, operators, and manufacturers [42]. Because the Maintenance Planning Data (MPD) presented the maintenance tasks individually, operators could develop their customised maintenance program based on their needs. Aircraft manufacturers issue the MPD document and follow the guidelines of the MSG-3 [38]. This customised maintenance program presents an overview of all the tasks and their respective interval times. The maintenance planners aim to combine tasks with a similar due date into a maintenance check.

Planning the maintenance checks for a large heterogeneous fleet is a complex issue. In practice, maintenance checks are scheduled by experienced maintenance operators, which is time-consuming as most of the planning is done manually [14]. According to Deng et al. [14], using the manual planning approach, a feasible maintenance schedule is found but not an optimal one. There are operational and computational tools at hand to receive an optimal solution.

2.2.1. Literature

This section gives an overview of the literature based on publication date, which makes it possible to see the evolution of maintenance planning. The first papers were published in the seventies of the 20th century.

In 1977, Boere [9] came up with a simulation model (one of the first) as a tool to assist in scheduling maintenance. Air Canada just added WB aircraft to their fleet and needed help fitting those aeroplanes into their manually scheduled maintenance planning. The objective of this simulation model was to minimise the loss of flying hours between successive checks due to premature planning of checks. They achieved a 5 % increase in flight hours.

In 1989, Feo and Bard [17] introduced a model for the maintenance routing problem. However, because this is more related to assigning aircraft to slots, it is not within the aim of this research. Later, in 1996, Gopalan and Talluri [20] developed a Polynomial Time Algorithm to tackle the maintenance routing problem. An aircraft is routed to a maintenance station every three days. This is a relatively short-term solution and cannot be used for long-term scheduling. Again, the focus is not on how much maintenance is required but only from a maintenance provider's perspective.

In 2000, El Moudani and Mora-Camino [16] proposed a dynamic programming model to tackle the fleet assignment problem, solve the maintenance scheduling problem, and minimise maintenance costs. To solve the assignment problem, a heuristic approach was used. A heuristic approach is an approach to get a quick best-guess result. Because many of these problems require long computational times, heuristics can help cut this down. However, because heuristics serve as shortcuts, they do not always lead to optimal results.

Sriram and Haghani [43] developed a formulation with a heuristic approach to solve the maintenance schedule. The objective was to minimise the maintenance cost and cost related to aircraft re-assignment due to delays. Problems arose when further developing the formulation due to the increased complexity, obstructing the model from finding an optimal solution. In 2006, Sarac et al. [40] proposed a Branch-and-Price algorithm to solve the maintenance routing problem. This algorithm can be used as an operational tool for solving daily routing problems and aims to minimise maintenance costs.

Lan et al. [28] took a different approach to the aircraft scheduling problem. The objective was to optimise flight departure times to minimise passenger disruptions. The most important factor in this approach is the passenger or client, which differs from the previous objectives, which focused on cost or fleet availability. The key was to create a robust plan to reduce the delays' occurrence and impact, thereby increasing service.

Fli [1] came with an optimisation model to maximise the fleet availability for military aircraft. The issue of determining which aircraft should fly, for what duration, and which planes should undergo maintenance procedures was resolved by developing a mixed-integer bi-objective linear programming model. In 2014,Başdere and Bilge [8] formulated an Integer Linear programming model to solve the maintenance routing problem. The model is solved with the use of Branch-and-Bound and Heuristics. This model has a weekly planning horizon and aims to maximise the utilisation of the total remaining flying time of the fleet. This focus on flying time is typically a view from the flight provider's perspective. Extra flying time must be achieved by performing maintenance more optimal.

Maher et al. [34] introduced a new method to guarantee that an adequate number of aircraft routes are available daily for maintenance-critical planes to receive maintenance during the night. It was solved as a single-day aircraft maintenance routing problem and thereby focused on short-term planning. One of the main objectives was to create robust planning that makes airlines less susceptible to schedule perturbations and thus minimises the maintenance cost. Hockers [23] Came with an analysis of the TAT of the light checks of a Boeing 737 aircraft. They found that aircraft tasks had to be divided into under and above-the-wing tasks. A phase-gate work strategy was introduced to minimise the TAT of the aircraft. The same counts for van den Hoed [48], where an advanced task planning model was designed. Here, the model divided the aircraft into multiple zones and introduced a phase-gate work strategy to minimise the TAT of heavy checks. The focus on cost and/or TAT is from a maintenance provider's perspective. The focus is clearly only to improve the maintenance operations.

In 2020, Deng et al. [14] proposed a practical dynamic programming-based method for the long-term aircraft maintenance check scheduling problem. The objective was to minimise the wasted interval between checks, thus increasing aircraft availability. It had a four-year planning horizon and was one of the first long-term models. This is similar to the Boere [9] back in 1977. In 2021 Andrade et al. [6] proposed a Reinforcement Learning approach to optimise the long-term scheduling of maintenance for an aircraft fleet. The objective was to schedule checks as close to their due date as possible, thus minimising the number of checks and increasing fleet availability. It is built based on already-developed dynamic programming methods. The aim to minimise the time between checks is a problem solved from a flight provider's perspective.

Lee and Mitici [30] did a multi-objective analysis of condition-based aircraft maintenance. Two types of CBM were assessed: Sensor monitoring and RUL prognostics. As a result, it was found that CBM based on RUL prognostics can significantly impact maintenance costs. The types were simulated in a Discrete event simulation for ten years of operation. The general objective was to keep aircraft systems operational while minimising cost and maximising service quality. These objectives were put as parameters to measure and compare results. Tseremoglou et al. [46] came up with a comparative study of optimisation models for Condition-based maintenance scheduling of an aircraft fleet. The most significant models were a Mixed integer linear programming (MILP) and a Deep Reinforced Learning (DRL) model. The results show that the DRL approach achieves better results concerning scheduling prognostics-driven tasks and requires less computational time. In contrast, the MILP model produces more stable maintenance schedules and induces less maintenance ground time [46]. The objective was to prevent tasks from going due and ensure high fleet availability, schedule stability and efficient task interval utilisation. Mitici et al. [35] also developed data-driven RUL prognostics based on the increasing availability of condition-monitoring data for aircraft systems. The objective was to predict the optimal replacement time better. As a result, this approach led to a cost reduction of 53 % compared to the traditional maintenance strategy. Again, the main objectives are cost and minimising ground time from the maintenance provider's perspective.

Table 2.2: Maintenance planning objectives and whether they are from a maintenance, flight or service provider perspective. Second, if the maintenance focused on weekly minimum maintenance requirements or more on overall planning into large checks.

Source	**Year**	**Objective**	**WMMR**	**Maintenance provider**	**Flight provider**	**Service provider**
[9]	1977	Minimise flight hours lost			x	
[17]	1989	Minimise cost		x		
[20]	1996	Route AC to maintenance slot		x		
[16]	2000	Minimise cost		x		
[43]	2003	Minimise cost		x		
[40]	2006	Minimise cost		x		
[28]	2006	Minimise passenger disruption				x
[1]	2010	Maximise fleet availability			x	
[8]	2014	Maximise flying time utilisation			x	
[34]	2014	Minimise cost		x		
[23]	2017	Minimise TAT		x		
[48]	2018	Minimise TAT		x		
[14]	2020	Minimise flying hours waste			x	
[6]	2021	Minimise time between slots and due date		x		
[30]	2021	Minimise cost		x		
[46]	2023	Minimise maintenance ground time		x		
[35]	2023	Minimise cost		x		

Heuristics play an important role in maintenance planning due to the complexity

An overview of several maintenance planning methods is presented in Table 2.2. Various differences between the models can be observed. From 1977 to 2021, aircraft maintenance scheduling changed regarding planning horizon, objective, problem and solving technique. Because of the difficulty and complexity of the problem, heuristics played a considerable role in maintenance scheduling and is used for all maintenance routing problems to find the optimal solution. Only Deng et al. [14] and Andrade et al. [6] did not find optimal solutions based on heuristics. These sources are relatively new, thus concluding that heuristics are no longer required to determine the optimal solution. This means that the problem is either otherwise constructed or programming is more developed, and thus, it could handle the complexity of the problem.

Weekly maintenance requirements are overlooked

In the table, it can be seen that most papers do not consider the weekly maintenance requirements. This seems obnoxious because weekly maintenance requirements have a bigger impact on the flight schedule than a once every 3 months A-check. Gopalan and Talluri [20] is one of the only ones with the short focus of assigning the aircraft to a maintenance slot every three days. However, he does not dive into the actual requirements. It has to do with making optimal use of slots instead of determining what slots are necessary and how long they need to be.

Cost and profit main drivers of improving maintenance planning

It is clear from the literature that although differently described, all models are related to costs and profits. This means there is no focus on optimal aircraft health and safety. Maintenance is seen as a chore. Every paper mentions the 'Letter Checks' as the basic rule of thumb and thus does not explore different maintenance scheduling from an aircraft health perspective. Only Gopalan and Talluri [20] did not have profits as its primary objective.

Change from short to long-term maintenance planning

Another development is the change from a maintenance routing problem to a maintenance check scheduling problem. The most recent literature tackles the maintenance scheduling problem, while earlier literature tackles the maintenance routing problem. Except for Boere [9], the first discussed paper, who tackled the maintenance scheduling problem. As a result, papers [9], [14] and [6] all have longer-term scheduling horizons, while other authors described a relatively short-term horizon from 1 day up to 6 months. One possible explanation for this is the way that the aviation industry works. As mentioned in chapter 1, the aviation industry is highly competitive. Most airlines focus for this reason on short-term gains instead of longer-term solutions. However, airlines recently found it crucial for survival to look at long-term scheduling. This could be explained by COVID-19 causing such disruption that airlines reconsidered their long-term strategies because of future uncertainties regarding the return to aviation. Another explanation could be the complexity of long-term planning. In most early papers, heuristics played a considerable role in determining an optimal solution. Only in recent years, with new methods and technologies, it became easier to plan long-term maintenance.

Condition-based maintenance is relatively new to aircraft MRO

Another important point in those papers is the focus on scheduling preventive maintenance as efficiently as possible. Thus, it could be assumed that airlines are not ready yet to use new maintenance strategies such as predictive or condition-based maintenance. Even though condition-based maintenance was already mentioned in 1975, it is already in practice in other industries where fault diagnostics play a role, such as the Automotive industries, the process/manufacturing industry, and IT infrastructure [39].

Focus on performing maintenance at a single location

Lastly, it is noticed that most papers focus on maintenance by one maintenance provider instead of multiple. This differs from other industries where different providers perform maintenance at different locations. The focus on a single location is largely due to the complexity of performing maintenance at multiple locations, as these locations must be integrated into the maintenance program. Outsourcing maintenance to third parties can be costly, so most airlines prefer a single location and provider strategy.

Mostly traditional maintenance strategies

Thus, maintenance planning methods differ over time, and the vision of planning optimal maintenance has changed over the years. Airlines now use different techniques that apply to their needs best, and there is currently no preferred method. It depends on many variables, such as fleet size, fleet type, maintenance department size and skills. However, it is clear that all the papers discussed in this chapter were based on the current frame of aircraft maintenance, which is the letter checks. A scenario where maintenance providers use new technologies such as CBM, cooperation between airlines to improve maintenance performance and a phase-gate strategy to improve check performance has not yet been introduced.

2.3. State of the art in task clustering

After planning maintenance slots and checks, task designation for these checks and slots is next. There are thousands of components on a plane that require maintenance. With the advent of MSG-3, it became easier for airlines to build their own customised maintenance program [41]. In this program, specific task designations for aircraft maintenance are mentioned. This task designation is typically known as task clustering, where tasks are clustered into recurring maintenance slots. Clustering becomes very important because over a thousand maintenance tasks must be performed on an aircraft. It is known that task clustering can positively affect the maintenance operation. However, there are many different ways in which task clustering can be executed. Clustering, in general, is an umbrella term because it does not specify how it is clustered. There is not much literature on this subject because airlines want to keep this data private due to the competitiveness of the airline industry [49]. The clustering of maintenance tasks is seen as combinatorial optimisation. A combinatorial optimisation problem is a problem where there is an optimal solution to be found based on a combination of variables and constraints [32]. One famous example of a combinatorial optimisation problem is the Travelling Salesman Problem (TSP). The objective is to find the shortest route for a Travelling Salesman who starts from his home city, has to visit several cities and then returns to his home city. The main difficulty for this problem is the immense number of possibilities [29]. The same applies to the clustering of maintenance tasks. Many tasks have constraints and must fit within a specific maintenance slot.

Clustering is the process of grouping maintenance tasks into packages [37]

MUCHIRI and SMIT [37] mentions two approaches that can be used to cluster maintenance tasks: a Top-Down and a Bottom-Up approach. A Bottom-Up approach is where what maintenance is to be done is evaluated. Considering the MPD document, each maintenance task is first analysed individually to extract data. This data holds information about its interval, workforce and tool requirements for execution. The primary information considered is its maintenance interval. This interval is discussed in section 1.1. After the maintenance interval is considered, tasks requiring the same condition, procedure and cost are clustered in a maintenance package [37].

A Top-Down approach is where the aircraft utilisation (in Flight Hours and Flight Cycles) at an annual, weekly and daily level is analysed. Annual level data show seasonal patterns, while the weekly and daily levels do not reveal specific patterns [37]. The weekly and daily levels become more apparent when each weekday is considered individually. One reason is that planners do not focus on the utilisation per aircraft but on aircraft availability at any given moment. The allocation of maintenance slots follows the patterns found in this data. Fixed slots such as the A-check and C-check are allocated annually, while slots given ad-hoc are on a weekly and daily level [37].

Maintenance task packages and checks can be clustered into maintenance clusters by combining the two approaches. The clusters can be static (Base maintenance) or dynamic (line maintenance). Static clusters have fixed tasks assigned to them and are performed at fixed periods, while dynamic clusters may have more variable content performed more frequently [37].

Clustering is not only necessary to organise maintenance activities but also but it is also critical for reducing maintenance costs[32]. The maintenance costs for task clustering are often expressed in person-hours. One reason is that most tasks do not have an individual price regarding material fees, repair or replacement costs. Tasks have person-hours ascribed to them, which provide a solid indicator for maintenance costs, according to Muchiri and Smit [36]. Many models aim to reduce maintenance costs, which can be expressed in person-hours. However, person-hours are lost when completed 'too early' or 'too late' concerning the due date of the component. Sriskandarajah et al. [44] developed a genetic algorithm to schedule train maintenance optimally to reduce the loss of person-hours. He looked at a case study of the Hong Kong train system with a C0-check frequency every 2.5

years. The effect of doing the C0-check a month early was expressed in the loss of 7961 person-hours for the entire life span of the train. This loss could then be expressed in person-hours costs and extra downtime. In this downtime, the aeroplane cannot transport passengers and thus loses out on earning profits. Correctly clustering maintenance tasks has a massive impact on maintenance costs.

2.3.1. Literature

In 2009, MUCHIRI and SMIT [37] developed one of the first models to cluster maintenance tasks. The goal was to optimise maintenance during maintenance slots using a simulation model. It started by simulating the aircraft utilisation and calculating when a component turns due. After this, parts fit into a cluster and maintenance clusters were generated. In 2012, Hölzel et al. [24] developed an optimisation method for maintenance task packaging. He proposed a prognosis-based maintenance concept and developed a depth-first-search branch-and-bound algorithm to solve the combinatorial optimisation problem. The goal was to minimise aircraft maintenance downtime and cost. In 2015, Li et al. [32] introduced an improved Fuzzy C-means clustering model. This model's tasks are clustered in checks and executed as line maintenance. This comprehensive model considered many aspects such as RUL, work skill, Zone and Cost. However, as information about the maintenance task was limited, no optimal solution was gained. The data was limited due to the complexity. Later, in 2016, Li et al. [33] developed an Adaptive Genetic Algorithm based on cluster search. Clustering can be seen as an optimisation model, and GA is an efficient optimisation method. The first phase starts by sorting tasks based on their RUL and thus requires preventive maintenance all around the same time. In the second phase, an optimal maintenance interval is obtained within the sorted task packages, minimising the cost rate.

In 2017, Muchiri and Smit [36] came with an adaptation to his earlier clustering models focusing on line maintenance instead of base maintenance. The model aimed to group tasks into packages that can be executed at extended maintenance intervals, thus increasing aircraft availability. However, his definition of line maintenance differs from that of this research. He describes line maintenance as the maintenance done by the airline itself in a hangar, not by third-party contractors. The result was a slight decrease in maintenance costs for the Boeing 737NG. In 2018, Senturk and Ozkol [41] proposed a more flexible maintenance structure instead of the rigid 'letter checks'. In this structure, maintenance tasks were performed during periodic checks and whenever the aircraft was on the ground for any reason. The objective was to minimise the aircraft ground time, especially regarding maintenance and thus increase aircraft availability. This concept was enabled by the design of software that simulated aircraft ground time for different alternatives of the checking system for a horizon of 5 years.

In 2019, Witteman [49] developed a practical maintenance packaging model. He formulated Mixed-Integer Linear Programming with two stages to solve the task allocation problem. The first stage pre-determined the workforce to allocate daily to each aircraft under maintenance. In the second stage, the task allocation problem is solved by independently allocating tasks at the work shift level and per workforce skill for each aircraft. In 2021, Witteman et al. [50] formulates the task allocation problem as a time-constrained variable-sized bin packing problem. He proposed a constructive heuristic to solve this problem with an efficient iterative process based on the worst-fit decreasing. The article divided the planning horizon into variable-size bins for allocated tasks. These tasks were subject to available labour power and deadlines. The main goal was to decrease computation time and create a model to solve the allocation problem.

Task clustering method is overall treated as a combinatorial optimisation problem

An overview of several maintenance task clustering methods is presented in Table 2.3 and shows a variety of differences between methods. The first thing noted is the difference in the description of the problem. It is either an Allocation problem or a Combinatorial optimisation problem, while the allocation problem could be defined as a combinatorial optimisation problem. The only exception is given by Senturk and Ozkol [41], who treat it as a simple utilisation problem. Another issue is the year of publishing. While maintenance planning methods went back to 1977 [9], the task clustering problem is relatively young. This could be due to the complexity of the problem or that people did

Table 2.3: Task clustering methods

Name	Year	Objective	Person-hours	RUL	Zone	Cost	Work-skill	Priority
[37]	2009	Optimise execution during maintenance		x				
[24]	2012	Minimise downtime and cost				x		
[32]	2015	Decrease computation time	x	x	x	x		
[33]	2016	Minimise cost		x		x		
[36]	2017	Increase aircraft availability		x		x		
[41]	2018	Minimise downtime	x	x	x			
[49]	2019	Ensure airworthiness	x				x	
[50]	2021	Decrease computation time	x	x				

not see a reason to switch from manual task clustering to computational tools.

Due to the complexity of the combinatorial optimisation problem, some literature focuses on decreasing computational time

Significant differences can be found in the objectives of the articles. Two articles, namely Li et al. [32] and Witteman et al. [50], aim to decrease computation time for the task allocation problem. The reason that the two articles still have this as an objective is because of the complexity of the problem. As mentioned earlier in this section, the combinatorial optimisation problem is an NP-hard problem. In most cases, it is not even possible to solve. As for these two articles, they tried to treat it differently so it could be simplified and solved. However, they both had obstacles, and no optimal solutions were found. Thus, it could be assumed that it is not yet possible to efficiently cluster maintenance tasks entirely by using programming and simulation tools without the intervention of maintenance planners. Although the objectives were not met, they found improvements in task clustering, and it might be possible to solve this soon. There could also be found distinctions in the methods. These differences are because every article tries to tackle the same problem differently. Objectives differ from the up-time perspective to the downtime perspective to minimise cost. Thus, different methods are being used to solve them.

Tasking is sorted on RUL and/or cost

The way that tasks are sorted is, in most cases, similar, namely Remaining-Useful-Life and or cost. This seems the most logical because it is ideal that tasks are clustered in packages of tasks with the same RUL. It is not very cost-efficient if tasks are completed long before their RUL. Only Witteman [49] tried to cluster tasks differently, although the RUL was still held into consideration. He clustered tasks on work shifts and work skills because it would mean that maintenance slots are being used most efficiently. Hockers [23] made the distinction between above and under-the-wing maintenance. Under-the-wing maintenance included tasks such as engine, wings and wheels, and above-the-wing included tasks such as cabin repairs. Only two persons can perform checks in a cockpit, so it is good to sort tasks based on their compliance with other tasks because of these limitations.

Focus on clustering tasks into which check but not on how to perform tasks within check

The task clustering articles did not focus on efficiently performing the tasks during the check. Not all tasks can be performed at the same time. For example, only two workers could be in the cockpit during a maintenance check, while the cockpit could require 20 tasks. It is essential to schedule the maintenance tasks in a specific order to be performed during the check to decrease the Turn-Around-Time (TAT). van den Hoed [48] and Hockers [23] focus on organising tasks within a maintenance check or slot. Thus, a feeling is created that maintenance planning, task clustering, and task organisation are all separately solved problems while all being part of aircraft MRO. Aircraft MRO is a rigid process because after the first problem is solved, it becomes a constraint for the following problem. At the same time, there is limited feedback to rearrange the first problem based on the needs of the second or the third problem. Thus, for future efficiency of total aircraft MRO, it would be ideal to combine all these problems to find an optimal solution that optimises all difficulties instead of independent optimisation. However, due to the complexity of the issues, it is not yet possible.

Focus on clustering tasks into letter checks

Another thing that was noticed between the articles is how the maintenance checks and slots are organised. Most articles focus on task clustering with the already pre-determined 'letter checks'. This means that constraints were put in that there is an A-check every 2-3 months. The objective then was to cluster the task into this check. Only Hölzel et al. [24] and Senturk and Ozkol [41] also focus on how checks should be organised. They both developed a single task-orientated concept, while other articles have a multi-task-orientated concept. Using the single task-orientated concept, the maintenance schedule can look different from the commonly known 'letter checks'. However, like the other articles, Senturk and Ozkol [41] still focuses on preventive strategies. Only Hölzel et al. [24] considers a different maintenance strategy, which is not just based on preventive and corrective maintenance strategies but is a prognosed-based strategy.

2.4. Theories to improve the planning

After gaining background information about aircraft maintenance planning and task clustering, theories will be discussed to help improve the operations. Lean Six Sigma is one of the theories that can stimulate improvement. Lean Six Sigma is a powerful and widely adopted theory for process improvement and problem-solving in many industries. It is a hybrid approach combining Lean Manufacturing and Six Sigma theories. These two theories bring a distinct but complementary set of tools and methodologies. Lean Manufacturing focuses on eliminating waste and increasing value delivery to customers. on the other hand, Six Sigma focuses on reducing process variation and defects, leading to consistent, high-quality outputs. In the following sections, both of these theories will be explained.

2.4.1. Lean Manufacturing

Lean Manufacturing is an established theory. At its core, Lean manufacturing maximises value while minimising waste in all process aspects. The driving force behind this theory is efficiency, quality and continuous improvement. The elimination of waste and increasing customer value efficiency, quality and continuous improvement have been around for thousands of years. However, only in modern times does the term Lean manufacturing find its way into the literature. It is mostly associated with two major car production companies. The first time it came into practice was in the early 20th century in the United States by Henry Ford. He revolutionised the automobile industry by placing a moving assembly line into the factory. This changed the car industry from being high-skilled to a mass-production industry [51].

The next big evolution in Lean Manufacturing came from Japan. From the car manufacturer Toyota. They came up with what is now called "The Toyota Way, " which has now turned into Lean Manufacturing. Lean Manufacturing is centred around waste in the organisation. Waste can be defined as: "Any operation in a process which does not add value to the customer is considered waste" [22]. Thus, the goal is to identify and then eliminate waste. This leads to stable production with decreased cost, reduced time and increased quality.

Another major aspect of lean manufacturing is standardisation. Standardising operations leads to working more efficiently and a decrease in variability [12]. This standardisation can be performed in several ways, and categorisation is one of them. By categorisation certain aspects of the operation, there is a decrease in the variability. In this case, standardising the maintenance types and tasks based on priority efficiency can be increased.

2.4.2. Six Sigma

The second of the Lean Six Sigma theories is Six Sigma. At its core, Six Sigma wants to reduce variation and cost while trying to achieve continuous improvement [11]. It relies heavily on statistical tools and methods to achieve this. It finds its origin in the mid-1980s with a company called Motorola, and it employs a structured problem-solving approach called DMAIC, which stands for:

- Define

- Measure
- Analyse
- Improve
- Control

Six Sigma has been fully applied across various industries, including Aviation. Its structured and data-driven approach has enabled organisations to streamline processes, reduce waste, enhance product and service quality, and achieve significant cost savings. It does not focus on cutting costs by minimising certain aspects. It focuses on improvement and a better utilisation of the operation to stimulate an improved process.

2.4.3. Value stream map

One way to incite Lean Six Sigma in an organisation is to create a Value stream map. This is part of the Lean Manufacturing theory. It is a visual representation of the entire end-to-end process. VSM helps organisations analyse and improve their processes by identifying waste. Thus, the main goal of VSM is to create a detailed picture of the current state of the process. This is how the source of waste could be identified. VSM thus "facilitates the identification of the value-adding activities in a value stream and elimination of the non-value-adding activities" [45]. Thus, value-add and non-value add activities are found if a divide is made in the activities. The non-value add consists of two activities: Necessary non-value add and Unnecessary non-value add. This categorisation is shown in Figure 2.1. This is also known as a value contribution, where activities are analysed and assigned a value.

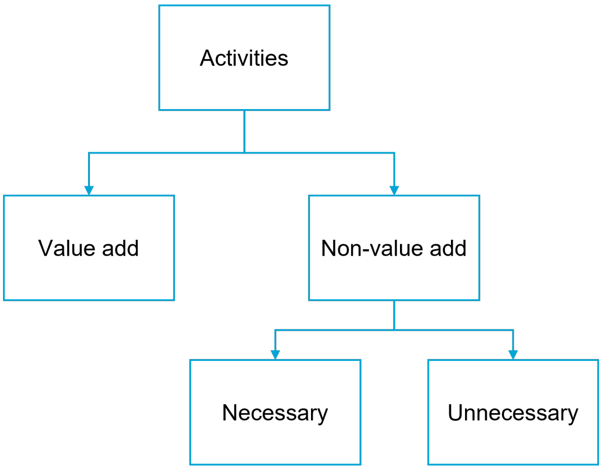

Figure 2.1: Value and Non-value added activities

After finding and performing the value contribution, three main tasks must be performed: optimising, minimising and eliminating. The value-add activities should be optimised, the necessary non-value add should be minimised, and the unnecessary non-value add should be eliminated. The value-add should be optimised because this brings the most value to the company and customer. How to optimise depends on what the core business is of the company. For example, for an airline, this is flying. If flying is optimised, most value is created for the company. Necessary non-value add are activities that must be performed but do not add value to the company. For example, for an airline, this is embarking. Embarking is necessary because passengers cannot board the plane without it. However, an aircraft is standing still and inactive during that time. That is why it is a non-value-added activity. Finally, there are unnecessary non-value-added activities. For example, the free time between disembarking and embarking, when an aircraft is standing still, and nothing is being performed on the aircraft. This free time should be either minimised, or it should be filled differently so that it becomes value-add. In chapter 4, the value contribution will be completed on the airline.

2.4.4. Operational excellence

Operational excellence is a valued business philosophy and approach to incite Lean into an organisation. It focuses on achieving the highest efficiency, effectiveness, and quality levels in an organisation's operations. It involves optimising processes, reducing waste, minimising errors, and consistently delivering value to customers and stakeholders. Operational excellence aims to create a culture of continuous improvement and innovation within the organisation. A key aspect is that the process is seen as an ongoing journey rather than a final destination [26]. However, measuring the improvement by setting certain goals first is crucial. This could be operational goals but also financial goals.

Operational excellence is an approach that is often used in the manufacturing industry. However, this approach is also applicable to aircraft maintenance. Achieving operational excellence requires organisations to assess their operational processes and employee management practices thoroughly. In certain instances, a willingness to transform the organisational culture becomes imperative. Embracing a culture of ongoing adaptability empowers companies to adopt methodologies and unlock subsequent advantages effectively.

Key benefits of operational excellence include Optimised workflows, standardised work and outcomes, accountability and employee empowerment. Standardised work and, outcomes and accountability are important in aviation. The more often a check is performed, the better the performance should become. By shifting towards a weekly maintenance program, the operational excellence of the maintenance operation can be improved.

2.4.5. Process stability

One of the key factors in operational excellence is setting KPIs. These KPIs could be used to measure improvement. One crucial KPI in the aviation industry is stability, which is difficult to measure. The use of a capacity analysis could measure the stability. This analysis is used to measure whether the company can execute the demands. When the process is being defined, the aim is to ensure reserved maintenance falls within the Upper and Lower Specification Limits (USL, LSL). Process Capability measures how consistently a process is within specifications. The idea of this is very simple. The operator desires a process centred over the nominal and spread narrower within the Upper and Lower Specification Limits.

One crucial factor in the process capability study is consistency. This consistency is expressed in C_p and C_{pk}. C_p indicates if the process is whether the process spread is narrower than the specification width. C_{pk} indicates the process's centring and the spread relative to the specification width. These tools can be used to test whether the process is stable. C_{pk} can be considered to be more crucial than C_p. This is because C_p only considers the spread while C_{pk} considers spread and location. This means it is easier for the operator to adjust the C_p than the C_{pk}. The aim should be first to acquire a high C_{pk} because this indicates the stability is more profound. If that is set, the C_p can be adjusted to match the requirements better.

Now that C_p and C_{pk} are known, the next step is to know how to calculate them. First, the Specification width has to be calculated. The spec width is a basic calculation of the Upper Spec Limit (USL) minus the Lower Spec Limit (LSL). Next comes the process width. The process is the difference between the maximum and minimum values. $C_p = Specwidth/Processwidth$. The equation for C_{pk} consists of the distance from the mean to nearest spec limit D_s and the distance from the mean to process edge D_p and is as follows:

$$C_{pk} = D_s/D_p \tag{2.1}$$

$$C_p = Specwidth/Processwidth \tag{2.2}$$

The following analogy explains the C_p and C_{pk}. Imagine a pilot trying to park a plane in a hangar. If the plane is too wide, it won't fit. If it's narrower than the hangar opening but not centred, it won't make it in and will likely hit/scrape one of the sides. Hitting one of the sides of the hangar is equivalent to not reserving enough maintenance or too much maintenance. But if the plane is narrow enough and well-centred, the plane will fit. The aim is to have a narrow and well-centred process width relative to the spec limits.

2.5. Literature gap

After discussing the literature, the four questions at the start of the chapter can be answered. 1) What does traditional aircraft maintenance look like? Traditional aircraft maintenance evolved around large hangar checks called 'letter checks'. Over time, letter checks decreased to fit the airline's planning better. These rigid letter checks simplify maintenance planning due to consistency and length.

2) What is the state of the art in maintenance planning? First, the literature around maintenance planning is still focused on traditional maintenance checks and does not dive into weekly maintenance requirements. Secondly, maintenance planning has been developed solely from the maintenance provider's perspective. Hardly any literature tries to fit maintenance planning into the overall airline planning. Thus, a gap identified is maintenance planning from a holistic airline perspective that considers all crucial stakeholders in planning.

3)What is the state of the art in task clustering? It is found that most tasks are clustered on their RUL or due date. However, what is noticed is that most checks do not consider time availability constraints, which means the vision is relatively short-term. It is focused on a single check and clustering the tasks as best as possible. No prioritisation is provided related to the airworthiness of tasks in case of time shortages. Providing this prioritisation can help maintenance providers make choices when ground time is scarce, and choices have to be made.

4) What are theories that could be used to improve the planning? The main theories are around Lean Six Sigma. Lean Six Sigma is a powerful and widely adopted theory for process improvement and problem-solving in many industries. Many theories fit within the real of Lean Six Sigma, these are value stream mapping, operational excellence and process stability. These tools provide handles for grasping the operations. They allow waste identification, measure current performances, and stimulate improvement.

3

Current state of processes at KLM E&M

This chapter focuses on the current state of processes at KLM. Below, some questions are listed that will be answered in this chapter.

- What is the current state of processes at KLM?
- What are the stakeholders in planning?
- How do the stakeholders cooperate?
- How can the planning improve?

3.1. Current state of processes

Before improvement is possible, the current state of processes is examined. The first crucial step in understanding the current state is identifying the stakeholders. KLM has four main stakeholders: Fleet services (FS), KLM E&M, Network and the Operation Control Centre (OCC). These stakeholders' names are adjusted for a generalised current state assessment. They are all providers somehow: FS is a plane provider, KLM E&M is a maintenance provider, Network is a flight provider, and the OCC is a service provider. These four providers form the core of the airlines' operation. However, they all have different objectives and definitions. These differences can cause a lot of waste in the organisation. Thus, identifying the waste and the difference is crucial in working towards a combined objective and balance between the providers. The providers all have their input in the airline's operation, which will be highlighted in the following sections. The plane provider is not considered because this research focuses on airline planning. The plane provider owns the planes and lends the planes to the flight provider for flights and hires the maintenance provider for maintenance. The plane provider has desires and requirements on how much maintenance is required and which activities must be performed, such as painting the plane. However, because they are not involved in airline planning, they are left out of the scope of this research. So they remain one of the critical stakeholders of the airline, but they do not function in the planning triangle shown in Figure 3.1.

These stakeholders' inputs come together in the MFT (Maintenance, Flight and Turn time) plate called the MFT. An example of the MFT is shown in Figure 3.2. The aircraft types and registrations are seen in the MFT in the left column. The dates can be found from left to right, and the individual planning for that registration is in each row. This planning includes maintenance, flights and turn time, thus being called the MFT plate. This is the overall planning of the airline, and every stakeholder has their individual input.

The MFT plate is built so there are time slots and time between slots. These slots could be two things: either a flight slot or a maintenance slot. A flight slot has a code for the destination of the flight. If it has one code, the flight slot includes the round trip. If the flight has a code with multiple abbreviations, it also has multiple destinations. For example, the aircraft goes to Bahrain first, and

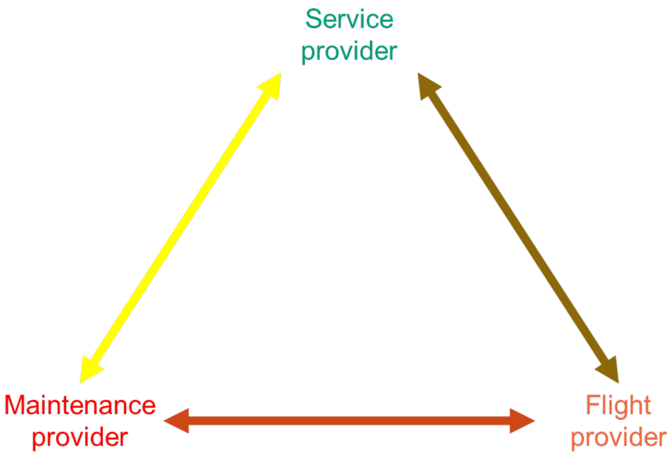

Figure 3.1: The planning triangle. The airline has four main providers: Plane, maintenance, flight and service. However, only three of them are involved in planning, and together, they form the core of the operation of the airline

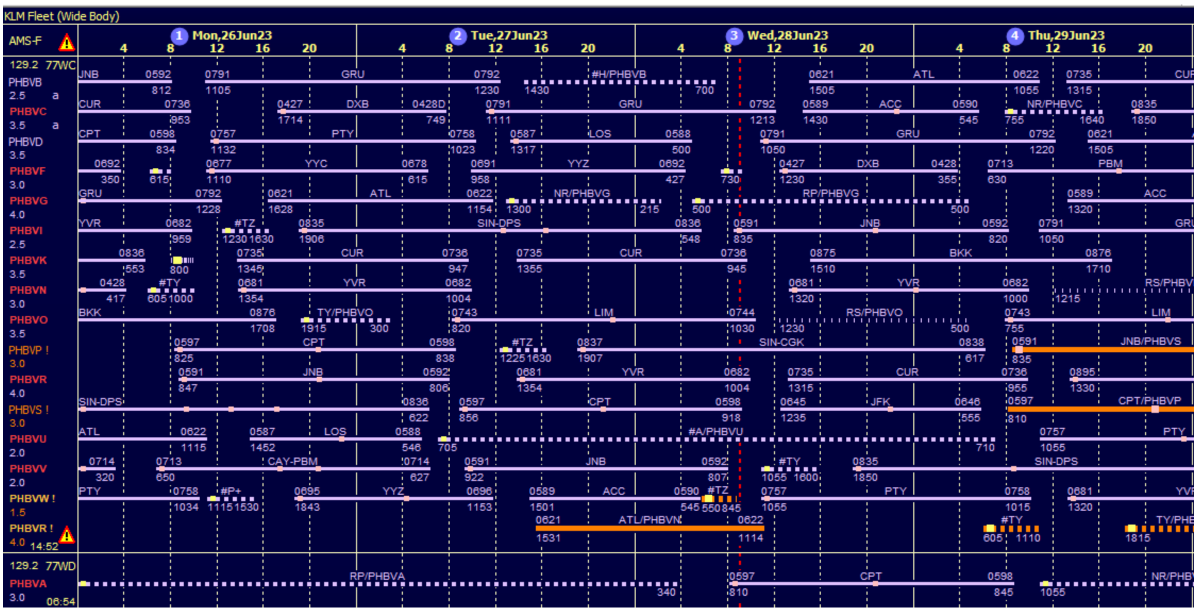

Figure 3.2: An image of the MFT (Maintenance, Flight and Turn time) plate of a single week, with the different plane registrations, is shown in the first column. The further columns represent the days of the week, with flights and maintenance as the bars according to length. The MFT plate shows the overall airline planning.

from Bahrain, it goes to Muscat, Oman. The maintenance slots could also have multiple different codes depending on the maintenance slot type. There could be more than 40 different maintenance slot types.

An aircraft is either in a flight or in maintenance slots. However, the time between these slots is called the turn time or free fleet space. The total planning of maintenance, flights, and turn time is a cooperation between the stakeholders, which will be identified in the next section.

3.2. The Stakeholders

This section will highlight the stakeholders in planning.

Maintenance provider is in charge of ensuring the aircraft is airworthy and safe

KLM E&M is the maintenance provider for KLM, and the task of the maintenance provider is to execute maintenance on the aircraft and ensure it remains airworthy. Maintenance providers must comply with the rules set in part 145 by the flying authorities. These rules and regulations set when and how each maintenance task should be performed. Each maintenance task has its due date, and the job of the maintenance provider is to plan enough ground time for maintenance so that it can perform all maintenance tasks. It also determines how much extra ground time for maintenance should be reserved in case of unplanned/corrective maintenance work. The maintenance provider gets the plane provider's objective to ensure the aircraft's airworthiness and safety. If not enough maintenance is planned and performed, it reduces safety, airworthiness and reliability.

Safety is the main focus of the maintenance provider because safety is critical for the airline's survival. Accidents are quickly fatal in the aviation industry; thus, fatal accidents and breakdowns should be avoided. Therefore, it is essential to reserve sufficient time for maintenance activities. This ground time for maintenance is considered downtime. Because when maintenance is being performed, it can not fly passengers or cargo and thus does not bring profit to the airline. That is why maintenance focuses on decreasing the downtime of an aircraft. This downtime can be reduced by improving maintenance planning, task clustering or task order execution.

One of the goals of the maintenance provider is to plan as much maintenance as possible. However, in aircraft maintenance, there are a lot of maintenance tasks which can not be foreseen. Thus, even though the maintenance provider wants a preventive maintenance strategy, corrective maintenance is required. The goal of the maintenance provider is to plan as much preventive maintenance as possible.

- Job: Perform maintenance
- Objective: Ensure airworthiness and safety
- Reason: Safety is critical to prevent accidents and unwanted breakdowns
- Focus: Minimising downtime

Service provider is in charge of ensuring the airline's operation is stable

The KLM OCC is the service provider for KLM. The task is to execute the operation and make sure the operation is feasible. It is in charge of the airline planning 10 days in advance. This allows them to shuffle with the aircraft assignment to flights and maintenance. The feasibility of the operation depends on the time buffers between flights and the balance between flights and maintenance. If the buffer is too small, flights must be cancelled or delayed. An imbalance in the harmony between flights and maintenance also leads to extra disturbances in the operation, thus affecting stability. One of the reasons for aiming for a stable operation is customer experience, and another is high cost due to cancellations and delays. Delays and cancellations cause high costs, can significantly impact the experience, and should be minimised. The minimisation of disturbances to the operation can be achieved by finding a balance between flights and maintenance.

- Job: Making sure operations are feasible
- Objective: Ensuring stable operations
- Reason: Stable operations are crucial in ensuring customer satisfaction and low cost due to the depletion of delays and cancellations

- Focus: Balance between flights and maintenance and checking feasibility

Flight provider is in charge of ensuring profits

The KLM Network is the flight provider for KLM. Their task is to select flight destinations and connecting flights. The aim of this is to choose profitable destinations. These are primarily popular destinations which attract many customers. Another task is to make the overall planning based on the inputs of the other providers. The provider's inputs are their wishes to ensure they complete their objectives. Making flights is the core business of an airline. Flights are the way profits are earned. Thus, many airlines focus on maximising the uptime of flights. The flight provider urges the maintenance provider not to plan too much downtime for maintenance. More profits can be earned if this additional downtime is transformed into uptime. Thus, the flight provider urges the other providers to minimise the downtime to maximise uptime.

- Job: Select destinations and connections and make overall planning
- Objective: Ensure that there is flying
- Reason: Flights are core business and ensure profits for the airline
- Focus: Maximising uptime

These three providers form the core of KLM and its operations. Thus, these providers must work together to allow the airline to operate as best as possible. However, a misalignment can be found between them regarding objectives and orientation. This misalignment causes waste in the organisation and should be cleared.

3.3. The cooperation between the stakeholders

Although the stakeholders have different objectives and focus, they are all part of the same company and thus also have to work together. In the next couple of sections, these cooperations will be described.

The service and flight providers work together on flying as much as possible while maintaining stability

The service and flight provider have to work together on several issues. Their objectives are to ensure that there are flying and stable operations. They are both in charge of planning. However, the service provider works only short-term while the flight provider works long-term. Thus 10 days before the execution of the planning, the planning is transferred from the flight to the service provider. The combined objective is to fly as much as possible while maintaining a certain level of stability. This stability can be obtained by planes that arrive and depart on time. More flying is allowed at the expense of stable operations when it seems profitable; however, it is not always preferred. Thus, these two providers seek a balance between as many flights as possible against maintaining stability.

The maintenance and service provider work together on safety and customer service

Also, the maintenance and service providers have to work together. Their objectives are to ensure airworthiness safety and stable operations. As mentioned, the service provider is more costumer-orientated than the other providers. The maintenance provider plays a significant role in that. There are differences between budget airlines and more high-end airlines. In most cases, a high-end airline is more willing to execute maintenance, specifically cabin maintenance, than a budget airline. This maintenance is important for customer experience, and the service provider is willing to provide enough time for maintenance on the aircraft. Also, safety plays a huge role, especially in the aviation industry, where safety is a top priority. The service provider is only willing to send out an aircraft when it is safe; thus, it depends on the maintenance provider. The combined objective of the maintenance and service provider is to ensure all aircraft in operation are safe and the quality is high to provide the best service to the customer.

