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Title: **Redesign of Airframe MRO processes from an uptime perspective –** a case study at KLM Engineering and Maintenance Airframe Services

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Title (in Dutch) Herontwerp van Airframe MRO-processen vanuit een 'uptime'-perspectief

Assignment: Master's thesis

Confidential: Yes, until: August 31, 2022

Initiator (university): dr.ir. D.L. Schott

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Date: August 11, 1017

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Subject: **KLM Airframe MRO improvement**

KLM Engineering & Maintenance performs different types of maintenance, repair and overhaul. One of them is airframe MRO and there are always continuous improvements wanted. Performing airframe MRO as fast as possible with a high quality and for the lowest costs is the desired output.

Several researches has been performed for other departments for MRO at KLM Engineering & Maintenance (engine and components) and KLM E&M has requested for also a new research at the airframe MRO department so that the output of the processes could be improved. The main focus is wanted for the wide body aircraft at KLM E&M, but it is also wanted to get more insights of the overall airframe MRO chain.

The assignment is to analyse the current processes of airframe MRO at KLM E&M and show possible solutions that can improve the output of the airframe MRO processes. The following approaches and goals need to be considered in this research:

- A definition of the current system and measurements
- Analysis of the performances of airframe MRO, finding the root cause for the constraints
- Solution alternatives for improving the output of the airframe MRO processes

The report should comply with the guidelines of the section. Details can be found on the website.

dr. ir. D.L. Schott

Preface

Dear reader,

When running at Amsterdam Schiphol Airport to the gate in order to catch your flight and when you finally sit in your seat and know the aircraft will not depart without you anymore, the big hangars at the other side of the airport can be seen. Wandering what happens over there and how cool it must be to really walk in and around the big aircraft. This was exactly how I thought and I was able to explore this world for the past seven months as I conducted my graduation internship at KLM Engineering & Maintenance.

The work lying in front of you represents the result of my master thesis project to finally complete my master studies Transport Engineering and Logistics (TEL) at the Delft University of Technology. The aim of this project was to improve the output of airframe MRO processes, especially for the wide body aircraft of KLM during an 'A-check'.

This master thesis project could not have been completed without the help of many others and therefore I would like to take this opportunity to thanks these people.

First of all, I want to thank Alex Gortenmulder and Guus Philips van Buren for the opportunity to conduct my thesis project at KLM Engineering & Maintenance at the Lean Six Sigma Office. They challenged and helped me a lot with their knowledge, enthusiasm and feedback that led to this completion. Secondly, I want to thank all colleagues at Airframe Services who helped me with providing the data and sharing their time and knowledge with me. Thirdly, I want to thank dr. ir. D.L. Schott and dr. W.W.A. Beelaerts van Blokland for their critical questions, scientific perspective and guidance that helped me a lot.

Finally, I want to thank all my fellow interns, friends, family and especially my parents and Julie for their enormous patience, support and input. Everybody, I can finally say: I'm finished!

Enjoy reading,

Amsterdam, August 2017

Jeroen Hockers

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Executive summary

An airline is able to achieve more profit (from an operational perspective) by increasing their amount of flights with the means of increasing its fleet size or achieve a better aircraft utilization or by decreasing their costs. This research focussed on achieving a better utilization of the aircraft.

The utilization of the aircraft depends on different factors. In general, the flight plan determines the aircraft utilization. Although the utilization of the aircraft can be increased by demanding more flights due to changes of the flight plan, it is depended of the maintenance plan of the aircraft. Both the flight plan and the maintenance plan has big influence on each other and for both it means the aircraft must be available for any of the plans. In order to achieve more uptime availability, maintenance should be done as quick as possible and without leaving open work.

This research is conducted at KLM Engineering & Maintenance (KLM E&M) located at Schiphol Airport, which is an airline third party MRO provider and a division of the Air-France KLM holding. Currently, there is gap between the desired performance of airframe MRO at KLM E&M and the current performance. This research aims to contribute to solving this problem by answering the following research question:

"How can the output of airframe Maintenance, Repair and Overhaul processes be improved from an uptime perspective?"

In order to answer this research question a framework has been used following 5 main steps, first defining the research problem and defining evaluation criteria's for the case study, secondly the current state is measured which resulted in a development of a theoretical preliminary model. Thirdly, this model is checked and used to analyse the system constraints. Next [4], solution alternatives were designed and lastly [5] the designed solution alternatives are tested and the results are evaluated to find the best solution.

Defining the system & criteria

Different criteria's were found from literature and practice in order to evaluate several solution alternatives. Four different criteria were determined, namely: Turnaround time, Process cost, Product quality and Process quality.

Current state measurements

The current state of the Airframe MRO is measured on different levels and performances. First the Process quality is measured for the deferred defects (WIP) for the overall KLM E&M Airframe MRO chain. The deferred defects had a total average of 599/day which resulted in exceeding the target level. The research then focused on the checks for wide body aircraft in hangar 11 and the average turnaround time for those checks are:

	A-check	H-check	M-check	AOG-check	TD-check
Average TAT (hours)	42.67	33.56	12.06	33.74	16.33

A more in-depth focus for this research followed for the A-check. It was measured that the on time performance of the check is not 42% (measured by KLM E&M), but 15%.

A theoretical preliminary model was developed in order to redesign the process of the current check and to cope with the currently limitations of the data. The model uses a phase sequence in which each phase must be completed before the next may start. Also 2 teams were created: 'Under the Wing' (currently lengthwise- and crosswise-team) and 'Above the Wing' (currently cabin-team)

Analyse system constraints

For the overall Airframe MRO chain it was found that current control lacked consistent handshakes/agreements. As this research then focused on the A-check and specifically of a Boeing 777-300. It was found that 'Under the Wing' activities was constraining the output of the airframe MRO process. The main constraint was formed by misaligning resources with the demanded workload of the check.

Design of solution alternatives

Different solution alternatives were designed based on first exploiting the constraint, then elevating the constraint and finally the creation of the desired world solution. Resulting in five solution alternatives: exploit (norm), exploit (later shift), exploit (core shift), elevate (extra men) and desired world (2 shifts).

Test and evaluate the solutions

The designed solution alternatives are then implemented in the theoretical preliminary model and the results are shown below. Each solution alternative was also tested for a clean aircraft policy.

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Current state	25:29	4:17	60:09
Exploit: Norm	23:05	4:17	46:12

Exploit: Norm (clean)	23:54	0:00	45:23
Exploit: Later start of shifts	21:15	4:17	23:04
Exploit: Later start of shifts (clean)	22:20	0:00	22:55
Exploit: Core shift	20:25	4:17	28:46
Exploit: Core shift (clean)	20:35	0:00	25:38
Elevate: Extra men	18:04	4:17	86:01
Elevate: Extra men (clean)	18:10	0:00	83:45
Desired world: 2 shifts	16:28	4:17	116:20
Desired world: 2 shifts (clean)	16:28	0:00	120:08

The best solution alternative is found by using a Multi Criteria Analysis combined with the Analytical Hierarchy Process. The previously determined criteria are used for this analysis and after the analysis and sensitivity test the best solution could be determined.

The most favourable and overall best solution from the analysis is the 'Desired world' alternative with following a clean aircraft policy (no WIP after the check). However, other solution alternatives also have a high overall score and they all follow the same principle. Namely, get the resources in tune with the demanded workload by implementing a core shift.

Answering main question

How can the output of airframe Maintenance, Repair and Overhaul processes be improved from an uptime perspective?

Following a good structured framework by first defining the case and measuring, ensured a good analysis for identifying the main constraint in the process. Different solution alternatives can then be created that focusses on the constraints. The constraints can then be exploited or elevated in order to improve the output of the process. It was found from literature and tested in this research that airframe MRO can be improved by implementing Phase-Gate methodology and concentrating resources within the phases.

Recommendations, further research & limitations

First it is recommended to implement phases within a check where all resources are working on the same goal, namely finish all the tasks of the phase before working on tasks of another phase (so called Phase-Gate).

Then it is recommended for KLM E&M Airframe Services to plan the available resources (man) in tune with the workload by implementing a core shift and follow a clean aircraft policy. It is advised to start the check with a small group of men and then the core shift should be present when the aircraft is inside the hangar and grounded. Also, it is essential that clear handshakes/agreements are in place between all process steps within the overall airframe MRO chain.

Furthermore, it is advised for KLM E&M Airframe Services that further improvements are made for the current way of writing and signing off tasks during a check. Currently there is no control how this happens and therefore resulting in unreliable data or not complete data. It is advisable that the data really shows when and for how long the mechanics/GWK's worked on each task. This only can improve future analyses and gives the opportunity for continuous improvements. Another data improvement is to determine which task belongs to the different phases, as now they already have a 'phase-code', but the current 'phase-codes' are too broad.

This analysis should be done on multiple A-checks in order to have a better analysis and a more robust conclusion of the analysis. A good way is by simulating the checks in order to test the impact of implementing Phase-Gate within the checks. Also, a recommendation is performing an analysis for determining which tasks are critical within a phase, so the resources are well appointed to those tasks.

Another recommendation is that the mechanics/GWK's can see the progress of the check and easily know where the focus of resources should be so they could help one another.

From a scientific aspect, it is advised to use the theoretical model at different airframe MRO processes to test if it can improve the output performance. The theoretical model could easily be adapted to any airframe MRO process as the phases could be changed.

The main limitation of this research is the useable data. There is a lot of data available but the data do not provide instantly the needed things. A lot of manual checks had to be done in order to perform an analysis. This resulted in the next limitation, namely the focus of the research is only based on a single A-check. This limits the robustness of the made conclusions and recommendations. This research is limited by the focus on only the main constraint, but other smaller constraint were neglected. All the solution alternatives are focussed on this main constraint but it is possible that other solutions could be better than some of the designed solutions. Also the modelling of the different solution are limited by made assumptions in the specifications of the model.

Executive summary (in Dutch)

Voor een vliegtuigmaatschappij is het mogelijk om hun winst te vergroten (vanuit een operationeel perspectief) door een vermeerdering van vluchten uit te voeren met de hulp van de vlootgrootte te vergroten of door meer gebruik te maken van de huidige vloot of de kosten te verminderen. Dit onderzoek richt zich op het beter benutten van de vliegtuigen.

Het gebruik van het vliegtuig hangt af van verschillende factoren. In het algemeen bepaalt het vluchtplan het gebruik van het vliegtuig. Hoewel het gebruik van het vliegtuig kan worden verhoogd door meer vluchten uit te voeren door veranderingen van het vluchtplan, hangt het af van het onderhoudsplan van het vliegtuig. Zowel het vluchtplan als het onderhoudsplan hebben grote invloed op elkaar en voor beide geldt dat het vliegtuig beschikbaar moet zijn voor elk van de plannen. Om meer beschikbaarheid te creëren voor het vluchtplan dient onderhoud zo snel mogelijk te gebeuren en zonder openstaand werk.

Dit onderzoek is verricht bij KLM Engineering & Maintenance (KLM E&M), gevestigd op de luchthaven van Schiphol, een MRO-leverancier van een derden luchtvaartmaatschappij en een afdeling van het KLM-luchtvaartmaatschappij Air France. Op dit moment is er sprake van een kloof tussen de gewenste prestatie van de airframe MRO afdeling bij KLM E&M en de huidige prestaties. Dit onderzoek beoogt bij te dragen tot het oplossen van dit probleem door de volgende onderzoeksvraag te beantwoorden:

> "Hoe kan de prestatie van de onderhouds-, reparatie- en revisieprocessen van vliegtuigonderhoud worden verbeterd vanuit een 'uptime'-perspectief?"

Om deze onderzoeksvraag te beantwoorden is een structuur aangehouden op basis van 5 hoofdstappen. Allereerst is het onderzoeksprobleem gedefinieerd en zijn de evaluatiecriteria vastgelegd voor de casestudie. Ten tweede is de huidige staat gemeten die resulteerde in de ontwikkeling van een voorlopig theoretisch model. Ten derde is dit model gecontroleerd en gebruikt om de systeembeperkingen te analyseren. Vervolgens [4] zijn oplossingsalternatieven ontworpen en ten slotte [5] zijn de alternatieve oplossingen getest en zijn de resultaten geëvalueerd om de beste oplossing te vinden.

Definiëren van het systeem & criteria

Er zijn verschillende criteria gevonden uit literatuur en de praktijk om verschillende oplossingsalternatieven te evalueren. Vier verschillende criteria werden vastgesteld, namelijk: doorlooptijd, proceskosten, productkwaliteit en proceskwaliteit.

Huidige toestand metingen

De huidige toestand van de Airframe MRO wordt gemeten op verschillende niveaus en prestaties. Eerst wordt de Proceskwaliteit gemeten door middel van de uitgestelde defecten (WIP) voor de totale KLM E&M Airframe MRO-keten. De uitgestelde defecten hadden een gemiddelde van 599 per dag, wat resulteerde in het overschrijden van het doelniveau. Het onderzoek richtte zich vervolgens op de onderhoudsbeurten voor de grootste vliegtuigen gevestigd in hangaar 11 en de gemiddelde doorlooptijd voor die onderhoudsbeurten is:

	A-check	**H-check**	**M-check**	**AOG-check**	**TD-check**
Gemiddelde doorlooptijd (uur)	42.67	33.56	12.06	33.74	16.33

Het onderzoek richtte zich verder op de ‘A-check’. Er is gemeten dat de oplevering prestaties van de check niet 42% bedraagt (gemeten door KLM E & M), maar 15%.