The flight and maintenance provider wants to find the right balance between flights and maintenance

The flight and maintenance providers are always a bit of each other's opposites. Flight is labelled uptime, and maintenance is labelled downtime to be each other's opposite. This means that one always comes at the cost of the other. Thus, their combined objective is to find the right balance between uptime and downtime. Both maintenance and flights are an essential part of the airline's operation. Although there is a general understanding that more flights are more profitable than more maintenance, finding the right balance can sometimes lead to friction. This balance also has to be found for corrective vs. preventive maintenance. Where the maintenance provider prefers preventive, the flight provider can prefer corrective. Because preventive does not always mean it is absolutely necessary, and corrective is. Thus, the flight provider feels it is reserving time for maintenance even that could be used for flights. This is where the two providers collide. This is because maintenance can not be executed during flying time or vice versa. This correlation is shown in Figure 3.3. It can be seen that there is a clear correlation between flights and maintenance.

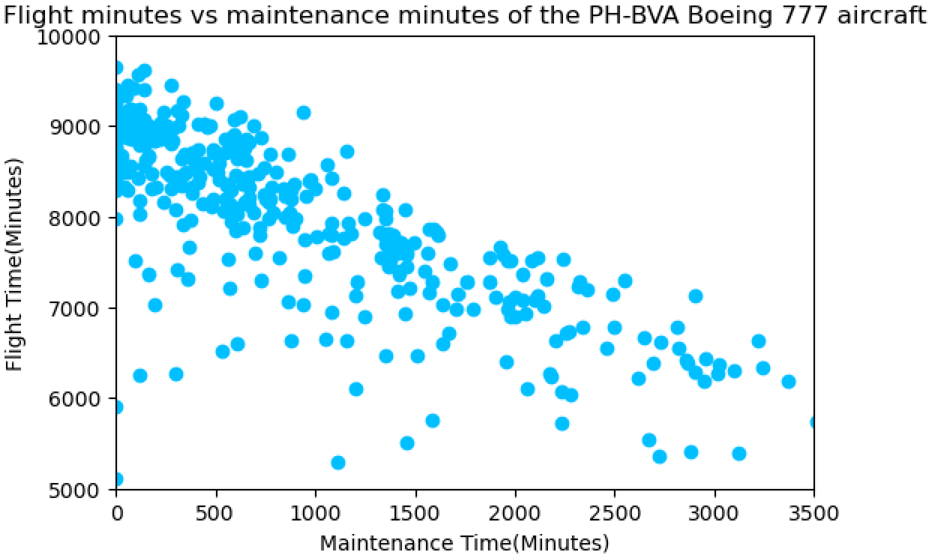

Figure 3.3: It shows the balance between flights and maintenance. On almost all occasions, much flying is paired with little maintenance and the other way around. This leads to a correlation between them spread from top left (much flying, little maintenance to bottom right (little flying, much maintenance)

3.4. Waste in the planning

When making the MFT, the providers' inputs and constraints are considered. This means that constraints bind the MFT. These constraints mostly come from the service and maintenance provider, and the flight provider has to plan optimally with these constraints in mind.

Minimum turn time is set by the service provider

The service provider requires enough time between slots to handle disturbances and do all tasks required during turn time. Thus, a time is set between flights and maintenance slots so it can maintain stable operations. This minimum required turn time differs per aircraft type. Different activities are completed in the turn time. However, these activities do not find their way back into the MFT. This leads to waste in the organisation because it is unclear what could be and couldn't be done in the turn time. In Figure 3.4, the turn time between flights can be seen. However, this looks like a black box, and what can be done in the turn time is unclear. It looks like there is much time to, for example, execute maintenance. However, in reality, the turn time is already booked.

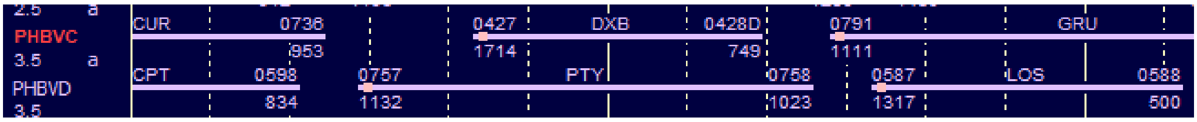

Figure 3.4: Example of the turn time between flights in the MFT plate. The activities that occur in this time are not displayed in the MFT plate, which means it can be interpreted differently

The turn time starts when the aircraft arrives at the gate, and disembarking can begin. Disembarking does not show in the MFT plate, even though it costs time. So, certain maintenance tasks can not be executed in that time. Also, it does not mean that the aircraft is available. However, in the current definition of fleet availability, KLM holds it as when the aircraft is available. Fleet availability is an important KPI for an airline, and it tells how much the fleet is available for flights. At KLM, the fleet availability includes flying time and turn time.

After disembarking, it is usually time to start the embarking. This means the aircraft is not truly available for maintenance activities. So, fleet availability does not mean availability for maintenance. Some tasks are performed during the embarking and disembarking times, including pre- and post-flight checks. The service provider sets the time for how much is required for the disembarking and the embarking and, thus, how much is required for the total turn time.

This turn time is also important between flights and between a flight and maintenance slot. In the turn time between flight and maintenance, different activities apply. Maintenance can be executed at the platform, which means close to the gate and in the hangar. To both of these locations, an aircraft needs to be towed. Towing to the platform can take up to 30 minutes while towing to the hangar can take up to 60 minutes. These activities also are not shown in the MFT plate, although the aircraft is unavailable during this time. In Figure 3.5, a part of the MFT plate is shown where there is a hangar check after a flight. It looks like the time there is available, while it is not.

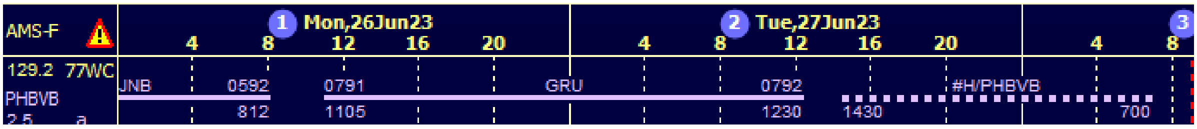

Figure 3.5: Example of the MFT plate where maintenance is located. Activities such as disembarking, embarking and towing are not shown in this plate

That means several activities fall into the turn time, which are not categorised or shown in the MFT plate. It is crucial to have this envisioned to prevent problems and misunderstandings about what can be done in this turn time. These activities pre-set times in minutes are Combi-embarking, disembarking, embarking, towing hangar and platform. The time left within the turn time is free time that could be used for maintenance or other activities. In Table 3.1, a list of the activities that already have a pre-set time can be seen. Also, it can be seen that there is a difference between the sum of disembarking and embarking compared to the Combi-embarking. The reason for this is that some of the activities within disembarking are similar to embarking, and thus, it can be done within less time.

Maintenance requirements set by the maintenance provider

The maintenance provider has more constraints when it comes to planning. There are many different types of maintenance with different requirements. These requirements differ in time requirements and frequency. It thus becomes a difficult question as to what the ground time requirements are for maintenance. Some maintenance codes are easier to plan; one example is the aircraft A-check and C-check because it has a constant and low frequency. However, there are also a lot of other tasks that

Table 3.1: Activities that could be within the turn time per aircraft type in minutes

activities/aircraft type	777-200	777-300	787-100	787-900	A330
Combi-embarking	130	130	120	120	120
Disembarking	50	45	45	45	45
Embarking	95	90	85	85	85
Towing hangar	60	60	60	60	60
Towing platform	15	15	15	15	15

have to be performed that have a frequency other than these larger checks.

The routine tasks that have a constant frequency and could be planned are not the only maintenance tasks because there are also a lot of non-routine tasks. Non-routine tasks are defects or other tasks that are found during inspections. All of these tasks have to be planned away in maintenance slots. Otherwise, flights have to be cancelled or delayed. However, reserving a lot of time for maintenance activities is tricky because it is at the expense of extra flights and, thus, uptime.

The maintenance provider asks for sufficient weekly ground time to handle the disturbances. The extra time that the maintenance provider requests is called TO-ruimte or Technical maintenance space for KLM. This term will be defined as WMMR or weekly minimum maintenance requirement for better understanding. For Airbus A330, the required amount of WMMR is determined based on the number of turnarounds at Amsterdam. The number of turnarounds is converted to several WMMR slots with a specific length. There are three length types: > 21:50, 9:50-21:50 and 3:50-9:50. The Boeing WB fleet has a different rule. Here, the total WMMR reserved is 2x 168 hours, two full maintenance lines for WMMR, which comes to 336 hours of WMMR per week. This number, however, has not changed in a decade, even though the fleet size and content have evolved over time. This seems to be an outdated rule. This rule of the Boeing fleet is displayed in Figure 3.6.

> **"336 hours of WMMR per week has remained unchanged for more than 20 years, even though fleet size and content have changed."**

There is also a misunderstanding regarding what maintenance should be performed in the WMMR slots. This misunderstanding is generally between the maintenance and flight provider. This misunderstanding is shown in Table 3.2. Here, the different providers think about what WMMR is destined for. It can be seen that the flight provider put more maintenance slot types into the WMMR slots than the maintenance provider. This misunderstanding leads to the underperformance of the maintenance provider from a fight provider perspective.

Table 3.2: Misunderstanding of what WMMR is destined for

Providers/Slots	P+	H	TD	TY	TZ	NR	WK	AG	RP	E
Maintenance provider	x	x	x	x	x	x	x			
Flight provider	x	x	x	x	x	x	x	x	x	x

Since 2021, KLM has developed a different structure to replace the former WMMR slots. This was part of the fleet health pilot, where they replaced the WMMR slots with R-checks. R-checks is an idea from Delta Airlines, where an aircraft comes in for maintenance every week. These R-checks have three different lengths: 4, 5 and 9 hours. These R-check slot codes are called TZ and TY and have solved some of the misunderstandings between the providers. However, according to the flight provider, these R-checks are neither ideal. It depends on which KPI is the focus for scoring the performance. The R-checks changed how the maintenance provider measured their performance because the main KPI became fleet health. Fleet health is a KPI in which an aircraft's health is presented as the number of days the first task is due.

As mentioned earlier, most tasks have an interval and thus have a due date before which they have to be completed. The goal was to strive for fleet health between 10 and 14 days. Health between 10

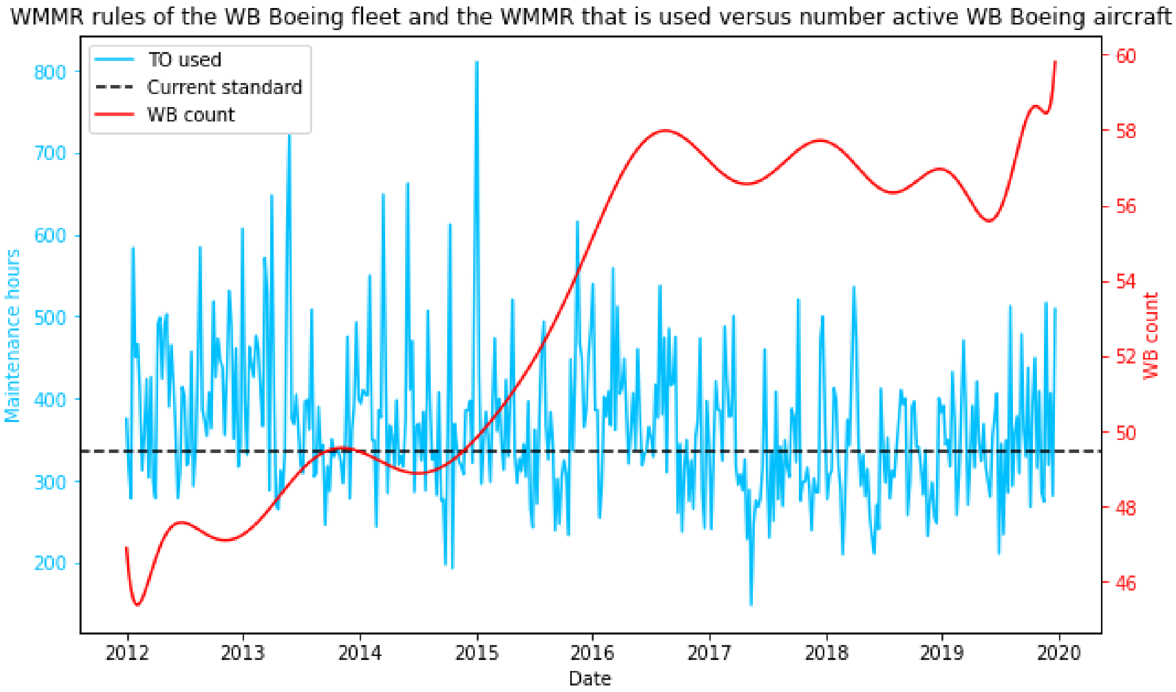

Figure 3.6: WMMR rules of the WB Boeing fleet and the WWMR that is used versus the number of active WB Boeing aircraft

and 14 days means no task is due in the next 10-14 days after completing the last R-check. Based on that information, it is possible to conclude that the aircraft does not need to come in for maintenance in the next 10-14 days, depending on the health. However, there are a few snags when it comes to this conclusion. Aircraft maintenance is very unpredictable. sometimes, an aircraft could fly four weeks straight without any major breakdowns, but other times, it only takes three days. The same is true for the fleet health. When an aircraft is delivered 'clean' with a fleet health of 12 at the end of an R-check, it does not mean it won't have to come in for maintenance in the next 12 days. That is one of the flaws of the R-check. The flight provider agrees with this insight. According to the flight provider, too much time is now reserved for maintenance, which could be spent flying. Thus assuring the airline could still perform with less time reserved. The flight provider does not prefer the term reserved ground time for maintenance. Because it can signify that more is reserved than required. It is crucial to understand how much ground time is required for maintenance and which maintenance. However, the flight provider does not have answers to the question of how much maintenance should then be performed.

3.5. Conclusion

In this chapter, the current state of the airline is detailed with the help of five sub-questions raised at the beginning. 1) What is the current state of processes at KLM? KLM is an airline that has multiple stakeholders who focus on different aspects of the airline. These four stakeholders are the plane, maintenance, service and flight provider. The stakeholders' inputs come together in the Maintenance, flight and turn time (MFT) plate, the final output of the airline's operations.

2) Who are the stakeholders in planning? Out of the four main stakeholders, three are involved in planning. These stakeholders are the flight, maintenance and service providers. The maintenance provider has to maintain the aircraft and has airworthiness and safety as its objectives. The service provider has to ensure the operations are feasible and stable. The Flight provider has to aim to fly, select its destinations, and create a flight planning that maximises aircraft utilisation.

3) How do the stakeholders cooperate? These three stakeholders have different jobs but also different objectives. This can cause friction at times when the objectives are not aligned. These three stakeholders have a relationship that looks like a triangle, where they communicate individually but not all together. The service and maintenance providers work together on safety and customer experience. The service and flight provider work together on flying and stability. The maintenance and flight providers work together on maximising uptime versus minimising downtime.

4) How can the planning improve? The planning can improve by setting definitions for currently unclear subjects such as weekly minimum maintenance requirements and time availability in the turn time. A Lean categorisation and definition can get rid of these misalignments.

4

Model Design

In this chapter, the design of the model will be central. Some of the questions that will be answered in this chapter are listed below.

- How would a model look that could value balance from an integral airline perspective?
- Can the maintenance be categorised?
- Can waste in turn time be identified and categorised

4.1. The Cyrus model

After analysing the current state of the airline's operations, it has become evident that there are significant issues that need to be addressed. The airline's organisational structure is fragmented, with communication occurring within isolated silos rather than effectively across the entire airline. Each stakeholder focuses on its own aspect of airline planning: flight, maintenance or service planning. Planning consists of scheduling maintenance and flight slots into the aircraft schedule. Service planning ensures enough time between the slots to perform the necessary tasks, such as inspections and embarking procedures. However, because each stakeholder focuses on its individual part of the planning, there is fragmentation in the organisation. To overcome this fragmentation and enhance operational efficiency, it is essential to introduce an integrated airline planning model that synchronises the different plannings intending to set a balance between flying and maintenance.

The proposed model takes a comprehensive approach by considering inputs from all stakeholders to conduct a holistic assessment of airline planning. It accommodates each stakeholder's unique needs and constraints while proposing a future state of planning that harmonises these perspectives. The model redefines stakeholder inputs, introducing new, standardised definitions that create an equilibrium between maintenance, flight and service planning. This equilibrium is established by setting the Weekly Minimum Maintenance Requirements (WMMR), rooted in the redefined prioritisation of maintenance tasks and types. The airline's capacity to effectively manage its weekly maintenance requirements is improved, reducing its vulnerability to unforeseen maintenance disruptions. By factoring in the inputs from all stakeholders, this approach achieves equilibrium between uptime and downtime.

The equilibrium between uptime and downtime is analogous to the balance between flight operations and maintenance. This balance is illustrated in the 'Cyrus Balance Zone' (as previously discussed in the example of Icarus), where the pursuit of flights corresponds to the sun, and excessive maintenance mirrors the sea. The area between them represents the balance zone, characterised by the presence of adequate maintenance and flights.

The aim of the model is to find the equilibrium presented by the silver plane in 4.1. The current equilibrium, as shown in Figure 4.1 by the red plane, favours the flight provider, with more emphasis on flying over maintenance, leading to excessive flying. The Blue plane represents an equilibrium favouring the maintenance provider, leading to excessive maintenance. The key importance is that the model considers all the stakeholders instead of only one so that the equilibrium between excessive flying and excessive maintenance can be established. In striking such a balance, uptime is assumed to increase.

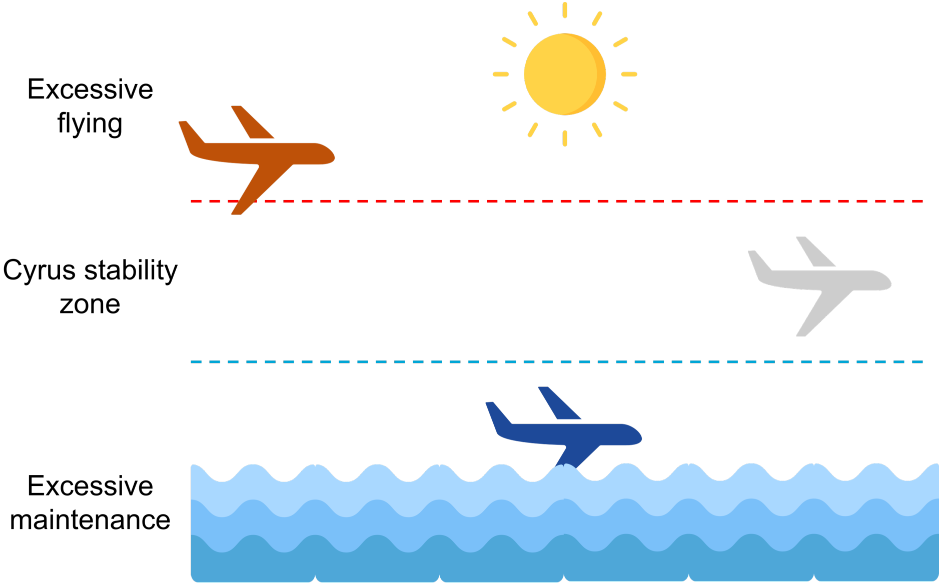

Figure 4.1: The Cyrus model tries to create a balance between uptime and downtime or between flights and maintenance

The model required to achieve balance and stability is named the Cyrus model because it wants to provide a holistic view of the ground time and the maintenance requirements. The Cyrus model is a centralised model that serves as a link between all the stakeholders; thus, it connects the separate silos. The proposed model is centralised because, currently, the decentralised state does not function optimally. This has to do with the fact that every stakeholder considers its interests a top priority, which leads to friction with the other stakeholders.

> **The Cyrus model is a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between flights and maintenance. This equilibrium enhances the airline's capacity to manage maintenance efficiently and should ensure greater uptime.**

Because it is a centralised model and provides a holistic airline perspective, it is named after Cyrus the Great, the first king of kings of the Achaemenid Empire. In this empire, there were many different kings who all acted in their interests and had different objectives. Cyrus the Great was the only one who saw the bigger picture; thus, from an empire perspective instead of a kingdom perspective. This centralised power with a holistic perspective allowed him to make better decisions. At the airline, there are also different kings or now-called stakeholders. They are the Maintenance, flight and service providers. This model tries to centralise the providers' insights together, as Cyrus did in the 6th century BC in Persia. This cooperation is depicted in Figure 4.2 where the Cyrus model stands at the centre of the airline operation.

The Cyrus integrates two models: a data model and a planning model. The data model consists of taking the stakeholder's inputs and combining and categorising the data, after which the data can be analysed. The next model is the planning model, where the data analysis outputs are combined to create a future state planning framework. The two main models are highlighted in Figure 4.3. The Cyrus model aims to acquire a balance between maintenance and flights; from that balance, it wants to increase the uptime.

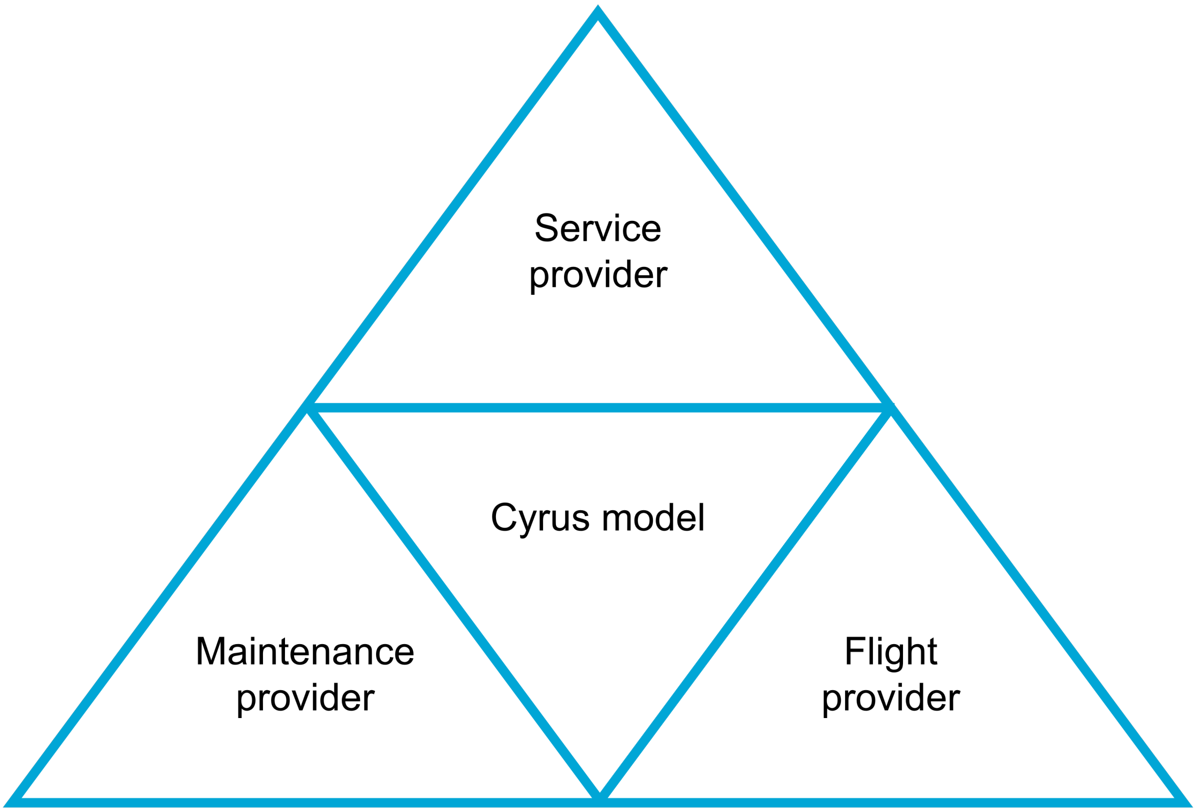

Figure 4.2: The provider's cooperation in the triangle and at the centre of the Cyrus model.

Making the data readable and combining the inputs of the providers

Stage one of the data model is to make the data readable and combine the inputs of the providers. The steps in this stage are highlighted in Figure 4.4. Data is extracted from the MFT plates, including all the flight, maintenance and fleet count info. In Figure 3.2, an MFT plate of a couple of days is shown. In this model, it was required to make data readable because it is not possible to read the MFT plates directly. This is because the MFT plates are imported as FLS files. These files are converted into TXT files because the model cannot read FLS files.

These TXT files are read in date order by model. However, because the FLS files are, for example, named "Cvp 08 Mar a", the model cannot read them in the correct order. Also, multiple years are analysed; thus, multiple '08 Mar' can be present. To prevent this problem, the names must be changed to the exact date. Which in this case is '2013-03-08 a'. This had to be done by hand and was a very time-consuming process, especially because there were over 575 FLS files to be converted to TXT files.

The TXT files contain data for a total of three weeks. This is for one week anteriorly and two weeks in advance. This allows that differences between the time planned and executed can be distinguished. This means that, in total, there are 52 TXT files per year if looking anteriorly. Available data ranges between 2009 and mid-2023. The next step is to convert the TXT to Excel files. The Excel files consist of three sheets: fleet count, flights, and maintenance. Each TXT file converts to one Excel file. These are essential because combined. They provide the complete behaviour of aircraft registration, type and count. In the following sections, these inputs will be expanded further.

The three Excel sheets also represent the different providers. Flights are the primary input of the flight provider, maintenance of the maintenance provider, turn time of the service provider and the fleet count of the plane provider.

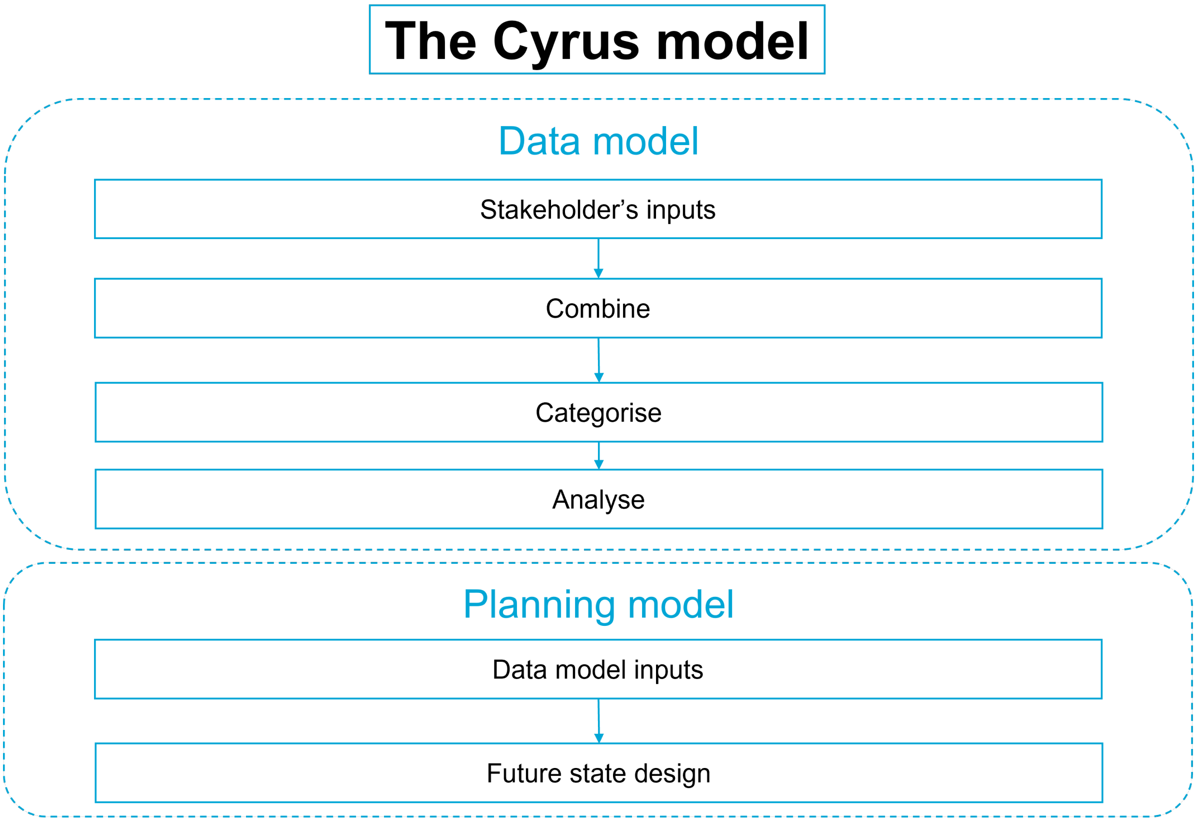

Figure 4.3: Cyrus model

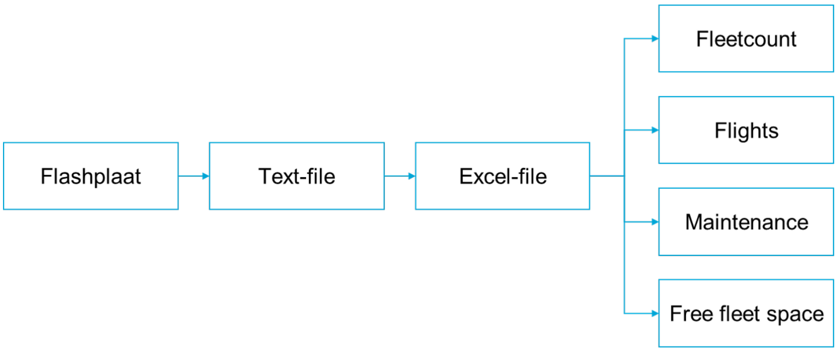

Figure 4.4: Stage one of the Cyrus model consists of taking the stakeholders inputs and combining them

4.1.1. Data inputs

This section highlights the data inputs for determining the ground time requirements. The four data inputs are fleet count, flights, maintenance and turn time.

Flights

The first retrieved data is flights, which is the flight provider's primary input into the MFT plate. The data that is being retrieved is all the flights that each registration makes. Each row in the file is one single flight, such as, for example, Amsterdam-Medellin. In another row, the return flight Medellin-Amsterdam is located. Each row has the time and date of departure and arrival. The difference between these values is calculated to provide the total flying time. This process is shown in Figure 4.5. This number is presented in minutes because it is the smallest and most detailed possible. Thus, a data frame is retrieved with all the flights with flying time. Other information that is present is the aircraft type and registration. Therefore, a single aircraft could be tracked. This allows differences between registration and types to be identified. It is also a necessary input for determining the turn time because it reads single registrations. For the flight data, it is assumed that all the registrations, types and flying times are correct.

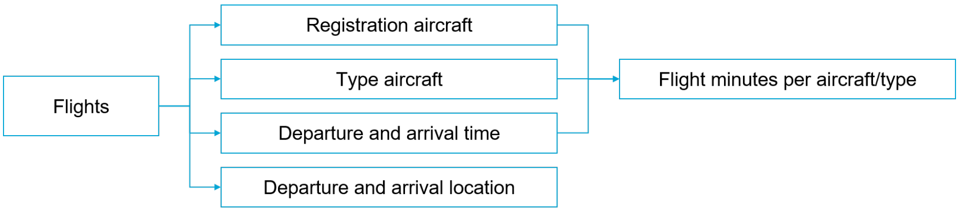

Figure 4.5: Data retrieved from flights

Maintenance

The second retrieved data is maintenance, which is the maintenance provider's primary input into the MFT plate. When looking anteriorly, The data is read the registration, type, maintenance code, and start and end time. This data can retrieve what kind of maintenance was executed per aircraft, per type, and how much. The difference between the start and end date is the total slot time. However, as explained later, the slot time differs from the adequate maintenance time. As for flights, it is the number of how much maintenance executed presented in minutes.

Thus, per registration and type, it can be shown how much maintenance was required in the past and how these maintenance slots were distributed. This process is shown in Figure 4.6. It is also possible to look at the planned maintenance in advance. However, this data is not yet put on registration and thus is not complete. It can be shown for when the maintenance is reserved and how much. For the maintenance data, it is also assumed that all the registrations, types, maintenance times and maintenance codes assigned to the slots are correct.

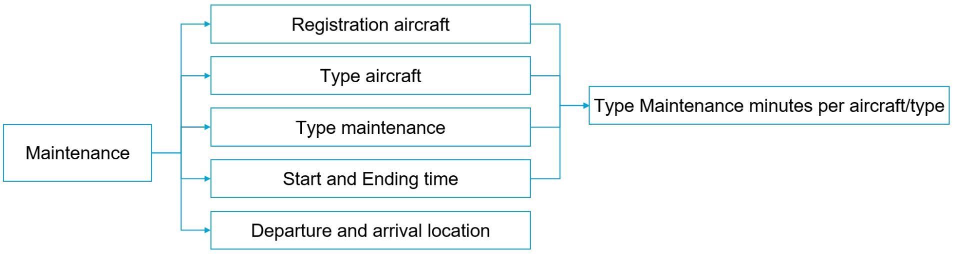

Figure 4.6: Data retrieved from maintenance

Turn time

The third retrieved data is the turn time, which is the service provider's primary input into the MFT plate. This data comes from a combination of the flight and maintenance data, and it wants to know the time between the slots. It is chosen only to select the turn time at the home airport of Amsterdam. This is because the goal is to assess how much of its ground time could be used for maintenance. Time spent abroad on the ground is deemed unusable in this research.

It was possible to retrieve this data because the flight and maintenance data has the departure and arrival airport codes. Therefore, it calculated the time difference between the slots and only selected the slots where the arrival airport was Amsterdam, and the departure code was also Amsterdam. This process is shown in Figure 4.7. The next step of interest was to calculate the effective free time of the aircraft. This process is shown in Figure 4.8. With the help of the activities shown in the previous chapter, it is possible to assess what time is spent on these activities and what time could be spent on maintenance. For calculating the effective free time, it is assumed that no maintenance can be performed during the other activities. Only pre- and post-flight checks can be done within Combi-embarking, embarking and disembarking. Currently, there are many occasions where maintenance is performed in the turn time. However, this does not show on the MFT plate and thus is difficult to consider. Some assumptions can be made regarding this, but this research assumes that maintenance is only performed in maintenance slots.

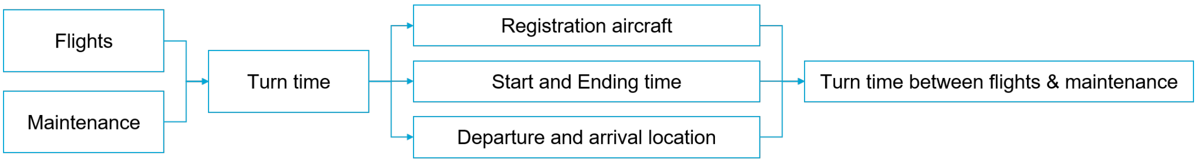

Figure 4.7: Data retrieved from for turn time

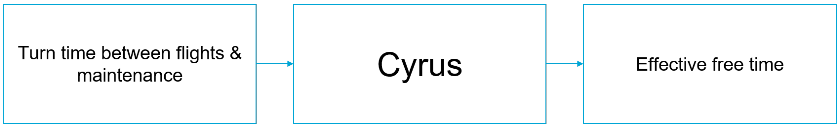

Figure 4.8: Effective free time calculation with the help of the Cyrus model

Fleet count

The last retrieved data is the fleet count, which is the plane provider's only input into the MFT plate. The fleet count is the number of aircraft in service for that particular week. This means that fleet content development can be tracked over time. The first information is the number of aircraft in service, and the second is the aircraft type. As mentioned in the previous chapter, the rules for WMMR have not been changed even though the fleet count and content have changed. The fleet count is thus a necessary required input.

There are, however, some irregularities in the fleet count data. The fleet count is based on the types. However, a type code can change when a large modification is executed. It has difficulty transitioning these new codes because it counts the new codes double, thus retrieving the double amounts of aircraft. This data is then constrained by hand to prevent such double counting. The fleet count is also required for calculating average requirements and performances for the entire fleet and per type. Because it also just counts the active aircraft in service, sometimes, an aircraft has no flight or starting maintenance slot in a week. It then counts on aircraft less than the actual count of aircraft. It is assumed here that the active count of aircraft in service is the total and correct amount of aircraft.

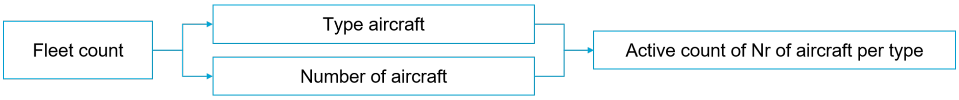

Figure 4.9: Data retrieved from fleet count

4.2. Categorisation

The next important step in the model is categorising maintenance slot types and turn time activities. Categorisation is part of the Lean manufacturing theories explained in chapter 2. One of the building blocks of lean manufacturing is standardisation. Categorisation is one of the ways to bring standardisation to the operation. The first is to bring categorisation to the different maintenance types and then evaluate the aircraft activities with the help of value mapping.

4.2.1. Maintenance types

There are so many maintenance slot codes at KLM that most people do not know them all. The total amount of maintenance slot codes is over 40 see Appendix. If the slot codes are finally all identified, the problem of which maintenance codes should be performed in the designated WMMR slots. In Table 3.2, the misunderstanding was pointed out between the providers of what to fit into the WMMR slots. To understand where this misunderstanding comes from, it is necessary to highlight aircraft maintenance tasks.

There are more than thousands of maintenance tasks that have to be performed on an aircraft. These tasks have different priorities because some affect safety and airworthiness, and others only affect customer experience. For example, a defect in the engine has a higher priority than a broken armrest because a defect in the engine affects safety directly, while a broken armrest does not. Thus, there are levels of importance when it comes to maintenance tasks. However, these tasks are defects and are thus unpredictable and non-routine. Many tasks on an aircraft are routine, and it is known when a task is due and what its occurrence frequency is. Thus, the airline plans many of these tasks into the available maintenance slots, which is the job of the maintenance provider. The maintenance provider believes only these plannable routine tasks and some non-routine work should be performed in the WMMR slots. At the same time, the flight provider believes that all tasks that come up should be performed in these slots. However, the question arises of how much ground time should be required for all the tasks or just a part. To solve this problem, a categorisation of maintenance is required. This categorisation will be performed in a couple of steps, highlighted in the next section.

First, the maintenance tasks have to be categorised, and they can be divided into two main categories: Routine and Non-routine tasks. The tasks can be split into five different types inside the two categories. These are Defects, Deferred Defects, Expected Defects, Weekly, AMP, and Engineering orders. An overview of the maintenance task types is presented in Figure 4.10.

> **Routine tasks are tasks of which the recurring interval of the task is known**

The AMP and weekly tasks are part of the routine tasks. These tasks are in the aircraft maintenance manual set by the aircraft manufacturer. AMP tasks can have different intervals, which can be in months, while weekly tasks have to be performed weekly. These tasks can contain pre- and post-flight inspections. Engineering order tasks can be both routine and non-routine. The routine engineering order tasks are because of specific preferences by the airline itself or because of updates from the aircraft manufacturer. These could also be reoccurring but are not part of the AMP tasks. They are part of the routine because they have a known interval.

> **Non-routine tasks are tasks of which the recurring interval of the task is unknown, or it has no recurring interval**

The Defects, Deferred Defects, Expected defects and partly Engineering orders are part of the non-routine tasks. Defects are faults found during flights or inspections that can be solved instantly. Deferred defects are defects that cannot be solved instantly and thus are deferred. Expected defects tasks are not a defect yet but will be planned preventive because the mechanic assumes it is about to defect. The maintenance provider sets manufacturer order tasks because of updates from the aircraft manufacturer. These tasks do not have specific intervals and it is possible that they only have to be performed once in a lifetime.

Second, now the maintenance tasks are identified, they should be given priority. This is because some tasks are more important than others regarding flight criticality, as explained before. The routine tasks have three main categories: mandatory non-extendable, mandatory extendable, and non-mandatory. For the non-routine tasks, there are two categories: Minimum equipment list (MEL) and Non-safety related equipment (NSRE). These two categories are subdivided into four, each representing a different due date: MEL A, B, C, and D, and NSRE 10, 20, and 120. MEL A has a due date

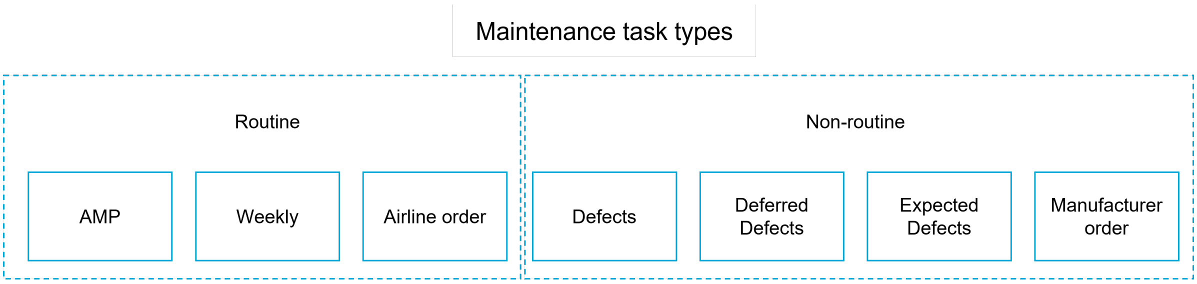

Figure 4.10: Maintenance task types split into routine and non-routine tasks

dependent on the task, while MEL B, C, and D depend on days. B, C and D have days until due of 3, 10, and 120 days respectively. NSRE 10, 20 and 120 are also 10, 20, and 120 days respectively. MEL A items are rare compared to the other MEL items and do not occur often. MEL and NSRE are part of the non-routine, while mandatory non-extendable, extendable, and non-mandatory are part of the routine. This relation is shown in Figure 4.11.

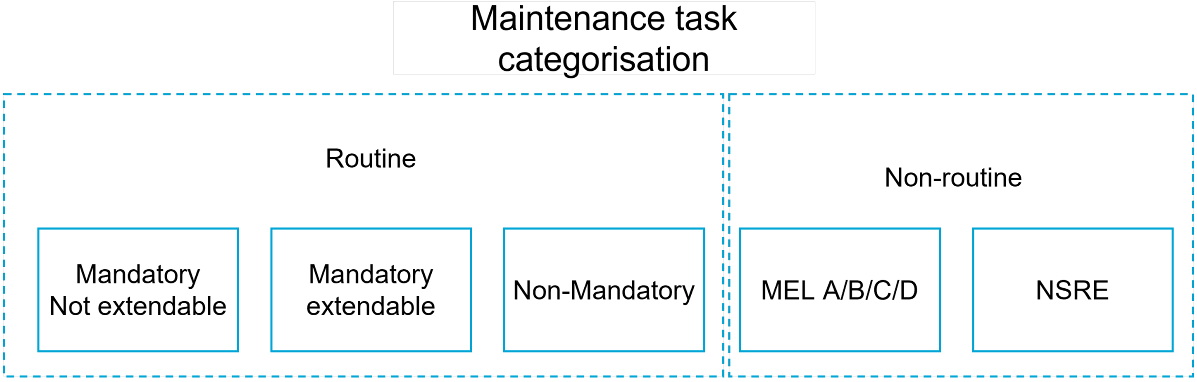

Figure 4.11: Maintenance task categorisation

Most maintenance tasks can be planned. However, some are easier to plan depending on the planning horizon. Also, depending on the categorisation, some tasks should have a higher priority to plan than others. This priority in planning is shown in Figure 4.12. Here, three different priority groups are identified: high planning priority, medium planning priority and low planning priority. The tasks are put into priority groups. High-priority tasks are crucial to airworthiness and have a short due date. Medium-priority tasks can be crucial for airworthiness but have a longer due date; thus, they do not have to be performed in the next check. Lastly, the low-priority tasks are not crucial for airworthiness and have long due dates.