Een voorlopig theoretisch model is ontwikkeld om het proces van de huidige checks te herontwerpen en om de huidige beperkingen van de gegevens te kunnen aanpakken. Het model maakt gebruik van een fasevolgorde waarin elke fase moet worden volbracht voordat de volgende kan starten. Ook werden 2 teams gecreëerd: 'Onder de vleugel' (momenteel langs- en dwars-team) en ‘Boven de vleugel’ (momenteel cabine-team).

Analyse van de systeembeperkingen

Voor de algemene Airframe MRO-keten bleek dat de huidige besturing een gebrek aan consistente handshakes / afspraken heeft. Vervolgens is dit onderzoek verder ingegaan op de A-check en specifiek op een Boeing 777-300. Er bleek dat de activiteiten onder de vleugel de prestatie van het MRO-proces van het vliegtuig beperken. De belangrijkste beperking is gevormd door de niet juiste afstemming van de middelen (monteurs etc) op de vereiste werklast van de check.

Ontwerp van oplossingsalternatieven

Verschillende oplossingsalternatieven zijn ontworpen op basis van eerst het uitbuiten van de systeembeperking, daarna het verheffen van de beperking en uiteindelijk de creatie van de gewenste oplossing. Het resultaat zijn vijf oplossingsalternatieven: exploiteren (norm), exploiteren (latere ploegen), exploiteren (kern ploeg), verheffing (extra mannen) en gewenste wereld - oplossing(2 ploegen).

Testen en evaluatie van de oplossingen

De oplossingen alternatieven zijn vervolgens geïmplementeerd in het voorlopige theoretische model en de resultaten worden hieronder getoond. Elk oplossingsalternatief werd ook getest op een schoon vliegtuigbeleid (geen openstaand werk na uitvoering van een check).

	Doorlooptijd (hh:mm)	WIP (werk-uren)	Verspilling van middelen (man-uren)
Huidige toestand	25:29	4:17	60:09
Exploiteren: Norm	23:05	4:17	46:12
Exploiteren: Norm (schoon)	23:54	0:00	45:23
Exploiteren: Latere start van ploegen	21:15	4:17	23:04
Exploiteren: Latere start van ploegen (schoon)	22:20	0:00	22:55
Exploiteren: Kern ploeg	20:25	4:17	28:46
Exploiteren: Kern ploeg (schoon)	20:35	0:00	25:38
Verheffing: Extra mannen	18:04	4:17	86:01
Verheffing: Extra mannen (schoon)	18:10	0:00	83:45
Gewenste Wereld: 2 ploegen	16:28	4:17	116:20
Gewenste Wereld: 2 ploegen (schoon)	16:28	0:00	120:08

De beste oplossingsalternatief is gevonden door middel van een Multi Criteria Analyse in combinatie met het Analytische Hiërarchieproces. De eerder vastgestelde criteria zijn gebruikt voor deze analyse en na de analyse en een gevoeligheidstest kon de beste oplossing worden bepaald.

De meest gunstige en algehele beste oplossing vanuit de analyse is het 'Gewenste wereld' alternatief met een schoon vliegtuigbeleid (geen WIP na de check). Hoewel andere alternatieven ook een hoge algemene score hebben, volgen ze allemaal hetzelfde principe. Namelijk dat de middelen (monteurs/grondwerktuigkundigen) in overeenstemming zijn met de vereiste werklast door een kern ploeg te implementeren.

Beantwoording van de hoofdvraag

Hoe kan de prestatie van de onderhouds-, reparatie- en revisieprocessen van vliegtuigonderhoud worden verbeterd vanuit een 'uptime'-perspectief

Door middel van een gestructureerde aanpak door eerst de case te definiëren en metingen te verrichten van de huidige toestand, zorgde er voor dat een analyse gedaan kon worden voor het vaststellen van een beperking in het proces. Er kunnen dan oplossingsalternatieven worden gecreëerd die zich richten op de beperkingen. De beperkingen kunnen dan worden uitgebuit of verhoogd om de prestaties van het proces te verbeteren. Uit de literatuur was gevonden en uiteindelijk getest in dit onderzoek, dat airframe MRO verbeterde prestaties kan waarmaken door middel van de 'Phase-Gate'-methodologie toe te passen en het concentreren van de middelen (mensen) gedurende de fases.

Aanbevelingen, verder onderzoek & limitaties

In de eerste plaats wordt aanbevolen fases te implementeren binnen een check waarbij alle mensen aan hetzelfde doel werken, namelijk alle taken van de fase afronden voordat ze verder gaan met taken van een andere fase (Phase-Gate).

Vervolgens wordt aanbevolen voor KLM E&M Airframe Services om de beschikbare middelen (mensen) af te stemmen met de werklast door een kernploeg te implementeren en een schoon vliegtuigbeleid te volgen. Het is aan te raden om de check te starten met een kleine groep mannen en vervolgens moet de kernploeg aanwezig zijn als het vliegtuig in de hangar en gereed is om de verdere werkzaamheden uit te voeren. Het is ook essentieel dat er duidelijke handshakes / afspraken zijn tussen alle processtappen binnen de algemene MRO-keten.

Verder wordt geadviseerd voor KLM E&M Airframe Services dat verdere verbeteringen worden aangebracht voor de huidige manier van afmelding van de taken tijdens een check. Momenteel is er geen controle over hoe dit gebeurt en dit kan resulteren in onbetrouwbare en/of onvolledige data. Het is raadzaam dat de data echt laat zien wanneer en voor hoe lang de monteurs / GWK's voor elke taak heeft gewerkt. Dit kan alleen toekomstige analyses verbeteren en biedt de mogelijkheid voor continue verbeteringen. Een andere dataverbetering is om te bepalen welke taak tot de verschillende fasen behoort, aangezien ze nu wel al een 'fasecode' hebben, maar de huidige 'fasecodes' zijn te ruim gekozen.

Deze analyse moet worden uitgevoerd op meerdere A-checks om een betere analyse en een robuuste conclusie van de analyse te krijgen. Een goede manier is om de checks te simuleren om de impact van de implementatie van Phase-Gate binnen de checks verder te testen. Een andere aanbeveling is om een analyse te doen om te bepalen welke taken kritisch zijn gedurende een fase, zodat de monteurs / GWK's goed ingedeeld kunnen worden voor die taken.

Vervolgens is het aanbevolen om er voor te zorgen dat monteurs / GWK's de voortgang van de check/fases kunnen zien en daardoor gemakkelijk weten waar de focus moet zijn zodat ze elkaar kunnen helpen.

Uit een wetenschappelijk oogpunt is het raadzaam het theoretische model te gebruiken bij verschillende airframe MRO-processen om te kijken of het de prestaties kan verbeteren. Het theoretische model kan makkelijk worden aangepast aan elk airframe MRO-proces, omdat de fases zo aangepast kunnen worden.

Dit onderzoek is beperkt door de nadruk op alleen de hoofdbeperking, terwijl andere kleinere beperkingen werden verwaarloosd. Alle oplossingsalternatieven zijn gericht op deze hoofdbeperking, maar het is mogelijk dat andere oplossingen beter kunnen zijn dan sommige van de ontworpen oplossingen. Ook de modellering van de verschillende oplossingen wordt beperkt door gemaakte aannames in de specificaties van het model.

List of abbreviations

Abbreviation	Explanation
AHP	Analytic Hierarchy Process
AOG	Aircraft On Ground
ASK	Available Seat Kilometer
B777	Boeing 777
CBBSC	Connected Business Balance Score Card
CCPM	Critical Chain Project Management
CPM	Critical Path Method
DD	Deferred Defect
DMAIC	Define Measure Analyse Improve Control
HPO	High Performance Organization
IDEF	Integrated Definition for Function Modelling
JIT	Just In Time
KLM	Koninklijke Luchtvaart Maatschappij
KLM E&M	KLM Engineering & Maintenance
KPI	Key Performance Indicator
MCA	Multi Criteria Analysis
MCC	Maintenance Control Center
MEF	Material, Equipment & Facilities
MRO	Maintenance, Repair & Overhaul
Mxi	Maintenix
OEM	Original Equipment Manufacturer
OTP	On time performance
PDSA	Plan Do Study Act
PSFC	Planning, Scheduling & Fleet Control
RPK	Revenue Passenger Kilometer
SIPOC	Supplier Input Process Output Customer
TAT	Turnaround Time
TOC	Theory of Constraints
TPS	Toyota Production System
TQM	Total Quality Management
WBS	Work Breakdown Structure

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Contents

Define Phase

1 Introduction

In this chapter the research context will first be described in section 1.1. Next the field of research (section 1.2) is discussed which will be followed by section 1.3 (practice analysis) where it will become more clear what this research is about. From this, the research problem is derived and discussed in section 1.4, followed by the research scope and objectives in section 1.5. The main research question and sub questions are then defined in section 1.6 and lastly the approach for this research is stated in section 1.7.

1.1 Research context

In 2016 a new record of 3.8 billion passengers were carried by commercial air transport and this is expected to almost double to 7.2 billion passengers in the year 2035 (IATA, 2016). Currently the global commercial air transport fleet size consists of more than 24,500 aircraft and by 2026 the active fleet is forecasts to become over 34,400 aircraft (Oliver Wyman, 2016)

Maintenance, Repair and Overhaul (MRO) is essential to ensure that aviation remains the safest mode of transport. So with an increasing fleet size, the demand for MRO also increases in order to guarantee the reliability and airworthiness of aircraft. The aircraft MRO market was expected to be worth $67.7 billion in 2016 and growing to over $98.9 billion by 2026. This represents an annual average growth rate of 3.9%.

With this expected growth, the aircraft MRO market is very significant, but with a lot of competing players. Different airlines, such as Air France-KLM and Lufthansa are competing against each other, but also competing with Original Equipment Manufacturers (OEM). The different players on the aircraft MRO market can be distinguished into four categories: OEM, in-house engineering, airline third party and independent third party (CAPA, n.d.).

MRO of aircraft can be divided in several main categories, namely:

- Airframe MRO
- Engine MRO
- Components MRO

The Airframe MRO was forecast at $16.0 billion for 2016 and $19.2 billion by 2026. The airframe MRO market is a low-margin, labour-intensive segment with an average annual growth rate of 1.8%. Engine MRO was expected to be $25.7 billion in 2016 with a growth rate of 5.3% annually to reach $43.0 billion by 2026. Lastly, the Component MRO was forecast to be $13.1 billion in 2016, growing to $18.6 billion by 2026 with an annual growth rate of 3.5% (Oliver Wyman, 2016)

1.2 Field of research

For an airline to make profit, the main principle is achieving a high turnover for the lowest possible costs. The strategy for each airline can be different to accomplish this, because there are a lot of factors that influence this.

Figure 1-1 shows an airline structure from an operational perspective, where it can be seen that different factors influence an airline. When looking from an operational perspective, an airline can increase turnover by increasing their Revenue Passenger Kilometer (RPK). It is a measure of the volume of passengers carried by an airline and a revenue passenger-kilometre is flown when a revenue passenger is carried one kilometer. The RPK can be increased by higher ticket prices, a higher passenger load factor of the aircraft with a higher Available Seat Kilometer (ASK). The ASK is the product of the number of seats and route distance (Budd & Ison, 2017).

The costs for an airline can be divided into multiple sections: direct operating costs, indirect operating costs and overhead costs. The direct operating costs can be decreased on different segments. From Figure 1-1 it can be seen that MRO is one of these segments.

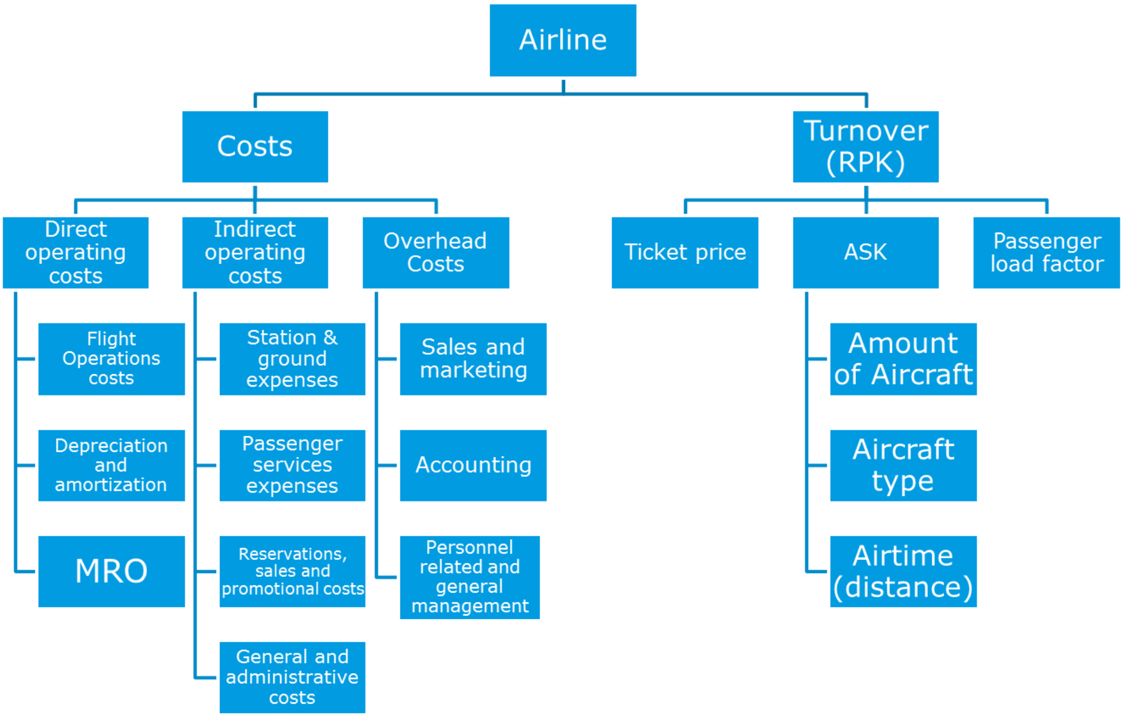


Figure 1-1: Airline structure from an operational perspective

Thus an airline is able to achieve more profit (from an operational perspective) by increasing their amount of flights by increasing its fleet size or achieve a better aircraft utilization or by decreasing their costs.

On average a new Boeing 777 cost €300 million (Statista, 2017) and for KLM it has a cost of capital of 9% for aircraft, which means €27 million/year. A mechanic cost KLM Engineering and Maintenance on average €50,000/year (KLM, 2016). Thus for the same price of 1 new Boeing 777, instead it is also possible to have 540 extra mechanics. So from a yearly cost perspective, instead of increasing the fleet size, it is better to achieve a higher aircraft utilization by ensuring the aircraft is airworthy due to the work of the mechanics.

1.2.1 Aircraft utilization

The utilization of the aircraft depends on different factors. In general, the flight plan determines the aircraft utilization. Although the utilization of the aircraft can be increased by demanding more flights due to changes of the flight plan, it is depended of the maintenance plan of the aircraft. Both the flight plan and the maintenance plan has big influence on each other and for both it means the aircraft must be available for any of the plans. This is also depicted in Figure 1-2 and it shows that the aircraft is the constraint for the maintenance- as well for the flight plan.

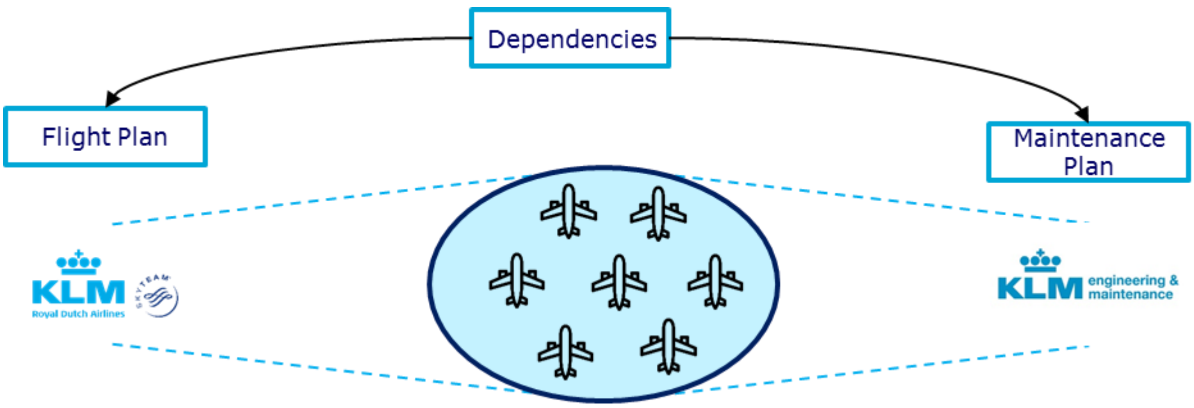


Figure 1-2: Dependencies for aircraft availability.

So as mentioned before, in order to increase turnover by increasing the aircraft utilization, it is needed that the aircraft is available to fly (uptime). Figure 1-3 shows that MRO has big influence on the quality of the aircraft but also on the ground time of the aircraft. The airworthiness of the aircraft is determined by the quality of it. If the aircraft is not airworthy, it is not available to fly (downtime). On the other hand, when the aircraft is on the ground for maintenance it is also not available to fly. Thus in order to achieve more uptime (the aircraft to fly), the downtime (aircraft not flying) needs to be a low as possible.

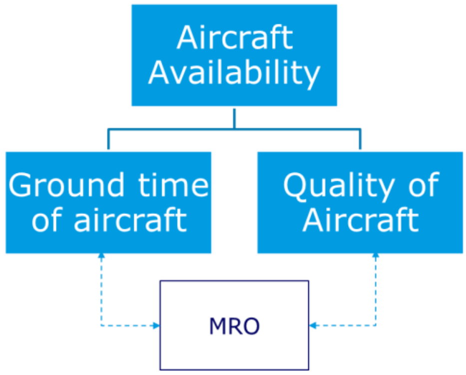


Figure 1-3: MRO influence for aircraft availability

1.2.2 KLM Engineering & Maintenance

This research is conducted at KLM Engineering & Maintenance (KLM E&M) located at Schiphol Airport, which is an airline third party MRO provider and a division of the Air-France KLM holding. KLM E&M employs over 5,000 people and is one of the largest aircraft MRO providers of the world (KLM, 2013). KLM E&M is divided in several segments, namely: Airframe services, Engine services and Components services. Where Engine services focus on organizing engine availability and providing engine MRO; components services focus on providing components MRO and availability organization and lastly, airframe services focus on organizing fleet maintenance and providing airframe MRO.

1.2.3 KLM Engineering & Maintenance Airframe services

This research will focus on Airframe services and specifically on providing airframe MRO. Airframe MRO is needed to maintain the airworthiness of the aircraft by applying scheduled and unscheduled inspections, replacements and modifications. The type and duration of the maintenance depends on the type of tasks that needs to be performed.

Figure 1-4 shows a simplified illustration of how airframe MRO can be performed by KLM E&M. After the arrival of an aircraft the opportunity for providing MRO to the aircraft is there. Small checks can be performed during the turnaround of the aircraft at the gate (ramp). But larger checks mainly occur in a hangar. For each type of check a different work package consisting of tasks to be performed is known. After the check the aircraft is ready for its next flight.

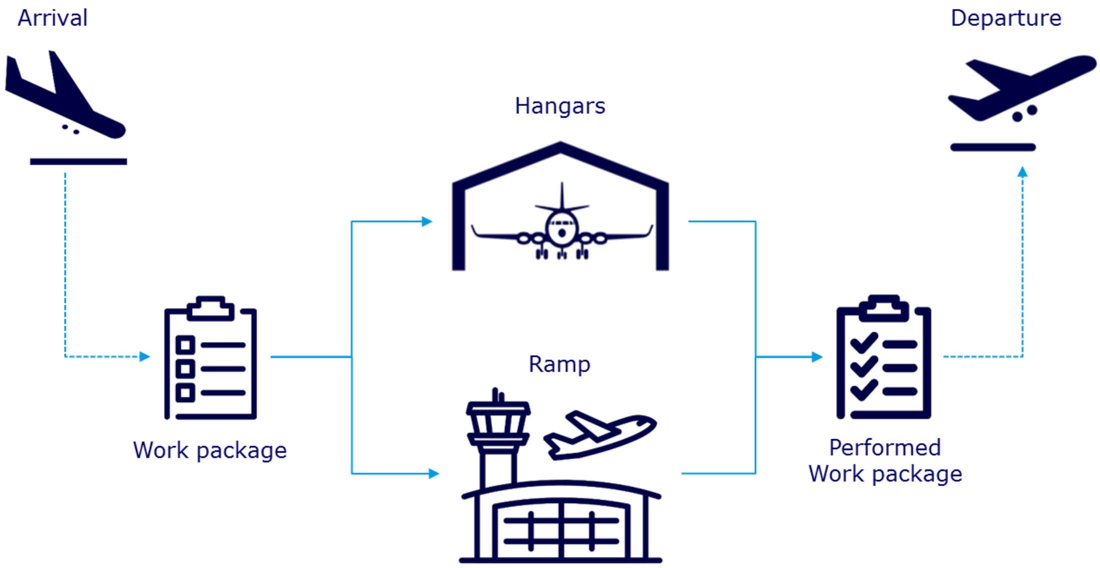


Figure 1-4: Simplified illustration of providing airframe MRO.

An example of a small check is the so called “pre-flight inspection”. Before every flight the inspection has to be done to ensure that the aircraft is fit for the intended flight. During this check, a walk around the aircraft has to be performed. This is an exterior inspection to ensure that the overall condition of the aircraft and its visible components and equipment are safe for the flight. There is looked at obvious signs for any structural impact damage, no leakage of fuel, oil or hydraulic fluids and that all doors/panels which are not in use are closed and secured (KLM, 2016).

Larger checks are more detailed inspections and mainly performed in a hangar and have a long duration. There are different levels of checks and they are often referred as “A-check”, “B-check”, “C-check” and “D-check”. The level of detail of the different checks are different from each other, where A-checks are the least comprehensive and occur frequently. On the other hand, D-checks are extremely comprehensive and occur only three to six times during the service life of an aircraft (Federal Aviation Administration, 2008). Although the different type of checks (A,B,C,D) are commonly used in the airframe MRO industry, it is up to the airframe MRO provider to assign the letter (A,B,C,D) to the check they perform. KLM E&M performs only A and C checks and the tasks that need to be performed during the B-check are spread out over other checks. KLM E&M used to have D-checks, but it was decided to outsource the D-check to a different airframe MRO provider.

1.3 Practice analysis

The work package for performing MRO to the aircraft consists of different types of tasks and can have different sources. As could be seen in Figure 1-4 the simplified illustration can be extended with the sources of the tasks and how they are performed. Depicted in Figure 1-5, the general sources for the input of the work package are shown. During the utilization of the aircraft there are many things that can happen to the aircraft. It could be from small things such as a passenger spilling coffee onto a seat or a reading light is not working properly, up to larger service requests such as a structural inspection needed from a bird strike. In Figure 1-5 this is illustrated as the input from an arriving aircraft and this is the first time a complaint/service request is added to the work package.

Furthermore, routine work that happens from time to time (the one more often than the other) are controlled and added to the work package by the engineering department. It can also occur that a modification or a specific service request (planned non-routine work) needs to be performed and the engineering department also controls this. Thus the engineering department adds “planned work” to the work package, as it is already known in advance that this work needs to be performed. The complaints/service request from the inbound flight are mainly unplanned, because most of the time the request for solving a complaint is known when the aircraft has just arrived (van de Werken, 2017).

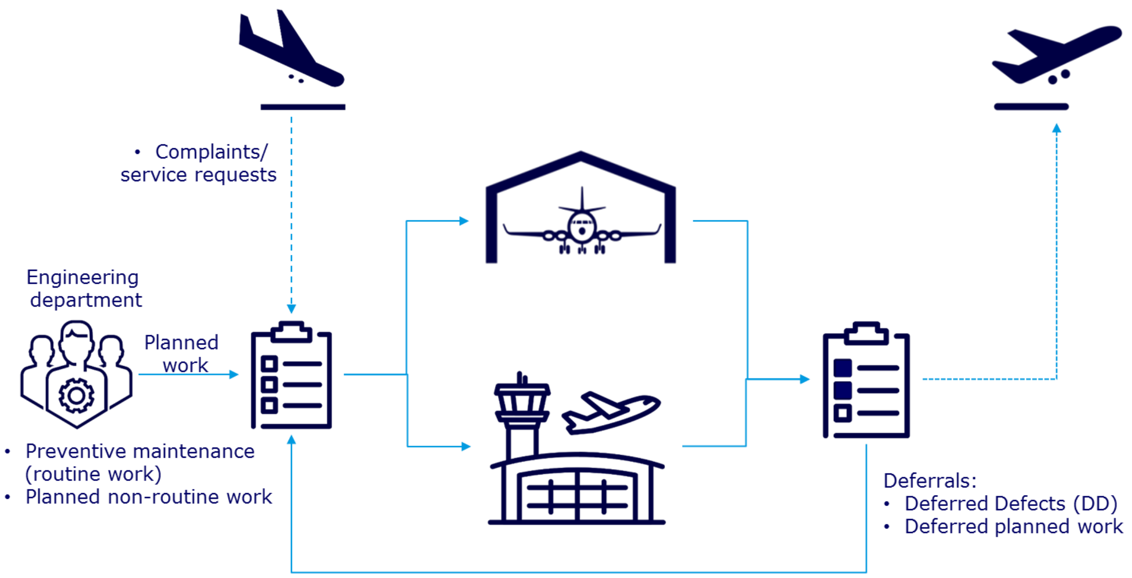


Figure 1-5: Process of input and output of airframe MRO work packages.