After categorising maintenance tasks, it is also important to categorise the maintenance code types on the check level instead of the task level. As mentioned in chapter 3, over 40 maintenance codes exist. In Appendix A, the meaning of each of these codes is explained. Not all of these codes are taken into account because not all are maintenance-related. These codes fit into different categories, similar to the maintenance tasks. One of the most important checks is the WMMR or weekly minimum maintenance requirements. In the MFT plate, this has the code name TO. TO is an overall maintenance requirement and can be used for all other maintenance codes. It is sort of the stem cell of aircraft maintenance because it can be used for the most needed maintenance type. However, as mentioned previously, there is a miscommunication between the providers regarding what maintenance should be performed in the WMMR. Several codes are filtered in the Cyrus model to analyse the categories individually.

However, some complications arise when considering a single aircraft on the registration level or fleet requirement on the fleet level. For example, an engine exchange for an aircraft occurs every 1-2

	High planning priority	Medium planning priority	Low planning priority
Routine	Mandatory non-extendable	Mandatory extendable	Non-mandatory
Non-Routine	MEL B MEL C	MEL D	NSRE

Figure 4.12: Maintenance task priority table

years. Thus, it does not fit into a weekly minimum maintenance requirement. However, because of the fleet size, there is almost an engine exchange weekly. However, in this research, because it looks to the WMMR on a registration level, it is assumed not to be part of the WMMR. This is because it does not occur every week and because it is not always known when it will occur. Thus, reserving ground time for such an event is excessive. This time could otherwise be used for flying. That is why a balance between maintenance and flying is so crucial.

Similar to the maintenance tasks, there is also a priority in the checks. There is again a high, medium and low priority. However, the priority works differently, and another category is called checks. Codes that fit into this category are the big checks, such as A and C checks and old codes that are now being performed in these checks are put into this category. The category with low priority consists of maintenance codes that happen irregularly and in the long term. This makes it impossible to consider when determining weekly maintenance requirements. Most medium priority codes are now performed in TO-space or R-checks but also consist of unplanned checks such as an AOG. Although they do not happen to be weekly, on the fleet level, they do. Thus, they fit into the weekly maintenance requirements but do not have high priority due to the unplanned nature of the check. Lastly, there are the high-priority codes. They are part of the weekly minimum maintenance requirement and thus have a high priority. The maintenance codes are overviewed in Table 4.1.

Table 4.1: All of the maintenance codes categorised into high, medium, low priority and checks

Maintenance codes/categories	High	Medium	Low	Checks
E			x	
A				x
B				x
C				x
D				x
H	x			
M		x		
AG		x		
BL			x	
BM		x		
CE				x
CL			x	
DE			x	
DI			x	
DR				x
FF			x	
LE			x	
LG				x
LP			x	
MO				x
NB			x	
NR	x			
OM			x	
ON			x	
P+	x			
PD			x	
PI			x	
PO			x	
RE			x	
RP		x		
RS			x	
RT	x			
SP			x	
TA			x	
TD	x			
TM		x		
TO	x			
TY	x			
TZ	x			
VW				x
WA			x	
WE			x	
WK	x			
WW			x	

The weekly minimum maintenance requirements are high-priority codes: H, NR, P+, RT, TD, TO, TY, TZ and WK. H is a hangar check. In this check, high-priority tasks are fitted, which have to be performed in the hangar. The opposite of the hangar check is the platform check with the code P+. Similar tasks are being performed here. However, these do not have to be performed in the hangar. Then, there is the NR slot or the No-Release slot. No release slots could be performed in the hangar or on the platform. This depends on the tasks. It is called an NR because a high-priority task is in this slot, and the NR slot is placed on the day before its due date. If the maintenance slot were not on the day before the due date, it would be either a Hangar or platform check. However, when an NR slot is given, it is impossible to move it because maintenance must be performed and cannot be postponed. Then, there is the TD check. A TD is a maintenance slot where high-priority tasks are being performed. Although TD is mostly used for corrective maintenance, preventive maintenance is also performed in these slots. TD slots are always performed in the hangar. The TO slot is already known. TO is reserved time for maintenance and can take many shapes. However, it is essential to note that the slot code TO is only considered when considering planned maintenance in advance. When the performed maintenance is analysed, the TO code is not considered. This is because if the maintenance slot still has the label TO after it is performed, it was not used for maintenance and thus should not be considered. Then there are the RT slots. RT stands for Reserve Technical and is similar to TO. However, it is an extra addition to the TO, specifically for Airbus aircraft. Then there are the TY and TZ checks. These only occur in 2021 and 2022. These are referred to as R-checks. As mentioned in Table 3.4, these checks can have different lengths. TY is an R-check which is performed in the hangar. TZ is performed on the platform. Lastly, there are the WK or Weekly checks. The WK slots are also specifically for Airbus aircraft. They occur almost weekly, and high-priority tasks are being performed in these checks. In the Cyrus model, the codes are filtered on priority to determine the WMMR on a historical basis.

4.2.2. Turn time valuation

As mentioned in the previous chapter, there currently is no insight into the activities that occur in the turn time. One part of the Cyrus model is to evaluate the different activities. These activities are combi-embarking, disembarking, embarking, towing hangar, and towing platform. According to Lean theory, every time an aircraft is on the ground, it should be used for a value-adding activity. Otherwise, it could be considered waste. As mentioned in the previous chapter, currently, there is no insight into the overall ground time of an aircraft. With the help of the Cyrus model, it is possible to identify how much time is spent on what activity. To identify waste, a value mapping or value contribution will be made of the entire ground time and, specifically, the ground time during the turn time. First, all the activities must be identified; some were already mentioned in this section. In Figure 4.13, all activities are shown.

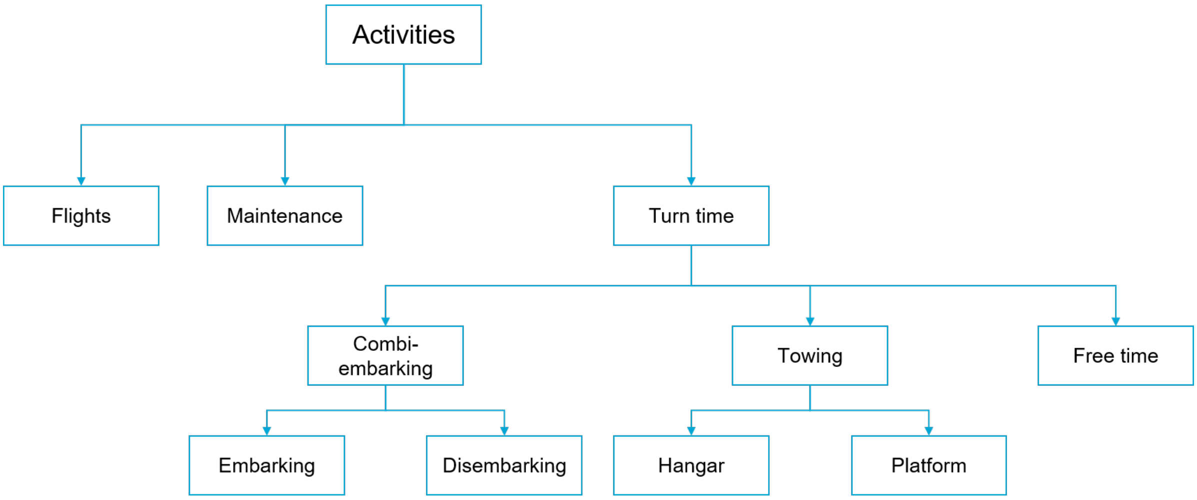

Figure 4.13: Aircraft activities

Now that all the activities are identified, deciding each activity's value contribution is crucial. How a value contribution works is described in chapter 2. The value contribution will be made to all the activities. The value contribution is shown in Figure 4.14.

Flight and maintenance are value-added activities because they bring value to the company. Flight is a value-added activity because it is the core business of an airline. Flying earns money and thus should be maximised. Maintenance is also a value-added activity, even though it is not through profits. Maintenance pays off by creating safety and stability for the airline. This means fewer breakdowns, defects and disturbances.

Next, there are the activities that occur in the turn time. Embarking and disembarking are necessary non-value-added activities. The reason that they are non-value-added is that they do not provide any value to the company. However, they are necessary because passengers can not board the plane without them. It is a time requirement between flights and maintenance. Towing is also a necessary non-value-added activity. The aircraft must be towed to the location to perform maintenance in the hangar, which is time-consuming and does not add extra value to the airline. Lastly, there are unnecessary non-value-added activities. Which in this case is free time. Free time fits into this category because it is a time when an aircraft is standing still, and nothing is being performed on the aircraft. According to the value stream map theory, unnecessary non-value-added activities should be eliminated. However, in this case, free time could be converted into value-added time. This can be done by performing maintenance in the free time and thus eliminating and minimising unnecessary non-value-added time.

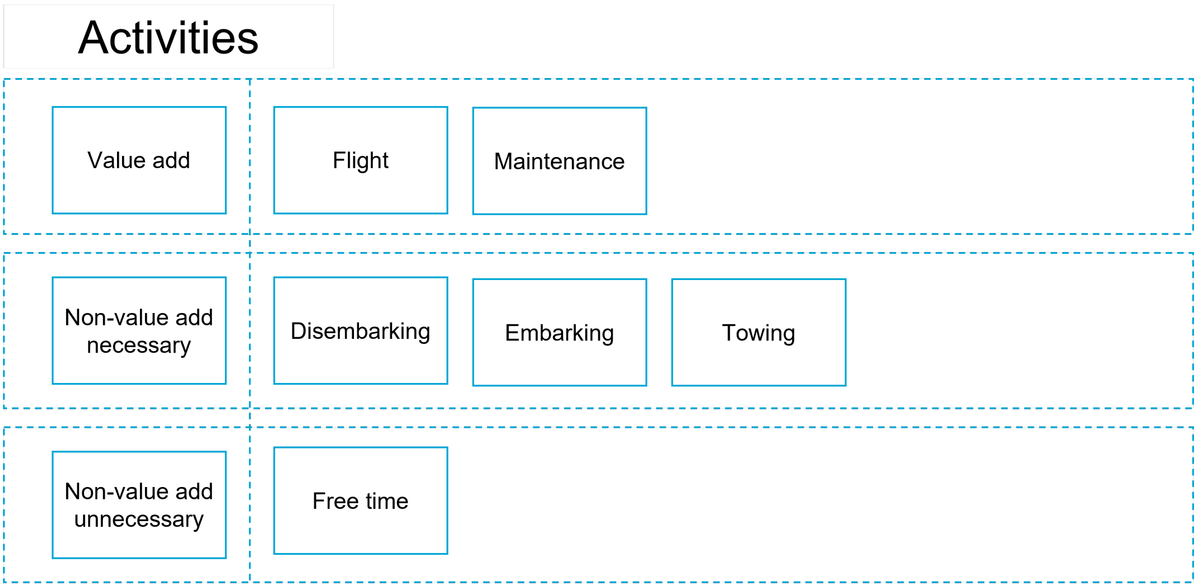

Figure 4.14: Value contribution of activities of an airline

To eliminate or transform the unnecessary non-value, add free time. First, the free time should be calculated. It should be noted that the turn time is also used for maintenance. However, based on the data imported from the MFT plates, it is impossible to determine whether the turn time was used for maintenance. This time could be used for maintenance, but it is not where the turn time is destined for. The turn time belongs to the service provider and could be used by the maintenance provider with their permission if needs be.

4.3. Conclusion

The model the result of answering the first question raised at the beginning of the chapter. 1) How would a model look that could estimate ground time requirements? The Cyrus model is designed as a centralised model between the stakeholders in planning. The Cyrus model aims to get stable planning from a holistic airline perspective. The model comprises several stages. In Stage one the inputs of the stakeholders are combined. In stage two, the data is retrieved from the sources and categorised. The analysis occurs in stage three, and a future state is designed in stage four.

2) Can maintenance types be categorised? This categorisation was completed on the maintenance codes and the maintenance tasks. The categorisation was performed as a prioritisation. High-priority tasks affect airworthiness and have a short due date, and high-priority codes are part of the weekly minimum maintenance requirements. This comes together in the third question on determining the maintenance ground time. The ground time can be determined based on the historical use of high-priority maintenance codes.

3) Can waste in turn time be identified and categorised? This was done with the help of the value mapping theory. Maintenance and flights are considered value-adding activities, while Disembarking, embarking, and towing are considered necessary non-value-adding activities. The remaining time, the free time, is considered an unnecessary non-value-adding activity. Lean theory suggests transforming this time into a value-added activity to decrease waste in the process.

5

Model analysis

In this chapter, the analysis of the model will be central. It starts with a short summation of the assumptions that are being made regarding data purity. Then, a short description of the importance of combining data, and afterwards, there is data analysis. It ends with a conclusion of the analysis. Some of the questions that will be answered in this chapter are listed below.

- What are important factors to consider for the weekly minimum maintenance requirements?
- What are the weekly minimum maintenance requirements?
- How should maintenance ground time be distributed?

The model had four main data sources: flights, maintenance, fleet count and turn time. Combining these sources is crucial in understanding the problem and the outcome. Separate conclusions could be drawn based on one source. However, this is not the overall picture the Cyrus model tries to create. For example, if only the flights of the 787 are being analysed. In Figure 5.1, it is shown that flight minutes increased from 2016 to 2019. On itself, it looks like a massive increase, however. If the 787 fleet count is also considered, the correlation becomes obvious. In Figure 5.2, this correlation is shown.

Data is available from 2009 till mid-2023. However, in most analyses, only 2012 to 2019 and 2022 are considered. This has to do with the fact that between 2012 and 2019, the fleet content was relatively stable, with Boeing and Airbus, and before 2012, the MD11 aircraft were also part of the fleet. 2020 and 2021 are not considered because they do not represent normal airline operational years due to COVID-19. Much of the fleet was on the ground during that time, and much maintenance could be performed without interfering with the flight program.

Assumptions

First, some assumptions must be pointed out before discussing the results and the analysis. The Cyrus model uses the MFT plates as input. However, these MFT plates are not always correct. Thus, some assumptions are made about the data's correctness and other factors that could not be extracted. It is assumed that:

- All maintenance codes are labelled correctly
- Maintenance slot lengths are equal to effective maintenance time
- No turn time was used for maintenance
- FTE remained constant in this period
- Work was executed by four FTE

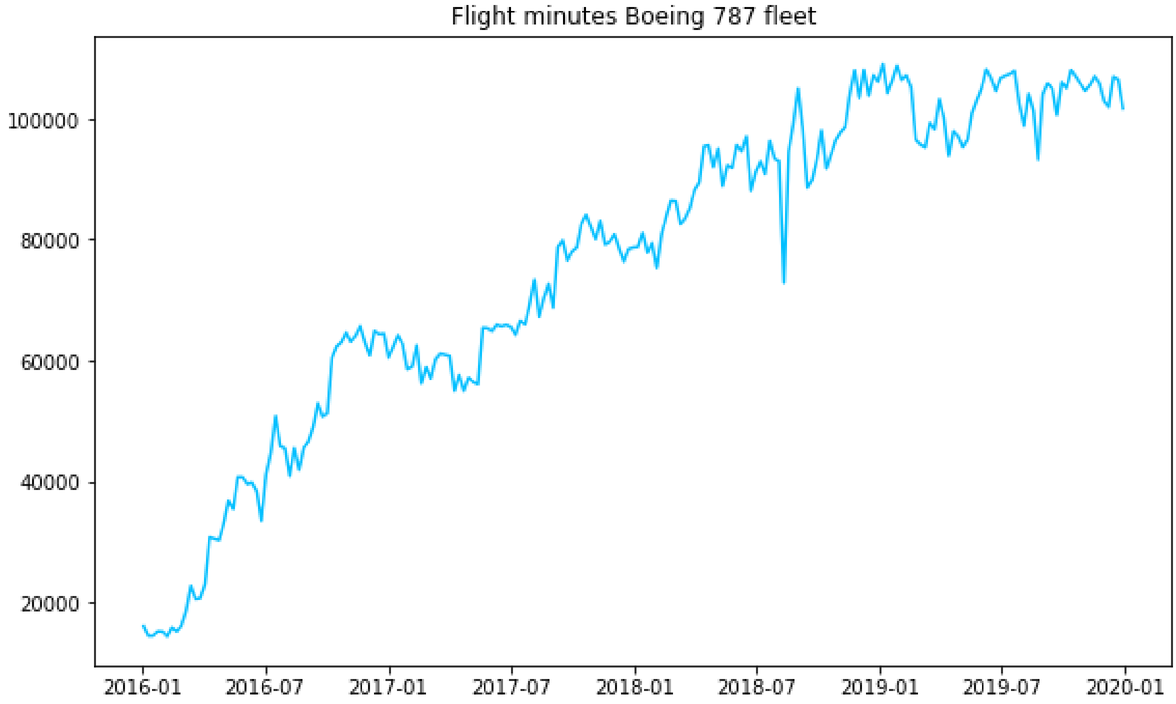

Figure 5.1: Flight minutes of the 787 fleet between 2016 and 2019

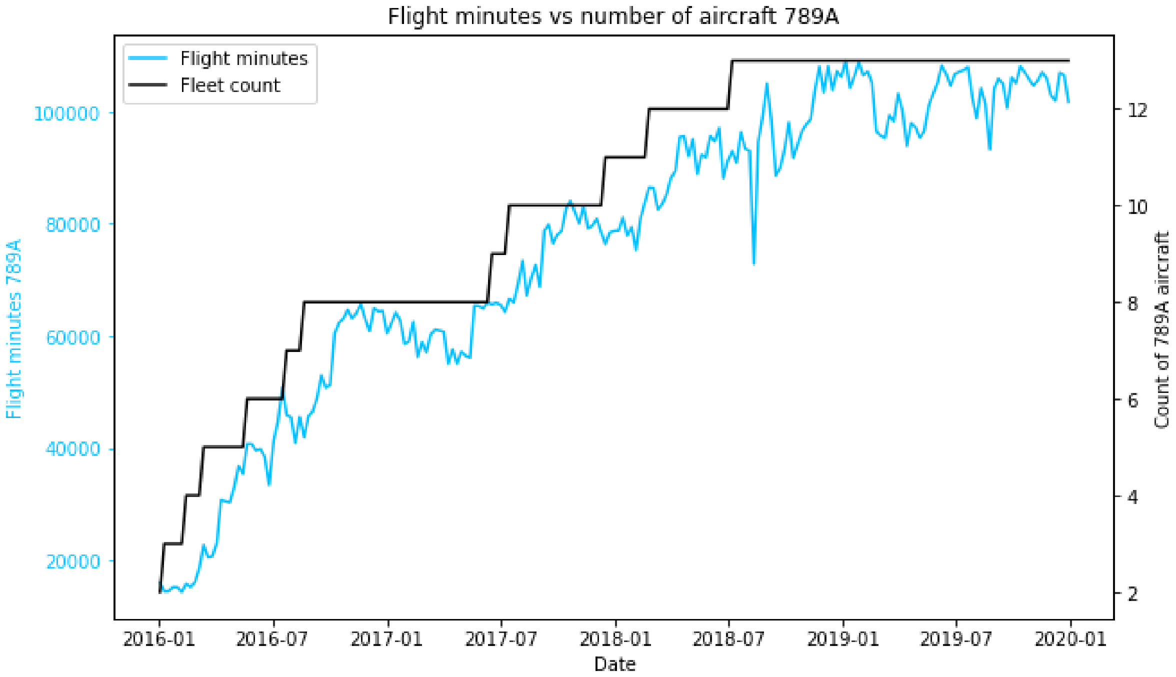

Figure 5.2: Flight minutes vs fleet count of the 787 fleet between 2016 and 2019

5.1. Trends in flights and maintenance

In this section, the data analysis will be highlighted. The analysis will be done with the help of several figures of the output of the Cyrus model. Different periods will be used to show different aspects of the airline operations. When determining the WMMR, it is crucial to identify the factors that affect the WMMR. Also, it is important to understand how the maintenance strategy looks and the overall trends that can be found.

The first step in the analysis is to identify trends in flights and maintenance. This overview of all the maintenance performed between 2012 and 2019 is displayed in Figure 5.3. The figure also shows a trend line and flows along a seasonal trend. In summer, the demand for flying is higher than in winter. Thus, the airline aims to fly more during the summer and perform more maintenance in winter. In the figure, it can be seen that maintenance is at its peak during the winter because larger checks are planned, which are avoided in summer.

A similar but opposite trend line can be spotted in Figure 5.4 because for the flights, the peak is thus to be found in summer. However, this seasonality trend gets more disturbed from 2017 onwards. In previous years, there always was a smooth peak, while in the final years, they were disturbed. This can be explained by the regulations changes of Amsterdam Schiphol Airport and the Dutch government. It was decided to decrease the total amounts of flight movements allowed by 2022. KLM thus decided to maximise the number of flights before the regulation change. However, this flight increase led to instability because the maintenance time did not increase with the flight time; see Figure 5.3.

In Figure 5.3 and Figure 5.4 trend lines are displayed. These trend lines are combined in Figure 5.5. The trends have a behaviour like a cosine and a sine function. The peak of flights is at the off-peak of maintenance and the other way around. This is expected because flights and maintenance can not coincide. The summer belongs to the flight provider, while the winter belongs to the maintenance provider. However, WMMR aims to have a constant demand for maintenance year-round, which means no seasonality in high-priority codes. In Figure 5.6, the trend for only the WMMR is shown. This trend has almost no seasonal trend; however, it does have a decreasing trend. So, WMMR should not follow a seasonality trend as applies to all maintenance.

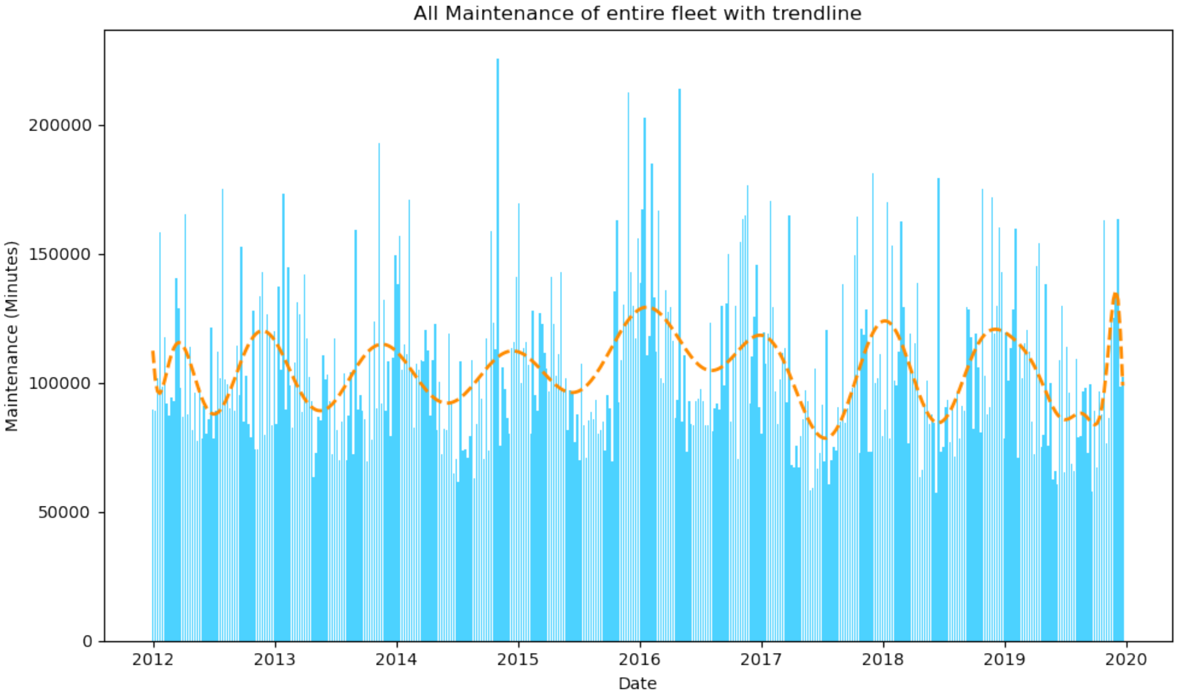

Figure 5.3: All maintenance that has been performed between 2012 and 2020 with the trend line

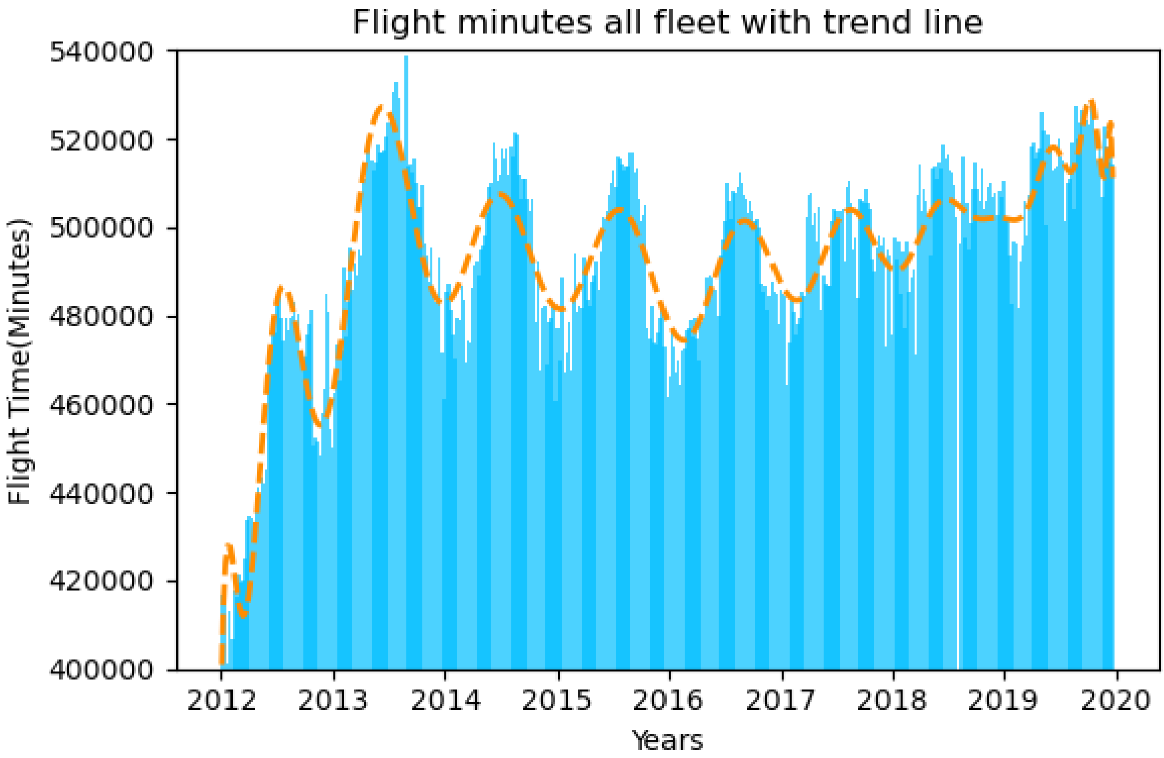

Figure 5.4: All flight minutes between 2012 and 2020 with trend line

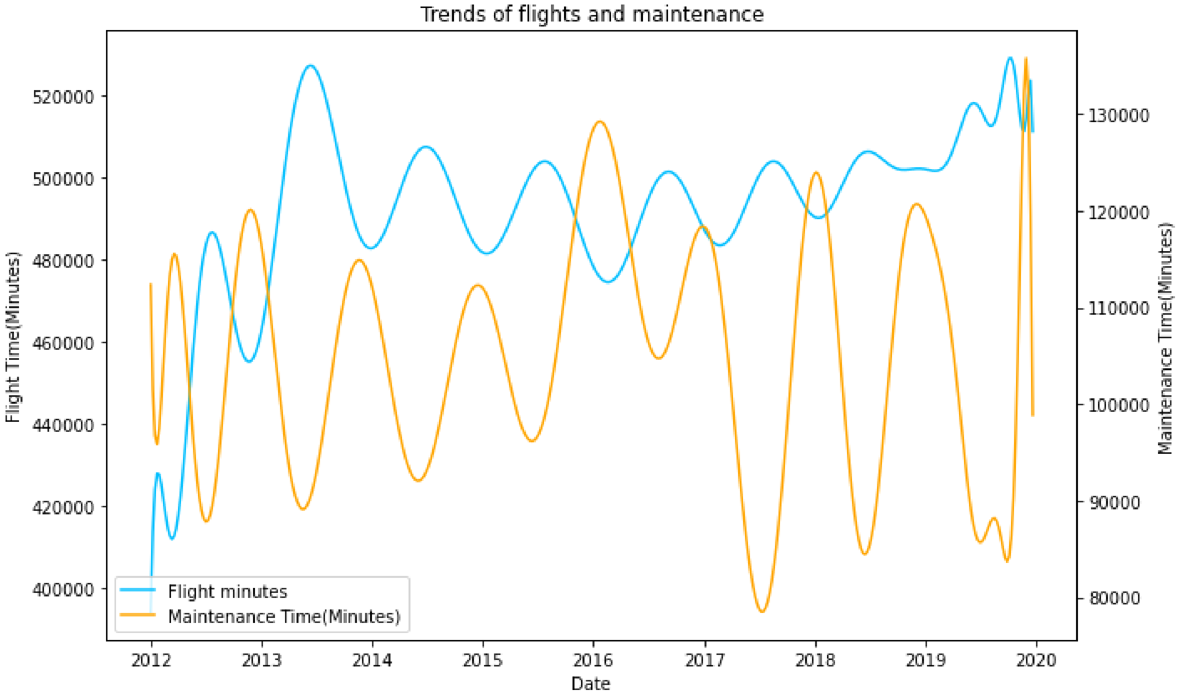

Figure 5.5: Trend of flights and maintenance

5.2. Fleet content development

Now, the trends in flights and maintenance are identified on a large scale. It is important to consider different aspects that influence the trends. One essential influence comes from fleet content

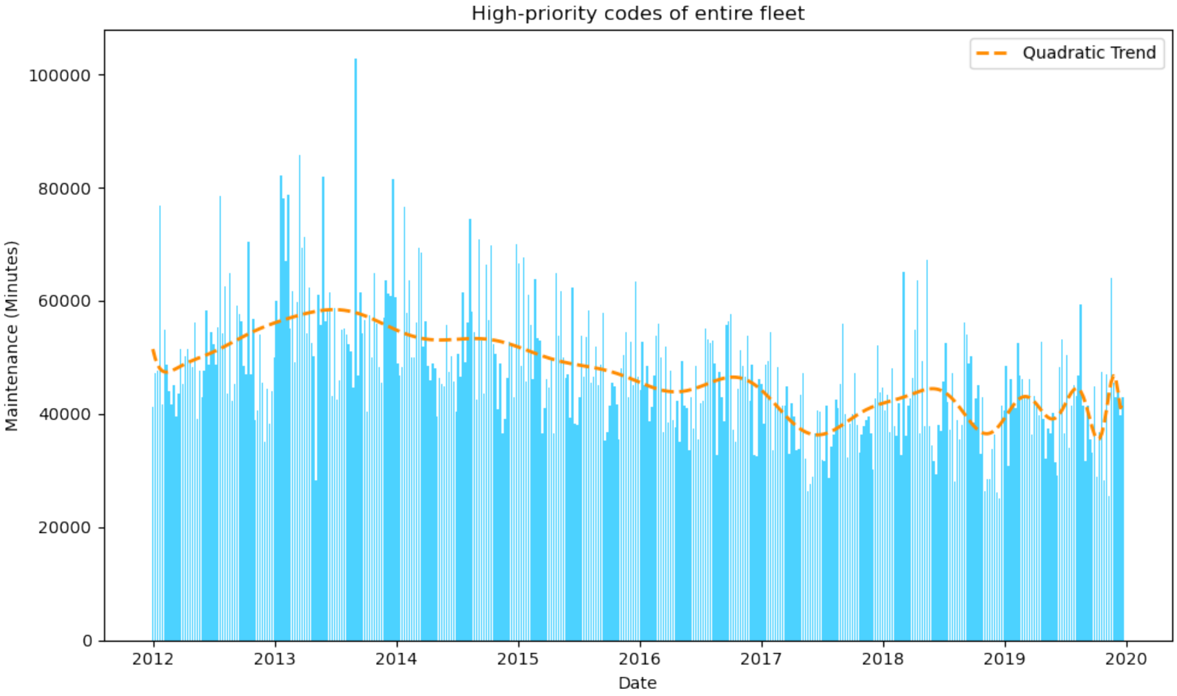

Figure 5.6: Trend of high-priority maintenance

development. As mentioned earlier, the rules for the weekly maintenance requirements on the ICA fleet remained the same even though the fleet content had changed. These new rules are crucial for creating new planning. However, the old requirements must be first investigated and analysed to determine the new rules. One way to determine that the rules are outdated is to look at the development of the fleet content. The fleet development is shown in Figure 5.7. It can be seen that the content has changed, replacing the 747 aircraft with the 787 aircraft.

5.3. Flights and maintenance relative to fleet content

Previously, all maintenance and all flights were displayed. However, these values were not relative to the fleet size and content. The fleet content has changed, and also the fleet size is different. Now, the share of each aircraft type is analysed.

In Figure 5.8, all the maintenance per type is displayed. However, this does not show the maintenance requirements relative to the number of aircraft. That is why the share of maintenance per type relative to the fleet size is calculated. First, however, the share of the type relative to the fleet is shown in Figure 5.9. This figure shows strange gaps in the share of Airbus in 2017 and 2019. These similar gaps are also found in Figure 5.7. This concerns some inconsistency in the fleet count data from the MFT plates. In this period, a new modification was performed on the airbus. This modification changes the type code from 332J-C to 332K-C, but because the MFT plates are per week, it is possible to count a plane double if the code change was that week.

The same calculation is done in Figure 5.10, except now it is for flight. Thus, the percentage is the share of which that type flies of all the flight minutes. A type with a low fleet percentage but a high flight percentage flies relatively more than the other types. In Figure 5.11, it is displayed for maintenance. Thus, the share of maintenance minutes per type of the total minutes. A high maintenance percentage combined with a low fleet percentage is unwanted because that type requires a lot of maintenance. What can be seen is that Figure 5.10 is relatively similar to Figure 5.9. When Figure 5.11 is being analysed, it is more difficult to read. Flights are a more stable process than maintenance. This is because there are a lot of checks that are multiple days or even weeks, while

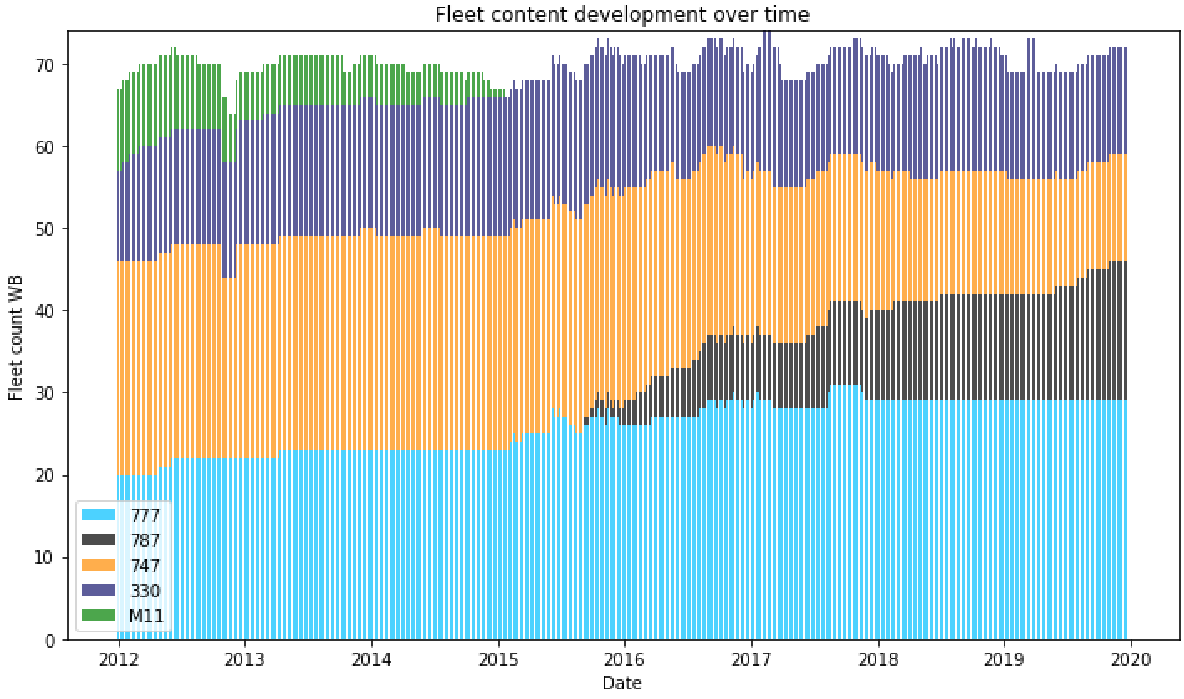

Figure 5.7: Content development of the fleet in the period 2012-2020

this cannot be said about flights. There are no 14-day flights. That is why the maintenance graph is more bobby than the flight graph.

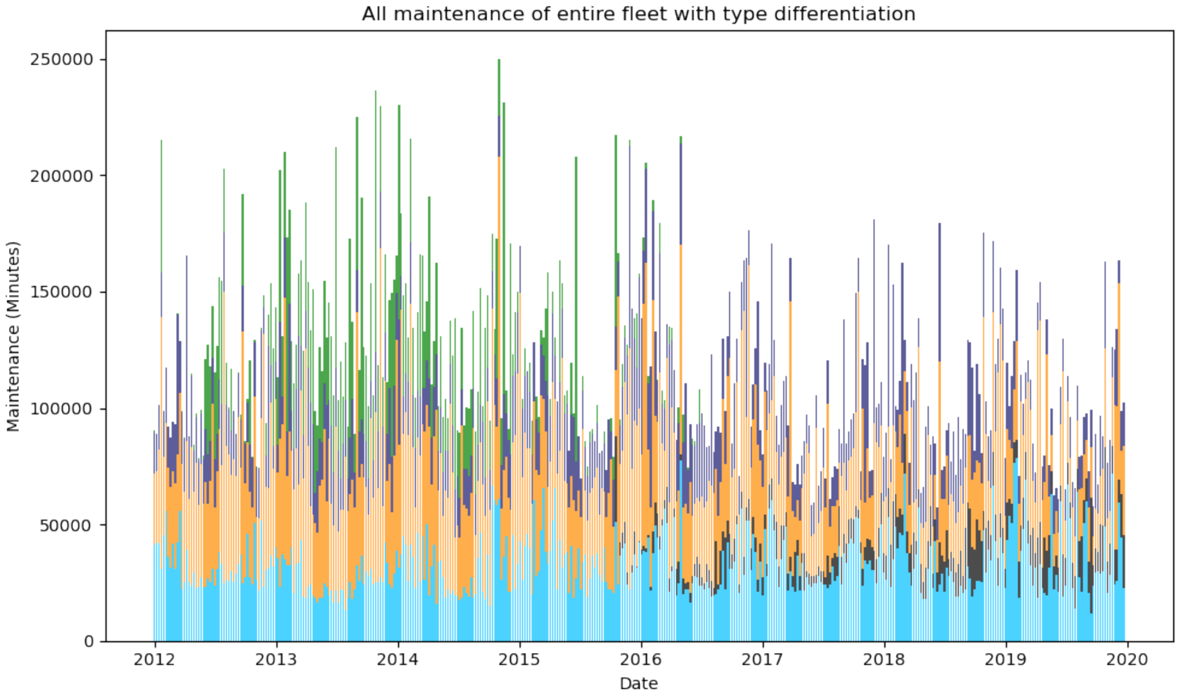

Figure 5.8: All maintenance with type differentiation

Thus, the maintenance requirements per type are different. This can be shown more specifically by plotting the maintenance percentages versus the count in the same graph. This allowed it to com-

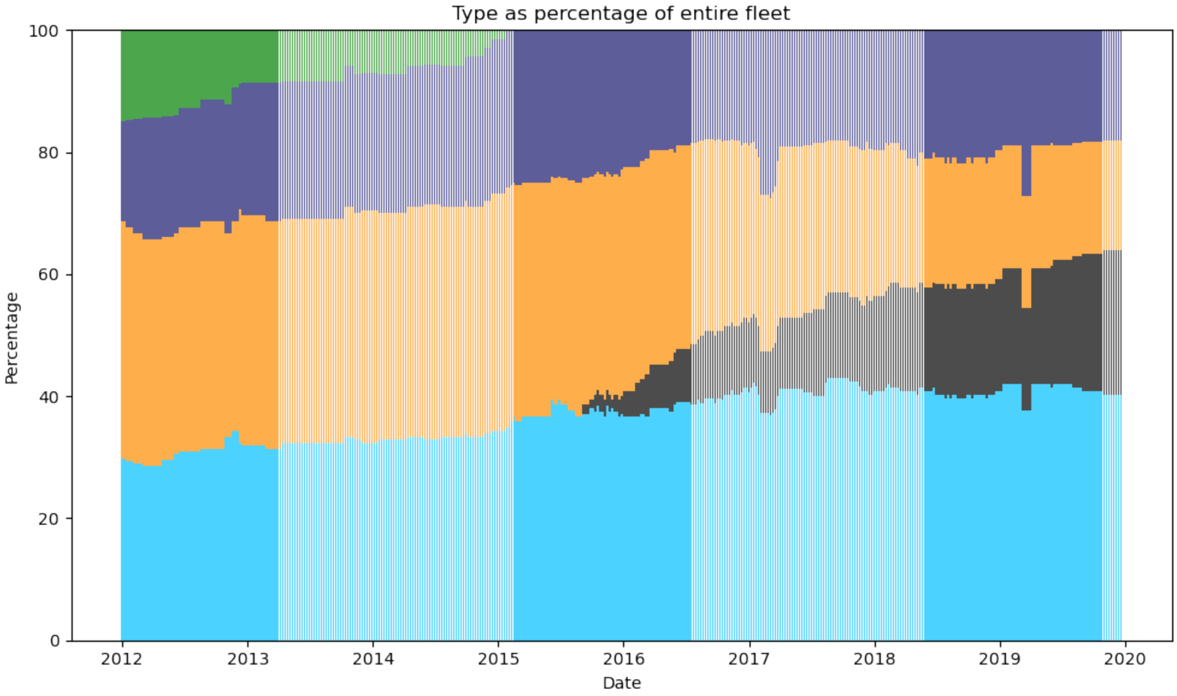

Figure 5.9: Type as a percentage of the fleet

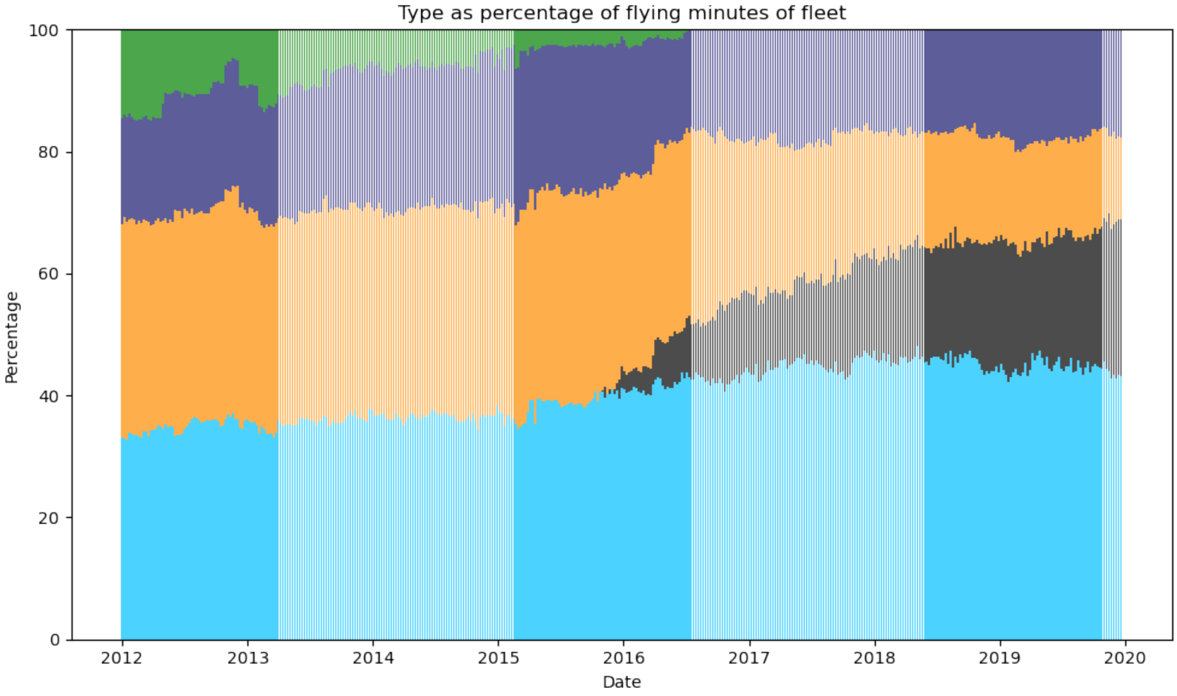

Figure 5.10: Type as a percentage of flight of fleet

pare the share of maintenance or flights with the count. In Figure 5.12, the combination of the flight share and count share of the 777 aircraft are plotted. A trend is that the share of flight minutes is continuously higher than the share of the count. This means the 777 is flying more than it should be based on the fleet size. Thus, it can be concluded that the 777 fleet is performing well. Then, in Figure 5.13, the share of maintenance with the count share is combined. Here, it can be seen that, on average, the share of maintenance is low compared to the fleet share. This means that the 777

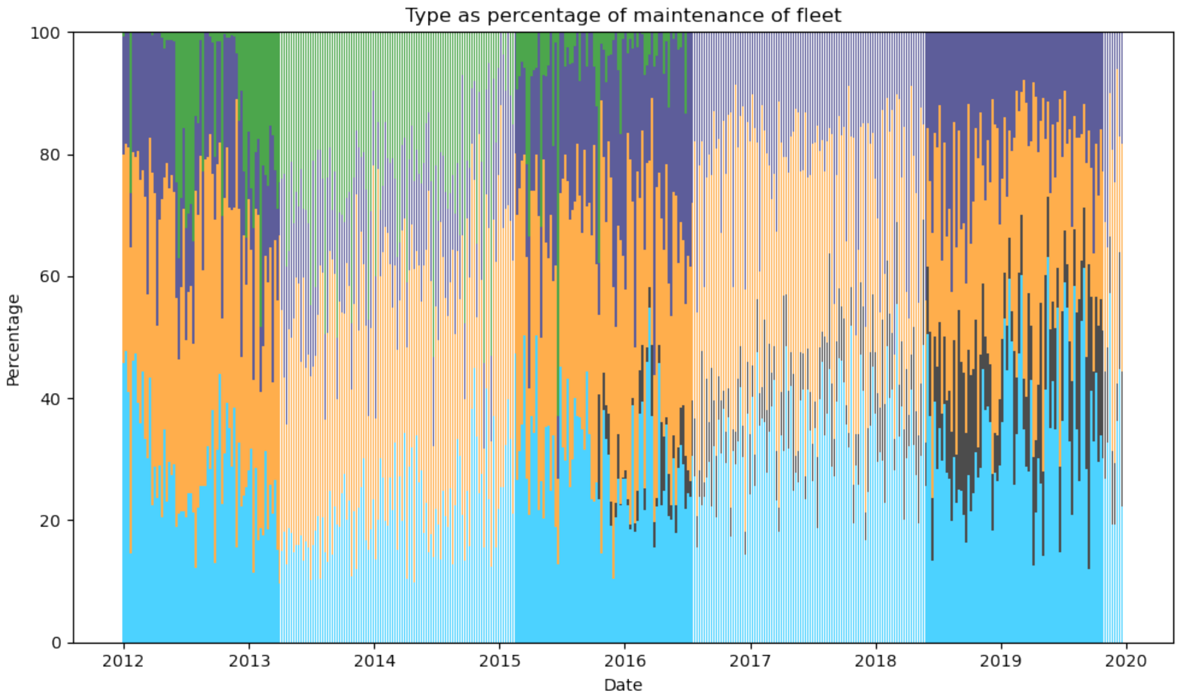

Figure 5.11: Type as a percentage of maintenance of fleet

requires relatively less maintenance than other types.