With the work package, the needed location for providing MRO is known. As mentioned in section 1.2.3, the location depends on the type of work. If the work can be done at the gate/ramp (line maintenance) it is more preferred than performing the work in a hangar, as the aircraft needs to be towed to the hangar and eventually back, and this means more downtime of the aircraft.

After performing MRO, not always all tasks are completed. Those tasks are the so called deferrals and they consists of deferred planned work and deferred defects (DD). The deferrals has to be performed at a later schedule, so these are input for the next work package.

1.4 Research problem

KLM E&M strives for contributing to the availability for having a high aircraft utilization and therefore more uptime. As mentioned, the airframe MRO has a big influence on improving the availability, but the performance is not well. The quality of the aircraft, which is measured by KLM E&M as the amount of deferred defects (not completed work), has risen above a target level. The target differs for the different type of aircraft divided in narrow body aircraft and wide body aircraft. The target level for the narrow bodies (Boeing 737) is 120 and for the wide bodies (Boeing- 747, 777 & 787, Airbus A330) the target is 500. When an aircraft has too many deferred defects, it is possible the aircraft is not airworthy enough.

Except of the quality of the aircraft, the performance of the on time deliveries of the aircraft (after performing MRO) is also poor. This means that aircraft are not finished within the scheduled turnaround time (TAT). The on time performance for narrow bodies was better than for wide body aircraft. Not all performances of on time deliveries are measured, but the main focus of KLM E&M is the on time performance of the A-checks. This was in 2016 for the narrow bodies 72% and for the wide bodies 42%. For each not on time delivery, a shift is needed in the scheduling of the aircraft for operation. This means that a change is needed for assigning an aircraft from one scheduled flight to another one in order to cope with the delay of the aircraft that is not delivered on time.

The TAT and quality of the aircraft are depended of each other, as there is more possibility to solve more tasks (reducing deferred work) with a higher scheduled TAT. But this works also contrary, as the TAT could be decreased which could cause more deferred work.

Due to the current performance of KLM E&M Airframe MRO and the problem context the following research problem is defined:

There is a gap between the desired performance and the current performance and it is not clear what drivers influence this gap. Furthermore, it is not known how the drivers can be improved and what the theoretical performance could be in terms of aircraft availability.

1.5 Research scope & Objectives

Research scope

As mentioned in section 1.2.3, this research is conducted at KLM Engineering & Maintenance at Schiphol Airport and more specifically, Airframe MRO will be the scope of this research. Figure 1-6 shows the previous described Airframe MRO process from a general perspective and the scope of this research is also depicted. The Airframe MRO chain that is considered in this research starts with the input of the work packages, then the execution of MRO and lastly the output the MRO referred as the (un)performed tasks of the work packages.

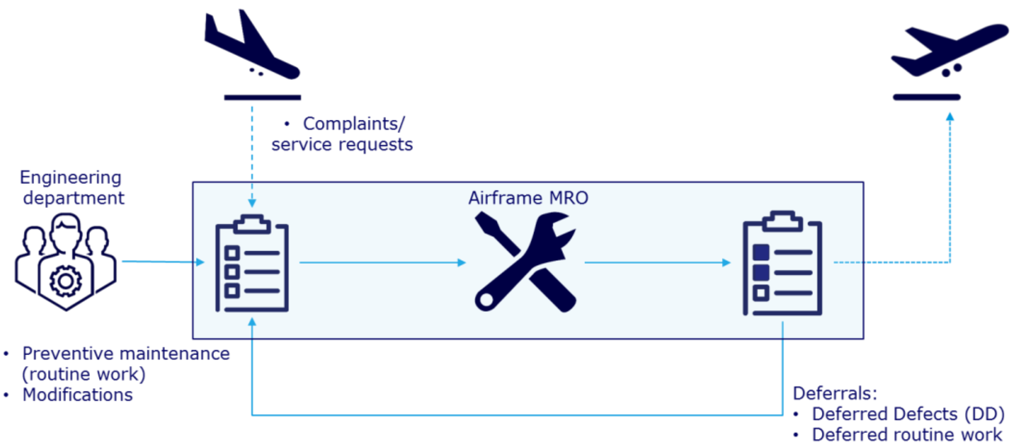


Figure 1-6: Scope of research.

Objectives and Deliverables

From the previous described problem statement (in section 1.4) and the scope of this research the following research objective is derived:

Identify current processes and constraints to improve the processes of an integral airframe MRO chain in order to increase the aircraft availability (for uptime) by reducing the turnaround time and deferrals of airframe MRO at KLM Engineering & Maintenance Airframe Services.

From this research objective the following deliverables are followed:

- Identification of the current process at KLM E&M Airframe Services.
- Model to identify the impact on assets and resources of KLM E&M Airframe Services by changes of the turnaround time and deferrals.
- Recommendations for KLM E&M Airframe Services for process improvements within the MRO chain.

1.6 Research questions

The following main research question is formulated based on the previous research objective:

"How can the output of airframe Maintenance, Repair and Overhaul processes be improved from an uptime perspective?"

To answer this main research question, sub-questions are derived. These sub-questions are shown in Table 1-1.

Table 1-1: Research sub questions

	Sub questions
1	What framework and methodologies can be used from literature to find and evaluate solutions for improving the output of Airframe MRO?
2	What criteria can be used to assess the different solution alternatives for KLM E&M Airframe Services?
3	What is the current state of the Airframe MRO process at KLM E&M Airframe Services?
4	What constraints are limiting the turnaround time and quality output of the Airframe MRO process at KLM E&M Airframe Services?
5	What solutions alternatives can improve the turnaround time and quality output of the Airframe MRO process?
6	What is the impact of these improvements on the aircraft availability (for uptime) and assets/resources at KLM E&M Airframe Services?
7	What is the best solution alternative from the designed alternatives to be implemented for KLM E&M Airframe Services?

1.7 Research approach

The research approach used for answering the main research question and subsequently the sub research questions is based upon the DMAIC cycle – Define, Measure, Analyse, Improve, Control (Reid & Sanders, 2010). The DMAIC approach is a known method from the Six Sigma methodology and consists of a study phase (Define Measure Analyse) and an improve phase (Improve Control). However, a real implementation of the improve phase is not part of this research. Instead of "Improve and Control" steps, this research will have slightly different steps.

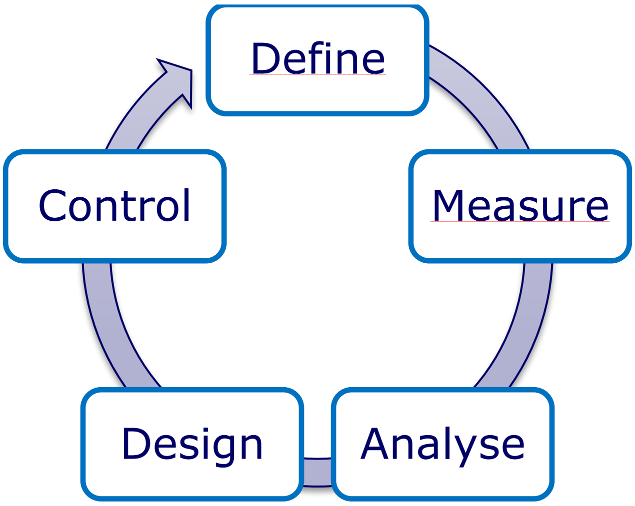


Figure 1-7: Research approach based upon DMAIC.

For this research the research design (Figure 1-7) of dr. W.W.A. Beelaerts van Blokland is used. This approach is an adapted version of the traditional DMAIC. The 'Improve' phase of the DMAIC is replaced by a so called 'Design' phase, where future state scenario's are developed for improvements and also tested. During the 'Control' phase, the impact of the different scenario's on assets and resources for improvement are evaluated. The different steps of the research approach (DMADC – Define Measure Analyse Design Control) from dr. W.W.A. Beelaerts van Blokland will be described below:

Define

During the Define phase, the problem is defined by stating the research context, field of research, research scope, main research questions and sub questions. Also, the method to be used for the research is chosen from literature. Here it is defined which steps are to be applied for the case study.

Measure

As part of the case study at KLM E&M Airframe Services, the current state of the airframe MRO process is investigated during this measure phase.

Analyse

During this analyse phase possible constraints in the current MRO process are identified by using data and made observations from the Measure phase.

Design

As mentioned, this phase is different from the traditional DMAIC (Improve) method, because during this research no implementation will be done. Instead, different future state scenario's will be developed to improve the Airframe MRO process by eliminate the constraints found during the Analyse phase.

Control

Also this phase is different from the traditional DMAIC (Control) method. Instead of real monitoring and controlling the process, this phase will focus on the impact of the different scenario's on assets and resources defined during the Design phase. Also, contributions to theory and practice will be discussed

The next chapter will investigate literature for applying a framework to increase the uptime availability of aircraft by reducing the turnaround time and improve quality of Airframe MRO, which will be applied to a case study at KLM E&M Airframe Services.

2 Literature review

This chapter is dedicated to find an answer for the first two research sub-questions as it is defined in section 1.6. The first sub-question is:

> "What framework and methodologies can be used from literature to find and evaluate solutions for improving the output of Airframe MRO?"

And the second sub-question that will be answered in this chapter is:

> "What criteria can be used to assess the different solution alternatives for KLM E&M Airframe Services?"

First, previous research is investigated in section 2.1 where a usable framework is chosen to use a basis for this research. Secondly in section 2.2, different process improvement methodologies our outlined and in section 2.3 different modelling tools for processes are discussed. Section 2.5 is dedicated for outlining the different key performance indicators for airframe MRO and finally in section 2.5 the answers for the stated sub-questions is given.

2.1 Previous research

At KLM E&M many previous researches has been done on different segments of KLM E&M. Most of all focussed on a practical problem and the goal of those researches is to solve those (local) problems. For this research a more generic approach is wanted that can be applied to Airframe MRO and more specifically, for a case at KLM E&M Airframe Services.

Previous research has been done by (Rozenberg, 2016) where she designed a comprehensive framework to analyse and improve engine MRO processes from an integral perspective. This framework is a step by step framework (Figure 2-1) with the use of different process improvement methodologies. This framework can be used as a basis for this research, as other process improvement and process modelling methodologies can also be very helpful for improving the output of airframe MRO. The process improvement methodologies will first be outlined in the next section.

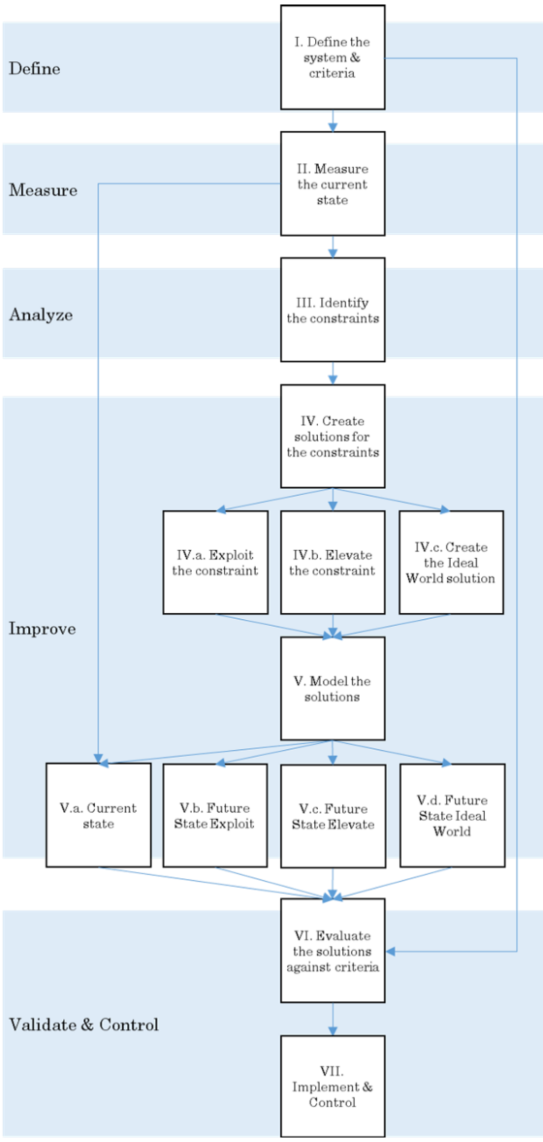


Figure 2-1: Literature framework from (Rozenberg, 2016)

2.2 Process improvement theories

Many different methodologies regarding process improvement theories can be found in literature. In this section a number of these methodologies are discussed. Started with Lean, then Six Sigma, Lean Six Sigma, Theory of Constraints, Total Quality Management, Critical Path Method, Phase-Gate and lastly Critical Chain.

2.2.1 Lean

As Lean is well known from Toyota in Japan, but in the 1920's the first lean principles emerged from the Ford production plants. It was Henry Ford who started with remaining the focus of activities that are of value for the customer, therefore eliminating activities that were non-value added to the customer. This resulted in elimination of waste of time and materials (Ayeni, Baines, Lightfoot, & Ball, 2011).

As mentioned, Lean is more well-known from Toyota and the "Toyota Production System" (TPS). 'Lean' became later a more popular term by (Womack, Jones, & Roos, 1990) with their book: "The Machine That Changed The World".