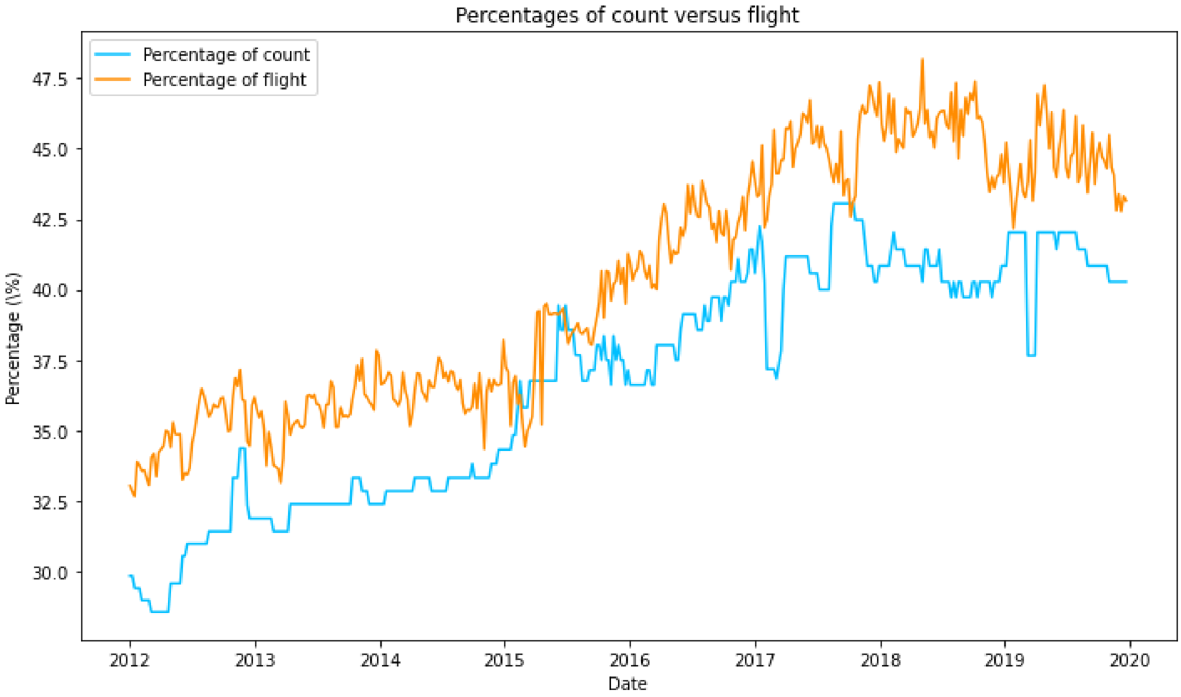

Figure 5.12: Flight share versus the count share

A common conception at KLM is that the maintenance requirements increase with an ageing fleet. This thought is based on the famous bathtub curve in the maintenance theory. The bathtub curve is a graph that models the failure rate with ageing. It is used to model the deterioration of machines

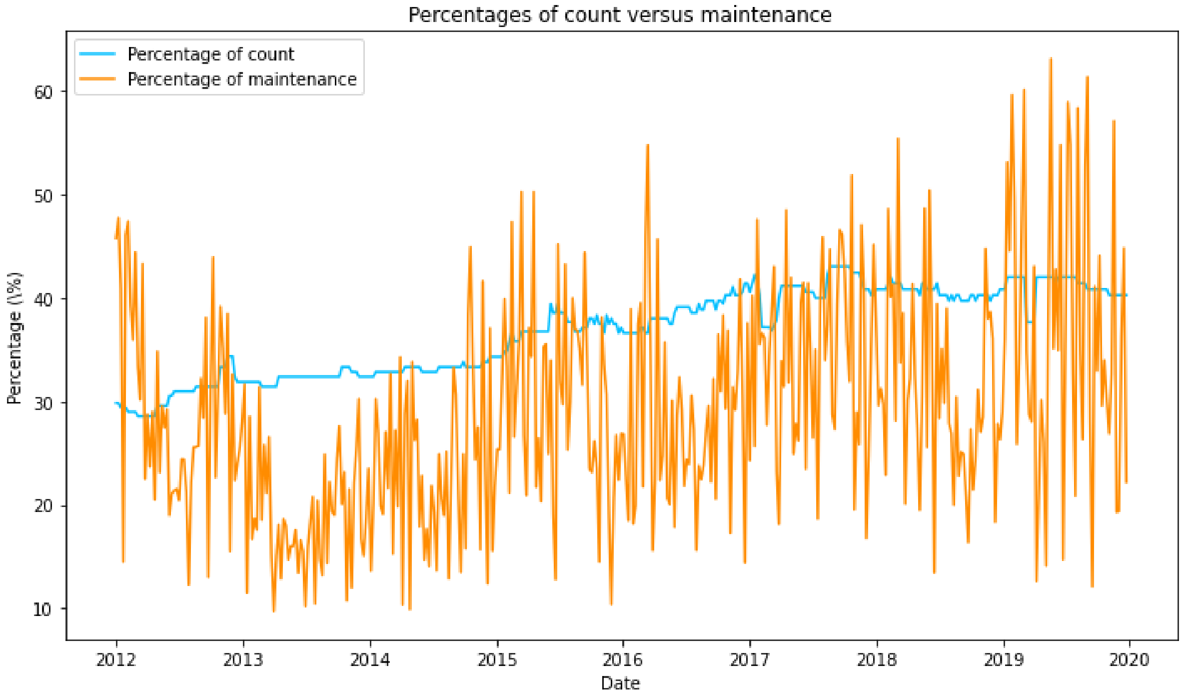

Figure 5.13: Maintenance share versus the count share

and equipment with age. It is called the bathtub curve because the line follows the cross-section of a bathtub. A maintenance bathtub curve is displayed in Figure 5.14.

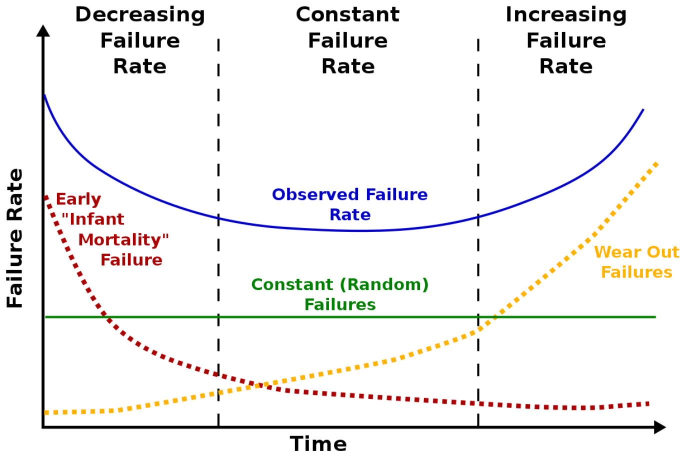

Figure 5.14: An image of a maintenance bathtub curve

The bathtub curve has three main regions, spanning the entire machine or equipment life. When taking aircraft as an example, the curve works as follows. When an aircraft is new in the maintenance program, there are a lot of teething troubles. Mechanics are unfamiliar with the aircraft; everything is new, and new tasks must be performed. This can cause many issues, so an aircraft requires much maintenance at the beginning of the life span. However, in time, mechanics learn to handle the aircraft better, the teething issues are dissolved, and the aircraft requires less maintenance. This region, where the aircraft requires little maintenance, wants to be maintained. However, according to the theory of the bathtub curve, when the aircraft is ageing, it will require more maintenance because it starts to age.

This theory in practice can be seen in the maintenance requirements of the MD11 aircraft. Starting in 2012, they were phased out of the KLM fleet. In Figure 5.15, the share of maintenance versus the share of count is laid out. It can be seen that the aircraft requires much more maintenance than its share of the fleet. Thus, it was in its final region of the bathtub curve. However, the question arises if this high maintenance demand is due to ageing or lack of maintenance. The lack of maintenance meant that when the maintenance provider knew they were getting phased out, it decreased the preventive maintenance planning of the aircraft. Also, current KLM workers say, "The M11 aircraft always was an unreliable aircraft". This is being questioned because an opposite view is retrieved from the 777 aircraft.

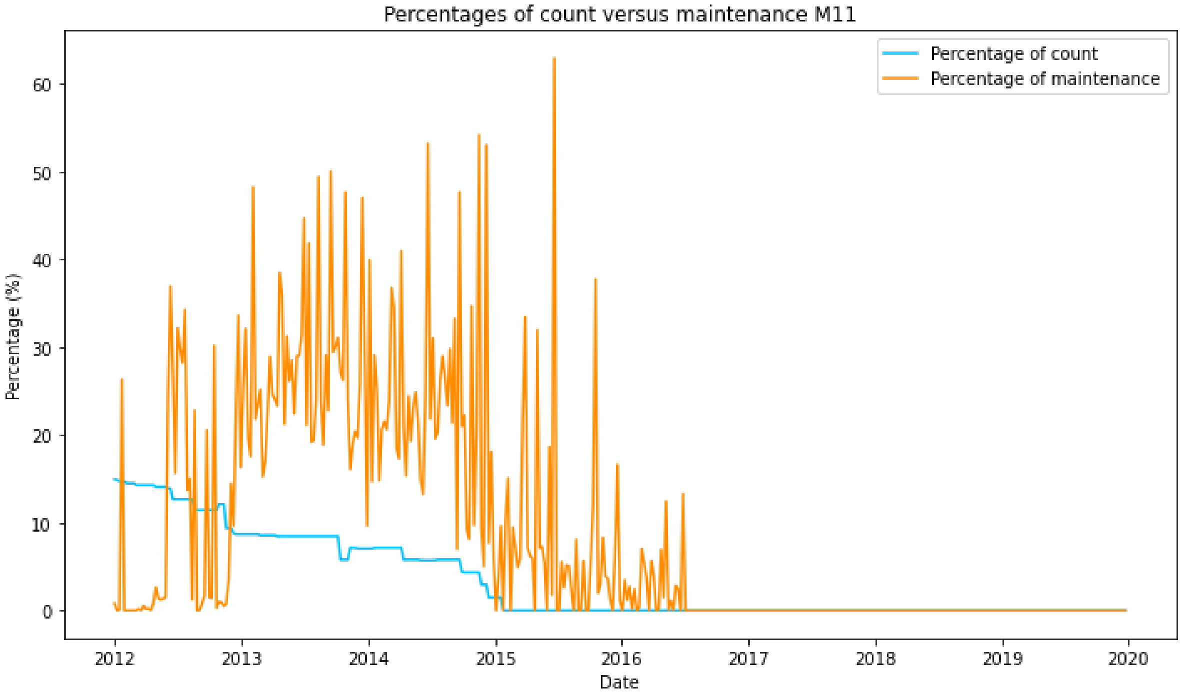

Figure 5.15: Maintenance share versus the count share of the M11 aircraft

Figure 5.16 displays the number of maintenance minutes performed on the registration PH-BQA aircraft. The PH-BQA is one of the oldest aircraft in the KLM fleet, aged 17 years by the end of 2019. An average WB aircraft retires around the age of 23.7 years in 2013 [18]. However, this figure does not show an increase in maintenance in this period. It could be that more findings and defects were found in the check. However, they can still solve them within the same maintenance ground time.

So, regarding the PH-BQA, it is possible to wonder if it does not fit into the ship of Theseus paradox. The Theseus' Paradox is a philosophical thought about whether an object that has had all of its components replaced remains fundamentally the same object. Theseus is one of the mythical founder-kings of ancient Athens in Greece. He was the 'hero' who sailed to the island of Crete to confront King Minos to release the Athenian prisoners. The children prisoners were rescued by Theseus, who slew the Minotaur in the labyrinth beneath the palace. They escaped to the island of Delos. Each year after, the Athenians commemorate this by taking the ship on a pilgrimage to Delos to honour Apollo. After centuries of maintenance on the ship by replacing, repairing and restoring it, philosophers asked if it was still the same ship when Theseus sailed to Delos with it. Almost no component was the same as it was centuries ago. The same could be said about the aircraft, not after centuries but after years of maintenance. As mentioned earlier, aircraft maintenance has many rules and regulations to make it as safe as possible. This means that so many components have been maintained, replaced or restored in that time. Is it the same old aircraft as when it came into service? Now, most of the critical components have already been updated or replaced at least once.

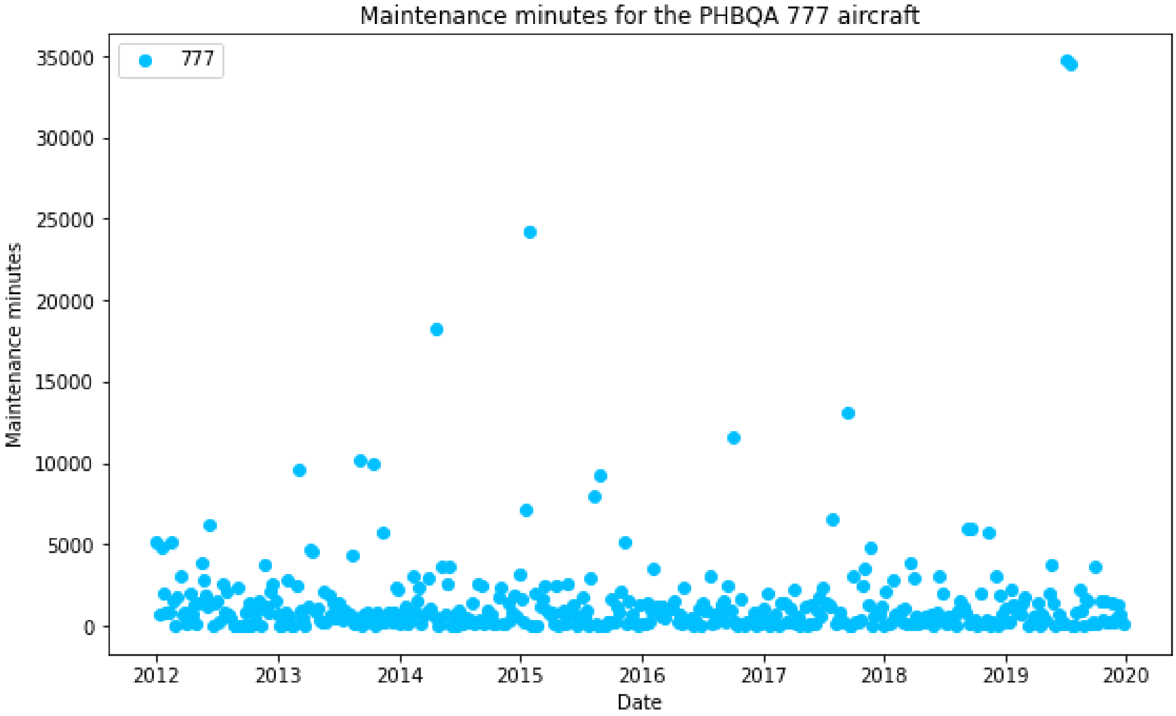

Figure 5.16: The maintenance requirement of the PHBQA 777 aircraft

To determine whether the maintenance requirements differ with age, the old PH-BQA 777 aircraft can be compared to a younger 777 aircraft, namely the PH-BVP. The PH-BVP came into service in 2016, which means it is relatively young. A difference can be found when looking at Figure 5.17. The younger aircraft has more zero maintenance weeks than the old aircraft. This also translates into a difference in their mean weekly minimum maintenance requirements. The Old aircraft has a mean of 6.95 hours per week, while the new aircraft has a mean of just 4 hours a week. In this case, the old aircraft needs almost 75 % more maintenance than a younger aircraft. However, the PH-BQA is a 777-200 type, while the PH-BVP is a 777-300 type. The difference is not there if the BVP is compared to an older aircraft of the same series. The PH-BVA is 8 years older than the PH-BVP, and the mean weekly minimum maintenance requirement is 3.8 hours, less than the younger PH-BVP aircraft.

Then, to verify this is not occasional, the Old-PH-BQA 777-200 is compared to the newest 777-200, the PH-BQP. For this comparison, the period between 2012 and 2019 is considered. The average of the old 777-200 is 7.34 hours per week, while the new has an average of 5.58 hours per week. This difference is 1.76 hours per week, which can be considered a lot. The average weekly maintenance requirements are posted in Table 5.1 to confirm this image. If a trend line of these maintenance requirements were plotted, it would show that the requirements of old aircraft are higher than young aircraft. Although it is not a precise number by which it increases yearly, there is an overall trend of increment. This indicates that maintenance requirements do increase with an ageing aircraft.

Table 5.1: Ranked from oldest (1) to newest (15) aircraft of the 777-200 fleet, where the first was phased-in in 2003 and the last 2007. This shows that new aircraft has lower maintenance requirements than an old one.

Aircraft	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Average weekly hours	7.34	6.39	7.57	5.96	6.42	6.58	5.83	6.23	5.45	5.91	5.94	6.91	5.95	5.99	5.58

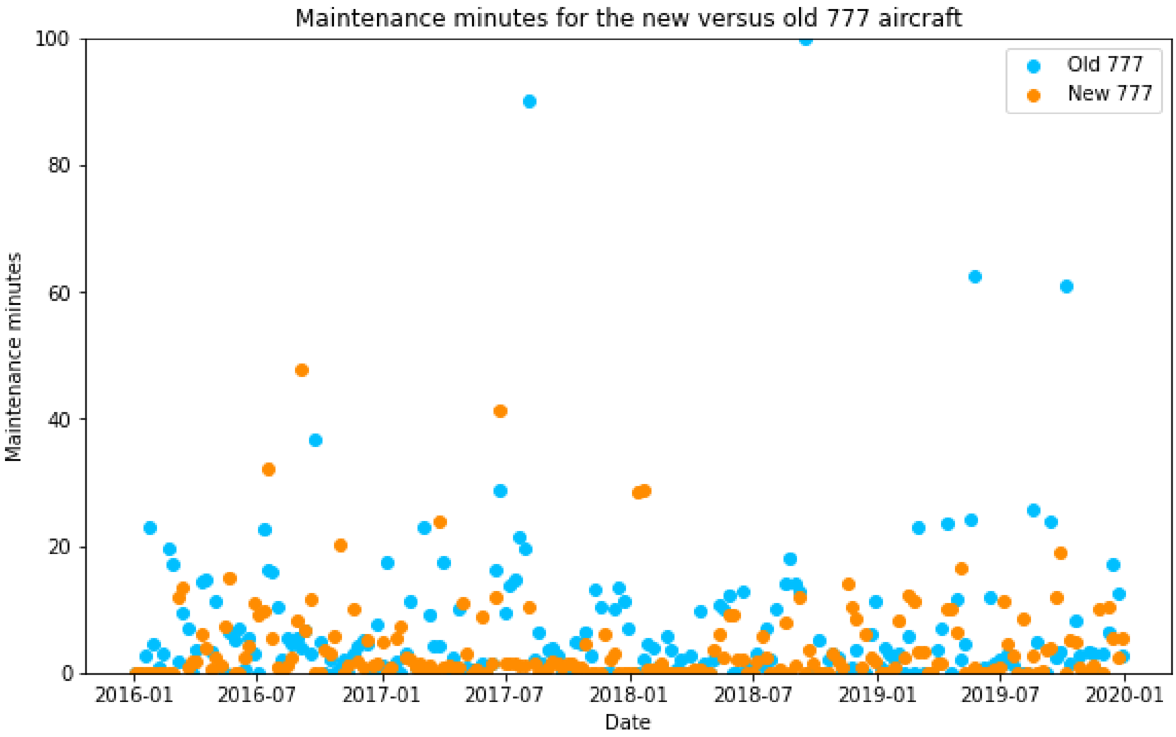

Figure 5.17: The maintenance requirements of an old versus a new Boeing 777 aircraft

A last way to indicate ageing is the number of active Deferred Defects. The first two of the same type but with different ages are shown in Figure 5.18. The colours orange and blue represent the two aircraft of the same type, the 777-300. It can be seen that there is no clear distinction between young and old aircraft based on Deferred Defects. However, there is a difference if the old PH-BQA is considered, which is a different type. However, this difference is mainly present until 2017. This could be explained by the fact that the deferred defects from 2016 started to be saved. Initially, there was an issue with the input of these deferred defects, which seems to be solved from 2018 onwards. Thus, a correlation is found between the types but not between the age of the aircraft.

Another thing that can be seen when looking at Figure 5.17 is there are also not many teething troubles for the young aircraft, even though this would be the case when the Bathtub curve is considered. One way to explain this is that the 777-type aircraft is already familiar to the mechanics. Thus, they do not have to learn new things and how the aircraft has to be maintained. The components and issues of the type are already known to the maintenance provider. This is similar to the theory of operational excellence. When tasks are standardised, or in this case, aircraft, they become easier to maintain and thus, less ground time is required for them. The operational excellence seen here should give airlines the insight that having a standard aircraft type is better for the operation. This type means the 777-type and not a difference between the 777-200 and 777-300. The 300 is a newer version of the 200 and, thus, has been further engineered. This means that many of the issues that a -200 type faced could be solved for the -300. Airlines could aim to get a more homogeneous fleet instead of a heterogeneous one.

The overall conclusion of the ageing fleet is that it is something to consider on an aircraft level. A new aircraft requires less maintenance than a new aircraft. However, because the fleet content is changing and new aircraft are added to the fleet continuously, on a fleet level, maintenance requirements remain similar.

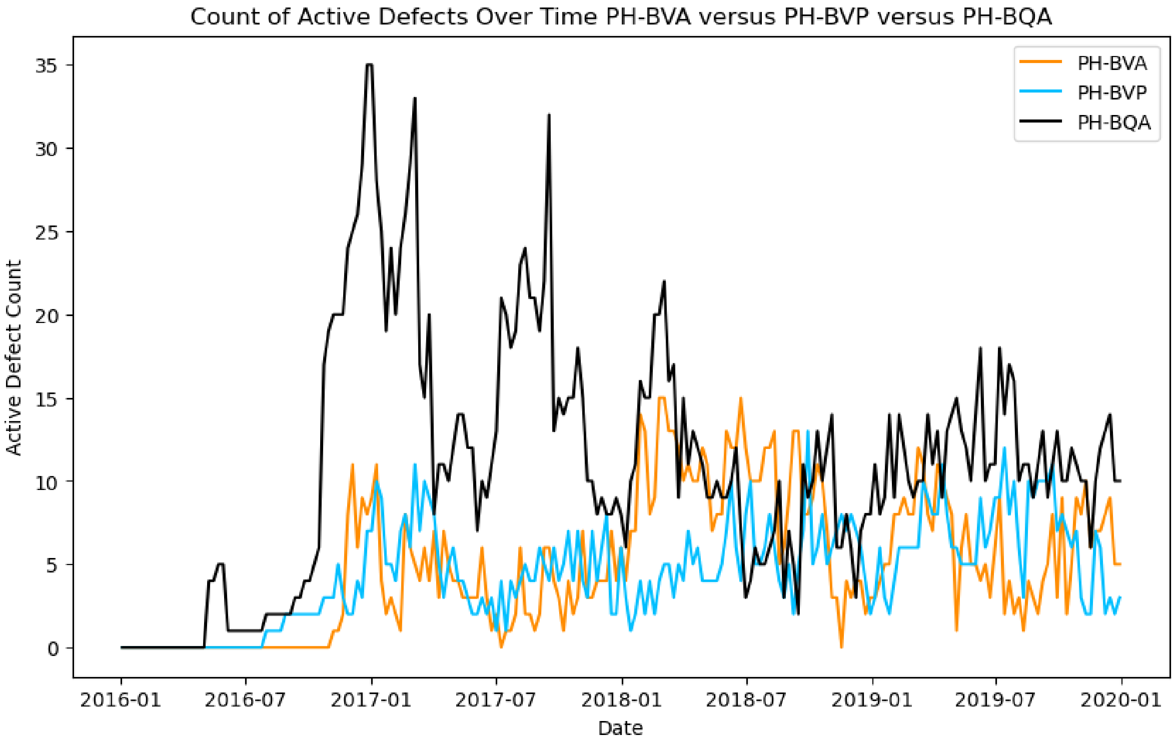

Figure 5.18: Active Defects overtime of the PH-BVA and the PH-BVP showing no age difference when it comes to active defects

5.4. High-priority maintenance codes

Until now, the entire maintenance time was the scope, which consisted of all the maintenance codes. This section's aim is to take the high-priority codes into account. These high-priority codes are the weekly minimum maintenance requirements (WMMR). It is suspected that the total amount of WMMR would increase when the fleet also increases. However, in Figure 5.19, it can be seen that the WMMR decreased for 2012-2020. Even if the maintenance-intensive MD11 aircraft (see Figure 5.15) is not considered, the amount of WMMR has decreased. The question that arises with the decrease in the total WMMR is if there was, at first, less WMMR planned or if the amount of planned maintenance remained constant and thus was not used. In Figure 5.20, the planned WMMR is shown over the same period. This figure shows that, generally, the amount of planned maintenance was less than the performed maintenance. To investigate this further, the differences are shown in Table 5.2. It can be seen that almost every year, the amount of performed maintenance is higher than the planned maintenance. This indicates that, in general, additional maintenance slots are created in the airline planning to fulfil the maintenance requirements.

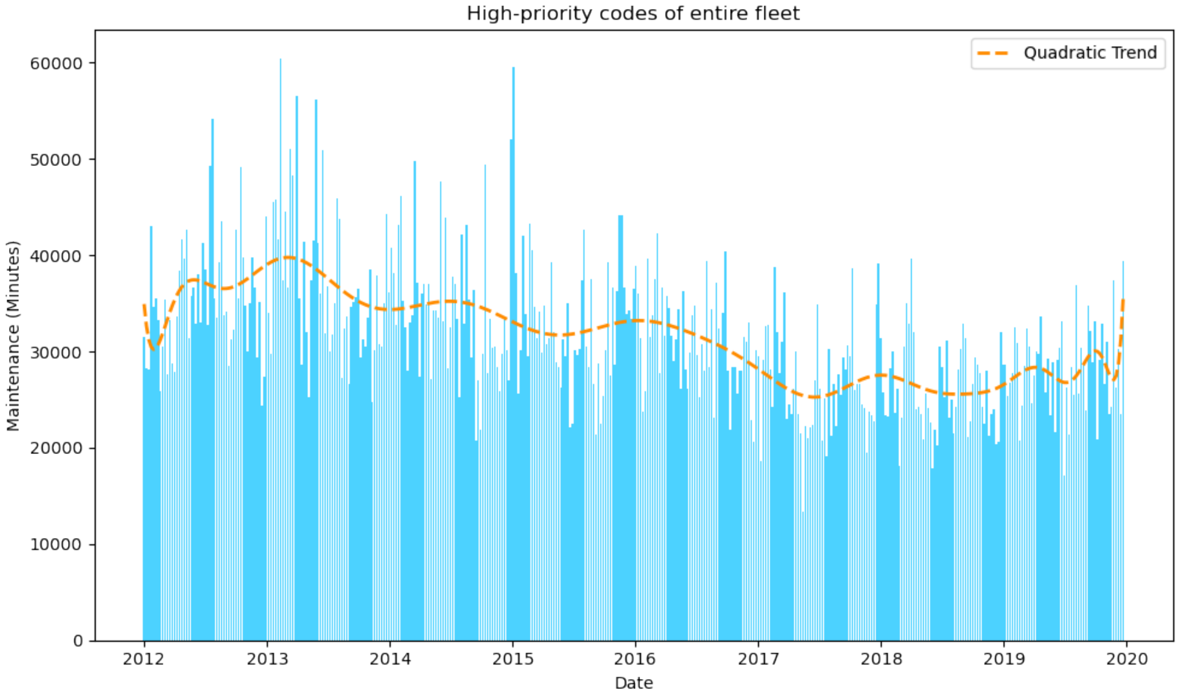

Figure 5.19: Weekly minimum maintenance requirements of the entire fleet between 2012 and 2020

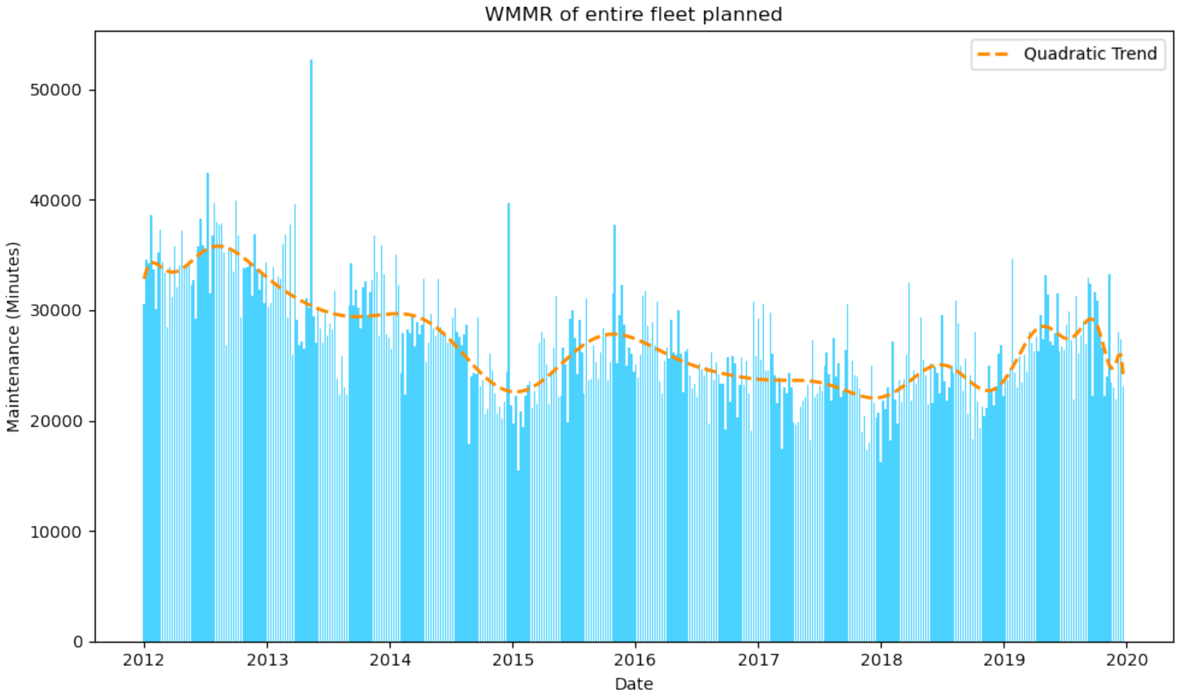

Figure 5.20: Planned weekly minimum maintenance requirements of the entire fleet between 2012 and 2020

In Table 3.4, the current rules for the amount of WMMR were explained. This was set for 336 hours per week for the Boeing fleet, independent of fleet content. To check how this rule performs compared to the requirements, the distribution of the WMMR is displayed in Figure 5.21. The vertical line in the figure is positioned at 336 hours. With 336 hours of reserved WMMR, 42.45 % of all the WMMR can be taken care of. It could be concluded that the airline only reserves enough maintenance time in just 42.45 % of the weeks over 8 years, and in 57.55 % of the weeks, additional maintenance

Table 5.2: The average yearly WMMR planned versus performed of the entire fleet in hours

Type/Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
Planned	576	519	454	430	427	394	403	460	479
Performed	588	626	567	555	520	441	435	469	473

slots must be created. When considering the whole fleet, the distribution is Figure 5.22 is acquired. In this case, the vertical line is positioned at the mean at 526 hours.

The distributions are crucial in determining the required amount of the WMMR. However, this required amount is dependent on the airline's strategy. If an airline desires to reserve enough maintenance for 80 % of the weeks, a higher WMMR is required than when the goal is only 30 % of the weeks. Currently, the percentage for the Boeing fleet is 42.45 %; however, this is not an actual objective of the airline. So, in the next section, the required amount of WMMR is calculated based on different strategies.

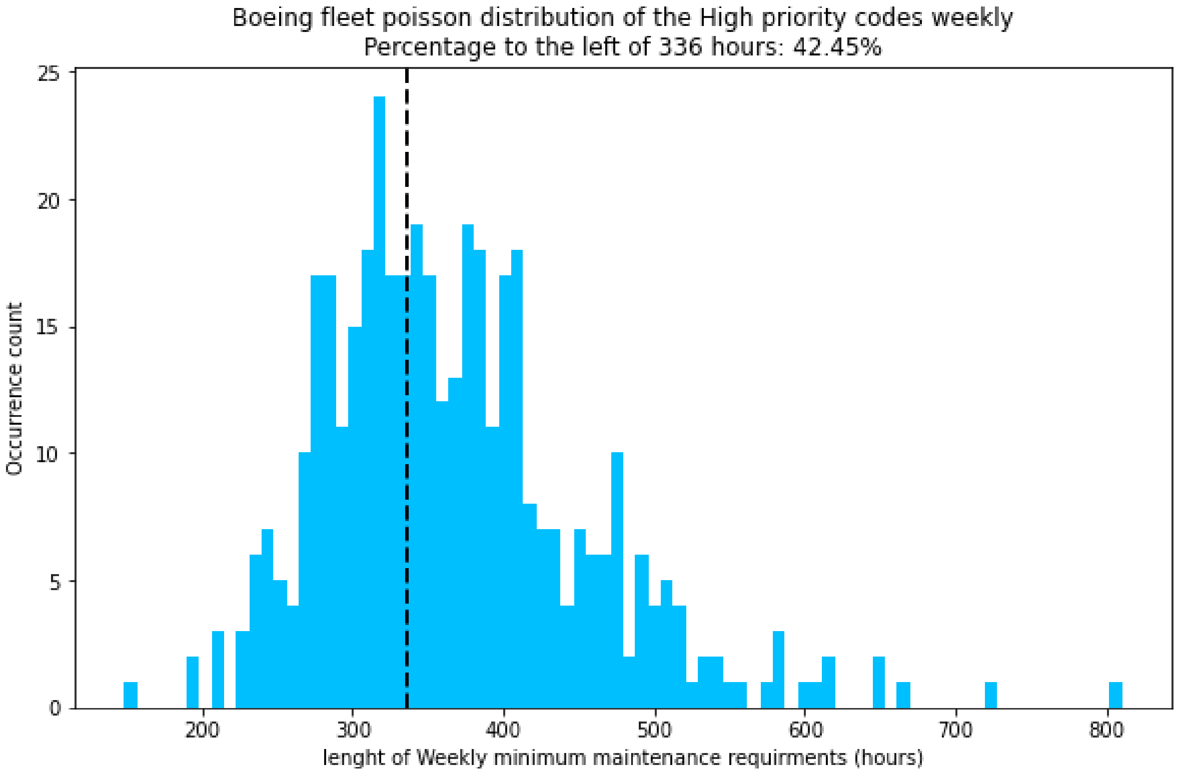

Figure 5.21: Distribution of the WMMR or high priority codes of the average weekly requirement for the Boeing fleet with the rule of 336 hours as a vertical line

5.4.1. WMMR per year

To conclude where the balance is, it is crucial to look back at recent years. The years 2012 until 2022 are analysed except for 2020 and 2021 due to COVID. The results are shown in Table 5.3. Four values are provided per year: the Mean and the standard deviation. It can be seen that there was a decrease in almost every aspect in the period between 2012 and 2019. However, this decrease does not mean that in 2019, less maintenance was required than in 2012. Because these values do not represent the right requirements, the years will be analysed separately with a capability analysis to determine the performance. The capability analysis is part of the Lean Six Sigma theories and can help determine which maintenance requirements lead to a stable maintenance planning basis.

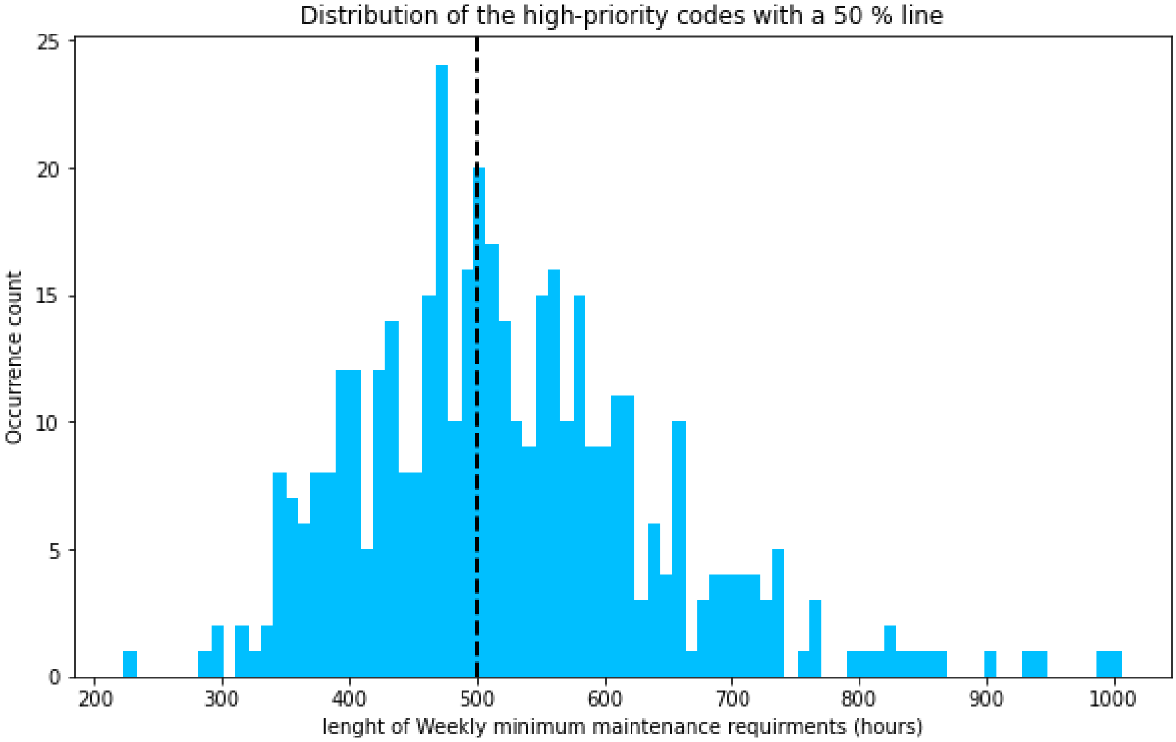

Figure 5.22: Distribution of the WMMR or high priority codes of the average weekly requirement for the whole fleet with the mean as a vertical line

Table 5.3: The mean of the WMMR per week per year

Type/Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
Mean	588	626	567	555	520	441	435	469	473
Std	101	134	108	121	84	85	80	69	111
Min	406	413	345	356	342	223	298	285	328
Max	902	1006	831	992	704	646	660	623	846

The performance will be presented as the stability that year. These stability calculations are an element of process capability analysis mentioned in subsection 2.4.5. The important KPIs for determining stability are the C_p and the C_{pk}. The Process and Specification width must be calculated first to calculate capability KPIs. The Specification Width is the difference between the Upper and Lower Specification limits, and the ones that will be discussed are 4σ, 6σ, 8σ and 10σ. 4σ represents the smallest Spec width with only four times the standard deviation. This means that from the mean, the distance to the upper and lower limit is two standard deviations. The smaller the Spec width, the more difficult it is to have stability. Because, normally, a smaller amount of the values falls between 4σ then 10σ. The different specification widths are displayed in Table 5.4.

The next step is to calculate the process width. the process width is the difference between the Upper or Lower Control Limit. The Upper limit is the maximum value, and the Lower limit is the minimum value in the process. In Table 5.3, the minimum and the maximum values are provided, and thus, the process width can be calculated. The process widths are displayed in Table 5.5.

The first KPI for stability is the Capability Index or C_p. This index is the ratio of the Specification width to the Process width. The other KPI is the C_{pk} or centred capability index, which is the distance

Table 5.4: The Specification width of the WMMR per year

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
4σ	404	536	432	484	336	340	320	276	444
6σ	606	804	648	726	504	510	480	414	666
8σ	808	1072	864	968	672	680	640	552	888
10σ	1010	1340	1080	1210	840	850	800	690	1110

Table 5.5: The Process width of the WMMR per year

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
Min	406	413	345	356	342	223	298	285	328
Max	902	1006	831	992	704	646	660	623	846
Process width	469	593	486	636	362	423	362	338	518

from the Mean to the nearest Specification limit divided by the Distance from the Mean to the Process edge. The KPIs are provided in Table 5.6. Lean Six Sigma aims to create a stable process. The stability of the process can be determined with the capability indices. An unstable process is where the C_p. and the C_{pk} have a value smaller than 1. A stable process is where the C_p. and the C_{pk} have a value larger than 1.33. Processes with a value for the C_p. and C_{pk} between 1 and 1.33 are barely stable. In the Table, the stability can be determined for different specification widths. No year would have a stable process when the specification width is 6σ. For 6σ, the only year with a stable process is 2016, with 2014 coming close to being stable.

Table 5.6: The Capability indices of the WMMR per year

Sigma	KPI/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
4	**Cp**	0.81	0.91	0.89	0.76	0.93	0.80	0.88	0.82	0.86
	Cpk	0.64	0.71	0.82	0.55	0.91	0.78	0.71	0.75	0.60
6	**Cp**	1.22	1.36	1.33	1.14	1.39	1.21	1.33	1.22	1.29
	Cpk	0.96	1.06	1.23	0.83	1.37	1.17	1.07	1.13	0.89
8	**Cp**	1.63	1.81	1.78	1.52	1.86	1.61	1.77	1.63	1.71
	Cpk	1.29	1.41	1.64	1.11	1.83	1.56	1.42	1.50	1.19
10	**Cp**	2.04	2.26	2.22	1.90	2.32	2.01	2.21	2.04	2.14
	Cpk	1.61	1.76	2.05	1.38	2.28	1.95	1.78	1.88	1.49

That 2014 and 2016 are stable years according to their C_p and C_{pk}. The overall weekly minimum maintenance requirement trend in this period could explain this. From 2012 till 2019, the amount of maintenance has decreased. 2014 and 2016 are years which are in the middle of this period. Thus, it could be assumed that before 2014, the amount of maintenance was too much compared to the requirements, and after 2016, the amount of maintenance was too little. However, if this is the case, this does not explain why 2015 was not operationally stable. However, one of the most important inputs is the maximum and the minimum value. 2015 has a relatively high maximum, and this affects the KPIs.

There are no stable years for 4σ as a specification width. This is because, with 4σ, there is a smaller window in which the maintenance has to fit. Thus, the maintenance requirements are less likely to fit within the smaller window, which makes the process more unstable. An opposite result can be seen for 8σ and 10σ. For these cases, the window size is increased. This allows more maintenance to fit within the slot. However, although stability is the aim, a higher C_p or C_{pk} value is not optimal. What is optimal is something that has to be determined by the airlines themselves. This can be due to personal preferences. An airline aiming to cater for the most cases will choose a higher σ value.

Thus, 2014 and 2016 are stable years with relatively small maintenance windows.

This capability analysis was calculated with the amounts of performed maintenance. However, it is interesting to consider the planned amount of maintenance with the performed maintenance. Thus, the planned mean is not inserted into the calculation, while the other values remain the same. The acquired results are shown in Table 5.7.

Table 5.7: The Capability indices of the planned WMMR per year

Sigma	KPI/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
4	**Cp**	0.81	0.91	0.89	0.76	0.93	0.80	0.88	0.82	0.86
	Cpk	0.62	0.55	0.57	0.43	0.61	0.67	0.62	0.79	0.60
6	**Cp**	1.22	1.36	1.33	1.14	1.39	1.21	1.33	1.22	1.29
	Cpk	0.93	0.83	0.86	0.65	0.91	1.01	0.93	1.18	0.91
8	**Cp**	1.63	1.81	1.78	1.52	1.86	1.61	1.77	1.63	1.71
	Cpk	1.24	1.10	1.15	0.86	1.21	1.35	1.25	1.58	1.21
10	**Cp**	2.04	2.26	2.22	1.90	2.32	2.01	2.21	2.04	2.14
	Cpk	1.55	1.38	1.43	1.08	1.52	1.69	1.56	1.97	1.51

Based on the planned amount of WMMR, all years have less stability, and different years became stable, namely 2017 and 2019. However, these years are only stable for 8σ, which is a high specification width. This year's performance can be explained by the airline's situation. Because of the limits regarding flight movements, the decision was made to make as many flights as possible at the expense of maintenance. However, if you structurally perform insufficient maintenance in the years after, it will pay back. However, because COVID-19 came and the aircraft was on the ground all the time, available for maintenance, this payback is not seen. However, it can be concluded that no year performed well based on the capability analysis. The capability will be included in developing a future state for airline planning.

5.4.2. Performance per aircraft per year

Capability analysis is not the only way to determine the stability. Other aspects that can be considered are the mean and standard deviation of flight and maintenance during this period. This is analysed for different aircraft types to consider the performance per type. Table 5.8 shows the yearly averages for WMMR per aircraft per type. Table 5.9 shows the yearly standard deviation for the WMMR per type in hours. The standard deviation is a critical measurement to determine stability. Few maintenance or flight fluctuations occur when the standard deviation is low, which is preferred. The reason why per aircraft is an important aspect is that it considers fleet development. It can be seen that for the Boeing 787, the data is unclean. The reason for this is the phasing-in of the aircraft type from 2015 on. 2022 is deviating from the previous years. This can be explained by the flight trends after COVID-19, even though Aviation quickly recovered after COVID. Still, flights have not reached the pre-COVID numbers. This is why the Mean flight hours per aircraft are relatively low and the mean maintenance hours are high compared to other years.

Table 5.8: The mean of the WMMR per aircraft in hours

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
777	7.46	6.62	6.28	5.66	5.46	4.81	4.39	2.62	7.78
787	0	0	0	1.69	5.86	5.43	6.26	6.23	11.85
747	9.61	9.23	8.67	8.81	8.21	7.50	8.06	9.50	7.97
330	11.70	8.99	8.68	8.68	9.76	8.24	7.32	8.68	10.77

Table 5.9: The standard deviation of the WMMR per aircraft in hours

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
777	2.30	1.96	1.86	2.58	1.73	1.24	1.62	1.39	1.89
787	0	0	0	5.92	5.16	3.19	2.47	3.90	4.24
747	2.14	3.31	2.91	2.69	2.28	3.02	2.50	3.90	8.41
330	2.04	2.71	2.14	2.19	4.06	2.42	2.52	2.09	6.85

Table 5.10: The mean of the flight hours per aircraft in hours

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
777	122.9	130.1	129.4	121.8	123.3	125.8	130.4	129.85	109.5
787	0	0	0	6.04	105.7	125.37	124.1	126.6	118.6
747	103.83	109.4	106.8	107.1	103.9	100.8	100.5	100.6	77.37
330	103.5	110.8	118.0	115.6	106.6	105.4	94.9	112.3	94.49

Table 5.11: The standard deviation of the flight hours per aircraft in hours

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
777	4.69	4.63	4.99	5.33	5.01	7.66	5.54	4.91	10.12
787	0	0	0	21.0	22.2	8.15	7.91	6.80	8.79
747	10.72	5.36	4.92	5.31	7.18	7.13	7.12	7.16	29.03
330	9.77	7.04	3.69	5.47	6.51	18.0	6.99	11.90	16.61

No real trend can be identified for most of the weekly minimum maintenance requirements per aircraft. 2014 and 2016 do not stand out positively, and other years mostly do not in a negative way. 2017 and 2019 show positive results with a low mean and standard deviation. For flight hours, no clear trend can be identified as well. Only a serious decline in 2022 for the Boeing 747 and the Airbus can be found. This applies to the mean and the standard deviation for these types in 2022. 2022 also is the year where the average flight hours per aircraft are the least of all years. However, 2017 and 2019 score worse when looking at the flight deviation because it is relatively high compared to the other years.

It is difficult to compare the years based on this data. However, 2017 and 2019 are pointed out in the capability analysis, mean values and standard deviations. Where 2019 has the best performance. When looking at the overall flight data in Figure 5.4, this was the year when most flight minutes were performed. This view of 2019 as a good performing year is further strengthened when looking at the difference between the performed and planned amount of WMMR in Table 5.2. Here, the difference between planned and performed is relatively tiny, indicating that not much extra WMMR had to be created. Based on the performances, WMMR amounts can be selected.

5.5. WMMR amount selection

In this section, different amounts will be selected for the WMMR. This will be done based on the process capacity analysis and the model results. The values will be fed into the model to determine whether they suit the airline's maintenance demands. From the previous analysis, it came forth that 2017 and 2019 were years with good performance. They had a mean WMMR of 441 and 469, respectively. These values are lower than the mean over the entire period, which is 526 hours per week. However, these are mean values, so they do not mean how much time was reserved in advance for maintenance. A tool that helps with determining the requirements is a cumulative calculation. This cumulative distribution is shown in Figure 5.23.

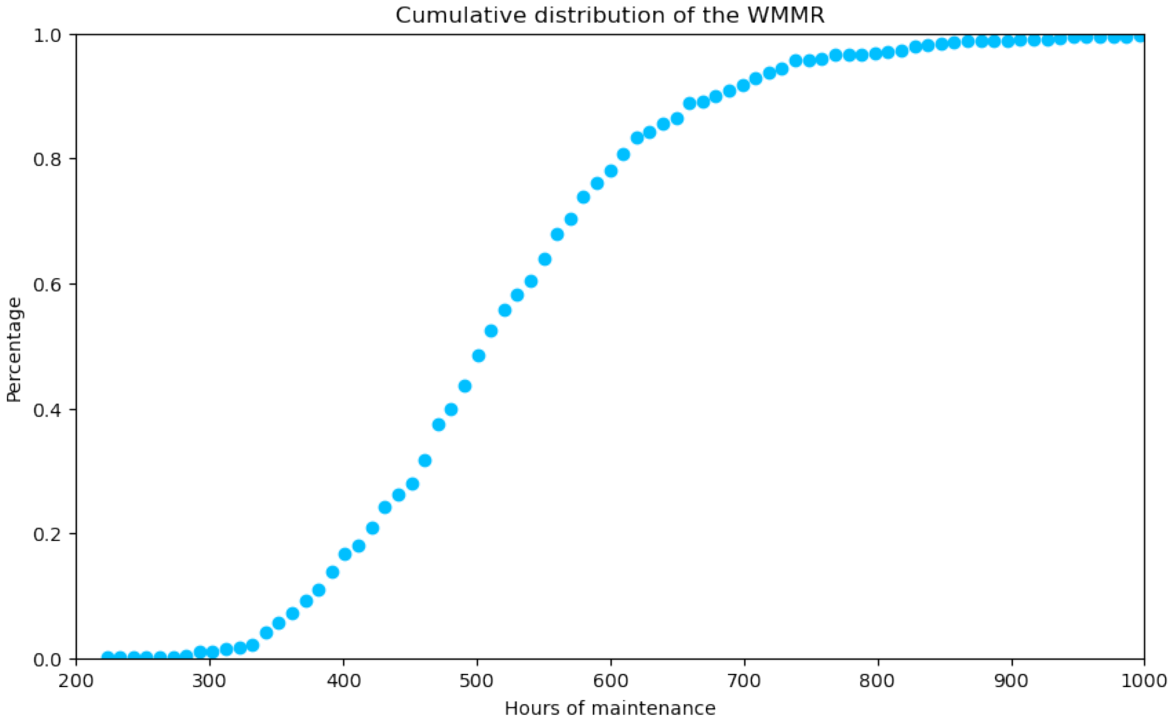

Figure 5.23: Cumulative distribution of the WMMR

A cumulative distribution function (CDF) tells you the probability that a random variable is less than or equal to a specific value. It accumulates probabilities as you move along the variable's range. The CDF starts at 0 and increases to 1, showing how likely lower values are. It's useful for finding probabilities and percentiles and understanding a distribution's characteristics. The cumulative distribution function is presented in such a way that it shows the hourly increase with each percentage. For example, to be at a percentile where the probability that the value will be less than 80% is 600 hours. If the aim is to have 90% of a probability that the value is lower, 700 hours is required. Thus, a number can be found where to find the right balance. But the aim should not always be to get the highest percentage because there comes a point when the increase in percentile does not justify the increase in the number of hours. In a normal distribution, this point is around 80 %. That is why it is an important probability to consider.

In Figure 5.23, 80 % of maintenance corresponds to a value of 602 hours. As mentioned earlier, the mean value is 526 hours. However, the mean is not similar to the 50th percentile. The mean value has the probability of it being lower is 55 %. With an increase of 14 % of the value, an increase of 25 % of the probability can be achieved. 14 % corresponds with 75 extra hours of maintenance. If another 75 hours are added to 601, 676 hours is the result. This number corresponds to 90% of all maintenance. Thus, with a similar increase now, instead of 25 %, there is only an increase of 10%. However, these values of 526, 601 and 676, which are 55, 80 and 90 %, respectively, are nowhere near the amount of planned maintenance. This amount is shown in Table 5.12. The amount of planned hours vs. the CD function is displayed here.

Table 5.12: Planned versus the CDF function with the probability of it being lower

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
Planned hours	576	519	454	430	427	394	403	460	479
Probability (%)	73.9	55.9	28.2	24.2	20.9	13.4	16.8	31.7	39.8

It can be concluded that currently, there is no standard in place at the airline that determines how much of the maintenance should be reserved time for. Next, it is important to understand what probability corresponds with what amount of hours. These values are displayed in Table 5.13. The right balance is where the step size in hours is still quite small compared to the step size in percentage. This equilibrium is more or less found at the 80th percentile. From the 80th to the 85th, the step size in hours increases, compared with the step size from 75 to 80 %.

Table 5.13: CD function with the probability of it being lower with the corresponding number of hours of maintenance

Probability(%)	20	30	40	50	60	70	75	80	85	90	95
Hours	415	453	478	500	534	564	580	601	630	674	726

In Figure 5.24, the cumulative distribution of the WMMR is displayed together with the 80th percentile. It can be seen that the 80th percentile is at the section in the figure where the steepness of the distribution is declining. After the 80th percentile, the percentile increase is relatively low compared to the increase in hours. Thus, it is the right balance for the maintenance ground time reservation.

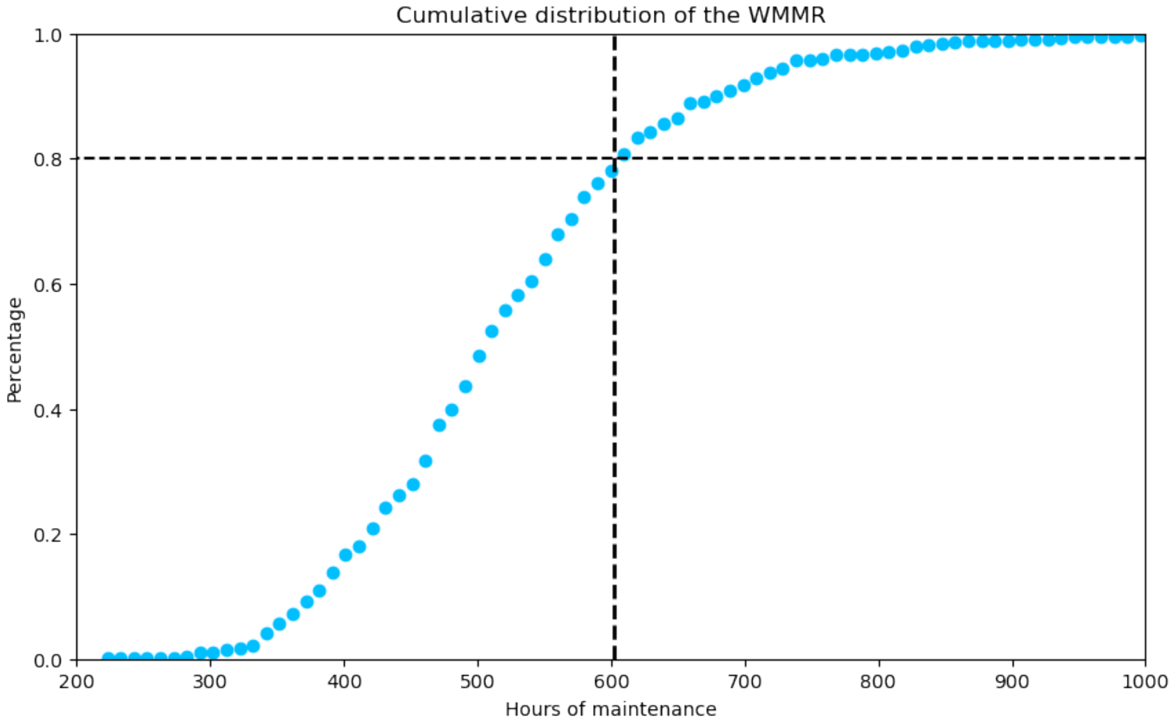

Figure 5.24: Cumulative distribution of the WMMR with the 80th percentile highlighted

Thus, based on these calculations and a selection of 80 %, the hours for the weekly minimum maintenance requirements come to 600. This means 600 hours of maintenance are required per week to fulfil 80 % of the high-priority maintenance demands. If this is calculated to a value of hours per aircraft, it comes to 8.6 hours of maintenance per aircraft per week. This number is received by dividing 600 by the average fleet count of 70 aircraft. However, it is also crucial to consider other probabilities. Thus, 50, 60 and 70 % will also be considered.

5.6. Medium priority maintenance codes

Now, the high-priority maintenance codes have been analysed. The next step is to analyse the medium-priority maintenance codes. These maintenance priorities include high-priority codes together with medium-priority codes. These extra medium-priority codes are mostly non-routine codes. In Figure 5.5, there was a trend between flight and maintenance. This trend showed that they had opposite peaks of each other, similar to a cosine and sine function. However, now, with more non-routine codes, this trend is reversed. Now, the maintenance peaks are identical to the flight peaks. This relation between the trends is shown in Figure 5.25. It can be concluded that these non-routine codes heavily impact the planning and are an effect of high flight hours.

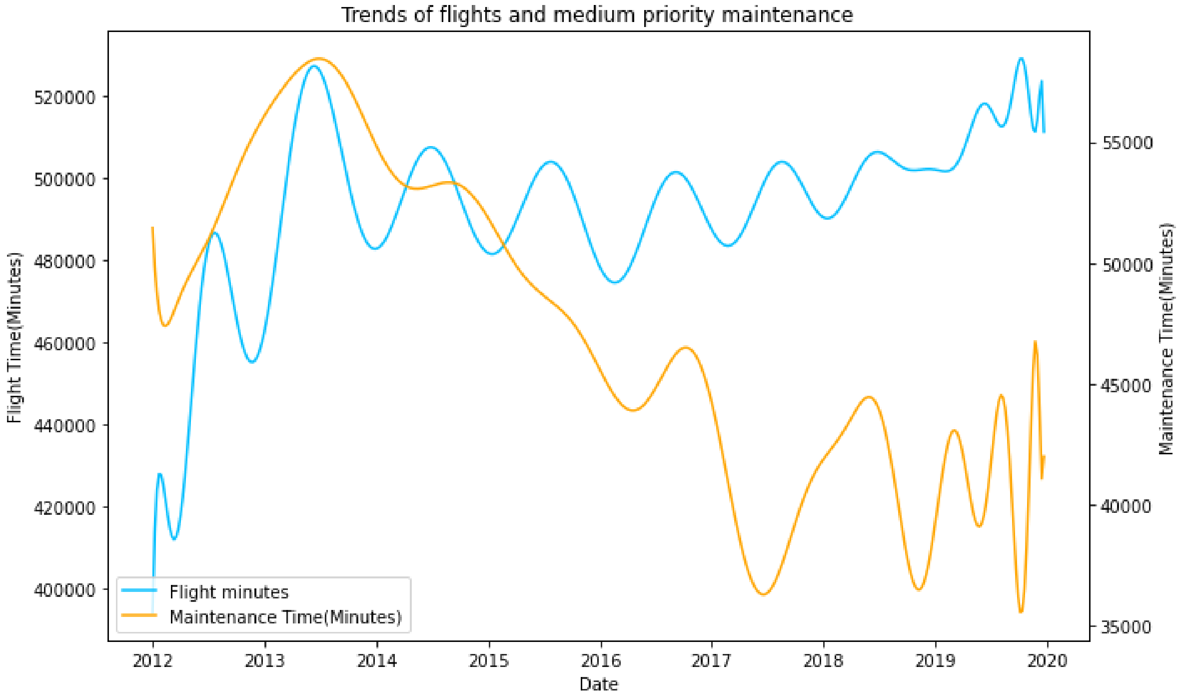

Figure 5.25: Trend of flights versus medium priority maintenance

Table 5.14: Average weekly hours spent on medium priority slots for the Boeing fleet and the whole fleet

Type/Year	2012	2013	2014	2015	2016	2017	2018	2019	Total
Boeing	603	591	565	579	573	516	549	551	566
All	831	980	874	826	748	657	685	693	786

In Table 5.14, the yearly average of hours per week spent on medium-priority maintenance is shown. This is separated into two categories: Boeing and the whole fleet. This separation is due to the WMMR rule set by KLM of the Boeing fleet. Next, it is essential to compare the high-priority with the medium-priority slots. This comparison is displayed in Table 5.15. The medium-priority requirement is much higher than the high-priority slots in all cases. The difference between them is found chiefly in AG and RP slots. These are corrective maintenance slots in cases of an Aircraft-On-Ground (AOG). These slots can take longer, especially at a location other than Amsterdam. These slots could take up to 4 to 5 times longer than AOG slots in Amsterdam. Thus, the image sketched here with the medium-priority slots is difficult to compare to reality. Because the medium-priority slots are not part of the WMMR, they will not be considered for determining the weekly requirements. However, if these slots were also part of the WMMR, the maintenance amount would increase significantly, which would be almost impossible for airlines. That is why these slots should not be considered for the WMMR.

Table 5.15: The amount of weekly maintenance for high and medium-priority slots

Category/Years	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
High-priority	588	626	567	555	520	441	435	469	473
Medium-priority	831	980	874	826	748	657	685	693	727

5.7. Conclusion

Thus, now that the analysis is finished answering some of the sub-questions compiled at the chapter's beginning is possible. 1) What are important factors to consider when determining weekly minimum maintenance requirements? the first step was to examine fleet content development and the differences between aircraft types. This analysis found that ageing is not a significant factor because the maintenance requirements do not increase massively with age. However, it could be seen that at a certain point, as was for the M11 aircraft, the benefits of keeping on to an aircraft are no longer worth it. Thus, at the end of the life of an aircraft, the maintenance requirements increase; however, this could be caused by many other aspects, such as it having a lower priority and not being used as much anymore. The most significant difference in maintenance requirements was found between types. It could be seen that the 777 aircraft, which has been part of the fleet for a long time, is so well-engineered and known to the maintenance provider that it requires less maintenance than the newer 787 aircraft. However, the 747 was also part of the fleet for a long time and had higher requirements. So there is also just the difference in type. The 747 is a larger plane, and its design is almost three decades older than the 777 aircraft. This could explain those differences. So, aircraft type is an essential factor to consider when determining the weekly minimum maintenance requirements because there are considerable differences between types.

2) What are the weekly minimum maintenance requirements? This question can not be answered directly because it depends on the strategy—the strategy means what percentage of maintenance would like to be reserved in advance. If this is only for 30%, then the WMMR are lower than when the goal is 80%. However, the direct answer is somewhere in between these values. Based on the historical data, the WMMR can be determined what the WMMR are for the different probabilities. An airline that is short on workforce capacity might not even be able to reserve 80 % of the maintenance even though that would be its aim. An airline should then make its decision based on its strategy and limitations. However, if 30 % is chosen as a strategy, the consequences should be understood. These consequences are that in 70 % of all weeks, additional, not planned maintenance slots are required. Or the maintenance has to be performed in other slots for which it is not designed.

The medium-priority slots are not to be considered for the WMMR. Reserving ground time for these non-routine checks is unrealistic in several ways. First, the amount of ground time that should be reserved is almost double compared to the high-priority slots, which makes it almost impossible for airlines to reserve. Second, the medium-priority slots are largely unpredictable in nature. This means that it is difficult to plan sufficient maintenance unless new technologies such as predictive and condition-based maintenance are used.

3) How should maintenance ground time be distributed? Based on the analysis of the occurrence and length of specific checks, a basic amount of checks and hours can be estimated. However, if only based on this data a distribution is made, it is solely out of the vision of the maintenance provider. However, the stakes of all the stakeholders should also be considered. The service provider requires a 130-minute turn time between flights and maintenance, and the flight provider requires the aircraft to be available for as much time as possible. Thus, how long these checks must be must consider all providers' limitations and constraints. In the next chapter, a future state will be designed to evaluate these constraints.

6

Future state design

In this chapter, a future state will be designed, and then this future state will be verified and validated. The following questions will be answered in this chapter:

- How would a future state look like?
- How can the model be verified?
- How can the proposed future state be validated?

In the previous chapter, the analysis was completed. It is time to combine the information from the analysis to design a future state. The first step is determining what checks will be used and their length. The next step is determining how often they will occur, depending on the probability goal. Finally, the impact on the plan will be calculated.

6.1. Slot types and occurrence

Now the WMMR and their probabilities are known, the next question is how to distribute this time throughout the week. This distribution will be determined based on slot lengths from 2012 to 2022. The high-priority slots will be analysed with the occurrence of the slot and the distribution of the slot lengths. For this analysis, the period for 2012-2019 is considered, and 2022 is left out of the scope. Thus, because they did not exist yet, the TY and TZ codes are taken out of consideration. The occurrence count per code is provided in Table 6.1. The second row shows how much of these codes occur every week on average.

Table 6.1: The occurrence count per check in the period 2012-2019 with the number of counts per week

Category/Check	**P+**	**H**	**TD**	**NR**	**WK**
Count	10574	1443	3352	6438	3660
Counts per week	25	3.5	8	15.5	8.8

Next, knowing how often a check occurs per aircraft is important. This could determine how often a check needs to be planned for an aircraft. For example, how often does an aircraft have a P+ of H check? This question is solved by dividing 1 by the (count per week/fleet count). The fleet count is taken to be 70 aircraft. However, because the WK codes only apply to Airbus, the Airbus fleet count is taken to determine their frequency, which is 17. These calculations' results are shown in Table 6.2.

Thus, from Table 6.2, it comes forth that an aircraft has a P+ check once every 2-3 weeks, an H check once every 20 weeks, a TD check once every 8-9 weeks, an NR check once every 4-5 weeks

Table 6.2: The occurrence frequency per check in the period 2012-2019

Category/Check	P+	H	TD	NR	WK
Frequency	2.8	20	8.8	4.5	1.9

and a WK check once every 2 weeks. Based on these results, it is possible to determine how many checks should be planned. Also, the length and whether it is on the platform or in the hanger can be determined. The next step is to consider the length of the checks. Similar to the overall maintenance distributions, a ratio must also be determined here. Because 100 % of the H checks are within 10 days, it should not mean that all H checks should have this length. Again, several probabilities are considered. The probabilities with outcomes are displayed in Table 6.3. The probabilities shown in Table 6.3 are determined by Poisson distributions. Thus, based on this information, a distribution will be designed in the next chapter.

Table 6.3: For every check what the amount of hours is for different probabilities

Probability/Check	P+	H	TD	NR	WK
50	2	8.1	10.2	3.7	2.9
60	2.9	11.5	13	6.35	3.6
70	4.1	16.7	16.3	9.6	4.1
80	6	21	20	14.8	5.7

6.2. Turn time

A part of the future design is a new use of the turn time. So, the turn time is the time between flights and maintenance, flights and flights and maintenance and flights. In subsection 4.2.2, an evaluation of the activities and their value to the operation was completed. This analysis aims to determine how much free time there is and how this could be used in a way that adds value. Currently, the turn time is also being used for maintenance. However, this does not show in the MFT plate. In the program that runs the MFT plate, there is a minimum time that has to be present between slots, which is the same as the Combi-embarking time. This causes a lot of trouble for the airline. When there is a slot flight-flight, there could be a turn time of 4 hours. From Lean Manufacturing, the aim would be to use much of this time for maintenance because there would still be much time left besides the embarking. The turn time minus the activities will be considered to determine the actual free time. Figure 6.1 shows a breakdown of the turn time. The codes are mentioned below the figure. The MFT plate is broken down into different levels in the Cyrus model. Level one is the level where the flight and maintenance slots are located. However, they do not provide any insight into what happens between the slots. Level 2 is where the turn time is located. Thus, it calculates the time between the slots. the third level breaks down the turn time into the activities it recognises. These consist of the activities such as embarking and towing. The towing depends on the maintenance slot, whether the maintenance is performed on the platform or in the hangar. The final level is level 4, where the remaining free time is calculated. This free time is non-necessary and non-value added and should be transformed into value-added activities according to lean manufacturing.

- CE = Combi-embarking
- DE = Disembarking
- E = Embarking
- TH = Towing hangar
- TP = Towing platform

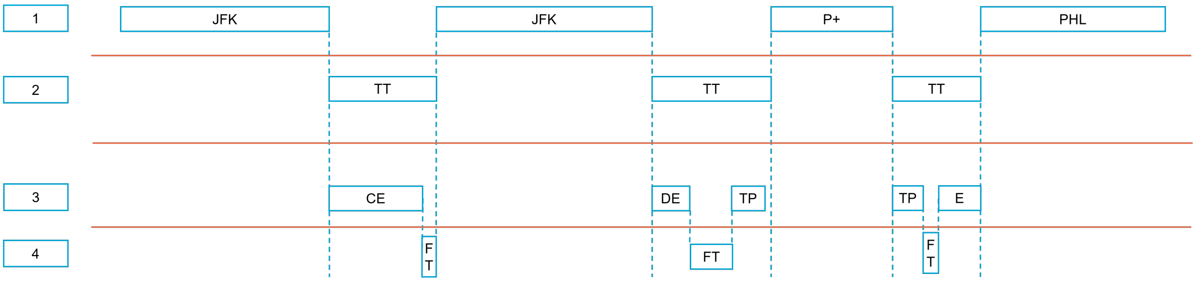

Figure 6.1: Turn time breakdown

- FT = Free time

First, the steps between levels 1 and 2 will be analysed. This is the turn time calculation based on the ending and starting times of slots and whether they are at Amsterdam Airport. This means that turn time positioned at other stations abroad is not considered. However, in an ideal world, maintenance would also be performed here if there is time. This is not part of the scope of this thesis and will not be considered potential maintenance time.

One crucial item that must be considered is a rule built into the tool that shows the MFT plate. This tool only allows a minimum time between 120 and 130-minute slots, depending on the aircraft type. This time is the same as the combi-embarking time. Thus, on all occasions, the minimum time should not exceed the combi-embarking time. Afterwards, when the exact times of flights are known, times less than the combi-embarking time could occur. That it does not occur is shown in Figure 6.2. A vertical line is drawn at the 2-hour mark. Just in a few cases, the turn time dips below two hours. Next, it can be seen that a large proportion of the turn time fits within 5 hours. However, these 5-hour and longer turn time slots do occur.

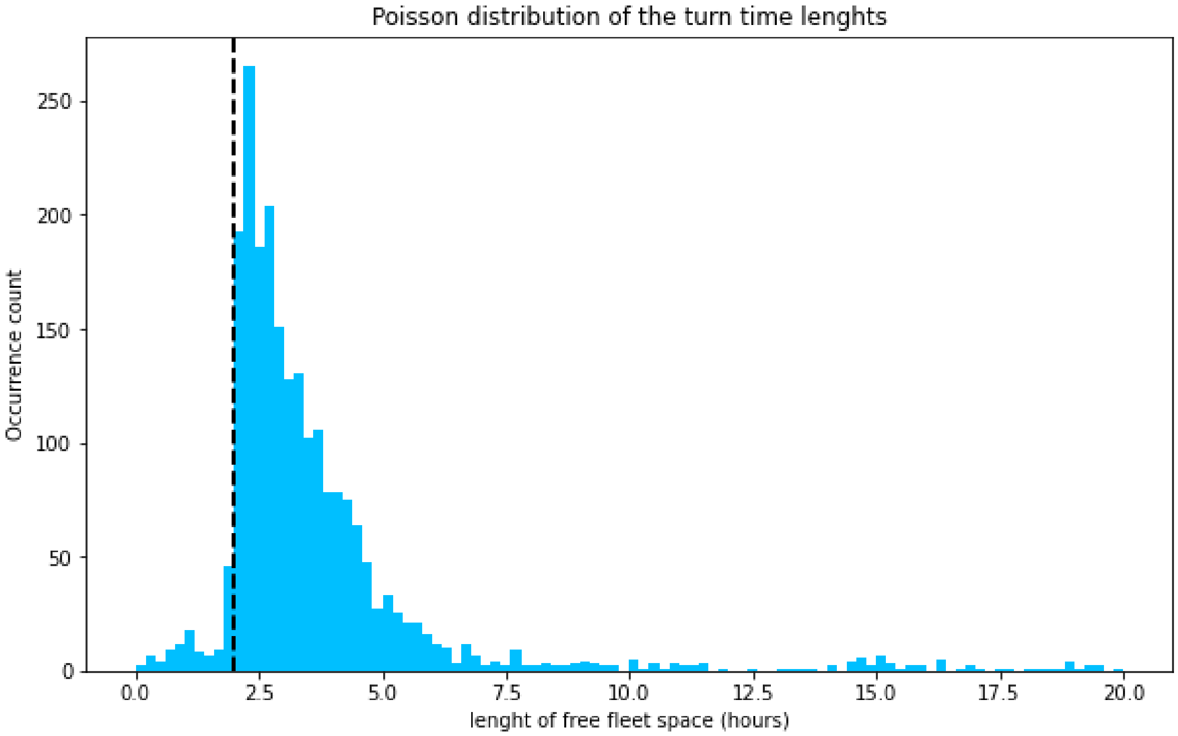

Figure 6.2: Poisson distribution of the turn time lengths

Now the turn time is analysed, it is time to move downwards to levels 3 and 4 of the breakdown in Figure 6.1. The step is straight towards level 4 by subtracting the values of level 3 from level 2. Three different kinds of free time are identified—the free time between flights, between flight and maintenance and between maintenance and flight. The three free-time distributions are displayed below. It can be seen in Figure 6.3 that the free time between flights is limited and, thus, difficult to fit in extra maintenance slots. It also shows that the airline can plan flights together to maximise utilisation. The free time between flights and maintenance slots is already larger than between flights shown in Figure 6.4. This is similar to the free time between maintenance and flight slots shown in Figure 6.5. This means that the airline cannot fit maintenance and flight slots together in the same planning as it can fit in flights. The failure to properly connect maintenance slots in flight planning causes much waste. If expressed in numbers, total free time before and after maintenance slots comes to 21 hours of waste per week. Better fitting the maintenance slots into the flight planning allows the airline to transform the waste into value-added maintenance time.

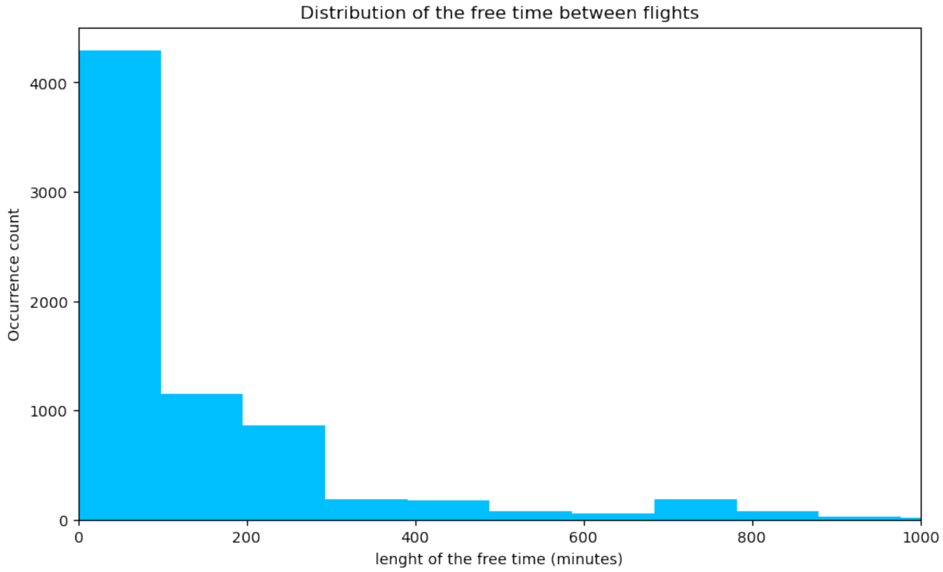

Figure 6.3: The free time between flights

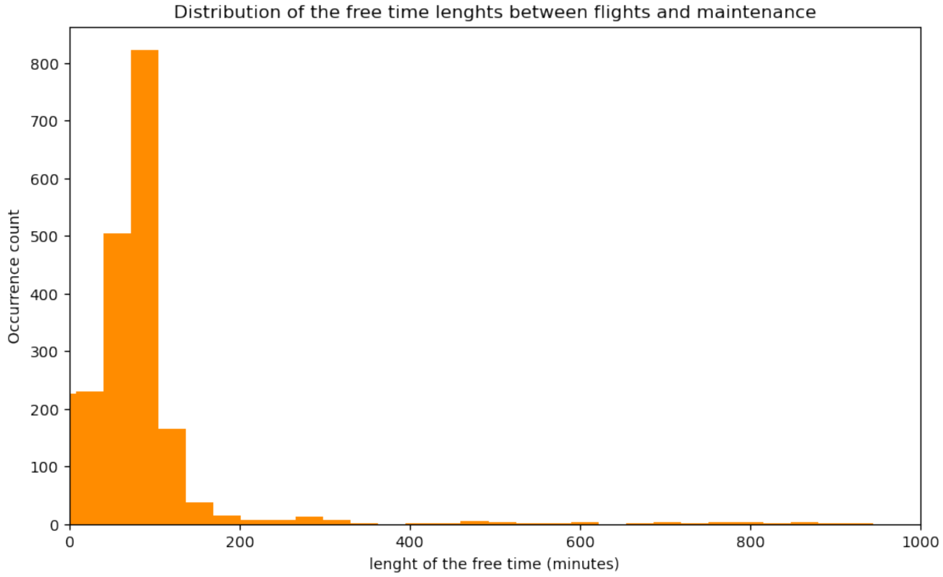

Figure 6.4: The free time between a flight and maintenance slot

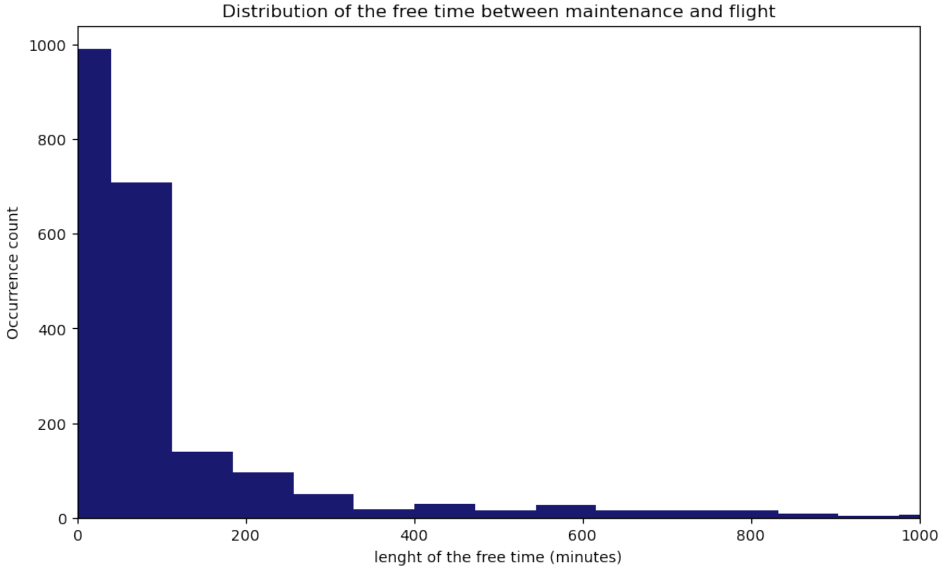

Figure 6.5: The free time between a maintenance and flight slot

The next step is to see whether it is possible to fit maintenance into the available free time. However, problems do arise when fitting. Because the minimum time between slots is always present, fitting a 2-hour maintenance slot into a 4-hour turn time gap is difficult. The way this works is as follows. For example, currently, there is a turn time between flights of 240 minutes. When calculating the free time, 130 minutes is subtracted from the 240 minutes, which comes to 110 minutes left for maintenance. However, when a maintenance slot is fitted in this space, the minimum time between the slots has to be at the front of the maintenance slot and at the back. This means that if maintenance wants to be fitted in there, it requires an extra 130 minutes. This problem is depicted in the following figures. First, Figure 6.6 shows the amount of time between two flights and the subtraction of the Combi-embarking time.

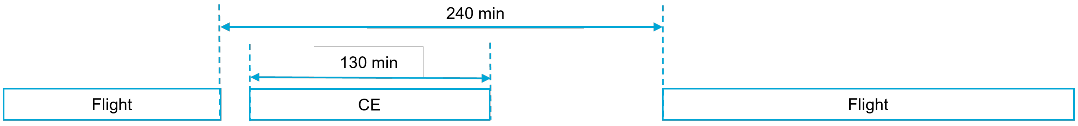

Figure 6.6: From this level, 110 minutes of free time could be used for maintenance

The next step, shown in Figure 6.7, is to fit a 110-minute maintenance slot into the 240-minute turn time. However, when the Disembarking, embarking and towing times are added, the total required time comes to 275 minutes, 35 minutes more than the time available.