Five core principles of the Lean organization are identified as:

1. The elimination of waste
2. The identification of the value stream
3. The establishment of flow through the process
4. Implementation of pull
5. Achieving continuous pursuit of perfection

The Toyota Productions System developed the so called the TPS House (Appendix B). Each element of the TPS House can be built by different Lean tools. A selection of those tools are summarized in Table 2-1.

Table 2-1: Lean Methodology Tools (Rozenberg, 2016)

House element	Goal	Tools
Stability	The foundation of the house – improvement is impossible without stability in the 4M's	4M; TIMWOOD ; SMED; Value Stream Map
Standardization	Create a standard process	5S ; Visual Management
Just-In-Time	To produce the right product at the right time in the right quantity	Takt Time; Kanban; Heijunka
Jidoka (Built-in Quality)	To prevent or detect defects early in the process	Poka-Yoke; Kaikaku (5 Why's); Andon;
Kaizen	To achieve customer satisfaction	

After identification of the Value Stream of the process, the main drivers of the process can be investigated. From Lean, the main drivers of a process are: waste in the process (TIMWOOD), 4M and flow. There are 7 types of waste defined with 'TIMWOOD' and stands for: Transport, Inventory, Motion, Waiting Time, Overproduction, Over processing, Defects and Skills. The 4M are four resources that are needed to execute a stable process and stands for Machine, Method, Material and Method (Art of Lean, Inc).

As (Ayeni et al., 2011) investigated Lean within the aviation MRO industry, several key findings where formulated, shown in Table 2-2.

Table 2-2: Key findings summary of Lean within the aviation industry (Ayeni et al., 2011) .

Topic	Key Finding/Issue
Interpretation of Lean	Lean is widely interpreted as a viable tool within the aviation industry albeit not sufficient by itself to realise all the goals set by the organisation.
The Focus of Lean	The focus of Lean within the aviation MRO industry is

	predominantly directed towards **waste reduction** as opposed to the creation or the enhancement of **value**.
Extent of the adoption of Lean	There is strong emphasis on the adoption of Lean within the MRO industry, although the extent of its adoption is yet to be ascertained.
Lean Implementation strategy	Various implementation strategies have been employed in the adoption of Lean, however, the moderating factors for its successful implementation strategy remains unclear.
Inhibitors of Lean	The lack of comprehensive understanding on Lean and its capabilities is evident within the aerospace industry thus hindering the successful adaptation of Lean to be plant specific. The difficulty in the accurate forecasting typically characteristic of the MRO industry results in practices that contradict ideals of Lean thus serving inhibitors to its adoption and or its advancement.
Enablers of Lean	A major driver for the adoption of Lean is premised on the assumption that MRO business pressures are consistent with what Lean can deliver.
Critical factor for successful Lean Implementation	Lean implementation success is reliant on the key project management strengths and skills of the person(s) tasked with the responsibility of the whole project. Any successful Lean implementation program will require the complete involvement of all staff.
Strengths and weakness of Existing Literature	There is paucity of Literature on the adoption of Lean in the aerospace MRO industry.

As can be concluded from Table 2-2, Lean is a viable tool within the aviation MRO industry, but on itself it is not sufficient to organize all the goals. Other strategies, such as Six Sigma, should be used in combination with Lean. Therefore the next section will discuss Six Sigma.

2.2.2 Six Sigma

Six Sigma is a methodology that is used to improve the quality of the output of a system. This quality is determined by the variation and number of defects of a process. Thus, the aim of Six Sigma is to decrease the amount of defects and variation of it. This means that statistically only 3.4 defects per million may occur in a process (Reid & Sanders, 2010).

The methodology from Six Sigma is called the DMAIC cycle, as mentioned in section 1.7. Where DMAIC stands for Define, Measure, Analyse, Improve and Control. Each of the steps is needed for the main goal, namely improving the quality of the process and several tools are available to accomplish this during each step. Table 2-3 shows available tools from Six Sigma for each of the DMAIC steps (iSixSigma).

Table 2-3: Six Sigma tools (iSixSigma).

DMAIC phase	Goal	Tools
Define	Define project goals and customer deliverables	SIPOC Diagram; Stakeholder Analysis;
Measure	Measure the process to determine current performance & quantify the problem	Process Flowchart; Process Sigma Calculation; Normality Plots;
Analyse	Analyse and determine the root causes of the defects	Histogram; Pareto Chart; Fishbone Diagram; Statistical Analysis; 5 Why's
Improve	Improve by eliminating defects	Brainstorming; Simulation; FMEA
Control	Control future process performance	Control Charts; Control Plan

2.2.3 Lean Six Sigma

The combination of Lean and Six Sigma is described by (Baker, 2003). Lean Six Sigma combines the two theories where its goal is to improve quality, cost, customer satisfaction, flexibility and process speed in order to maximize the performance of the system. (Jong & Beelaerts van Blokland, 2016).

This combination of Lean and Six Sigma can provide good tools to create improvements for current and new processes. Where Six Sigma uses statistical tools to uncover root causes and Lean can identify the so called 'low-hanging fruit' (easy steps to take to improve a process).

2.2.4 Total Quality Management

Total Quality Management (TQM) is like other management methodologies developed throughout the years and a methodology that is developed out of many others. It is a proactive (quality) management methodology instead of older reactive methodologies, where quality problems are corrected after their occurrence (Reid & Sanders, 2010). The key principles of TQM can be found in Appendix B.

The improvement quality projects follow the Plan, Do, Study and Act (PDSA) cycle. This four step cycle consists of first evaluate the current process in order to establish improvement plans and performance goals. The second step, Do, is to implement those improvement plans and to collect the data of the performance measurements. In the next step, Study, the desired performance goals are evaluated with the acquired data and is studied if goals are achieved by the improvements plans. Finally in the last step, Act, actions are taken based on the results of the previous step in order to achieve the goals (Reid & Sanders, 2010).

To measure the quality (in the 'Plan' step) different tools are available. A summary of the different tools that are used with TQM is given in Table 2-4.

Table 2-4: Seven tools of quality Control (Reid & Sanders, 2010)

Tool	Aim
Cause-and-Effect (Ishikawa) Diagram	Identify potential causes of quality problems, related to suppliers, workers, machines, environment, process, material and, measurements and other causes
Flowchart	Make the process visual so a clear picture is developed
Checklist	Collect information regarding the observed defects, identify main issues
Control Chart	Measure whether a process is operating within expectations relative to some measured value
Scatter Diagram	Shows relation between two variables (correlation)
Pareto Chart	Used to identify quality problems based to their degree of importance
Histogram	Shows the frequency distribution of observed values of a variable

2.2.5 Theory of Constraints

The Theory of Constraints (TOC) is first presented in a book called 'The Goal' by Eliyahu Goldratt in 1984 (Goldratt, 1984). In this book he introduces the concepts of TOC, in a fictional form of work but with a clear message that helps companies to achieve their goal.

The main principle of TOC is to find the constraints of a systems outcome and then to solve those constraints. By solving the constraints, the outcome of the whole system improves and not only locally. There are five steps defined to find and eliminate the constraint:

1. Identify the constraint
2. Exploit the constraint
3. Subordinate other activities to the constraint
4. Elevate the constraint
5. Prevent inertia from becoming the constraint

As stated in step 5, inertia must not become the constraint, therefore the cycle starts again.

2.2.6 Critical Path Method

Critical Path Method (CPM) is the traditional project management method used in every project type in every industry. The concept is intuitive, namely: build a plan like a recipe, with one task feeding the next. The critical path is a chain of tasks that determines the projects schedule and CPM states that project managers should identify and focus on the critical path (Prensa, 2002). Each task has an owner and the project will finish on time if every owner finishes their task on time, but eventually at any given time, one of the tasks will become the critical task. The critical path is the chain of tasks which contain those critical tasks.

In other words, a critical path is the longest duration path through a network of events and it is created by the following steps:

1. Identify the activities
2. Determine the sequence of the activities
3. Connect or create a network of the activities
4. Enter the completion time for every activity listed in step 1
5. Identify the critical path or the longest possible path to complete all activities

2.2.7 Phase-Gate

The Phase-Gate method deals with the high complexity that can overwhelm CPM. CPM works well in low complex projects, but most projects require so many tasks that the work breakdown structure (WBS) made for the CPM is too complex.

Phase-Gate is similar to CPM, but at a higher level. It divides each project into large subprojects called 'stages' or 'phases'. The phases are separated by the so called 'gates' or 'milestones'. Furthermore, the phases are typically defined to be the same for every project and therefore the main activities can also be defined for all projects as well (Ellis, 2016b). The four main advantages of Phase-Gate project management are:

1. Common activities for all projects.
2. Standardizing approval processes
3. Opportunities for continuous improvement
4. Provide a common framework for portfolio management

For this research, the checks of the aircraft have many tasks which can lead to high complexity and therefore the use of Phase-Gate could be made to 'standardize' the checks by assigning the tasks into phases.

Phase-Gate is focussed on the activities within a phase, whereas the next described methodology (Critical Chain) looks further than the activities within a project. This methodology will be described below.

2.2.8 Critical Chain

The critical chain methodology is based on TOC as described in section 2.2.5 and also find the constraint of a system. Goldratt wrote a new book after 'The Goal' (TOC) and is named 'The Critical Chain' (Goldratt, 1997). It states that the primary measure of project management effectiveness is schedule. For this measurement, the constraint is the path through the project network that has a longer duration than all the others. It is almost identical to the 'critical path' (section 2.2.6) but here it is called the 'critical chain'. The primary difference is the technique used in critical chain to avoid conflicts of resources (Ellis, 2016a).

Low Work In Progress

An important observation for Critical Chain Project Management (CCPM) is that the velocity of project execution is constraint by resources. Adding more work to the project does not improve the performance when the constraint is exceeded. Therefore, CCPM holds the principle of low Work In Progress (WIP). When WIP increases, more distractions are caused to the teams due to conflicting priorities and multitasking. Eventually, this will lead to longer project durations and longer project queues (Herroelen & Leus, 2001).

Low WIP can be achieved by concentrating the resources on the scheduled work and not allowing to start with other work when the previous work is not finished. This has proven to work for airframe MRO in order to improve the performance of airframe MRO processes (Goldratt consulting, n.d.).

Human behaviour delaying projects

CCPM creates a method to minimize the effects of human behaviours as they commonly cause reduction in team effectiveness. CCPM asserts five common tendencies in team members delay projects (Ellis, 2016a):

1. The inefficiency of multitasking
2. The student syndrome – start a project with small effort and when the deadline is near start to work at a maximum rate
3. Parkinson's law – tasks expand to fill the allowed time
4. Unintentional disincentives to speeding task execution
5. Protecting individual tasks at the expense of the project – focus should be kept on the critical chain

Full kitting

'Full kitting' is the practice of ensuring that everything is needed for a task, project or phase. It ensures that when a project/task is started it can proceed at full speed to completion. This avoids the waste incurred when a project starts and then stops or proceeds with partial effort. Full kitting is known from the critical chain methodology, but much of full kit is also built into Phase– Gate projects by ensuring all tasks in the previous phase are completed and obtaining steering committee approval before proceeding to the next phase.

Airframe MRO has high uncertainties, because the main activities consists of inspections and therefore unscheduled arisings are common practice. It is hard to predict those unscheduled arisings (findings from inspections) and it is wanted to know all possible arisings as soon as possible. If an inspection is performed somewhere at the end of the airframe MRO process, the chance exist that from the inspection something is found that needs repair. This is unwanted, because possible parts need to be ordered and there is less time available to solve the issue (Lufthansa Technik Maintenance International, 2013). Therefore, 'Full kitting' ensures that all inspections are first performed before continuing with other tasks.

2.2.9 Concluding remarks for combining Phase-Gate and Critical Chain

The Full Kitting principle from the Critical Chain methodology is much built into Phase-Gate projects. As (Ellis, 2016a) states, multitasking is inefficient, therefore a combination of phase-gate and avoiding multitasking can be made. As for airframe MRO it is wanted to have all inspections completed as soon as possible, thus all available resources should focus on the same phase during the project in order to complete the phase as fast as possible. All resources can only focus on the tasks within the phase they are working in. Figure 2-2 shows the benefit of Phase-Gate and not multitasking/multi-phasing. It shows clearly that each (total) phase is finished earlier without time-slicing and just focus on a single tasks, or in this case, a phase.