In Figure 6.8, the maintenance slot is fitted in the 240-minute turn time. The maintenance slot cannot extend more than 75 minutes. which is 35 minutes less than the previous maintenance slot. 75 minutes could still be sufficient to perform maintenance. However, the amount of tasks that could be performed is more constrained now.

The previous figures still sketch an ideal scenario. However, both scenarios are impossible because of the MFT program's rules. The real scenario, which would look like for KLM in practice, is shown in Figure 6.9. Here, between the slots, a time of at least 130 minutes has to be maintained. However, if a maintenance slot of 110 minutes wants to be performed, it now requires 370 minutes. Thus, it exceeds the previous turn time of 240 minutes by more than 2 hours, which is devastating to flight planning. Also, in the 370 minutes, new gaps of free time are created. 95 minutes of non-necessary, non-value-added waste is added to the operation.

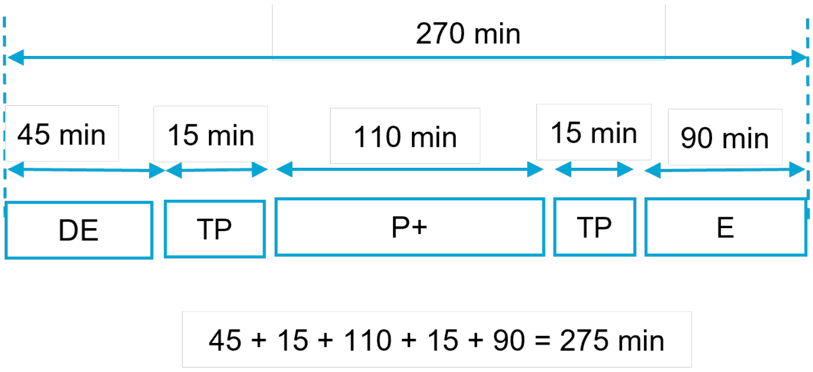

Figure 6.7: When fitting a platform maintenance slot of 110 minutes into the turn time, the total required time comes to 270 minutes

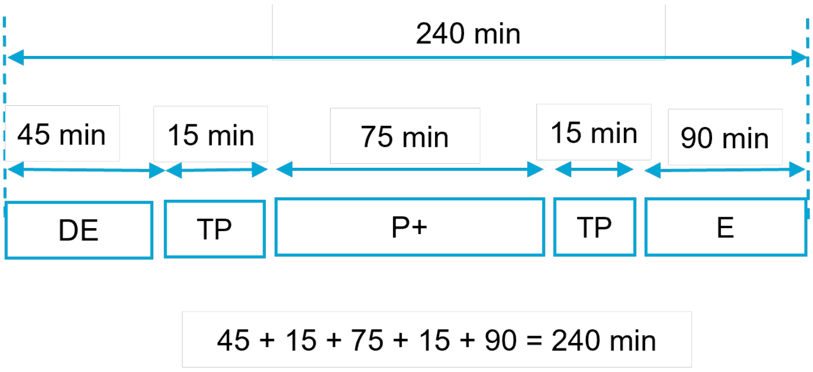

Figure 6.8: When fitting the maintenance slot back into the 240 minutes, a maintenance slot of just 75 minutes remains, which is 35 minutes less

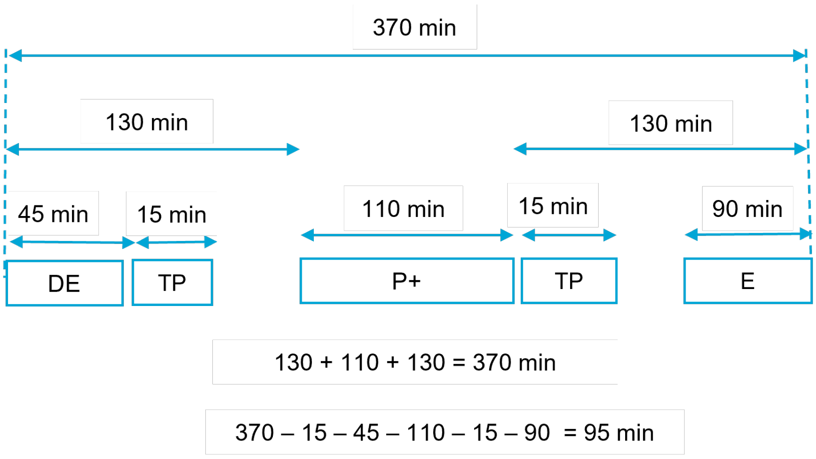

Figure 6.9: With the current rule of the MFT program in place, the total required time comes to 370 minutes

Thus, there is a program with officially planning maintenance slots in the turn time. Most maintenance during the turn time is not put into the MFT plate. That is why it does not show. However, this maintenance is also not bound by the constraints of the MFT plate. If the non-necessary, non-value-added time wants to be transformed into value-added maintenance time, these MFT constraints have to be reconsidered. However, if these rules of the MFT program are not considered, there is time available for maintenance. Thus, this is also where the data constrains this thesis.

6.3. Check length

The check length will be determined based on the length distribution per check and its impact on the plan. In this plan, the current constraint of the 130-minute rule for the MFT plate will be assumed to remain. This rule will impact how much it will say in the planning and how much actual time for maintenance there is. Also, the impact of a hangar instead of a platform check is considered.

First, the platform check will be considered. Based on the turn time length distribution, what kind of platform checks can be determined in the planning without interfering with the number of flights can be determined. The analysis shows that the most free time is before and after maintenance slots. However, if the new platform slots want to be fitted into the flight plan, the focus should be on the time between flights. The time an aircraft is not on the home site will be taken to determine the ideal time. Figure 6.10, shows a distribution of the turn around lengths. A turnaround is when an aircraft is away from its home location. For example, there is a flight at 20:00 from Amsterdam to New York. The following day, the aircraft arrived at Amsterdam again at 18:00, meaning the total turnaround time was 22 hours. In the turnaround time, two separate peaks are observed. The first peak is located around 24 hours. The second peak is located around 33 hours. These peaks are explainable. For 24 hours, the ICA fleet has either a day or night flight, and because most turn around consists of two flights, it will arrive back at its home location around 24 hours later. The 33-hour peak is explainable because there are occasions when an aircraft has a second destination flight. For example, there is a flight from Amsterdam to Singapore. Then, from Singapore, the aircraft has a second flight to Bali. From Bali, it goes back to Singapore and then back to Amsterdam. This second flight is shorter and will be done on the same day. However, this adds another 10 hours to the turnaround time.

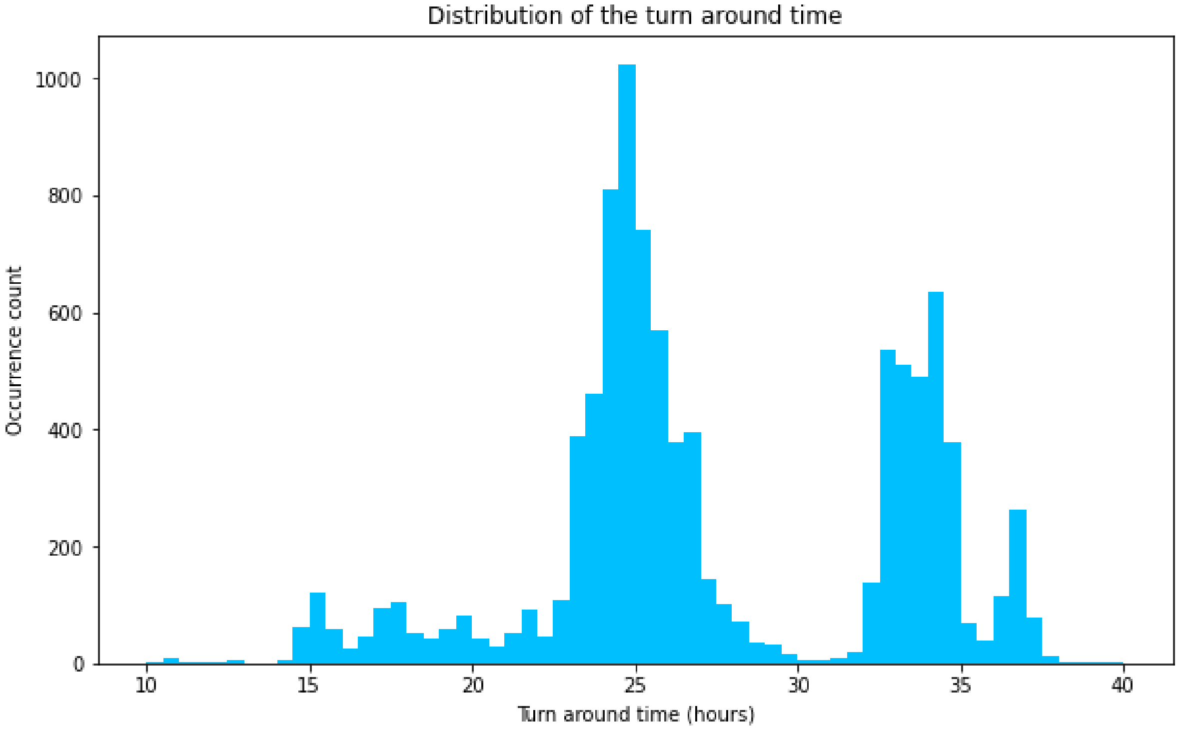

Figure 6.10: Distribution of the length of a turnaround

Based on the distribution in Figure 6.10, it can be determined that a 24-hour check is easy to fit into the flight plan. This is because an aircraft is then just not able to fly for an entire turnaround. However, the impact on the flight plan should also be minimised when planning shorter checks. For this, it is important to know when the aircraft arrives at the home location and when they depart again. Thus, in Figure 6.11 and Figure 6.12, the arrival and departure times are plotted respectively to see whether there is a specific interval in which most of the aircraft arrive and depart. A gap between the arrival and departure peak can usually be found, which is around 130 minutes or more. This is the exact time of the constraint. The time of departure or arrival is mostly dependent on the destination. This has to do with time differences with other countries. However, certain gaps can be found where maintenance could be possible without interrupting the flight schedule too much.

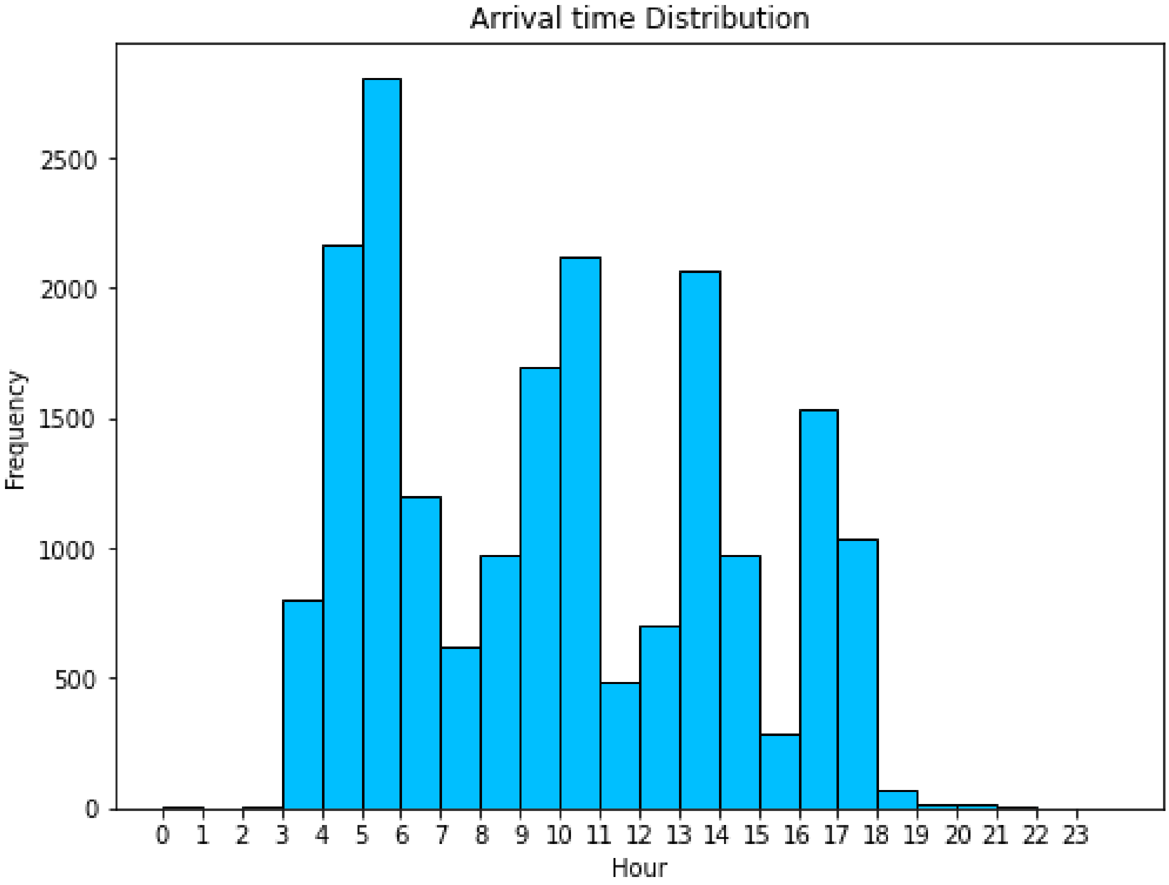

Figure 6.11: Arrival time distribution

Thus, based on these arrival and departure times, several slots can be identified that can be used for maintenance. However, this is not that straightforward. It can be seen that most of the arrival times are early in the morning, and departure times last until the afternoon. However, an aircraft that arrives at 5 o'clock in the morning will probably leave around 9 again. And thus, will not wait until 14:00 hours. To create longer time slots, aircraft have to be switched around, which creates more time for maintenance slots for some aircraft but will also decrease the turn time for other aircraft. This becomes an aircraft assignment problem to solve.

The identified slots are morning, midday, evening and night slots. These slot times and the number of available hours are shown in Table 6.4. An important note is that this is the time between the arrival and departure of an aircraft. This means the available time includes embarking and towing (if required). Thus, this is not the available maintenance time. Thus, the first for the morning slot means the aircraft becomes available between 5:00 and 7:00, and it becomes unavailable again between 12:00 and 14:00. Thus, its flight arrival is between 5:00 and 7:00. Its flight departure is between 12:00 and 14:00. This creates a slot which has a length between 7-9 hours. However, when an aircraft arrives between 5:00 and 7:00, it will be leaving again between 8:00 and 10:00. So it does skip the first wave of departure, which in a world without maintenance, it would take. This is similar to the other slots where a peak in departure follows 2 hours after an arrival peak. However, 130 minutes is too short to perform maintenance, so these turn time slots must be expanded to allow maintenance to be per-

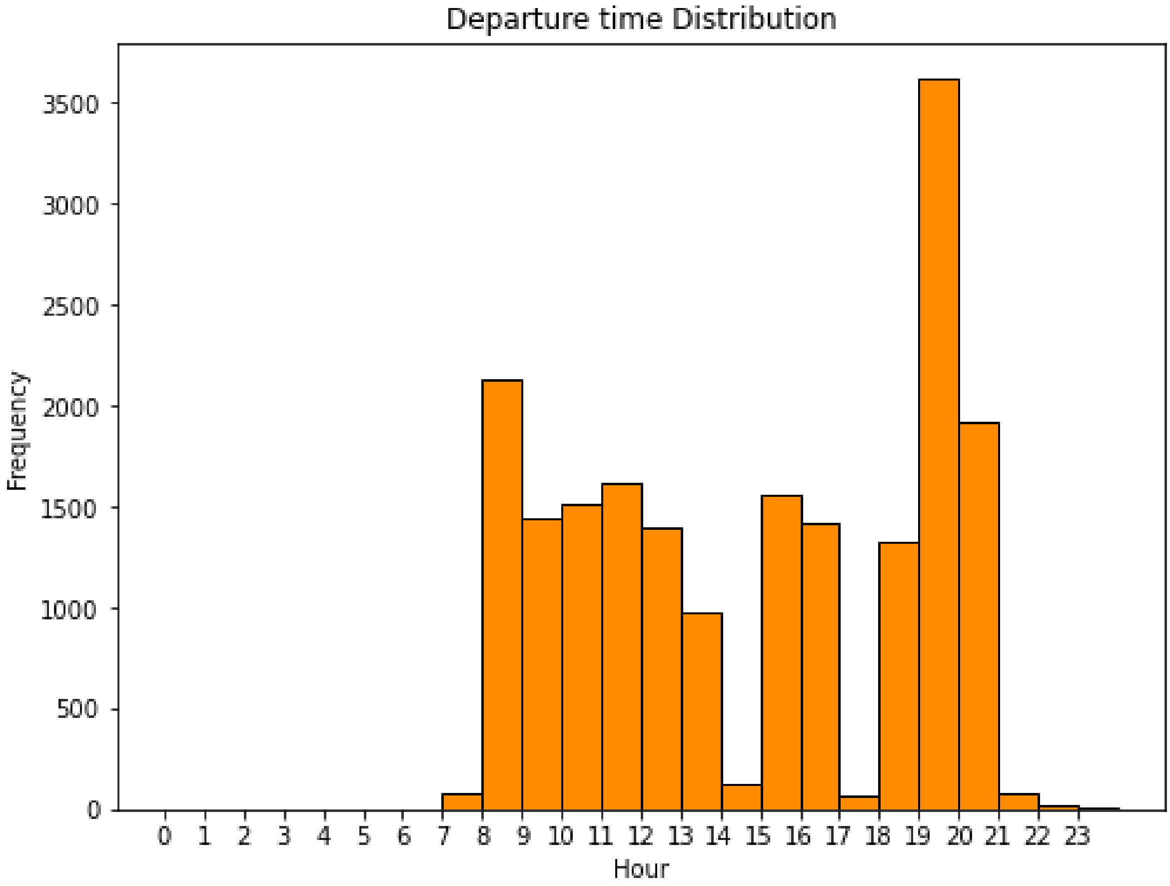

Figure 6.12: Departure time distribution

formed.

Table 6.4: Available periods in planning

	Time slot 1	*Available hours*
Morning	5:00-7:00 & 11:00-14:00	6-8
Midday	9:00-10:00 & 15:00-17:00	6-8
Evening	13:00-15:00 & 18:00-19:00	6-8
Night	19:00-21:00 & 7:00-9:00	12-14
All day	5:00-7:00 & 18:00-19:00	10-12

Based on these identified slots, slots can also be combined to require different lengths. These combinations are displayed in Table 6.5. Only combinations that can occur in one day are displayed because it is possible to tie even more slots together to retrieve a multiple-day slot. Again, the slot length is similar to the available maintenance time in the hangar.

So, now the slot periods are identified. The next step is to assign maintenance slots to these periods. However, there are some issues regarding this. If a 6-hour turn time slot is available during midday, it is impossible to fit a 6-hour maintenance slot. Because this maintenance slot can not exceed 6 hours, there are limits concerning the check length. This limit is more of a constraint explained in the previous chapter on the 130-minute rule. This means that when a 6-hour maintenance slot is

Table 6.5: Available slot combinations in one day

Morning	x					x					x
Midday		x				x	x			x	
Evening			x				x	x		x	
Night				x				x	x	x	x
All-day					x				x		
Slot length (hours)	2	2	2	9	9	4	4	12	20	18	14
P available (hours)	3.5	3.5	3.5	10.5	10.5	5.5	5.5	13.5	21.5	19.5	15.5
Slot Type	P	P	P	H	H	P/H	P/H	H	H	H	H

Table 6.6: Impact of maintenance slot on MFT plate

Planned length	*Actual time P*	*Actual time H*	*Total time*	*% of maintenance P*	*% of maintenance H*	*Add time*
0.5	1.9	0.5	4.8	39.7	10.3	2.7
1	2.4	1	5.3	45.3	18.8	3.2
1.5	2.9	1.5	5.8	50	25.7	3.7
2	3.4	2	6.3	53.9	31.6	4.2
2.5	3.9	2.5	6.8	57.3	36.6	4.7
3	4.4	3	7.3	60.2	40.9	5.2
3.5	4.9	3.5	7.8	62.8	44.7	5.7
4	5.4	4	8.3	65	48	6.2
4.5	5.9	4.5	8.8	67	50.9	6.7
5	6.4	5	9.3	68.8	53.6	7.2
5.5	6.9	5.5	9.8	70.3	55.9	7.7
6	7.4	6	10.3	71.8	58.1	8.2
6.5	7.9	6.5	10.8	73.1	60	8.7
7	8.4	7	11.3	74.3	61.8	9.2
7.5	8.9	7.5	11.8	75.4	63.4	9.7
8	9.4	8	12.3	76.4	64.9	10.2
8.5	9.9	8.5	12.8	77.3	66.2	10.7
9	10.4	9	13.3	78.1	67.5	11.2
9.5	10.9	9.5	13.8	78.9	68.7	11.7
10	11.4	10	14.3	79.7	69.8	12.2

planned, it does not mean a 6-hour gap between two flights; it is a gap of 10.3 hours. Because, before and after the maintenance check, a 130-minute gap should be maintained. This issue is overviewed in Table 6.6. In the first column, the planned check length is displayed. This is the length of the check, as it will be in the MFT plate. However, as explained before, the total time in the schedule between flights is larger. The total time is provided in the fourth column. So, if a maintenance slot of 1 hour is planned, in total, between the arrival and departure of flights, 5.3 hours are required.

There is also a difference if the check is a platform or hangar check. Because the towing times differ, the free time is higher for the platform checks. This free time could also be used for maintenance. However, if this is the goal, there is not much room in planning for delays. The second column displays the value of the planned check with the addition of free time. This is only relevant for the platform checks because there is no free time available for the hangar; thus, the third column has the same value as the first.

The fifth and sixth columns show the percentage of the total time that could be spent on maintenance for the platform and hangar, respectively. So, this is the actual time divided by the total time. Especially for the shorter checks, the hangar checks have a low utility compared to the platform check. As time increases, the utility and the difference between the hangar and platform become obsolete. This ratio is also the ratio of value-added time out of the total time. So, in the case of a hanger check of 0.5 hours, only 10 % is value-added, and 90 % is necessary non-value-added.

The main conclusion that can be drawn from Table 6.6 is that a short maintenance slot can have a massive impact on the flight plan. Especially for a hangar check, where the ratio of value added to non-value added is the lowest. Thus, the longer the check becomes, the better the ratio of value-added activities. However, it is difficult to set a hard line from where the ratio becomes worth it. The periods in Table 6.4 will be used to determine the planned slot time and the maintenance slot type. In the morning, an aircraft could be available between 6-9 hours. If that is converted to actual planning time, a maintenance slot between 1.7 and 4.7 hours can be scheduled. This is a relatively short slot, which means that if it becomes a hangar slot, the value-adding time ratio is low compared to a platform check. Thus, in this case, a platform maintenance slot should be preferred. Because the total time of 6-9 hours will slightly lean more toward the six-hour boundary, the planned slot will have a length of around 2 hours. If towing, disembarking and embarking are done on time, it becomes possible to perform almost 3.4 hours of maintenance. A hanger slot takes too much non-value-added time to be considered for this short slot. The is similar for a midday and an evening slot, where there is much non-value-added time if performed in the hangar. During the night slots, however, there are 12-14 hours available; in this period, a planned maintenance check between 7.5 and 9.5 hours can be performed. This is similar to an all-day slot. This slot could start after an early morning arrival and finish after a late evening departure. This also has a length between 12-14 hours.

Even though the range is between 6-9 hours, most of the time, the range is 6 hours or less. Only on certain occasions, more than 6 hours will be available. Thus, if stable planning wants to be designed, it should work within 5-6 hours. The night slots differ from this assumption because of the flight schedule. It is common to have between 12 and 14 hours available. In Table 6.7, the lengths of the slots per part of the day are displayed. The first columns show the check type, whether it should be performed at the hangar or the platform. The second column shows the total time required in the schedule, and the third column shows the effective time for maintenance. This does include the current buffer built in by the service provider. These slot times are acquired because they fit into a 24-hour time cycle. Thus, multiple distributions are possible in the form of a 24-hour cycle. Platform checks are not performed at night, so these slots only last less than 10-14 hours.

Table 6.7: Available slots, type and lengths and the actual time for maintenance on the platform for maintenance

Type	Total time	Effective time
P	6	2
P	8	4
P	10	6
H	8	4
H	10	6
H	12	9
H	14	10
H	16	12

One crucial aspect is that slots can be stuck together. If a morning slot has insufficient length, it could be combined with a midday slot. this means that the aircraft's available hours become 8 hours. This means that a 4-hour check is available. This is similar to a 5.4-hour platform check if no buffer exists. This allows the maintenance planning to be more flexible. Based on the occurrence of checks and the probabilities, it is not rare to also have 24-hour checks in a period of 10 weeks. In these cases, an all-day and night slot could also be combined. This is a similar case for all of the periods.

6.3.1. Task priority

Now the different check lengths are proposed, the task priority should be fitted into the schedules. As for checks, tasks were also categorised into priority categories. The distribution of tasks into the checks should also come with this priority. Unlike the papers in chapter 2, there is now a focus on weekly maintenance with more time constraints. Airworthiness is to be prioritised when the time is limited. Thus, scheduling the tasks in order of priority is crucial, starting with high, then medium and finally low-priority tasks. The shorter the check, the more focus should be on the high-priority tasks because if too many tasks are being planned in these slots, delays in flight planning become possible. This should be prevented; thus, it is often better to plan fewer tasks, but they are all completed. Now, because there is a switch to weekly maintenance planning, it becomes easier to pick up tasks in upcoming tasks because checks are plenty. This categorisation and prioritisation in tasks contributes to airworthiness and thus decreases the impact on flight planning.

6.4. Check distribution

Next comes how these checks have to be distributed and how often they occur. This will be done on the registration level. First, recovering the number of hours per aircraft per week is important. This was dependent on the aim for which probability was to be reserved. The number of hours per aircraft per week is displayed in Table 6.8. So, if the airline decides to reserve enough maintenance for 20 % of all weeks, the required hours per aircraft are 5.9.

Table 6.8: Weekly maintenance requirements per aircraft for different probabilities

Probability (%)	***20***	***30***	***40***	***50***	***60***	***70***	***80***
Total hours per week	415	453	478	500	534	580	601
Hours per aircraft per week	5.9	6.5	6.8	7.1	7.6	8.3	8.6

So, the slot lengths and the average weekly minimum maintenance requirement per aircraft are known. Now, a 10-week plan can be designed. For this, seven different strategies can be created. So, for each probability, another method is used. However, there are multiple things to consider when creating such a schedule. Even though performing every check on the platform seems preferable, many checks must be performed in the hangar. Based on the previous input of check frequency. the amount of checks and check types should be determined. However, it is almost impossible to present a working airline plan. Based on the data received, a preliminary schedule will be proposed. This preliminary schedule considers check occurrence, length probability and the identified slots in the schedule. Another consideration is the total daily time because airlines work with 24-hour workforce schedules. Thus, the checks proposed in Table 6.7 form a 24-hour cycle. So, a couple of identified checks and check lengths are listed in Table 6.9.

Table 6.9: Slot occurence

		30 %	50 %	80 %
Check type	**Length (hours)**	**Weekly occurrence**	**Weekly occurrence**	**Weekly occurrence**
P	2 & 4	3	2	2
H	24& 9	4	3	2

This shows how often the check should occur per aircraft. Now, it would be shown what this would look like in a proposed 10-week planning for a single aircraft. However, on a fleet scale, this can look different. Because a 20-hour slot is not 1 20-hour slot but two 9-hour slots combined, which creates a 20-hour maintenance slot. This depends on how many hangar or platform spots are allocated to the WMMR. This amount depends on the airline's available spot and the fleet count.

So, based on these results, a new plan can be proposed. The Cyrus slot distribution also differs from the current state. The new Cyrus state has slots planned in periods that fit better in the flight planning. This can cut excessive free time between Flights and maintenance, as is currently the case. This weekly maintenance should provide the planning with more stability than the corrective system that is in place at the moment. It must be noted that times can always be added up with each other to create larger slots if that is necessary. Also, if the aircraft goes in weekly for maintenance, it is possible to skip a week if other aircraft desire more maintenance. However, postponing maintenance should not be preferred. The new Cyrus state differs from the current state. It has a higher WMMR, thus giving the maintenance provider more time and opportunities to perform maintenance.

Thus, the Cyrus model's proposed plans should decrease the turn time waste because it fits better in the flight schedule. Also, the Cyrus plans will have a WMMR that better matches the historical maintenance requirements. Thus, the Cyrus plans will create a more stable process than the current state.

6.5. Verification

Part of this thesis is data verification. This is crucial because this must confirm that the data retrieved is correct. Otherwise, the results and further analysis are performed with incorrect data. There are a percentage of ways to verify data. The first is expert verification. Where parts of the data are shown to an industry expert, the expert can confirm whether the data is in accordance with the experience he feels. The following way to verify data is to compare it to other data sources within the airline. Because, in this thesis, a new data source is being used. If the results of this source are similar to the other sources, it confirms the data is correct.

6.5.1. Expert verification

The first way of verification is expert verification. Several data results will be discussed with experts from the airline. Next, data retrieved from the Cyrus model is compared to data from other sources within the airline and data is compared to natural limits.

Model verification by expert

The Cyrus model is a new model that reads the data of the MFT plates. To confirm that the data is correct, the multiple steps of the model have been gone through with an expert. To check step by step if the data retrieved is correct with the filtering and whether the data is plausible. This means the checking of flight lengths and maintenance lengths.

Arrival & departure times and slot lengths

The most common arrival and departure times were retrieved from the Cyrus model. These times showed subsequent waves of arrival and around two hours later departure. These waves were displayed in Figure 6.11 and Figure 6.12. The flight provider works with these waves of departure and arrival. Thus, the data was checked by an expert of the flight provider and an expert of the maintenance provider. Both recognised the different waves of arrivals and departures and that the slots between them would also have this length. Then, the maintenance provider confirms that in a 4.8-hour slot between arrival and departure, only a planned slot of 0.5 hours is possible. This also confirms the amount of waste in the turn time currently.

Planned and performed

One of the most essential findings was that the amount of performed maintenance is always higher than that of planned maintenance. This means that there is a structural shortage of maintenance time in planning. This seems unlikely because it would mean that additional slots are put into the schedule every week to perform all that maintenance. Asking experts whether they feel that they put in a lot of new maintenance slots instead of placing the maintenance work in already existing slots confirmed this finding. Weekly, extra slots are put into the planning. Thus, this confirms that the planned amount of maintenance is less than the amount of maintenance performed. However, to check this assumption of experts, two MFT plates are compared, one before and one after. Figure 6.13 shows the planned flights and maintenance slots as they were two weeks in advance, while Figure 6.14 shows the performed flights and maintenance slots in the same period but one week backwards. It is noted there are more P+ checks present than that there were TO-planned, which suggests that additional checks are created. Next, many times, there are these small slots between flights which do not have a maintenance code. These are maintenance slots created in the turn time. Because they are created at that moment, they do not have the planning constraints of the 130-minute turn time rule. However, based on these MFT plates, it can be concluded that many additional maintenance slots are created in the schedule.

6.5.2. Total minutes can not exceed weekly limit

In a week, there are 168 hours available. So, when counting the maintenance, flights and turn time, having more than 168 hours a week should not be possible. If this is generally the case, the data is not as pure as required. When the total amount of Flights, maintenance and turntime are added for this

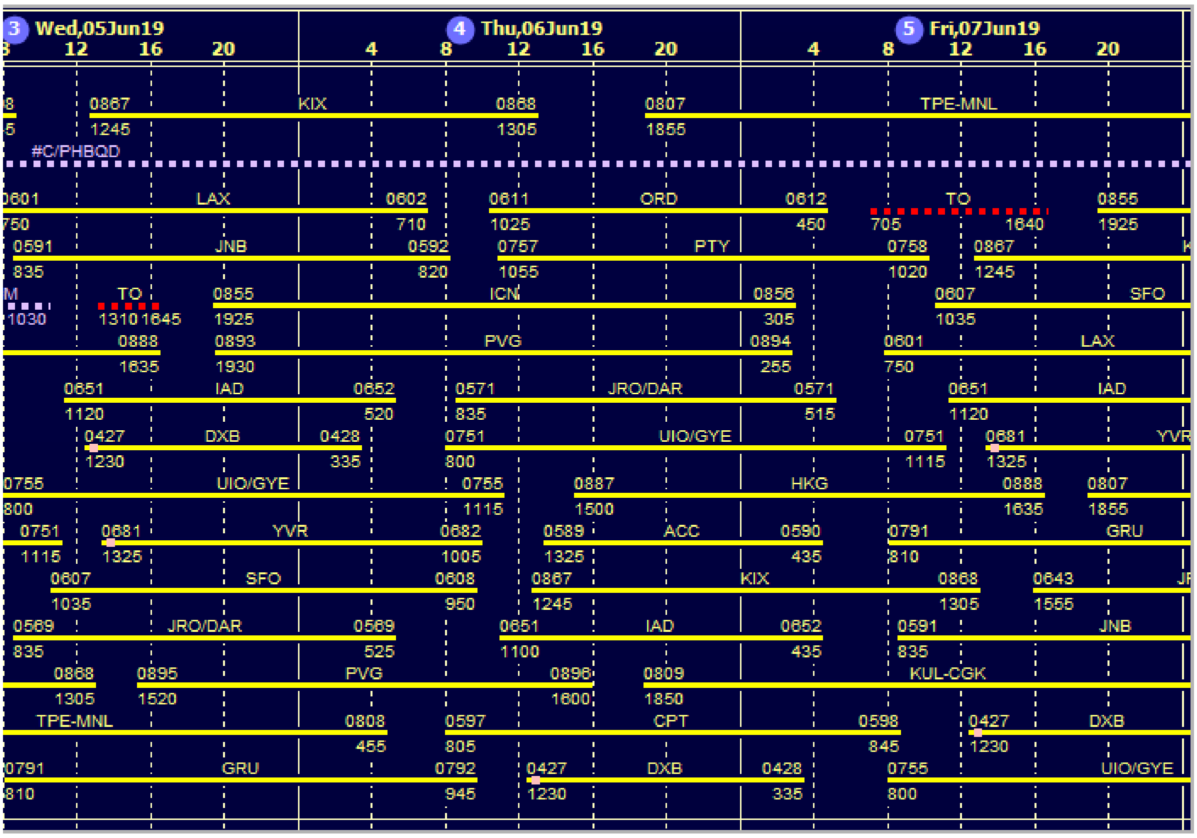

Figure 6.13: The planned flights and maintenance slots for the 777-200 aircraft

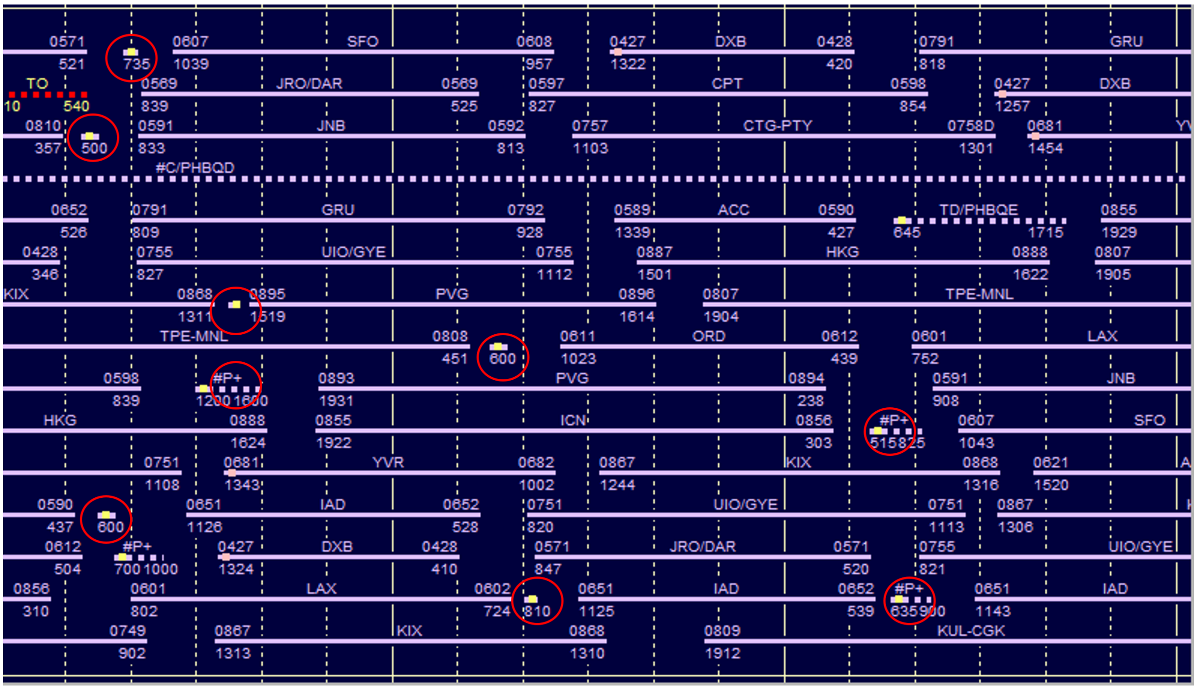

Figure 6.14: The performed flights and maintenance slots for the 777-200 aircraft

verification, a single aircraft is investigated. Flights, Maintenance and turn time are added together from 2012-2019. This provides the total amount of hours the aircraft was occupying these activities. There is also a maximum limit of the number of hours in 8 years. The total hours in these activities should not exceed the maximum time limit. The total number of hours comes to 67234, while the maximum time limit is 69888. This means the total number of hours does not exceed the maximum limit. Thus, it reads the times correctly. This difference explains why the Cyrus model does not read turn time between two maintenance slots. That is why they do not have the same value.

6.5.3. Fleet availability

One of the most known KPIs for an airline is fleet availability, which is also one of the most common goals to maximise this. The fleet availability can be expressed in hours or as a percentage of all available time. Because it is an essential KPI for an airline, KLM has monitored the fleet availability extensively. Because the fleet availability results from an equation with flights, maintenance and turn time as its input, it is possible to compare the results of the Cyrus model with internal sources. Fleet availability is the sum of flights and turn time, and fleet unavailability is the sum of maintenance time. The percentage of flights out of the total time comes to 53 % of the Cyrus model for 2022. Similar results are achieved when comparing the share of flight of the Cyrus model with internal KLM sources, which also provides a value of 53 %. This confirms that the data received by the Cyrus model is similar to other sources.

6.5.4. WMMR from theory

Some theories regarding maintenance requirements exist in the literature. These maintenance requirements can then be calculated, and the impact can be shown on the airline's operation when these requirements are implemented. One of the common rules comes from the Pareto ratio of 80/20. Thus, 20 % of all available time should be allocated for maintenance. Other sources also mention a percentage between 15 % and 20 %. This is similar to the KLM's standard implemented concerning their new Fleet health pilot. Here, the rule is that an aircraft is available 20 hours daily. The remaining four hours are reserved for maintenance. This comes to a percentage of 16.7 % of all time reserved for maintenance. To check this number, the total time allocated to maintenance has been calculated and is shown in Table 6.10

Table 6.10: Percentage of the total time that is allocated to maintenance

	2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
Percentage	16.3	20.2	19.4	16.9	17.1	13.9	14.9	14.3	12.9

In Table 6.10, the percentage of maintenance to total available time is displayed. For example, in 2013, out % of the hours open in a year, 20.2% of that amount was spent on maintenance. A trend could be identified that the percentage is declining in this period. Specifically 2022, the maintenance to total time ratio is relatively low. This could be the effect of the Fleet health pilot of KLM, which was in effect this year. However, most of these numbers are around 15 to 20 %. Now, it is crucial to compare these numbers to the numbers of the proposed future states of the Cyrus model. However, the Cyrus model only focuses on the WMMR; thus, first, it has to determine what percentage are the WMMR out of the total time allocated for maintenance. These numbers are shown in Table 6.11.

Table 6.11: The share of high-priority maintenance codes out of the total amount of maintenance

Years	2012	2013	2014	2015	2016	2017	2018	2019	2022
Percentage	30.6	26.3	24.9	28.0	25.9	27.0	24.7	27.9	31.0

In Table 6.11, it can be seen that the share of high-priority maintenance codes does not differ that much, and no trend can be observed in this period. The mean of the share comes to a percentage of 26.7%. Based on this percentage, the WMMR from theory can be calculated. The proposed WMMR amounts were for 30, 50 and 80 %, which coincide with 6.5, 7.1 and 8.6 hours per week, respectively. Based on the percentage of high-priority maintenance of the total, total maintenance is determined in a week. The numbers 6.5, 7.1 and 8.6 coincide with 24.3, 26.6 and 32.2 hours a week, which, if expressed as a percentage, is 14.5, 15.8 and 19.1, respectively. These values are similar to the current maintenance shares and thus can be considered realistic.

6.6. Validation

The final step in the future state design is validation. This step is essential to establish that the results from the Cyrus model are correct and if the future state has the positive impact it claims to have compared to the current state. First, the checks proposed by the Cyrus model will be recreated into a daily cycle. This is to validate whether the check lengths fit correctly into a day. Secondly, check the minimisation of waste in free time between slots, if it can be used for value-added activities. Then, four 10-week plans will be developed and then drawn wider to a yearly plan. Finally, a capability analysis will be performed on these plans to determine whether they have a higher stability.

6.6.1. Slot fitting

The checks proposed by the Cyrus model should be fitted into a daily cycle because otherwise, it causes inefficiencies regarding time distributions. For example, if one spot in the hangar is available for performing the WMMR, there are two checks. One of the checks is 5 hours, and the other is 9 hours, which means that most of the time, no maintenance is performed in the hangar because there are 20 hours available for maintenance. Thus, it is crucial that these checks fit together into a day to prevent any waste of this kind. The 10-week plan works with a P-2 and P-4 check representing a two- and a four-hour platform check. Then there is a H-6, H-9 and H-12 check representing a six-, nine- and 12-hour hangar check.

First, creating a daily plan validates the P-2 and P-4 checks. The platform checks are only performed during the day. They are input into Excel to check the fit, and the result is shown in Figure 6.15. Two different Platform lines are required to fulfil the requirements. One line is fully committed to P-2 checks, while the other is fully committed to P-4. A P-4 can be combined with another P-4 or a P-2 in high requirements. However, this should not be preferred because longer Hangar slots are available, which would not disrupt the planned maintenance schedule.

The P-2 schedule is as follows: The first aircraft arrives between 5:00 and 7:00 in the morning. These aircraft must then be disembarked and towed to the platform for maintenance. The check is two hours; after two hours, it will leave the platform to the gate so that it can catch the next flight wave between 12:00 and 14:00. At that time, the following aircraft that arrived in the 8:00 to 10:00 window was already in the disembarking process and was ready to leave for the platform. This aircraft is finished around 14:00 and is in time to catch the next flight wave at 15:00 to 17:00. Finally, the last aircraft comes in between 13:00 and 15:00 and is available for the slot between 15:00 to 17:00. This means that the final aircraft can make the final flight wave in the evening if it is back at the gate around 19:00.

A similar schedule is proposed for the P-4 slots, of which 2 can be performed during the day. However, One option is currently not discussed, and that is the option if the unnecessary non-value-added free time is minimised. This means the flight schedule is less flexible; however, more P slots can be performed during the day. The chances of an aircraft arriving on time

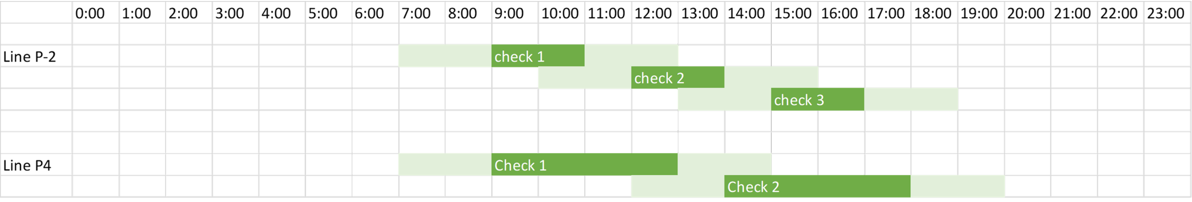

Figure 6.15: The schedule of how the P-checks do fit into a daily schedule, with buffer times between the checks

Next, a daily schedule will be built for the H-checks similar to the P-checks. Two lines are being examined: the H-6 & H-12 line and the P-9 line. In Figure 6.16, these two lines are shown, where Line H 1 is the H-6 & H-12 line, and Line H 2 is the H-9 line. The hangar checks require more time between them than the platform check because of towing and space constraints [4]. The figure shows that both slots fit into a daily schedule. However, the H-6 & H-12 line has some problems. This has to do with the distribution. If one line is fully committed to performing H-6 and H-12 slots, the ratio of H-6 to H-12 is one. However, H-6 slots should occur more often than H-12 slots because they have a higher occurrence probability. Thus, although these lines fit the schedule, Line H 1 does not go well with the slot distribution. Because the H-12 are less required, if they have the same occurrence as the H-6, they will probably not be filled with sufficient maintenance tasks. Thus, value-added maintenance time will be transformed into unnecessary non-value-added time, which is not preferred.

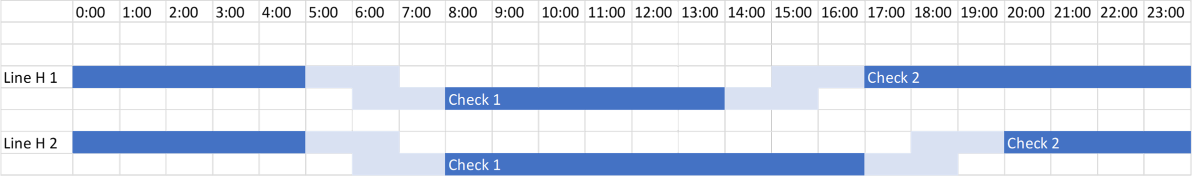

Figure 6.16: The schedule of how the P-checks do fit into a daily schedule, with buffer times between the checks

Thus, based on the recreating of the daily schedules, it can be concluded that the check lengths proposed by the Cyrus model fit into such a schedule. Thus, it is possible for airlines to perform these checks between flights and in a day, which means the Cyrus model proposed realistic check lengths. However, Because the ratio of H-6 to H-12 is not optimal because H-6 is required more often than H-12, Line H 1 will not be considered for the proposed plans.

6.6.2. Turning free time into value-added maintenance time

Another thing that the Cyrus model did is identify large amounts of unnecessary non-value-added free time in the planning. This free time could be transformed into value-add maintenance time if scheduled carefully. So for every P slot, if all free time is transformed into value-added maintenance time, 90 minutes extra is created, or one more check fits into the daily schedule. An example is when four instead of three P-2 checks are fitted into one day or three P-3 slots. According to the schedule, these checks do fit into a day.

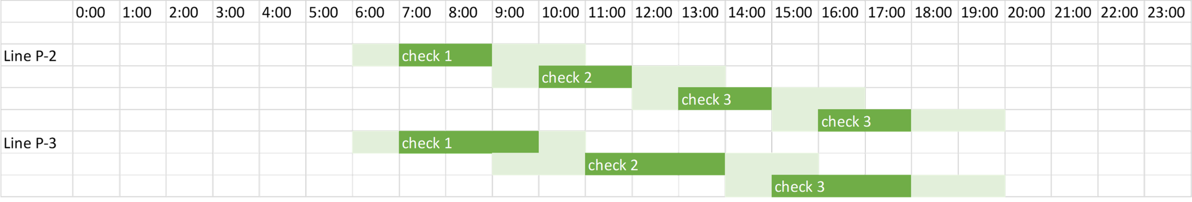

Figure 6.17: A daily platform line schedule if the unnecessary non-value added free time is used

However, a problem with such a tight schedule is that it leaves little flexibility for aircraft that do not arrive on time, and this is the case. At KLM, 80 % of the arrivals are on time. If the schedule is this tight, this leads to decreased flexibility and unused slots because aircraft are not there. This would cause extra waste on its own. Thus, it is better to have a bit more flexibility with the unpredictability of aviation. However, not applying a tight schedule does not mean there is no decrease in waste. Because the new checks fit better in the flight planning, the waste between flight and maintenance and maintenance and flight, which was the most, will decrease. Thus, the waste would decrease if the Cyrus future state is implemented. This decrease in waste is shown in Figure 6.18.

So, in the first line, there are four hours of waste, while in the second line, proposed by the Cyrus model, there is no waste. Using these three extra hours of maintenance every couple of weeks can increase stability because more maintenance can be performed with similar flight times.

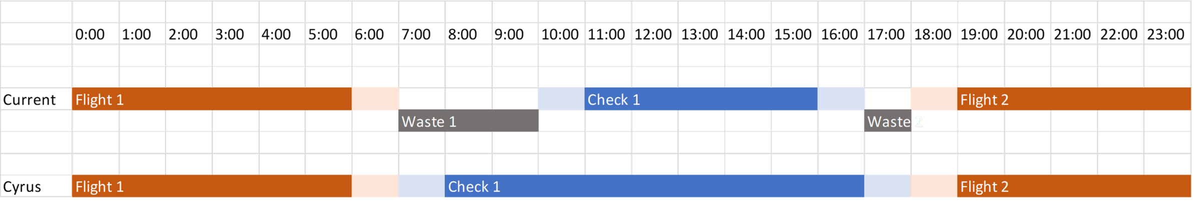

Figure 6.18: The current state is presented in the first line, where there is a 5-hour hangar check during the day; this leads to a lot of waste. The next line shows a future state proposed by the Cyrus model, which has no waste in it

6.6.3. 10-week planning

Based on the results of the Cyrus model, four 10-week plans consisting of several checks will be proposed that differ in check frequency and distribution. These plans contain the checks proposed by the Cyrus model and the check frequency. These four 10-week plannings are shown in Table 6.12, 6.13, 6.14 and 6.15. Plan one has the least WMMR, and plan four the most.

Table 6.12: WMMR 10-week planning for a single aircraft-1

Week	1	2	3	4	5	6	7	8	9	10
Effective maintenance	2	9	4	2	2	4	9	2	4	4
Type	P	H	P	H	P	P	H	P	P	H

Table 6.13: WMMR 10-week planning for a single aircraft-2

Week	1	2	3	4	5	6	7	8	9	10
Effective maintenance	2	4	4	9	2	4	9	2	4	9
Type	P	H	P	H	P	P	H	P	P	H

Table 6.14: WMMR 10-week planning for a single aircraft-3

Week	1	2	3	4	5	6	7	8	9	10
Effective maintenance	2	9	4	20	2	4	9	2	4	9
Type	P	H	P	H	P	P	H	P	P	H

Table 6.15: WMMR 10-week planning for a single aircraft-4

Week	1	2	3	4	5	6	7	8	9	10
Effective maintenance	2	9	4	20	2	4	9	2	4	9
Type	P	H	P	H	P	P	H	P	P	H

So, these tables show planning for a single aircraft and are a mix of hangar and platform checks with different lengths. It is crucial to notice that the effective maintenance time is shown, not the total time. This means it is not the total time in the schedule. The next step is to validate whether the schedules proposed lead to the desired results. The desired results are presented through the capability index and the probability. First, the schedules are considered yearly to determine the Average weekly WMMR per aircraft. It is taken from a 10-week to a yearly schedule to receive more reliable averages. Tables 6.16, 6.17, 6.18, 6.19 and 6.20 displays the count for the different schedules. Table 6.20 is also considered because this is the current state and thus allows the comparison of the proposed plans versus the current state.

Table 6.16: Plan 1 check counts and the average WMMR per aircraft in hours

Slot length (hours)	2	4	6	9	12	20
Count of checks	20	17	0	15	0	1
Average WMMR per aircraft per week (hours)	5					

Table 6.17: Plan 2 check counts and the average WMMR per aircraft in hours

Slot length (hours)	2	4	6	9	12	20
Count of checks	15	20	0	17	0	5
Average WMMR per aircraft per week (hours)	7					

Table 6.18: Plan 3 check counts and the average WMMR per aircraft in hours

Slot length (hours)	2	4	6	9	12	20
Count of checks	20	20	0	12	0	9
Average WMMR per aircraft per week (hours)	7.8					

Table 6.19: Plan 4 check counts and the average WMMR per aircraft in hours

Slot length (hours)	2	4	6	9	12	20
Count of checks	21	20	0	16	0	9
Average WMMR per aircraft per week (hours)	8.5					

Table 6.20: R-check check counts and the average WMMR per aircraft in hours

Slot length (hours)	4	5	9
Count of checks	18	17	17
Average WMMR per aircraft per week (hours)	6		

Based on these amounts, a capability analysis can be performed. However, minimum and maximum values are required for a capability analysis, which is unavailable for proposed scenarios. Thus, these values are determined based on historical data and the theoretical effects of weekly maintenance. Thus, some assumptions are made regarding these numbers. First is the standard deviation, considered equal to the average standard deviation between 2016 and 2019. This comes to a value of 85 hours. The next value to consider is the minimum value. The minimum value is not taken as the average between these periods because it is more dependent on the weekly maintenance amount because one of the effects of a weekly maintenance strategy is that the minimum should be close to the mean. Because there is weekly maintenance, which can differ per aircraft; however, on a fleet scale, the weekly amount should be similar to the mean value. The minimum value is chosen to be 85 % of the mean value and thus shoves along with an increased mean. The next value to determine is the maximum value. The maximum value is the average maximum between 2016 and 2019. This is done and not as a percentage of the mean because the maximum should not increase with an increasing mean. It might even decrease with an increasing mean. Thus, there comes the point when the reserved amount of WMMR is at the maximum value, so it can not be put out as a percentage as it is for the minimum. That is why the maximum value is 700 hours and remains constant with increasing reserved WMMR. Based on these values, the process is also calculated. These values are all displayed in Table 6.21.

The probability, C_p and C_{pk} can be calculated based on these values. The C_p and C_{pk} depend on the specification width, so these are shown for different widths in Table 6.22. The table also shows the probability. This probability is related to the distribution of the weekly maintenance requirements

Table 6.21: Values for different maintenance plans

Value/Plan	**Plan-1**	**Plan-2**	**Plan-3**	**Plan-4**	**R-check**
Reserved WMMR	350	490	550	600	420
Std	85	85	85	85	85
Min	298	417	468	510	357
Max	700	700	700	700	700
Max Dif	350	210	150	100	280
Process width	402	283	232	190	343

for 2012-2019.

Table 6.22: The probability and capability performance for the different plans proposed by the Cyrus model

Plans		**Plan-1**	**Plan-2**	**Plan-3**	**Plan-4**	**R-check**
Probability %		4	43	64	78	20
Sigma 4	**Cp**	0.84	1.20	1.46	1.79	0.99
	Cpk	0.57	0.95	1.33	2.00	0.71
Sigma 6	**Cp**	1.27	1.80	2.19	2.68	1.49
	Cpk	0.86	1.43	2.00	3.00	1.07
Sigma 8	**Cp**	1.69	2.40	2.92	3.58	1.98
	Cpk	1.14	1.90	2.67	4.00	1.43
Sigma 10	**Cp**	2.11	3.00	3.66	4.47	2.48
	Cpk	1.43	2.38	3.33	5.00	1.79

Based on Table 6.22, it can be determined that only Plan-3 and Plan-4 provide a stable process for all specifications widths. Plan-2 becomes stable at 6σ, the current R-check at 8σ and Plan-1 only at 10σ. Because plan 3 is only stable at 4σ, reserving less than 7.5 hours of maintenance per week per aircraft can be considered unstable. Thus, compared to the current state of the R-check, the Cyrus model proposed three plans that create more stability.

What does this stability do to the airline's operation? Some of the impacts of stable maintenance planning on the airline are posted below:

- Reduced Downtime: Stable maintenance planning helps minimise unscheduled aircraft downtime. This means that aircraft spend more time on revenue-generating flights, leading to increased revenue.
- Improved Operational Efficiency: Effective maintenance planning can reduce the time an aircraft spends on the ground for maintenance. This translates to quicker turnaround times, allowing airlines to operate more flights with the same fleet.
- Lower Maintenance Costs: Predictable maintenance schedules enable airlines to plan and budget for maintenance activities more efficiently. This can lead to cost savings by optimising the allocation of maintenance resources and reducing the need for last-minute, costly repairs.
- Enhanced Safety and Reliability: Well-planned maintenance ensures aircraft comply with safety regulations. This reduces the likelihood of in-flight incidents or disruptions, damaging an airline's reputation and resulting in financial losses.

- Extended Aircraft Lifespan: Effective maintenance planning can extend the lifespan of aircraft, delaying the need for expensive aircraft replacements or major overhauls.
- Improved Customer Satisfaction: Passengers appreciate punctuality and reliability. An airline known for on-time departures and arrivals due to stable maintenance planning will likely attract more customers and retain loyal ones.
- Fuel Efficiency: Well-maintained aircraft are generally more fuel-efficient. Airlines can save substantial fuel costs by ensuring that engines and other critical components are in optimal condition.
- Competitive Advantage: Airlines with efficient and reliable maintenance planning can gain a competitive edge in the market. They can offer competitive fares, better services, and more flight options, attracting more passengers.
- Financial Stability: By reducing unplanned maintenance expenses and optimising maintenance budgets, stable maintenance planning contributes to the overall financial stability of the airline.

The first item on the list is reduced downtime; this brings back the story of Icarus at the beginning of this thesis. Here, the balance had to be found between uptime and downtime. A lot of maintenance was similar to flying too close to the sea, and too much flying was similar to flying too close to the sun. Both situations are dangerous for the airline. Labelling the amount of WMMR directly to the uptime and downtime is difficult. The yearly uptime, downtime and waste numbers are shown in Table 6.23.

Table 6.23: Yearly uptime, downtime and waste performances

Categorie\Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
WMMR (hours)	8.22	7.41	6.48	6.14	6.1	5.6	5.75	6.57
Uptime (%)	63.7	703	70.1	69.9	67.5	68.5	68.7	71.6
Downtime (%)	16.3	20.2	19.4	16.9	17.1	13.9	14.9	14.3
Waste (%)	20	9.5	10.54	13.2	15.4	17.6	16.4	14.1

This table shows the importance of balancing between uptime and downtime. Uptime is formulated as flying, downtime is formulated as maintenance, and waste is the time between the two, so unused uptime or downtime. The first column shows the amount of WMMR in hours. It can be seen that there is no direct relation between the WMMR and uptime or downtime. For example, 2019 has a WMMR of 6.57 and downtime of 14.3, while 2018 has a lower WMMR of 5.75 and a higher downtime of 14.9. However, the waste shows a clear trend, which also coincides with the proposed amounts by the Cyrus model. The fewer hours of WMMR, the more waste there is. But also, if 2012 is examined with the most WMMR, the waste has increased and thus is inefficient. Less waste equals a more efficient system.

This means that an increase and downtime does not lead to a decrease in uptime but can also lead to an increase in uptime. Based on these results, rough calculations can be done for the impact of a WMMR of 6, 7.5 and 9 hours. Based on the table, it can be determined that a WMMR of 6 equals 15 %, and 7.5 equals 10 %. For 9 hours, it is more complex, but it is assumed that the amount of waste equals 15 %. If the WMMR is 27 % out of all maintenance, as is seen in Table 6.11, the amount of weekly maintenance comes to 22, 28 and 33 hours, respectively. 22, 28 and 33 hours equal 13.2, 16.5 and 19.8 % of the total time spent on maintenance. The respective uptime is acquired if the waste is added to this percentage, and the sum is subtracted from 100. The uptime for 6, 7.5 and 9 hours is 71, 74 and 65 % respectively. This means that an increase in WMMR leads to increased uptime; however, if the WMMR is too high, the uptime will decrease again. These calculations are rough, however, and no precise percentage of waste can be assigned to a WMMR, but it indicates a balance between 6 and 9 hours, leading to increased uptime. This is an increase in uptime as an image of Icarus in Figure 6.19.

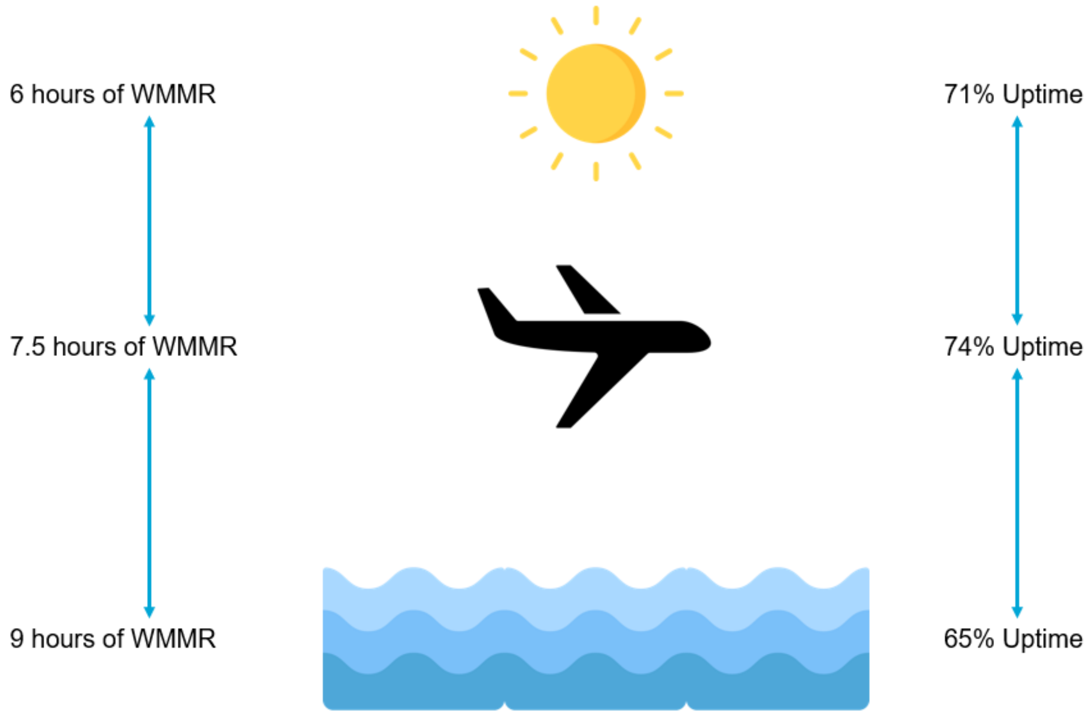

Figure 6.19: An aircraft shown as Icarus, where the balance is between the sun and the sea, which comes on and around 7-7.5 hours of WMMR

6.7. Conclusion

Three questions were raised at the beginning of this chapter. 1) What would a future state look like? Several future state plans were proposed by the Cyrus model. First, different checks were identified based on historical uses, how often they occurred, and their length. Based on these results, a Weekly maintenance strategy was proposed. Next was the challenge to identify turn time waste and the constraints of planning a maintenance slot into the flight schedule. After this, optimal gaps had to be identified in the flight schedule to minimise the interruption in flight planning. Multiple slots were found, such as morning, midday, evening, night and all day. Then, based on the required length of the checks, the space in the flight planning and the waste in turn time, optimal check lengths were identified as how often they should occur for different WMMR.

2) How can the model be verified? This was done by expert verification and data verification. The expert verification consists of consulting experts on the results. Suppose they see an agreement with reality and the results. If so, the model can be verified. The next step in verifying was to compare data to natural limits, airline data and theory calculations. Based on this, it could be concluded that the data seems to represent reality accurately.

3) How the proposed future state could be validated? The model results were validated by evaluating the proposed checks and plans. The Cyrus model proposes several plans to outperform the current state using stability—First, the proposed checks were validated by creating them into a daily cycle. Second, a decrease in waste was identified by applying the new check lengths compared to the current ones. third, The 10-week plans were created and scaled to yearly plans to determine the WMMR per aircraft in hours. These schedules were then analysed by a capability performance analysis to determine the stability of the process. 3 out of the 4 plans proposed were considered to be more stable than the current state. These results coincide with the hypothesis mentioned at the end of the future state design: Thus, the Cyrus model's proposed plans should decrease the turn time waste because it fits better in the flight schedule. Also, the Cyrus plans will have a WMMR that better matches the historical maintenance requirements. Thus, the Cyrus plans will create a more

stable process than the current state.

7

Conclusion

7.1. Research conclusion

This project aimed to create a balance between uptime and downtime with the help of an integrated centralised airline planning model that can be used to estimate weekly minimum maintenance requirements based on Historical flight and maintenance data. This aim was translated into a research question that needed to be answered, which was formulated as:

> **How to value the balance between aircraft up and downtime from a multi-stakeholder perspective?**

The research was composed of multiple sub-questions to answer the central research question. The literature review analysed traditional aircraft maintenance, maintenance planning, and task clustering. Traditionally, maintenance focused on extensive "letter checks", which is still seen as the state of the art in maintenance planning. However, current maintenance planning lacks focus on weekly requirements and a holistic airline perspective. Task clustering also lacks focus on the priority of tasks regarding airworthiness and time constraints. This gap calls for better cooperation between stakeholders and clear maintenance definitions. The maintenance definitions can be given by categorisation of maintenance types. This categorisation comes from Lean manufacturing in the form of standardisation.

The Cyrus model is a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between excessive flights and excessive maintenance. Striking such a balance is assumed to increase the uptime.

It comprises a data and a planning model with stages for data processing, combining, analysis, and designing a future state. The analysis addressed sub-questions, including the impact of aircraft type on maintenance requirements, ageing, weekly minimum maintenance requirements (WMMR) determination, and task categorisation. The aircraft type significantly influences maintenance requirements, with older aircraft types requiring more maintenance. The WMMR depends on an airline's strategy, which means that if an aircraft only reserves enough maintenance for 30 % of the time, it should be aware that in 70 % of the weeks, additional maintenance is required. Further, medium-priority slots are unsuitable for WMMR due to their unpredictability, unlike the high-priority slots, which agree with the Weekly minimum maintenance requirements (WMMR).

A future state maintenance was proposed after determining the WMMR and its distribution. This planning and distribution of maintenance ground time considered all stakeholders' constraints, such as service and flight providers. A future state design aligns maintenance checks with historical data, flight schedules, and turn time waste reduction. Based on this, multiple weekly maintenance plans were proposed, which differed in check frequency. These proposed plans claimed to provide a more stable airline operation than the current state. That is why Verification and validation were essential steps. Expert and data verification ensured the model's accuracy, while validation involved creating daily cycles, analysing waste reduction, and evaluating stability compared to the current state. Three out of four proposed plans were more stable, confirming the model's hypothesis.

Thus, returning to the main research question, where a balance was to be found between uptime and downtime from a multi-stakeholder perspective. A system focusing too much on uptime leads to much unpredictability, resulting in planning instability. A system that focuses too much on downtime creates a stable system from a maintenance perspective but loses sight of flying, as in the Icarus example. Therefore, a balance is found in performing Weekly minimum maintenance requirements (WMMR). These WMMR should be fitted into the airline planning in accordance with the flight plan and the service plan. By performing the WMMR in slots P-2, P-4, and H-9, the balance is found to be near 7.5 hours or higher of maintenance per week per aircraft.

The optimal stakeholder cooperation is presented in Figure 7.1. The balance is achieved by increasing the downtime. This allowed the maintenance provider to plan sufficient maintenance to prevent unwanted demand peaks. Not only was the amount of weekly maintenance increased, but the slot lengths also differed. The slots are now better aligned with the flights, decreasing the waste in the planning. The increase in downtime leads to a larger decrease in waste, this means that more time becomes available for flights and thus uptime increases. Based on calculations, the uptime can increase to 74 %, which is higher than all the years in the last decade. Thus, the assumption that striking such a balance would increase the uptime is considered valid.

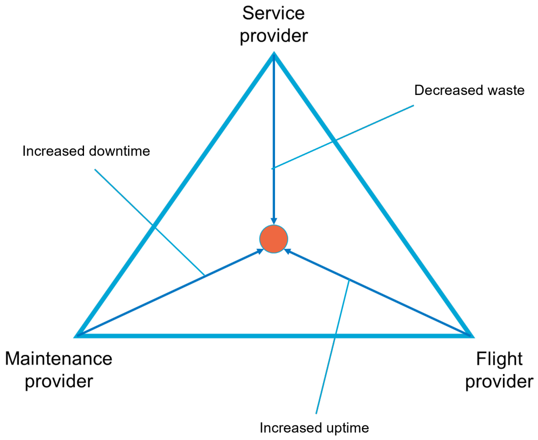

Figure 7.1: The balance achieved by the Cyrus model, where the centre of power is at the centre of the stakeholder triangle

In summary, the research addressed sub-questions, covering topics from traditional maintenance to the Cyrus model's development, verification, and validation, ultimately leading to a balance between excessive flying and excessive maintenance based on inputs of multiple stakeholders instead of one. This balance can eventually lead to an increase in the uptime. Thus, a quote was found that applied to this future state compared to the current state as mentioned in chapter 4, the Cyrus model was named after Cyrus the Great, the king of kings. As did Cyrus, this model found the balance between the stakeholders and kings and brought stability to his empire. One critical aspect of how he brought this stability is presented through a quote from Cyrus himself, shown below.

7.2. Contribution to academic literature

With the research question answered, it is time to highlight the contribution to academic literature. First, maintenance planning focuses on the 'Letter checks' and turns blind to weekly minimum maintenance requirements. Secondly, maintenance planning is solely from a maintenance provider's perspective. Focused on how they could perform maintenance without considering flight or service planning. This research tries to fill that gap by focusing on weekly maintenance requirements from a multi-stakeholder perspective.

“Diversity in council, unity in command”

Cyrus the Great 600-530BC

Then, the gap for task clustering was found that most tasks are clustered on their RUL or due date. However, what is noticed is that most checks do not consider time availability constraints, which means the vision is relatively short-term. It is focused on a single check and clustering the tasks as best as possible. No prioritisation is provided related to the airworthiness of tasks in case of time shortages. Providing this prioritisation can help maintenance providers make choices when ground time is scarce, and choices have to be made.

So, the contribution to academic literature is a centralised model that looks at a different aspect of aircraft maintenance planning: weekly maintenance requirements. Weekly maintenance requirements greatly impact flight planning compared to an A-check, which occurs every 2-3 months. So, the focus in the literature on these ’letter checks’ clearly makes the weekly requirements more underexposed than they should be. This research tries to expose the weekly requirements and how they would fit into the overall airline planning and measure the stability of several proposed plans.

7.3. Limitations and recommendations for further research

In conclusion, this paper discusses the limitations encountered during the research and provides recommendations for future studies. The main limitations observed were the scope of the research and the lack of financial outcomes. The study did not consider the workforce capacity, a vital aspect of performing maintenance checks. It requires not only mechanics and engineers but also ground personnel for towing, cleaning, etc. The airline KLM is experiencing workforce-related problems, which could constrain the implementation of maintenance checks. Hence, it is important to consider the workforce as a constraint while conducting further research.

Moreover, the Cyrus model did not allow the improved stability to be expressed in financial gains, which is a crucial aspect for airlines. This lack of financial outcomes is a limitation of this research. The difficulty of expressing maintenance ground time into costs and translating increased stability into financial benefits is something worth researching further. Thus, the additional gained uptime, which is 3 % more, can be translated into flights and thus into profits. 3 % extra uptime means 5 hours a week per aircraft extra for flying yearly, which adds up to 262 hours. If this time can be translated to flights, it would mean a massive increase in profit. If a round trip is around 24 hours and the profit is around 500.000 per trip, 10 round trips can be added per aircraft, which adds up to $5mln$ per aircraft; on a fleet level that has a massive impact. Thus, the translation of additional uptime to flights in combination with the financial assessment of flights is deemed highly interesting.

Next to the financial gains of the balance, it would also be interesting to perform a sensitivity analysis of the balance between uptime and downtime. Cyrus now expressed rough numbers when comparing WMMR with uptime, downtime and waste percentages. A sensitivity analysis could try to explore this balancing process more carefully. So, if my WMMR goes from 7.5 to 7.7, what is the impact on my uptime, downtime and waste?

Finally, this research did not focus on new techniques, such as predictive or condition-based maintenance, which can significantly impact maintenance planning. Determining better when every task is due can be essential to minimise the weekly minimum maintenance requirements. Hence, further research on minimum maintenance requirements could be explored from a predictive maintenance perspective. This research is a top-down analysis of the WMMR, while a bottom-up analysis focusing on minimum required tasks can be of interest and could be explored further in future research.

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Appendices

A

Appendix A

A.1. Maintenance codes

Code#	**Name**
##1	Engine change 1
##2	Engine change 2
##3	Engine change 3
##4	Engine change 4
##E	Engine change
##A	A-check
##B	B-check
##C	C-check
##D	D-check
##H	H-check
##M	M-check
#AG	Repair (AOG) platform
#BL	Block-week
#BM	Base maintenance
#CE	Central Engineering order
#CL	Cabin cleaning
#DE	Deco-program
#DI	Disinfestation
#DR	Draining
#FF	Ferry Flight
#LE	Training Flight
#LG	Landing Gear change
#LP	Long Parking
#MO	Modification
#NB	Not available
#NR	No release
#OM	Configuration change
#ON	Maintenance
#P+	Maintenance platform
#PD	Post-delivery modification
#PI	Phase-in
#PO	Phase-out
#RE	Extra spare
#RP	Repair (AOG) Hangar
#RS	Spare
#RT	Spare technicaol
#SP	Hours save
#TA	TA-check
#TD	TD-check
#TM	TM/TO-check
#TO	Technisch onderhoud
#TY	TY-check Hangar
#TZ	TZ-check Platform
#VW	Voorloopwerk C/D/Mod
#WA	Exterior cleaning
#WE	AC weighing
#WK	Weekly check
#WW	Waterwash

Designing a centralised model to value balance between aircraft uptime and downtime from an integral airline perspective

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Abstract.
This research aim was to design a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between flights and maintenance. This equilibrium enhances the airline's capacity to manage maintenance efficiently and ensures greater uptime. The model addresses the important aspects of airline planning, including maintenance, flight and operation planning. Lean Six Sigma theories serve as a framework to combine the different plannings. The key importance is that the model considers all the stakeholders instead of only one so that the equilibrium between excessive flying and excessive maintenance can be established. In striking such a balance, uptime is assumed to increase.

Purpose
Airline planning involves many aspects, such as flight, maintenance and service planning. Each of these plannings has a different stakeholder that holds their part of the planning as the top priority. This led to a fragmented airline organisation and non-optimal airline planning. It is important to combine the aspects of these plannings into an integral airline planning.

Design/Methodology/approach The problem was solved by taking a theory-oriented approach and using Lean Six Sigma tools to improve and combine the plannings. This was done by finding a balance between excessive flying and excessive maintenance. Data came from the airline planning tool that showed maintenance and flights performed, and tools such as value stream mapping, capability analysis and standardisation were used.

Findings
It was found that an increase in uptime can be ensured by finding the balance between aircraft and maintenance. Increasing maintenance in the form of weekly minimum maintenance requirements allowed for more capable planning, which supported more uptime. In case of a higher weekly minimum maintenance requirements, a higher uptime could be achieved.

Originality/value
The originality was found in the combination of the different planning. From this perspective, a balance was found where maintenance was increased, and uptime would also increase. Where uptime is crucial for the airline, an increase in it could lead to an increase in profits, this would also be a key next step in further research to consider the financial aspect.

Keywords: Airline, Maintenance planning, Airline MRO, Lean Six Sigma, Process stability, Flight planning, Weekly minimum maintenance requirements.

Paper Type:Case study

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1 Introduction

In 2022, over 3700 million people took to the skies.[1] During COVID-19, passengers dropped from 4500 million in 2019 to 2100 million in 2021 which means it is back on the rise again. More than 33.8 million flights and only six fatal aircraft incidents occurred in 2022,[2] which leads to an average of 1 fatal accident every 5.63 million flights. The number of fatalities decreased massively over the past decades[3] while the number of flights and passengers increased in those decades.[1] This means that aviation is safer than ever. One of the significant contributors to aircraft safety is Maintenance, Repair and Overhaul (MRO). With aircraft renewing and ever-increasing competition in the aviation industry, aircraft maintenance is under tremendous pressure to reduce cost and increase aircraft utilisation.

1.1 Problem statement

Maintenance, flight and operations planning are handled separately by different operators. The maintenance operator focuses on optimising the maintenance planning, the flight operator focuses on optimising the number of flights, and the service operator focuses on the time between the two. This complicates overall planning because they all have different objectives that collide and obstruct each other. Also, from a maintenance perspective, there is a focus on the large 'letter checks', which are the traditional form of aircraft maintenance set up by aircraft manufacturers decades ago. However, maintenance is a continuous requirement and should be done at intervals between the letter checks. These are the weekly minimum maintenance requirements (WMMR).

Another problem is miscommunication between stakeholders, who have different definitions regarding maintenance planning. The airline invented terms to code specific maintenance jobs. However, this coding has no clear priority distinction and categorisation, which makes it unclear what codes are used for plannable maintenance and what for unplanned maintenance. Thus, clear categorisation and definition combined with determining the weekly maintenance requirements is crucial for the airline's operation and achieving a value balance between flights and maintenance.

The third problem is a misunderstanding of the activities that occur between flights. Current planning tools show an empty gap in the schedule, indicating free time. Thus, a misconception arises for several stakeholders that maintenance activities can be performed in that time. A categorisation of these activities can help understand what is currently occurring in this 'free time' and, if there is any free time, how it could actually be used.

1.2 Research questions

How to value the balance between aircraft up and downtime from a holistic perspective?

- What is Aircraft MRO?
- What is the state of the art in aircraft maintenance, maintenance planning, task clustering?
- What Lean theories could be used to improve the planning?
- What is the current state of planning at the airline?
- How would a model look that could estimate ground time requirements based on several important inputs?
- Can the maintenance requirements be categorised, and how would this look?
- Can waste in waiting time be identified and categorised?
- What are important factors to consider for determining ground time requirements?
- How can the maintenance ground time be determined?
- What would be a future state of planning that considers all stakeholders?
- How can the proposed model be verified and validated?

1.3 Research methodology

This research is conducted as a case study of the airline and follows a clear methodology. The methodology is taken from[4] and distinguishes two types of research: practice- and theory-orientated research. To make this distinction is essential for the effect of the research.

> ”Practice-oriented research is research where the objective is to contribute to the knowledge of one or more specified practitioners.”[4]

> ”Theory-oriented research is research where the objective is to contribute to theory development. Ultimately, the theory may be useful for the practice in general.”[4]

This research is more theory-orientated but closely related to the practice and focuses on theories around maintenance requirements and planning. Because it is theory-orientated, a specific step by step guide will be retained. The first phase is the theory-exploring phase, which explores theories in planning and Lean Six Sigma. Snee2010Lean-Six-Sigma-getting-better-all-the-time describes Lean Six Sigma as a well-structured theory-based methodology to improve performances. This step aims to identify the practical problems and define the research questions, followed by an overview of the literature. This results in a research problem and a scope already presented in this chapter. The second phase is theory-building, where an analysis of the current situation will be drawn that helps in the next step in this phase: model development. In this step, the model design will be detailed. The third phase is theory-assessing, which includes model analysis, a future state design and finally, model verification and validation.

2 Literature review

This section will highlight the literature on traditional aircraft maintenance, maintenance planning, task clustering, and Lean Six Sigma.

2.1 *Traditional aircraft maintenance*

Traditional aircraft maintenance is maintenance in the form of letter checks executed in a hangar. Traditional aircraft maintenance is a strategy set up by aircraft manufacturers decades ago aiming to ensure that the aircraft is safe to operate. Letter checks are hangar checks wherein several maintenance tasks are clustered into a larger package. In most cases, these maintenance tasks are defined by aircraft manufacturers with the help of operators and authorities. Each task has a suggested interval within which it must be executed. In most cases, this interval is more of an obligation than a suggestion. The interval can be displayed in different ways, such as flight hours, cycles or calendar days. Whatever due date comes first will be maintained.

Maintenance tasks with similar intervals are clustered in so-called ”Letter checks”. The letter checks traditionally consisted of four letters: A, B, C and D. In Table 1, the letter checks and their traditional Type, Interval and Maintenance Tasks are presented. Most MRO providers no longer use the four letters and have switched to a more efficient system consisting of two letters.

Table 1 Traditional representation of ”Letter checks”[5]

Checks	Maintenance Type	Interval	Maintenance Task
A	Light Maintenance	2-3 months	External visual inspection, filter replacement, lubrication etc.
B	Light Maintenance	Rarely mentioned	Tasks are commonly Incorporated in to successive A-checks
C	Heavy Maintenance	18-24 months	Thorough inspection of the individual systems and components
D	Heavy Maintenance	6-10 years	Thorough inspection of most structurally significant items

The four-letter system coincides with the objectives of the aircraft manufacturers. That is to maintain the aircraft as extensively as possible; however, extensive maintenance collides with the airline’s desire to minimise downtime. Airlines value the uptime of an aircraft highly because it ensures the most profit, while manufacturers have uptime less high as a priority. The question arises if the traditional letter check system is more advantageous for the manufacturers than the airlines. Although airlines switched to a two-letter system, the traditional letter check remains the basis of aircraft maintenance. Designing a maintenance strategy can have multiple demand drivers. These demand drivers can be manufacturers, crew, airline and maintenance providers. Currently, the main driver of the maintenance strategy is the aircraft manufacturer.

2.2 *Airline structure*

After highlighting traditional aircraft maintenance, the airline’s structure should be identified. The airline has four key stakeholders: the plane, maintenance, flight and service provider. The plane provider is the owner of the planes; the maintenance provider performs maintenance; the flight provider performs flights; and the service provider is in charge of the turn time between flights to make it operable. Out of these four, only the maintenance, flight and service providers are involved in making the airline’s planning. How the cooperate is shown in Figure 1.

2.3 *State of the art in maintenance planning*

Maintenance planning is crucial in overall airline planning. Maintenance planning is always under continuous pressure from the airline and becomes crucial for maintenance providers because of the need to reduce

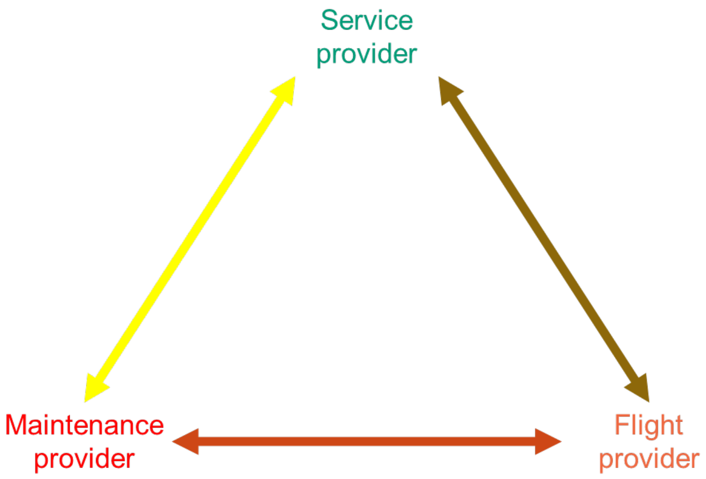

Fig 1 Stakeholders in planning

maintenance costs and increase aircraft utilisation.[6] How an airline performs is related to security, quality, efficiency, costs and speed of the maintenance operation.[7] These five factors are directly related to the performance of the maintenance planning department.

> **”Planning the maintenance of an aircraft involves monitoring aircraft or equipment conditions to determine when work is due in the short, medium, and long term”[8]**

The literature focuses on planning letter checks and assigning aircraft to them. The drives of optimising the maintenance planning are minimising the costs for,[9],[10],[11],[12],[13][14] and.[15],[16][17] and[18] have minimising ground time as the main driver. Thus, maintenance planning leaves out other essential stakeholders in planning, such as the flight and service provider. Without considering the other stakeholders, optimal airline planning is impossible. An overview of the literature on maintenance planning is provided in Table 2.

Table 2 Maintenance planning objectives and whether they are from a maintenance, flight or service provider perspective. Second, if the maintenance focused on weekly requirements or more on overall planning into large checks.

Source	Year	Objective	WMMR	Maintenance provider	Flight provider	Service provider
[19]	1977	Minimise flight hours lost			x	
[9]	1989	Minimise cost		x		
[20]	1996	Route AC to maintenance slot		x		
[10]	2000	Minimise cost		x		
[11]	2003	Minimise cost		x		
[12]	2006	Minimise cost		x		
[21]	2006	Minimise passenger disruption				x
[22]	2010	Maximise fleet availability			x	
[23]	2014	Maximise flying time utilisation			x	
[13]	2014	Minimise cost		x		
[18]	2017	Minimise TAT		x		
[17]	2018	Minimise TAT		x		
[24]	2020	Minimise flying hours waste			x	
[25]	2021	Minimise time between slots and due date		x		
[14]	2021	Minimise cost		x		
[16]	2023	Minimise maintenance ground time		x		
[15]	2023	Minimise cost		x		

2.4 *State of the art in task clustering*

After planning maintenance slots and checks, task designation for these checks and slots is next. There are thousands of components on a plane that require maintenance. With the advent of MSG-3, it became easier for airlines to build their own customised maintenance program.[26] In this program, specific task designations for aircraft maintenance are mentioned. This task designation is typically known as task clustering, where tasks are clustered into recurring maintenance slots. Clustering becomes very important because over a thousand maintenance tasks must be performed on an aircraft.

Table 3 Task clustering methods

Name	Year	Objective	Person-hours	RUL	Zone	Cost	Work-skill	Priority
[6]	2009	Optimise execution during maintenance		x				
[27]	2012	Minimise downtime and cost				x		
[28]	2015	Decrease computation time	x	x	x	x		
[29]	2016	Minimise cost		x		x		
[30]	2017	Increase aircraft availability		x		x		
[26]	2018	Minimise downtime	x	x	x			
[31]	2019	Ensure airworthiness	x				x	
[32]	2021	Decrease computation time	x	x				

The papers on task clustering focus on clustering tasks on due dates or costs; see Table 3. They mainly cluster the tasks into single checks with a shorter planning horizon that does not work with time availability constraints because there is no thought on the next check. Because the checks are clustered on due date and costs, there is no clustering related to the priority of the tasks. This priority comes in the form of its criticality towards airworthiness. Providing this prioritisation can help maintenance providers make choices when ground time is scarce, and choices have to be made.

2.5 *Lean Six Sigma*

After gaining background information about aircraft maintenance planning and task clustering, theories will be discussed to help improve the operations. Lean Six Sigma is one of the theories that can stimulate improvement.[33] Lean Six Sigma is a powerful and widely adopted theory for process improvement and problem-solving in many industries. It is a hybrid approach combining Lean Manufacturing and Six Sigma theories. These two theories bring a distinct but complementary set of tools and methodologies. Lean Manufacturing focuses on eliminating waste and increasing value delivery to customers. on the other hand, Six Sigma focuses on reducing process variation and defects, leading to consistent, high-quality outputs.