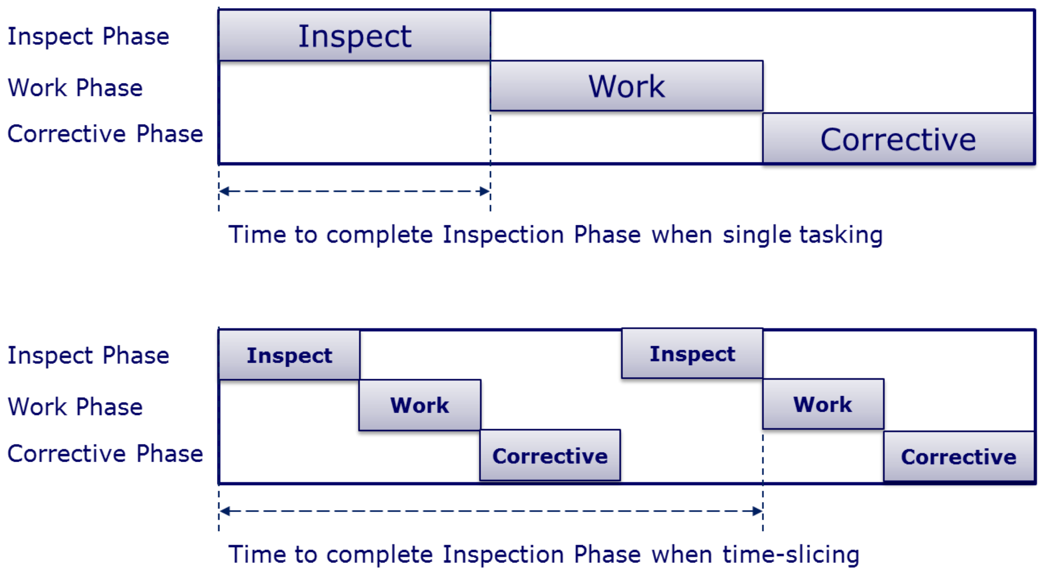


Figure 2-2: Inefficiency of multitasking/multi-phasing

2.2.10 Process improvement methodologies summary

In this section a summary will be given of the previous described process methodologies and their applicability for this research will be evaluated. In the last column of Table 2-5 the applicability of the different methodologies are stated for the different stages of this research approach.

Table 2-5: Summary of process improvement methodologies and applicability.

Methodology	Key elements	Aim	Usefulness	DMADC
Lean	Eliminate waste, identify value stream, flow, pull,	Pursuit of perfect value in processes	Lean is a viable tool, however Lean alone cannot adequately improve	-

	continuous improvement, PDCA	through elimination of waste	processes	
Six Sigma	Value drivers, DMAIC cycle, statistical analysis, root causes	Decrease variation and number of defects in processes	Can be used to improve existing processes. It provides an analytical framework that encompasses all stages of an improvement project	-
Lean Six Sigma	Eliminate waste on analytical basis	Combines Lean and Six Sigma	Combination of Lean and Six Sigma provides the tools to create ongoing business improvement	**DMADC**
Total Quality Management	Customer focus, use of quality tools, quality in processes	Proactive quality approach: build quality into process and product design	Focus lies on product quality improvement instead of throughput/TAT, however TQM covers tools that can be used to identify bottlenecks and root causes in this research	**A, D**
Theory of Constraints	Bottlenecks, exploit and elevate	Increase flow in a system	Good method to find solutions for bottlenecks when these are found	**A, D**
Critical Path Method	Identification of activities and sequences	Increase focus on the critical sequential tasks	Method to identify the critical tasks of a project	**A, D**
Phase-Gate	Create phases for complex projects, standardizing projects	Provide a common framework for projects	Providing airframe MRO could be standardized in terms of phases in a check	**A, D**
Critical Chain	Find constraint of a system with avoiding conflicts of resources	Increase flow in a system and minimize human behaviours	Good method to find bottlenecks and avoid human behaviours	**A, D**

2.3 Modelling of processes

This section will focus on tools to model processes for airframe MRO. As process modelling is extensively used nowadays and is becoming more and more the principle of organising the business, a huge range of approaches can be used. This section will discuss a number of those tools that later on will be used for this research.

2.3.1 Gantt chart

A Gantt chart is a matrix that lists all tasks or activities to be performed in a process on the vertical axis. Each row contains a single activity and the horizontal axis represents the duration of the different tasks. Therefore, a Gantt chart relates a list of activities to a time scale. This type of chart is a simple graphic representation but a downside is that they do not show clear dependencies between activities (Aguilar-savén, 2004).

2.3.2 Flow chart

A flow chart is a formalised graphic representation of work or manufacturing process, organisation chart, program logic sequence or similar formalised structure (Lakin, Capon, & Botten, 1996). Symbols are used to represents operations, flow direction, data and equipment, to define, analyse or for a solution of a problem. Visualising of a process with a flowchart can quickly help identify inefficiencies or bottlenecks where the process can be improved. The main benefit of a flowchart is that it is easy to use, but they also can get very large which is not suitable for a simple overview of a process (Aguilar-savén, 2004).

2.4 Key Performance Indicators for Airframe MRO

Most maintenance providers, including KLM E&M, are focused on their most important factors which are typically the quality, the turnaround time (TAT) and the price (Ayeni et al., 2011). Those factors are interrelated outputs of the MRO process and can be visualized in a triangle as shown in Figure 2-3. The main goal of the MRO process is to achieve a low TAT with a high quality and for low costs.

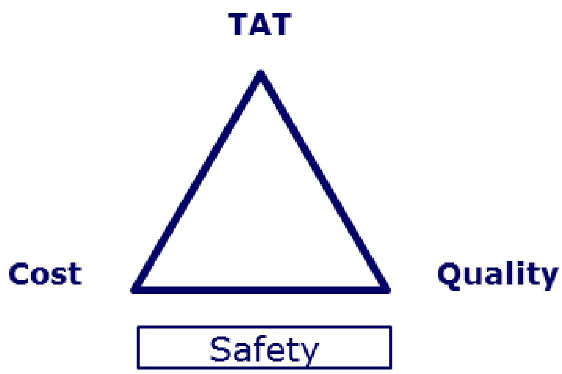


Figure 2-3: Main MRO process output interrelation (Ayeni et al., 2011)

The goal of this research is to provide different solution alternatives to improve airframe MRO processes at KLM E&M. To evaluate the different solutions, the impact on different criteria need to be determined. From the previous described performance indicators, the criteria that need to be used can be derived. A goal tree (de Haan & de Heer, 2012) is used to determine and depict the different criteria in Figure 2-4. The main goal of airframe MRO should be increasing the availability for utilization of the aircraft (uptime availability). From this, sub-goals can be derived, these goals are based on the previous described triangle of known MRO performance indicators, namely TAT, quality and cost. Those are defined as the result key performance indicators (KPI). The result KPI's can be transformed into lower-level goals, which are forming the criteria for assessing the possible solution alternatives.

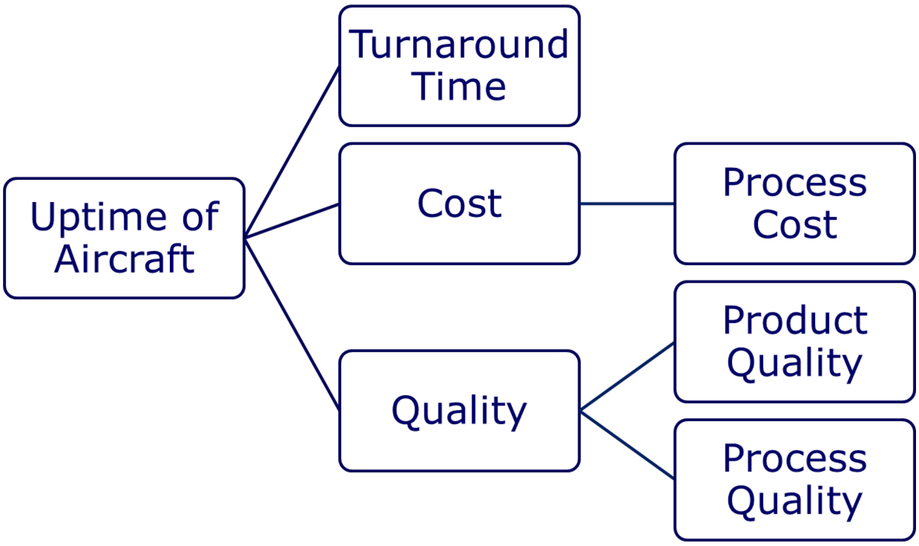


Figure 2-4: Goal tree Airframe MRO Services

2.4.1 Turnaround Time

The first criteria is the turnaround time of airframe MRO. The TAT is the time that is needed for performing airframe MRO and therefore downtime of the aircraft from an uptime perspective. With a shorter TAT for each check, which is a decrease in downtime there is more uptime availability.

2.4.2 Process Cost

The second criteria is process cost, which can be expressed by the amount of resources needed and therefore the productivity/efficiency of them. With a high productivity/efficiency are less resources needed in order to achieve the main goal.

2.4.3 Product Quality

The product quality of the airframe MRO can be seen as the result of a check. From an uptime perspective the quality is good enough when the aircraft is declared as airworthy. The result of the checks is that it always deliver an airworthy aircraft, otherwise the check is not finished. Therefore, the desired performance of this criteria is always met.

2.4.4 Process Quality

The quality of performing airframe MRO (process) is if all tasks that were scheduled are actually performed. Thus, all deferred work indicates that the process did not achieved the highest process quality. All deferred work can be seen as work in process (WIP) as this work is still on the 'to-do'-list for the airframe MRO.

2.4.5 Criteria for solution alternatives

From the previous described sections the criteria for assessing the solution alternatives can be defined. The solution criteria are defined as:

- Turnaround Time
- Process Cost – expressed in man-hours
- Product Quality – expressed in airworthiness
- Process Quality – expressed in WIP

With this criteria a different triangle can be made based on the known key performance indicators as stated in section 2.4 (TAT, cost and quality) for airframe MRO processes (Figure 2-5).

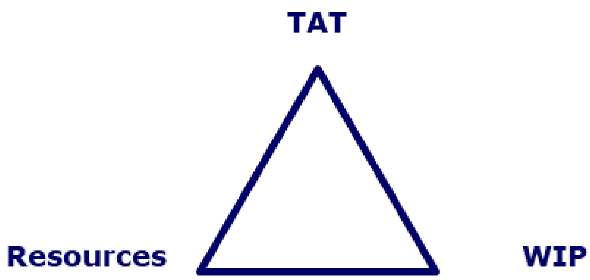


Figure 2-5: Airframe MRO process key performance indicators

From an uptime perspective the aircraft is airworthy after each check, otherwise the check is not finished. Therefore the criteria 'product quality' is not part of the triangle.

2.5 Conclusion literature review

This chapter was dedicated to answer the first two sub questions. The first sub question is:

> "What framework and methodologies can be used from literature to find and evaluate solutions for improving the output of Airframe MRO?"

From literature, methodologies and a framework has been found to improve processes and subsequently model the processes. The framework that will be used consists of several steps:

1. Definition of the system and determination of criteria
2. Measurement of the current state of the system
3. Identification of the constraints limiting the output of the system
4. Design of future state scenario's for improvement
    a. Exploiting the constraint
    b. Elevating the constraint
    c. Creating 'Ideal World' solution
5. Model the future state scenario's
    a. Current state
    b. Future state (exploiting constraint)

    c. Future state (elevate constraint)
    d. Ideal state
6. Evaluate the impact of the scenario's on assets and resources

The second sub question that is answered in this chapter is:

"What criteria can be used to assess the different solution alternatives for KLM E&M Airframe Services?"

From literature different criteria are found for assessing the different solution alternatives, namely:

- Turnaround Time
- Process Cost – expressed in man-hours
- Process Quality – expressed in WIP
- Product Quality – expressed in airworthiness

Only the first three will be used for assessing the alternatives as the 'product quality' is always met after a check, otherwise the check is not finished.

Measure Phase

3 Current State – Case Study

This chapter aims to give more insights of the case study at KLM E&M Airframe Services and answering the next research question:

"What is the current state of the Airframe MRO process at KLM E&M Airframe Services?"

Therefore, the organization will be discussed in section 3.1 to give more insight in where the case study is conducted and what current policies are and where airframe MRO is performed. Next, the strategy and current used performance indicators which are used by KLM E&M are outlined in section 3.2. The applied tools are discussed in section 3.3 to measure the current state. After that, the current state of the overall airframe MRO is outlined in section 3.4. After this the research will focus on wide body aircraft MRO and this is further discussed in section 3.5. Even a further scope of this research is made, more specifically the A-check, and this will be explained in section 3.6. In section 3.7 the current state of a single A-check will be more explained and from this current state a theoretical preliminary model is developed which will be outlined in section 3.8. Lastly, the answer to the sub question, as stated above, will be answered in a concluding section (3.9).

3.1 The organization

As described in section 1.2.2, KLM Engineering & Maintenance is part of the maintenance division of the Air-France KLM holding. Airframe Services is a segment within KLM E&M and is responsible for providing airframe MRO.

There are several locations at Amsterdam Schiphol Airport where KLM E&M provides its airframe MRO. Each location also has its own management team and all have to deal with the new 'High Performance Organization' (HPO) implementation. HPO is a project aiming for a more agile, lean and efficient company (KLM, 2016). This means for all organizations within KLM that a decrease in management layers will be implemented and functions will be centralized. An example of a principle of HPO for airframe MRO is the concept of 'Teaming' and 'Ownership'. It is the intention that a team of mechanics are responsible for the output of airframe MRO for their assigned aircraft. It is the intention that a team will be assigned to a set of registration numbers of aircraft and they will be the 'owner' of them. In other words, the state of those assigned aircraft is the responsibility of the team and they can choose how and when to work on them.

3.1.1 Airframe MRO locations

There are several locations (at Schiphol Airport) where airframe MRO is provided and the type of needed airframe MRO determines where the aircraft is located. As mentioned in section 1.2.3, the different types of checks determines if the aircraft needs MRO in a hangar or if it is possible at the gate/ramp (line maintenance).

Line Maintenance

KLM E&M provides airframe MRO at the gate/ramp for all type of aircraft, which can be divided in 'wide body' aircraft (e.g. Boeing 747/777/787, Airbus A330) and 'narrow body' aircraft (e.g. Boeing 737). If MRO is needed in a hangar, the type of aircraft and type of check determines in which hangar it will be performed.

Hangar 11

In hangar 11, MRO is provided only for wide body aircraft (except for Boeing 787) that have an A-check, H-check, M-check (only for Boeing 777), TD-check or AOG-check. It is the intention to have one A-check per day and on Tuesday have two A-checks at the same time. The H-check is a check for out of phase tasks that does not fit in the A-check and also deferrals from an A-check are performed during this check. The M-check is only for the Boeing 777 type of aircraft. Between two A-checks for the same aircraft is an M-check. The TD-check is dedicated for solving deferrals or complex problems. In the ideal world a TD-check is never needed. Lastly there is the AOG-check; AOG stands for 'Aircraft On Ground'. This means that a problem is serious enough that the aircraft is not airworthy, therefore this problem needs to be solved before the aircraft may fly again.

Hangar 12

Hangar 12 is dedicated for the narrow body aircraft and also for the Boeing 787. The A-check, H-check and AOG-check are performed here. The checks for the narrow body aircraft were previously performed in a hangar 10, but since 2017 this all moved to hanger 12 and hanger 10 is now out of use.

Hangar 14

In hangar 14 are the more 'heavy' checks; The C-check is performed here and this was also the location of the D-check. This D-check is not performed anymore at KLM E&M, because KLM outsourced this to another airframe provider situated in China.

3.1.2 Maintenance units

KLM E&M Airframe Services has multiple maintenance units and the previous described locations are also part of them. But there are also other maintenance units known at KLM E&M and they will be described below.

Maintenance Control Center

The Maintenance Control Center (MCC) is responsible for the fleet availability for KLM and other customers. They determine where and when an aircraft needs MRO and that the output of airframe MRO is what the customer expects it to be.

Planning, Scheduling & Fleet Control

The 'Planning, Scheduling & Fleet Control' (PSFC) is a new department within KLM E&M due to HPO. PSFC is responsible for planning and scheduling the maintenance tasks and checks if it is achievable to perform the tasks. They must check if the necessary resources are in place in order to perform MRO.

Material, Equipment & Facilities

The 'Material, Equipment & Facilities' (MEF) is responsible for all materials and equipment that is needed to perform MRO. They make sure that the desired materials and equipment are available at the desired location.

3.2 Strategies

For KLM E&M Airframe Services the performance of airframe MRO is also focussed on the previous described process outputs (TAT, Quality & Cost). They are currently measured using a Connected Business Balance Score Card (CBBSC) where the performance indicators for KLM E&M Airframe Services are outlined in Table 3-1.

Table 3-1: Airframe MRO performance indicators KLM E&M

MRO performance indicator	Description
TAT: A/H/M/TD/AOG-check punctuality %	Percentage of aircraft that is delivered within the agreed TAT.
TAT: C-check punctuality %	Percentage used of the agreed TAT.
Quality (number of Deferred Defects)	The number of Deferred Defects divided in operational and non-operational Deferred Defects
Cost (productivity) %	Planned man-hours vs spent man-hours

Turnaround Time punctuality

As Table 3-1 shows there are 2 different descriptions for the on time delivery of the aircraft after performing airframe MRO. For the A/H/M/TD/AOG-checks, the aircraft is on time when it is delivered within the agreed time it was planned for. However, this is different for the C-check where the performance is presented as the percentage of the used time versus the available time. Thus, a C-check was on time when the percentage is 100% or less.

Quality

KLM E&M measures the quality of the airframe MRO process by the amount of deferred defects. The deferred defects can be divided into two sub-categories, namely: operational and non-operational deferred defects. Further explanation about the different type of deferred defect will follow further on.

Cost

The cost of airframe MRO at KLM E&M is measured by the productivity presented as a percentage. The planned man-hours are compared to the actual spent man-hours.

3.3 Tools used for current state measurement

During the literature study, in chapter 2, different tools are identified to aid in measuring the current performance of processes. For this case at KLM E&M, several of those tools are used to measure the current state and therefore giving more insights of the current performance of the airframe MRO. In this section the used tools will briefly be explained.

3.3.1 SIPOC Diagram

A SIPOC Diagram is a tool used to identify all relevant elements of a process (iSixSigma). SIPOC stands for Supplier – Input – Process – Output – Customer. The SIPOC diagram gives an overview of the inputs and outputs of a process and which suppliers and customers are influencing or influenced by the process.

3.3.2 Flowchart

From Total Quality Management (Reid & Sanders, 2010) a tool can be used for measuring the current state. This tool is a flowchart and is a graphical representation of a process which use symbols to represent elements. Those elements can be different things such as flow direction, operations and equipment.

3.3.3 Probability Plots & Histograms

A probability plot is a statistical tool used to show the distribution of measured values. With a probability plot the fit of a distribution is evaluated to the measured values, which estimate percentiles (Minitab, 2017). With the use of histograms the frequency distribution of the measured values can be showed (Reid & Sanders, 2010).

3.3.4 Used Datasets

For the measurements of the current state of the airframe MRO at KLM E&M different datasets are used. A description of the different datasets can be found in Appendix C.

3.4 Current state overall Airframe MRO

In this section the different previous described tools are used to measure the current state of airframe MRO at KLM E&M. In section 1.3 and 1.4 the airframe MRO chain was discussed briefly, but this is not sufficient for measuring the current state of the airframe MRO. A more elaborated measurement is needed to fully understand the current airframe MRO chain. This section starts with the previous discussed tools that will be applied and ends with qualitative observations that were made during this research.

3.4.1 SIPOC of the airframe MRO chain

The overall airframe MRO chain is presented in a SIPOC diagram depicted in Figure 3-1. In the first and last column the supplier/customer can be seen. For airframe MRO, the supplier is also the customer, because it delivers its own aircraft that needs service and receives its aircraft back for service. For this research the supplier/customer is divided in two groups: KLM and external airlines as this research will further on only focus on KLM aircraft. The airframe MRO order and report make up for the information in- and output. The unserviceable and serviceable aircraft are the physical in- and outputs of the airframe MRO. The process on a general level (for the whole airframe MRO chain) consist of 'aircraft preparation', 'inspect/work', 'test' and 'aircraft release'. The aircraft preparation is all the things that are needed before an inspection/work can be performed, such as connecting the ground power unit (electricity). During 'inspect/work', the needed inspections and work are performed which are followed by the 'test' process step. Finally the airframe MRO is finished when the aircraft is released, such as disconnecting the ground power unit.

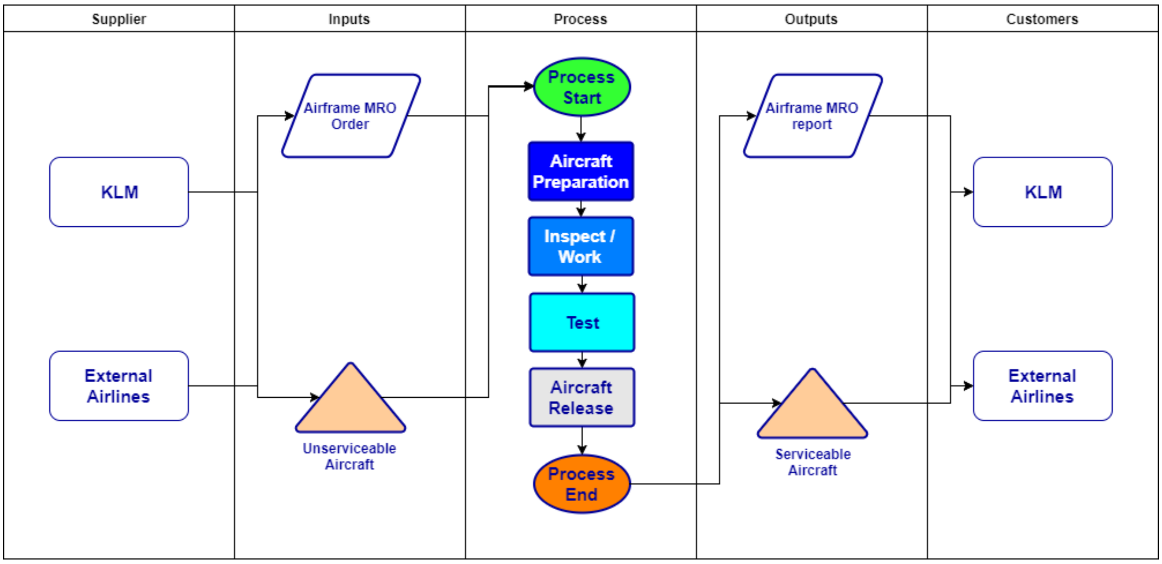


Figure 3-1: SIPOC diagram of the airframe MRO chain

3.4.2 Flow Chart airframe MRO process

The main process described in the previous section (3.4.1) will be more in depth outlined in this section with the help of a flow chart. Figure 3-2 shows the flow chart of the general airframe MRO process at KLM E&M. This flow chart shows the main processes and decision moments in the airframe MRO chain. First the aircraft is prepared for performing MRO, all tasks that are needed before an inspection or work can be done have to be prepared. Secondly, depending on the type of task, an inspection is performed to check the state of an attribute or if the task does not contain an inspection, work can be instantly performed, such as replacing a component. The purpose of an inspection is to determine if extra service is needed for the inspected attribute. If there is no 'finding', then there is no need for further work for that attribute. However, if a defect is found then there is a need for applying service/work. After performing work to the aircraft, this needs to be tested/ inspected if the performed work is sufficient for the airworthiness of the aircraft. Finally the aircraft is released and ready for service.

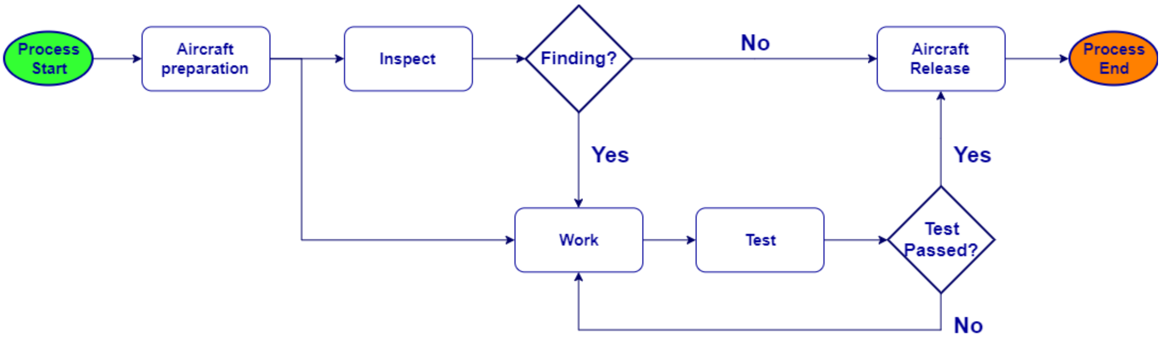


Figure 3-2: Flow chart of the overall Airframe MRO process

3.4.3 Current control of the airframe MRO chain

Figure 3-3 shows the current control chart of the airframe MRO. The airframe MRO process is influenced by the so called 4 M's (Machine, Method, Material and Man). If the 4M's are not available then there is no stable process (Art of Lean, Inc). Therefore, to have a stable airframe MRO process, the 4M's need to be stable, thus proper control is needed on the 4M's.