2.5.1 *Lean Manufacturing*

Lean Manufacturing is an established theory. At its core, Lean manufacturing maximises value while minimising waste in all process aspects. The driving force behind this theory is efficiency, quality and continuous improvement. The elimination of waste and increasing customer value efficiency, quality and continuous improvement have been around for thousands of years. However, only in modern times does the term Lean manufacturing find its way into the literature. It is mainly associated with two major car production companies. The first time it came into practice was in the early 20th century in the United States by Henry Ford. He revolutionised the automobile industry by placing a moving assembly line into the factory. This changed the car industry from being high-skilled to a mass-production industry.[34]

The next big evolution in Lean Manufacturing came from Japan. From the car manufacturer Toyota. They came up with what is now called ”The Toyota Way, ” which has now turned into Lean Manufacturing.

Lean Manufacturing is centred around waste in the organisation. Waste can be defined as: ”Any operation in a process which does not add value to the customer is considered waste”.[?] Thus, the goal is to identify and then eliminate waste. This leads to stable production with decreased cost, reduced time and increased quality.

Another major aspect of lean manufacturing is standardisation. Standardising operations leads to working more efficiently and a decrease in variability.[35] This standardisation can be performed in several ways, and categorisation is one of them. By categorisation certain aspects of the operation, there is a decrease in the variability. In this case, standardising the maintenance types and tasks based on priority efficiency can be increased.

2.5.2 *Value stream map*

One way to incite Lean Six Sigma in an organisation is to create a Value stream map. This is part of the Lean Manufacturing theory. It is a visual representation of the entire end-to-end process. VSM helps organisations analyse and improve their processes by identifying waste. Thus, the main goal of VSM is to create a detailed picture of the current state of the process. This is how the source of waste could be identified. VSM thus ”facilitates the identification of the value-adding activities in a value stream and elimination of the non-value-adding activities”.[36] Thus, value-add and non-value add activities are found if a divide is made in the activities. The non-value add consists of two activities: Necessary non-value add and Unnecessary non-value add.

2.5.3 *Process stability*

One crucial KPI in the aviation industry is stability, which is difficult to measure. The use of a capacity analysis could measure the stability.[37] This analysis is used to measure whether the company can execute the demands. When the process is being defined, the aim is to ensure reserved maintenance falls within the Upper and Lower Specification Limits (USL, LSL). Process Capability measures how consistently a process is within specifications. The idea of this is very simple. The operator desires a process centred over the nominal and spread narrower within the Upper and Lower Specification Limits.

One crucial factor in the process capability study is consistency. This consistency is expressed in C_p and C_{pk}. C_p indicates if the process is whether the process spread is narrower than the specification width. C_{pk} indicates the process’s centring and the spread relative to the specification width. These tools can be used to test whether the process is stable. C_{pk} can be considered to be more crucial than C_p. This is because C_p only considers the spread while C_{pk} considers spread and location. This means it is easier for the operator to adjust the C_p than the C_{pk}. The aim should be first to acquire a high C_{pk} because this indicates the stability is more profound. If that is set, the C_p can be adjusted to match the requirements better.

Now that C_p and C_{pk} are known, the next step is to know how to calculate them. First, the Specification width has to be calculated. The spec width is a basic calculation of the Upper Spec Limit (USL) minus the Lower Spec Limit (LSL). Next comes the process width. The process is the difference between the maximum and minimum values. $C_p = Specwidth/Processwidth$. The equation for C_{pk} consists of the distance from the mean to nearest spec limit D_s and the distance from the mean to process edge D_p and is as follows:

$$C_{pk} = D_s/D_p \tag{1}$$

$$C_p = Specwidth/Processwidth \tag{2}$$

The following analogy explains the C_p and C_{pk}. Imagine a pilot trying to park a plane in a hangar. If the plane is too wide, it won't fit. If it's narrower than the hangar opening but not centred, it won't make it in and will likely hit/scrape one of the sides. Hitting one of the sides of the hangar is equivalent to not reserving enough maintenance or too much maintenance. But if the plane is narrow enough and well-centred, the plane will fit. The aim is to have a narrow and well-centred process width relative to the spec limits.

2.6 Literature gap

The literature on aircraft maintenance, maintenance planning and task clustering was studied to design the model. However, gaps were identified in these areas. There was a focus on traditional aircraft maintenance in the form of letter checks rather than more dynamic weekly maintenance planning. There was a lot of literature on optimising maintenance planning, but this was solely from a maintenance provider's perspective and did not consider the other essential stakeholders in planning. For task clustering, the literature focused on clustering tasks into large single checks based on RUL and cost, but tasks were not clustered based on their criticality regarding airworthiness. Thus, a centralised model that takes a multi-stakeholder perspective on weekly maintenance requirements is proposed to fill the gap.

3 Model design

After analysing the current state of the airline's operations, it has become evident that there are significant issues that need to be addressed. The airline's organisational structure is fragmented, with communication occurring within isolated silos rather than effectively across the entire airline. Each stakeholder focuses on its own aspect of airline planning: flight, maintenance or service planning. Planning consists of scheduling maintenance and flight slots into the aircraft schedule. Service planning ensures enough time between the slots to perform the necessary tasks, such as inspections and embarking procedures. However, because each stakeholder focuses on its individual part of the planning, there is fragmentation in the organisation. To overcome this fragmentation and enhance operational efficiency, it is essential to introduce an integrated airline planning model that synchronises the different plannings intending to set a balance between flying and maintenance.

The proposed model takes a comprehensive approach by considering inputs from all stakeholders to conduct a holistic assessment of airline planning. It accommodates each stakeholder's unique needs and constraints while proposing a future state of planning that harmonises these perspectives. The model redefines stakeholder inputs, introducing new, standardised definitions that create an equilibrium between maintenance, flight and service planning. This equilibrium is established by setting the Weekly Minimum Maintenance Requirements (WMMR), rooted in the redefined prioritisation of maintenance tasks and types. The airline's capacity to effectively manage its weekly maintenance requirements is improved, reducing its vulnerability to unforeseen maintenance disruptions. By factoring in the inputs from all stakeholders, this approach achieves equilibrium between uptime and downtime.

The equilibrium between uptime and downtime is analogous to the balance between flight operations and maintenance. This balance is illustrated in the 'Cyrus Balance Zone' (as previously discussed in the example of Icarus), where the pursuit of flights corresponds to the sun, and excessive maintenance mirrors the sea. The area between them represents the balance zone, characterised by the presence of adequate maintenance and flights.

The aim of the model is to find the equilibrium presented by the silver plane in 2. The current equilibrium, as shown in Figure 2 by the red plane, favours the flight provider, with more emphasis on flying over maintenance, leading to excessive flying. The Blue plane represents an equilibrium favouring the maintenance provider, leading to excessive maintenance. The key importance is that the model considers all the stakeholders instead of only one so that the equilibrium between excessive flying and excessive maintenance can be established. In striking such a balance, uptime is assumed to increase.

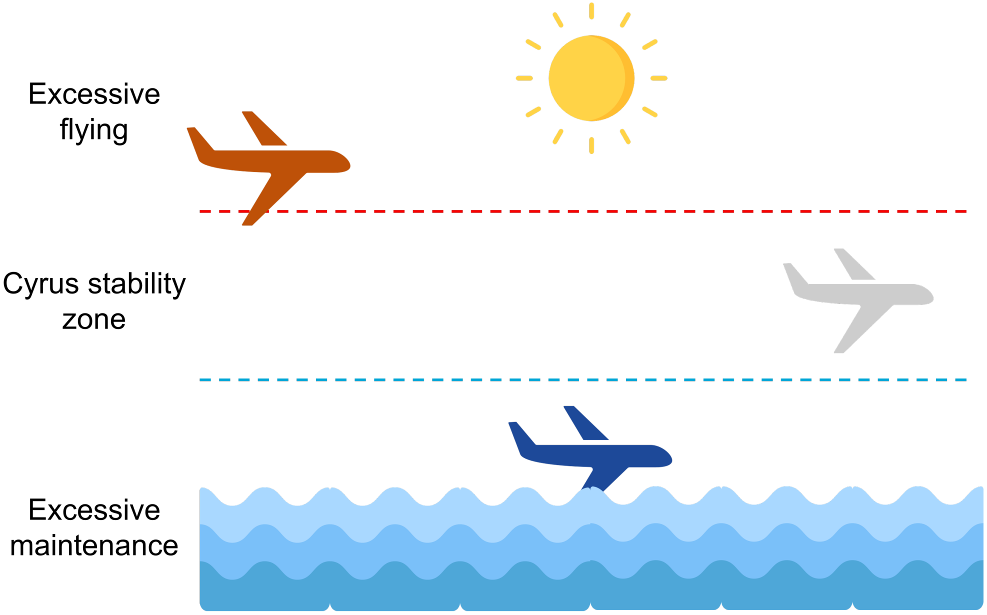

Fig 2 The Cyrus model tries to create a balance between uptime and downtime or between flights and maintenance

The model required to achieve balance and stability is named the Cyrus model because it wants to provide a holistic view of the ground time and the maintenance requirements. The Cyrus model is a centralised model that serves as a link between all the stakeholders; thus, it connects the separate silos. The proposed model is centralised because, currently, the decentralised state does not function optimally. This has to do with the fact that every stakeholder considers its interests a top priority, which leads to friction with the other stakeholders.

> **The Cyrus model is a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between flights and maintenance. This equilibrium enhances the airline's capacity to manage maintenance efficiently and should ensure greater uptime.**

Because it is a centralised model and provides a holistic airline perspective, it is named after Cyrus the Great, the first king of kings of the Achaemenid Empire. In this empire, there were many different kings who all acted in their interests and had different objectives. Cyrus the Great was the only one who saw the bigger picture; thus, from an empire perspective instead of a kingdom perspective. This centralised power with a holistic perspective allowed him to make better decisions. At the airline, there are also different kings or now-called stakeholders. They are the Maintenance, flight and service providers. This model tries to centralise the providers' insights together, as Cyrus did in the 6th century BC in Persia. This cooperation is depicted in Figure 3 where the Cyrus model stands at the centre of the airline operation.

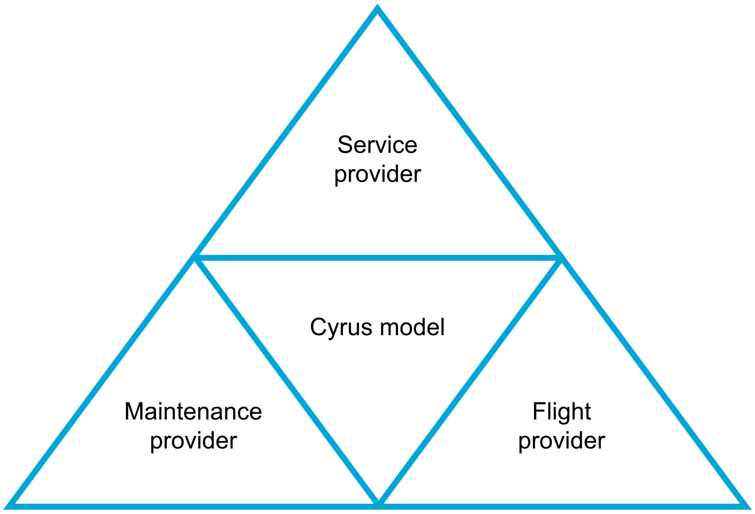

Fig 3 The provider's cooperation in the triangle and at the centre of the Cyrus model.

The Cyrus integrates two models: a data model and a planning model. The data model consists of taking the stakeholder's inputs and combining and categorising the data, after which the data can be analysed. The next model is the planning model, where the data analysis outputs are combined to create a future state planning framework. The two main models are highlighted in Figure 4. The Cyrus model aims to acquire a balance between maintenance and flights; from that balance, it wants to increase the uptime.

3.1 Categorisation

An essential aspect of the model is categorising maintenance types and tasks. One of the building blocks of Lean Manufacturing is standardisation. Categorisation is one of the ways to bring standardisation to the operation, as did Anand2009DevelopmentSystems. The categorisation affects the maintenance tasks and types. There are thousands of maintenance tasks; however, some tasks affect the airworthiness of an aircraft more than others. When ground time for maintenance is scarce, it has to be decided which tasks to complete first. Based on this, a prioritisation of tasks has been completed. Tasks that have a short remaining-useful-life and a critical for airworthiness that fall in the high-priority category should be completed first. After this, the medium-priority tasks should be completed, which have a longer RUL or are less critical for airworthiness. Finally, the low-priority tasks have a long RUL and do not affect airworthiness.

Next was to categorise maintenance types with similar priority categories for the tasks. Based on maintenance type categorisation, the weekly minimum maintenance requirements (WMMR) can be determined. The WMMR are high-priority maintenance slots that occur weekly and are mostly reserved for high and medium-priority tasks. Medium-priority maintenance types are unpredictable and thus difficult to consider for the weekly minimum maintenance requirements focusing on preventive maintenance. Low-priority slots do not occur frequently and thus should not be considered weekly. The final category is the checks; checks are the traditional letter checks, and because they are so settled in the maintenance schedule, they are not considered for WMMR. Even the tasks in the checks are high-priority, and this letter check strategy could change to a more weekly basis strategy.

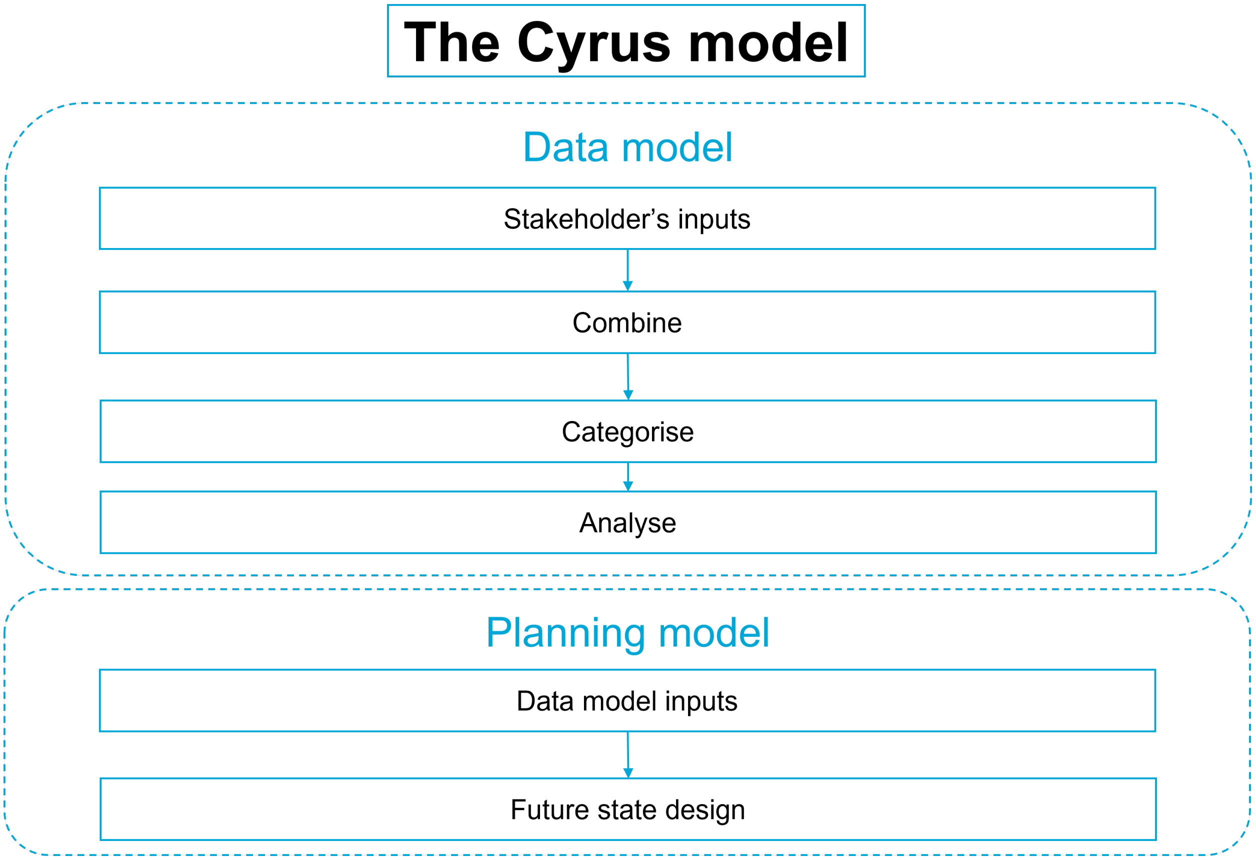

Fig 4 Cyrus model

3.2 Evaluation

The next aspect of the model is the evaluation of the turn time. The turn time is a black box in the current schedule, the empty space between flights and maintenance slots. One part of the Cyrus model is to evaluate the different activities. Disembarking, embarking, and towing are known as necessary non-value-added activities. On the other hand, maintenance and flights are considered value-added activities. The free time, the time between slots after subtracting the necessary non-value-added activities, is referred to as the unnecessary non-value-added activity. Lean theory advocates for minimising necessary non-value-added activities and eliminating unnecessary ones.

4 Model analysis

This section details the model analysis.

4.1 Factors for the WMMR

To obtain stability, the WMMR have to be determined. However, many aspects could influence the WMMR, such as aircraft age, type, and seasonality. An ageing aircraft is commonly associated with an increasing maintenance demand. Planes of the same type but different ages have been examined to test this hypothesis. On average, newer aircraft require less maintenance, but this does not apply to all aircraft. Therefore, it is difficult to label the yearly increased maintenance demand per aircraft. So, age is not considered for the WMMR; the fleet composition is something to consider. Different aircraft types can have massive different maintenance requirements. Thus, an individual assessment of the requirements per type should be of value. However, because this research focuses on the whole fleet, only an average of all the types is considered. Until now, the airline had weekly maintenance requirements that did not depend on fleet size and composition. However, the fleet size is also something to consider. If an aircraft has a weekly maintenance requirement, adding an extra plan to the fleet should also increase the total amount of maintenance. Even though there is a seasonal trend in maintenance and flights, the seasonality for the WMMR is negligible; thus, a constant WMMR could be maintained all year round. So, for the WMMR, the historical uses of the high-priority slots will be assessed, in combination with the fleet size, to determine the average WMMR per aircraft in hours.

4.2 WMMR

To estimate the WMMR, the historically used and planned WMMR are analysed. These values are shown in Table 4. These values are inserted into a distribution of all WMMR in 2012-2019 to check whether sufficient maintenance was planned. The distribution of the WMMR is displayed in Figure 5.

Table 4 The average yearly WMMR planned versus performed of the entire fleet in hours

Type/Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2022**
Planned	576	519	454	430	427	394	403	460	479
Performed	588	626	567	555	520	441	435	469	473

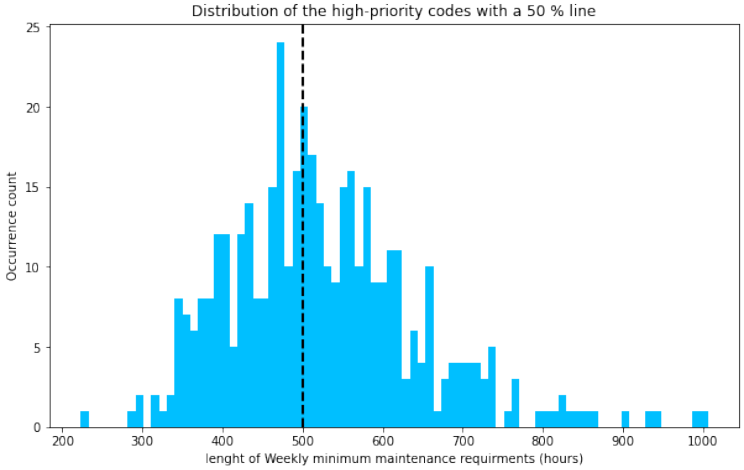

Fig 5 Distribution of the WMMR or high priority codes of the average weekly requirement for the whole fleet with the mean as a vertical line

Now that the yearly values are known, the years are analysed by a capability analysis, which shows how capable the planning was in these years. Most years did not turn out to be stable. The results of the capability analysis are shown in Table 5. Based on the results of the capability analysis, it can be concluded that in this period, insufficient maintenance was planned. The next step is determining how much WMMR should be required to acquire the balance.

5 Future state design

In the previous section, the analysis was completed. It is time to combine the information from the analysis to design a future state. The first step is determining what checks will be used and their length. The next

Table 5 The Capability indices of the planned WMMR per year

Sigma	KPI/Year	2012	2013	2014	2015	2016	2017	2018	2019	2022
4	**Cp**	0.81	0.91	0.89	0.76	0.93	0.80	0.88	0.82	0.86
	Cpk	0.62	0.55	0.57	0.43	0.61	0.67	0.62	0.79	0.60
6	**Cp**	1.22	1.36	1.33	1.14	1.39	1.21	1.33	1.22	1.29
	Cpk	0.93	0.83	0.86	0.65	0.91	1.01	0.93	1.18	0.91
8	**Cp**	1.63	1.81	1.78	1.52	1.86	1.61	1.77	1.63	1.71
	Cpk	1.24	1.10	1.15	0.86	1.21	1.35	1.25	1.58	1.21
10	**Cp**	2.04	2.26	2.22	1.90	2.32	2.01	2.21	2.04	2.14
	Cpk	1.55	1.38	1.43	1.08	1.52	1.69	1.56	1.97	1.51

step is determining how often they will occur, depending on the probability goal. Finally, the impact on the plan will be calculated. The final steps of the future state design are verification and validation.

5.0.1 Slot types and occurrence

Based on historical uses, it can be determined how often the high-priority maintenance slots occurred. This occurrence was when the strategy of WMMR was focused on corrective maintenance. If the switch to preventive maintenance wants to be made, the checks have to occur more often. So, it can be determined how often a check should occur if it wants to be fitted into the preventive maintenance strategy.

The next step is to identify how long these maintenance slots were by making a distribution of the historical slot lengths. Based on this, it can be determined how often a check had a certain length. For example, the platform check had an occurrence every three weeks and 50 % of the time, it was 2 hours or less. It means that if platform checks of two hours are planned, in 50 % of the cases, more time is required than the two hours, so longer platform checks are required.

5.0.2 Turn time

Now the slot lengths have been determined, how the ground time can be used efficiently should be investigated. A turn time evaluation was done to identify all the activities that occur during turn time, such as towing and embarking. However, issues were found when planning maintenance in the available free time in the turn time. This concerns current planning rules, where 130 minutes must be between slots, flights and maintenance. Thus, fitting maintenance in free time is more time costly than expected.

5.0.3 Check length

The next step of the future state is to identify the available time slots. Maintenance planning should aim to match the flight planning; otherwise, much ground time goes to waste. Thus, to prevent this, periods available for maintenance were identified in the flight plan based on the arrival and departure times. These periods are posted in Table 6 and comprise a morning, midday, evening, night and all-day slot. These slots could be combined; for example, a combination of a morning and midday shift creates more ground time.

However, these time slots in the previous table are arrival and departure times; thus, the available hours are the time between arrival and departure. As mentioned, a planned slot requires much extra time in the flight schedule. This information is posted in Table 7. This means that if a 1-hour check is planned, the actual time required in the schedule is 5.3 hours. The free time in the turn time that counts as unnecessary non-value-added time can be transformed into value-added time if the planning is set tight. That means that the free time is eliminated; however, it is at the expense of flexibility in planning. The amount of maintenance that could be performed on the platform in case of such a tight schedule is posted in the second

Table 6 Available periods in planning

	Time slot	*Available hours*
Morning	5:00-7:00 & 11:00-14:00	6-8
Midday	9:00-10:00 & 15:00-17:00	6-8
Evening	13:00-15:00 & 18:00-19:00	6-8
Night	19:00-21:00 & 7:00-9:00	12-14
All day	5:00-7:00 & 18:00-19:00	10-12

Table 7 Impact of maintenance slot on MFT plate

Planned length (hours)	Actual time P (hours)	Total time (hours)	% of maintenance P	% of maintenance H
1	2.4	5.3	45.3	18.8
2	3.4	6.3	53.9	31.6
4	5.4	8.3	65	48
6	7.4	10.3	71.8	58.1
9	10.4	13.3	78.1	67.5

column. The final two columns present the percentage of the total time in the MFT plate that is spent on maintenance. Based on the previous inputs, the different checks identified were 2- and 4-hour platform checks and 9-hour hangar checks.

5.1 Verification

The proposed checks and the data need to be verified. Two methods were used for verification: expert and data verification. First, expert verification focuses on the planned versus performed amounts of maintenance. The data in Table 4 implies that new additional maintenance slots are created in the MFT plate in the week of operation. To check this, two MFT plates are compared, namely the planned and the performed MFT plate of the same week. Thus, based on these MFT plates, it can be concluded that many additional maintenance slots are created in the schedule. Additional expert verification included the model verification, arrival and departure times, and available periods.

Next is the data verification, which includes natural time limits, fleet availability comparison and a WMMR calculation from theory. The time limit means that the total amount of flights, maintenance and turn time should not exceed the maximum limit, for example, for a single aircraft, not more than 168 hours a week. Data showed that this was rarely the case, only on a couple of occasions. These occasions were investigated and included large checks beyond the weekly limits. The next verification method is the comparison of the fleet availability. Airlines have extensive data on fleet availability because it is one of their KPIs. To verify the data, the fleet availability of the model is compared to the fleet availability of the airline's dashboards for the year 2022. The data of the fleet availability matched each other, thus could be concluded that the data accurately represents reality.

5.2 Validation

Now the data is verified, the future state can be validated. This step is essential to establish that the results from the Cyrus model are correct and if the future state has the positive impact it claims to have compared to the current state.

5.2.1 Slot fitting

The first step of the validation is slot fitting. The Cyrus model proposed several slot lengths: 2- and 4-hour platform checks and 9-hour hangar checks. Now, it must be validated that such slots fit the daily schedule. To do this, these daily schedules are created with the maintenance check. In Figure 6, a daily schedule for 2 and 4-hour platform checks is created. This check perfectly fits the periods between arrivals and departures in the future state. Similarly, a daily schedule for the Hangar checks of 6 and 9 hours is created and is shown in Figure 7. Also, a daily schedule for 6-hour hangar checks is created; however, if all ground wants to be used for maintenance, a 6-hour check coincides with a 12-hour hangar check. These checks are, however, not as necessary; thus, it is chosen only to use 9-hour hangar checks in the proposed schedule.

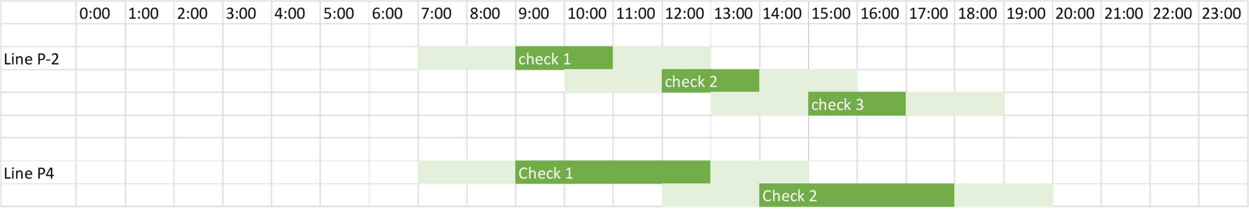

Fig 6 Validation of the platform checks into a daily schedule

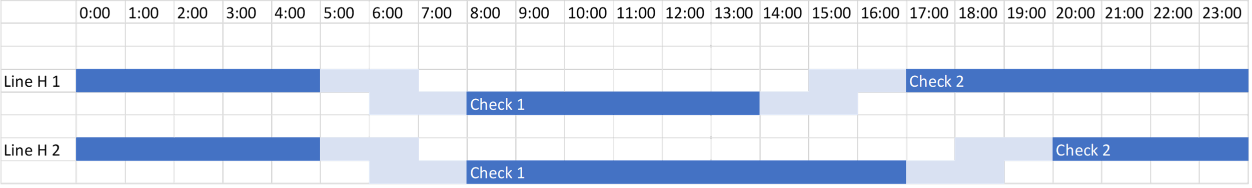

Fig 7 Validation of the hangar checks into a daily schedule

Why then not combine a 6-hour with a 9-hour hangar slot? Such a daily schedule has a lot of waste. To exemplify this issue, two schedules are compared. One is the current state, where there are 5-hour hangar checks, and the second is the proposed state. These daily schedules are shown in Figure 8, and in the upper schedule, the waste is three hours compared to the lower schedule. That is why the Cyrus model only uses 9-hour hangar slots or a multiplication of a 9-hour slot.

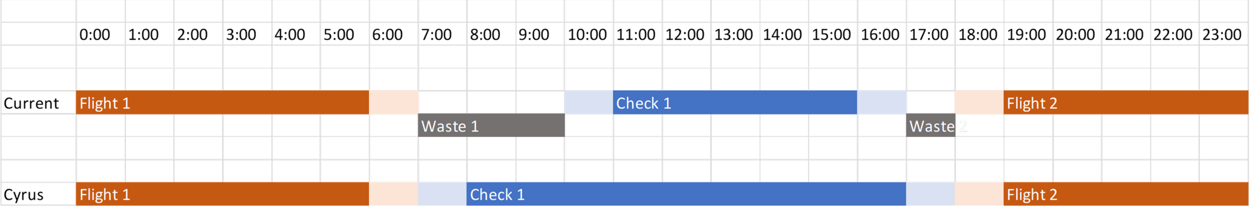

Fig 8 The waste of ground time if the hangar checks are not matched

5.2.2 Proposed plannings

Next is the validation of the proposed plans. Four proposed plans have a different check occurrence and thus have different average WMMR. The four scenarios are listed below together with the current state:

- Plan 1: This plan has a WMMR of 5 hours per aircraft and consists of 2, 4 and 9-hour checks

- Plan 2: This plan has a WMMR of 7 hours per aircraft and consists of 2, 4 and 9-hour checks
- Plan 3: This plan has a WMMR of 7.8 hours per aircraft and consists of 2, 4 and 9-hour checks
- Plan 4: This plan has a WMMR of 8.5 hours per aircraft and consists of 2, 4 and 9-hour checks
- Current state: This plan has a WMMR of 6 hours per aircraft and consists of 4, 5 and 9-hour checks

A capability analysis is performed on these plans to test their performance. However, minimum and maximum values are required for a capability analysis, which is unavailable for proposed scenarios. Thus, these values are determined based on historical data and the theoretical effects of weekly maintenance. Thus, some assumptions are made regarding these numbers. First is the standard deviation, considered equal to the average standard deviation between 2016 and 2019. This comes to a value of 85 hours. The next value to consider is the minimum value. The minimum value is not taken as the average between these periods because it is more dependent on the weekly maintenance amount because one of the effects of a weekly maintenance strategy is that the minimum should be close to the mean. Because there is weekly maintenance, which can differ per aircraft; however, on a fleet scale, the weekly amount should be similar to the mean value. The minimum value is chosen to be 85 % of the mean value and thus shoves along with an increased mean. The next value to determine is the maximum value. The maximum value is the average maximum between 2016 and 2019. This is done and not as a percentage of the mean because the maximum should not increase with an increasing mean. It might even decrease with an increasing mean. Thus, there comes the point when the reserved amount of WMMR is at the maximum value, so it can not be put out as a percentage as it is for the minimum. That is why the maximum value is 700 hours and remains constant with increasing reserved WMMR. Based on these values, the process is also calculated. These values are all displayed in Table 8.

Table 8 Values for different maintenance plans

Value/Plan	**Plan-1**	**Plan-2**	**Plan-3**	**Plan-4**	**R-check**
Reserved WMMR	350	490	550	600	420
Std	85	85	85	85	85
Min	298	417	468	510	357
Max	700	700	700	700	700
Max Dif	350	210	150	100	280
Process width	402	283	232	190	343

The probability, C_p and C_{pk} can be calculated based on these values. The C_p and C_{pk} depend on the specification width, so these are shown for different widths in Table 9. The table also shows the probability. This probability is related to the distribution of the weekly maintenance requirements for 2012-2019.

Based on Table 9, it can be determined that only Plan-3 and Plan-4 provide a stable process for all specifications widths. Plan-2 becomes stable at 6σ, the current R-check at 8σ and Plan-1 only at 10σ. Because plan 3 is only stable at 4σ, reserving less than 7.5 hours of maintenance per week per aircraft can be considered unstable. Thus, compared to the current state of the R-check, the Cyrus model proposed three plans that create more stability.

Table 9 The probability and capability performance for the different plans proposed by the Cyrus model

Plans		**Plan-1**	**Plan-2**	**Plan-3**	**Plan-4**	**R-check**
Probability %		4	43	64	78	20
Sigma 4	**Cp**	0.84	1.20	1.46	1.79	0.99
	Cpk	0.57	0.95	1.33	2.00	0.71
Sigma 6	**Cp**	1.27	1.80	2.19	2.68	1.49
	Cpk	0.86	1.43	2.00	3.00	1.07
Sigma 8	**Cp**	1.69	2.40	2.92	3.58	1.98
	Cpk	1.14	1.90	2.67	4.00	1.43
Sigma 10	**Cp**	2.11	3.00	3.66	4.47	2.48
	Cpk	1.43	2.38	3.33	5.00	1.79

The first item on the list is reduced downtime; this brings back the story of Icarus at the beginning of this thesis. Here, the balance had to be found between uptime and downtime. A lot of maintenance was similar to flying too close to the sea, and too much flying was similar to flying too close to the sun. Both situations are dangerous for the airline. Labelling the amount of WMMR directly to the uptime and downtime is difficult. The yearly uptime, downtime and waste numbers are shown in Table 10.

Table 10 Yearly uptime, downtime and waste performances

Categorie\Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**
WMMR (hours)	8.22	7.41	6.48	6.14	6.1	5.6	5.75	6.57
Uptime (%)	63.7	703	70.1	69.9	67.5	68.5	68.7	71.6
Downtime (%)	16.3	20.2	19.4	16.9	17.1	13.9	14.9	14.3
Waste (%)	20	9.5	10.54	13.2	15.4	17.6	16.4	14.1

This table shows the importance of balancing between uptime and downtime. Uptime is formulated as flying, downtime is formulated as maintenance, and waste is the time between the two, so unused uptime or downtime. The first column shows the amount of WMMR in hours. It can be seen that there is no direct relation between the WMMR and uptime or downtime. For example, 2019 has a WMMR of 6.57 and downtime of 14.3, while 2018 has a lower WMMR of 5.75 and a higher downtime of 14.9. However, the waste shows a clear trend, which also coincides with the proposed amounts by the Cyrus model. The fewer hours of WMMR, the more waste there is. But also, if 2012 is examined with the most WMMR, the waste has increased and thus is inefficient. Less waste equals a more efficient system.

This means that an increase and downtime does not lead to a decrease in uptime but can also lead to an increase in uptime. Based on these results, rough calculations can be done for the impact of a WMMR of 6, 7.5 and 9 hours. Based on the table, it can be determined that a WMMR of 6 equals 15 %, and 7.5 equals 10 %. For 9 hours, it is more complex, but it is assumed that the amount of waste equals 15 %. If the WMMR is 27 % out of all maintenance, as is seen in **??**, the amount of weekly maintenance comes to 22, 28 and 33 hours, respectively. 22, 28 and 33 hours equal 13.2, 16.5 and 19.8 % of the total time spent on maintenance. The respective uptime is acquired if the waste is added to this percentage, and the sum is subtracted from 100. The uptime for 6, 7.5 and 9 hours is 71, 74 and 65 % respectively. This means that an increase in

WMMR leads to increased uptime; however, if the WMMR is too high, the uptime will decrease again. These calculations are rough, however, and no precise percentage of waste can be assigned to a WMMR, but it indicates a balance between 6 and 9 hours, leading to increased uptime. This is an increase in uptime as an image of Icarus in Figure 9.

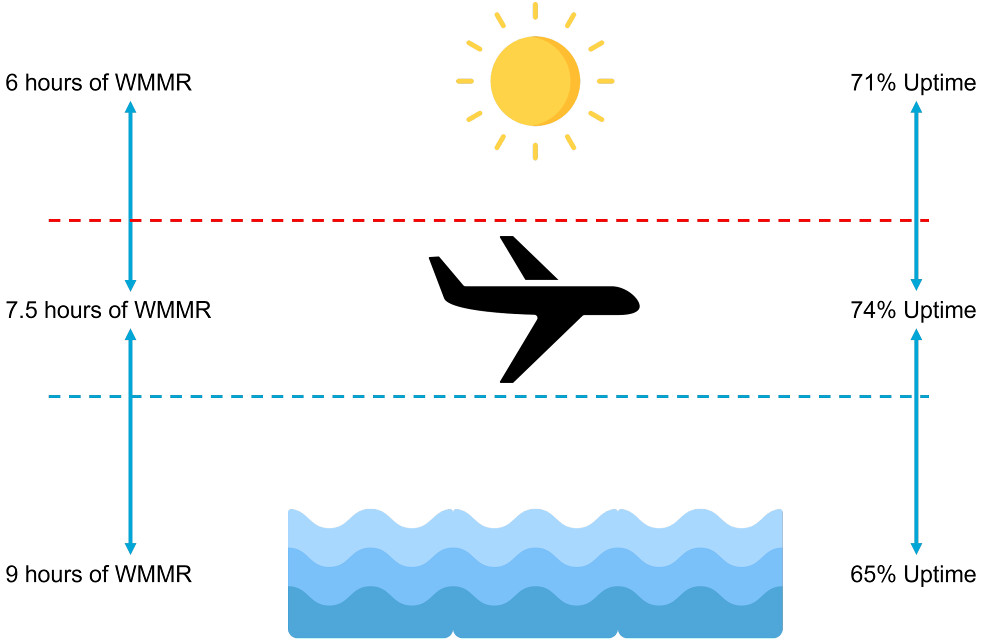

Fig 9 An aircraft shown as Icarus, where the balance is between the sun and the sea, which comes on and around 7-7.5 hours of WMMR

6 Conclusion

This project aimed to create a balance between uptime and downtime with the help of an integrated centralised airline planning model that can be used to estimate weekly minimum maintenance requirements based on Historical flight and maintenance data. This aim was translated into a research question that needed to be answered, which was formulated as:

> **How to value the balance between aircraft up and downtime from a multi-stakeholder perspective?**

The research was composed of multiple sub-questions to answer the central research question. The literature review analysed traditional aircraft maintenance, maintenance planning, and task clustering. Traditionally, maintenance focused on extensive ”letter checks”, which is still seen as the state of the art in maintenance planning. However, current maintenance planning lacks focus on weekly requirements and a holistic airline perspective. Task clustering also lacks focus on the priority of tasks regarding airworthiness and time constraints. This gap calls for better cooperation between stakeholders and clear maintenance definitions. The maintenance definitions can be given by categorisation of maintenance types. This categorisation comes from Lean manufacturing in the form of standardisation.

The Cyrus model is a centralised model that redefines definitions, standardises maintenance by categorisation, and reduces waste by introducing new slot lengths, leading to an equilibrium between excessive flights and excessive maintenance. Striking such a balance is assumed to increase the uptime.

It comprises a data and a planning model with stages for data processing, combining, analysis, and designing a future state. The analysis addressed sub-questions, including the impact of aircraft type on maintenance requirements, ageing, weekly minimum maintenance requirements (WMMR) determination, and task categorisation. The aircraft type significantly influences maintenance requirements, with older aircraft types requiring more maintenance. The WMMR depends on an airline's strategy, which means that if an aircraft only reserves enough maintenance for 30 % of the time, it should be aware that in 70 % of the weeks, additional maintenance is required. Further, medium-priority slots are unsuitable for WMMR due to their unpredictability, unlike the high-priority slots, which agree with the Weekly minimum maintenance requirements (WMMR).

A future state maintenance was proposed after determining the WMMR and its distribution. This planning and distribution of maintenance ground time considered all stakeholders' constraints, such as service and flight providers. A future state design aligns maintenance checks with historical data, flight schedules, and turn time waste reduction. Based on this, multiple weekly maintenance plans were proposed, which differed in check frequency. These proposed plans claimed to provide a more stable airline operation than the current state. That is why Verification and validation were essential steps. Expert and data verification ensured the model's accuracy, while validation involved creating daily cycles, analysing waste reduction, and evaluating stability compared to the current state. Three out of four proposed plans were more stable, confirming the model's hypothesis.

Thus, returning to the main research question, where a balance was to be found between uptime and downtime from a multi-stakeholder perspective. A system focusing too much on uptime leads to much unpredictability, resulting in planning instability. A system that focuses too much on downtime creates a stable system from a maintenance perspective but loses sight of flying, as in the Icarus example. Therefore, a balance is found in performing Weekly minimum maintenance requirements (WMMR). These WMMR should be fitted into the airline planning in accordance with the flight plan and the service plan. By performing the WMMR in slots P-2, P-4, and H-9, the balance is found to be near 7.5 hours or higher of maintenance per week per aircraft.

The optimal stakeholder cooperation is presented in Figure 10. The balance is achieved by increasing the downtime. This allowed the maintenance provider to plan sufficient maintenance to prevent unwanted demand peaks. Not only was the amount of weekly maintenance increased, but the slot lengths also differed. The slots are now better aligned with the flights, decreasing the waste in the planning. The increase in downtime leads to a larger decrease in waste, this means that more time becomes available for flights and thus uptime increases. Based on calculations, the uptime can increase to 74 %, which is higher than all the years in the last decade. Thus, the assumption that striking such a balance would increase the uptime is considered valid.

In summary, the research addressed sub-questions, covering topics from traditional maintenance to the Cyrus model's development, verification, and validation, ultimately leading to a balance between excessive flying and excessive maintenance based on inputs of multiple stakeholders instead of one. This balance can eventually lead to an increase in the uptime. Thus, a quote was found that applied to this future state compared to the current state, the Cyrus model was named after Cyrus the Great, the king of kings. As did Cyrus, this model found the balance between the stakeholders and kings and brought stability to his empire. One critical aspect of how he brought this stability is presented through a quote from Cyrus himself, shown below.

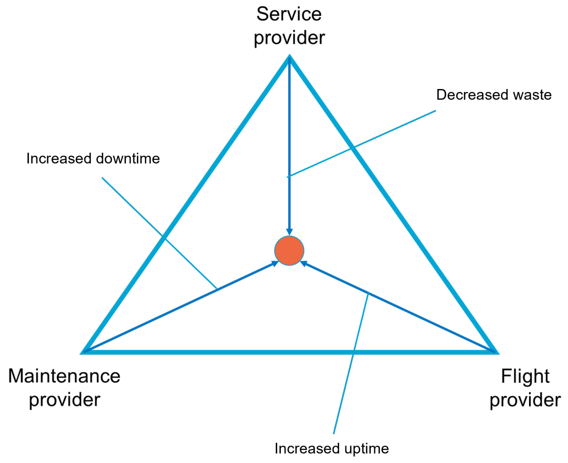

Fig 10 The balance achieved by the Cyrus model, where the centre of power is at the centre of the stakeholder triangle

> “Diversity in council, unity in command”
>
> Cyrus the Great 600-530BC

Acknowledgments

S.Hooijschuur thanks W.W.A Beelaerts van Blokland and R.R. Negenborn for their support, guidance and critical comments during this research. S. Hooijschuur furthermore thanks the Airline and P.H.L. Crombach for providing the opportunity and facilitating the research performed.

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