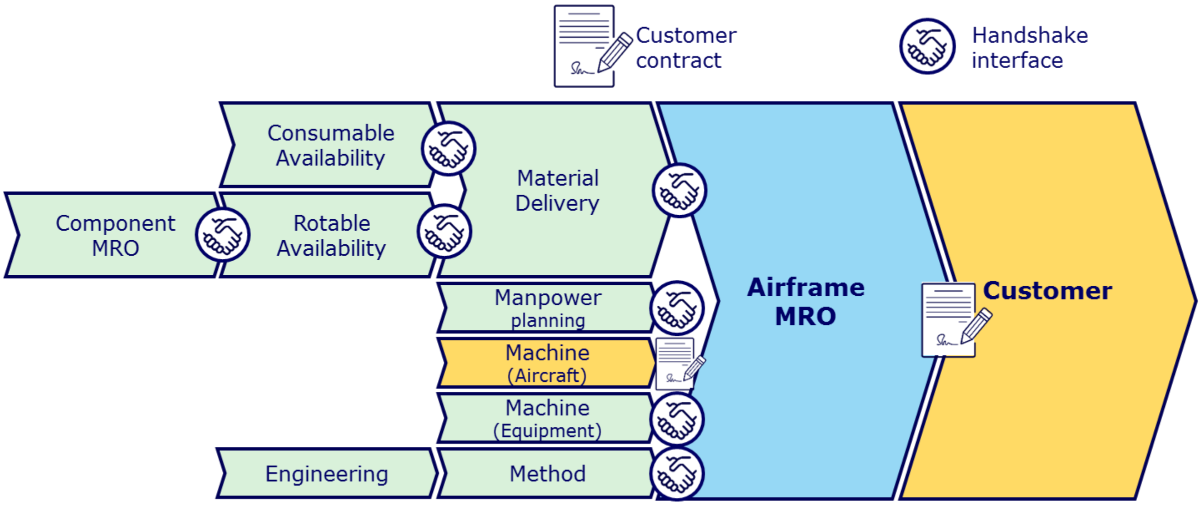


Figure 3-3: Current organizational control of the Airframe MRO

There is a 'process owner' for the entire airframe MRO chain, this is Vincent Hooff and there are so called 'process managers' that each is responsible for a part that influence the total airframe MRO chain. Figure 3-3 shows the customer, which in this case is fleet services and for airframe MRO there are multiple managers, each for a different location (mentioned in section 3.1.1) where airframe MRO can be performed. For Line maintenance the process manager is Marcel Bakker, and for Hangar 11, 12 and 14 are respectively Rob van der Slot, Perwien Meriwani and Marjanne van Winkoop. They all have a customer contract with the customer (fleet services) when to deliver the aircraft after MRO, but also when they can begin MRO to the aircraft. Therefore, in Figure 3-3 the aircraft is depicted as one of the 4M's (Machine: aircraft). Discussions are possible about if this is part of the 4M's as this also can be seen as the object for performing airframe MRO. From interviews it was concluded that this is part of the 4M's, because it can have a big influence on the performance of the airframe MRO as the scheduled finished time is fixed.

Material

For each location the same process managers are responsible for the 4M's. Marc Kesting is the process manager for 'Material', he is responsible for the delivery of the material to the locations where the airframe MRO is performed. In order to deliver material, they obviously need to be available to deliver. The material can be divided into two groups: consumables and rotables. Consumables are parts that are replaced with new one when they need to be replaced, rotables on the other hand are components that undergoes MRO. Marc Kesting is also responsible for the availability of the consumables. The responsible manager for the rotables is someone different, namely Patrick Hartwijk. As mentioned the rotables undergoes MRO and there are also different process owners for this component MRO, namely Axel Colen and Willem Heuvelman.

Manpower

The process manager for 'Man' is Taco Brouw. He is responsible for the department Planning, Scheduling and Fleet Control (PSFC). In general, he is responsible for planning and scheduling that all the 4M's are in place for performing airframe MRO. Therefore, he is also responsible as depicted in Figure 3-3 for the 'Manpower' planning.

Machine

As mentioned, 'Machine' is dived; into Machine: aircraft and Machine: equipment. For performing airframe MRO the equipment that is needed must also be in place. The process manager responsible for the equipment is also Marc Kesting as he is responsible for the 'Material, Equipment & Facilities' (MEF) maintenance unit.

Method

The method to perform airframe MRO is the responsibility of the engineering department. They are responsible for providing proper manuals and guidelines for performing MRO.

Handshakes

Figure 3-3 shows between each organizational section a so called 'handshake' or 'customer contract' sign. As mentioned, to have a stable airframe MRO process, the 4M's need to be stable as well. Therefore clear handshakes/contracts are needed between each organizational section, so everybody knows what the expectations are for each other (Philips van Buren, 2017). Without it, everybody can perform how they feel like in order to achieve their own goals which can be not in line with the main goal. A handshake is in place when a good definition of the desired handshake is defined, and how it can be measured by chosen KPI's and monitored so it can be evaluated. The handshake must also be evaluated after a chosen time to evaluate if the current handshake is still contributing to the desired performance of the integral airframe MRO chain.

During the investigation of the current handshakes by interviewing all the previous mentioned process managers it was found that there is a clear lack of good defined handshakes. A more elaboration about the desired handshake will be described next.

Handshake for Material

First it was observed that there is a handshake for 'Material Delivery', but not for all locations where airframe MRO is performed. The material delivery handshake is in place only for hangar 11. There is an agreement between the two process managers; that material will be delivered within one hour from the moment a material request is placed at the location where all materials are located that are needed for a check. Also there is a handshake for the 'consumable availability', which is defined as: a service level of 98% must be met. This means that 98 times of 100, the consumable material must be available when a request is done. Therefore, 98% of all consumable material request must be delivered within one hour (only for hangar 11). There is no handshake for the availability of rotables for all locations.

For all other locations (hangar 12/14 and Line maintenance) there are no handshakes in place for material.

Handshake for Manpower

The Planning Scheduling & Fleet Control department is as mentioned responsible for planning the manpower capacity for each check on all locations, but there are not clear handshakes in place. However, this is currently in progress as this department is new due to changes in company organizational structures.

Handshake for Machine: Equipment

Also for Machine: equipment there are not clear handshakes. The only thing that MEF checks is if the equipment is available when they see the tasks that need to be performed. If the equipment is available at that moment, the needed equipment is defined as available, but in the time between this check and the actual performing of the task, the equipment could be used somewhere else which lead to a possible non-availability. However, this non-availability is not identified, because the equipment was defined as available and not checked again after a positive availability.

Handshake for Machine: aircraft

As mentioned, the aircraft is also part of the 4M's, as it influence also the airframe MRO process. Because if an aircraft is delivered too late to the airframe MRO providers, the available time for airframe MRO has decreased, because the finish time is a fixed time at KLM E&M. If the finish time was not fixed, but the TAT was fixed, then it did not matter when the aircraft arrived at the airframe MRO providers, because they still have the same time available to provide MRO.

Handshake for Method

It is not known if there are clear handshake for 'Method'. What is known is that for all maintenance tasks are manuals in place on how to perform the different tasks etc.

3.4.4 Currently measured output performance

Figure 3-4 shows the current used CBBSC (Connected Business Balance Score Card) of KLM E&M. It depicts the result KPI's for the year 2016. It can be seen that for Airframe the punctuality of the on time deliveries (TAT) is presented for the A-check and C-check. KLM E&M presents also the amount of the deferred defects, which in Figure 3-4 only the operational deferred defects are presented. Also the efficiency of the manpower is presented as the productivity of the men.

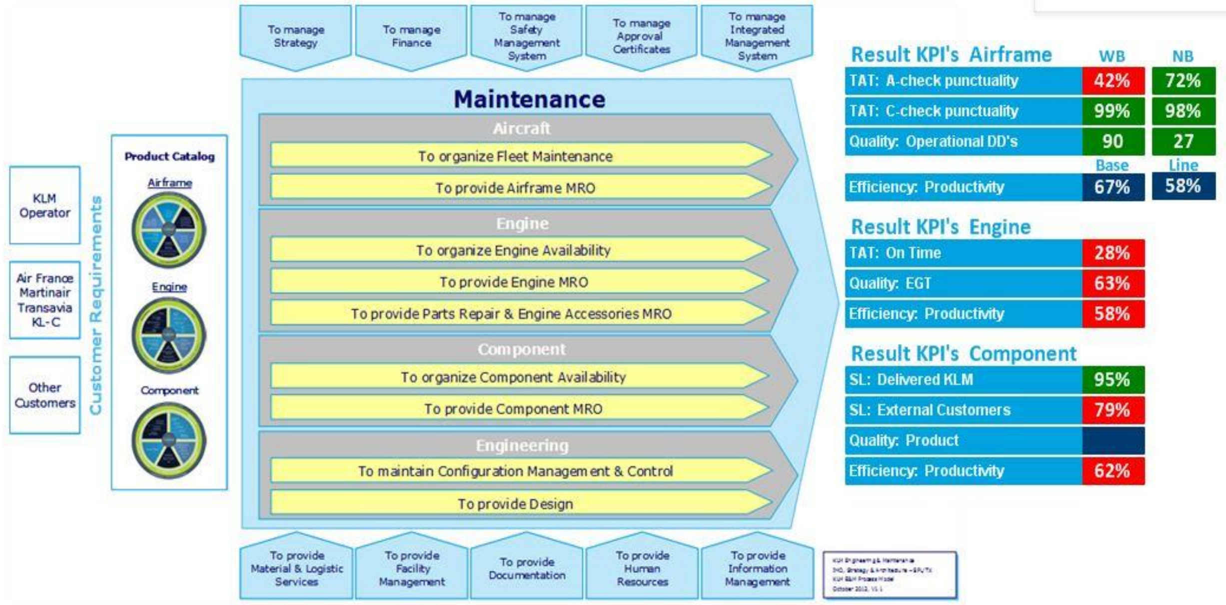


Figure 3-4: CBBSC KLM E&M

Figure 3-5 is a more detailed overview of only the CBBSC of KLM E&M Airframe Services. The same results are shown as in Figure 3-4, but also more results KPI's are presented, namely the number of technical delays (longer than 3 hours), the dispunctiality, the average length of technical delays at Amsterdam Schiphol Airport, the number of technical cancelations and the number of deferred defects that are again deferred.

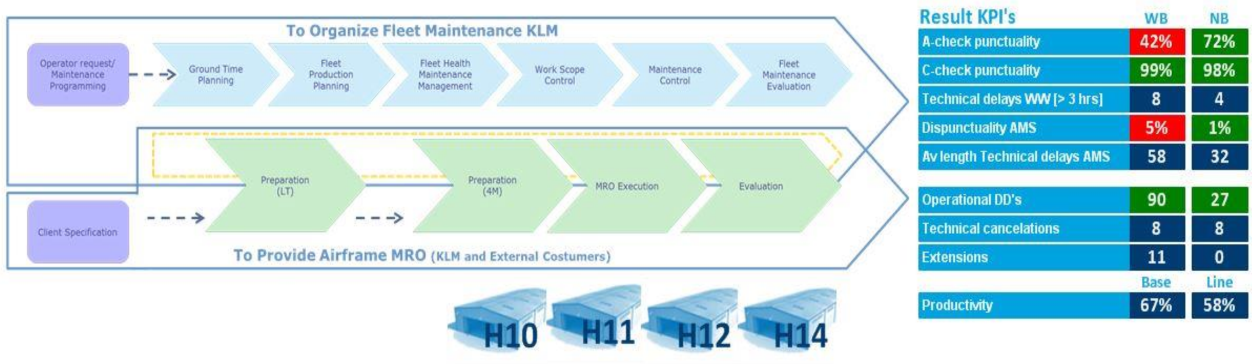


Figure 3-5: CBBSC KLM E&M Airframe Services

Process Quality (WIP)

As mentioned in section 2.4 the 'Quality' key performance indicators can be divided in process quality and product quality. As for the airframe MRO the result of the product quality is always positive because in the end the aircraft is airworthy again. The process quality is stated as the amount of work that has been performed during a maintenance check. So, if all work has been performed that was planned, the quality of the process is high (low WIP). All deferred work has to be done at a later time and therefore is still in process/progress which still causes downtime of the aircraft. Therefore, for this research it is stated that the quality KPI must be expressed as the work in process (WIP).

For the year 2016 the amount of deferred defects for the entire KLM fleet is presented in Figure 3-6. This means all deferred defects for all wide body and narrow body aircraft are presented together. It can be seen that from June the number of deferred defects started to rise.

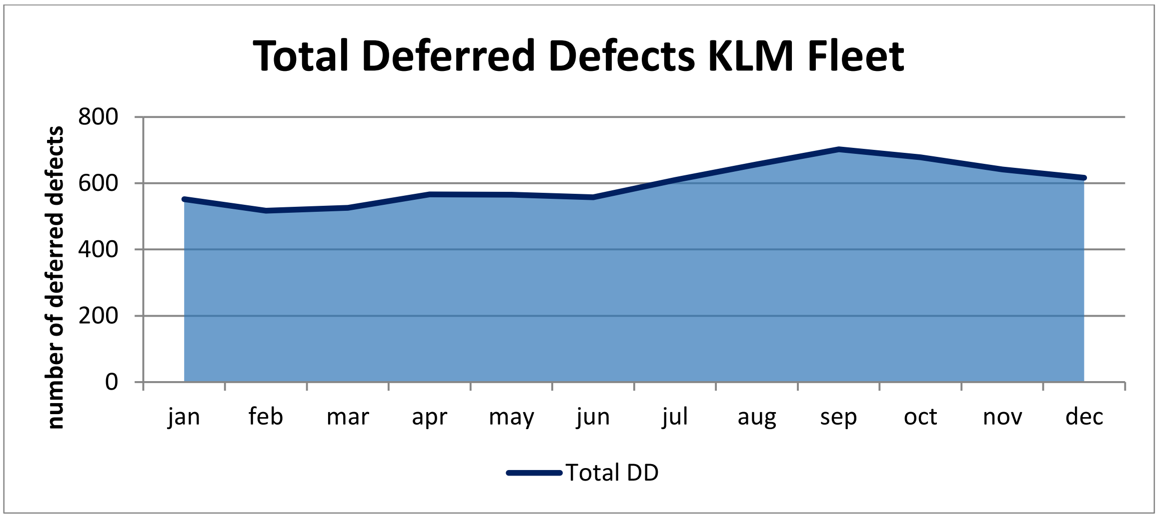


Figure 3-6: Deferred defects of total KLM fleet in 2016

At KLM E&M there is no overall target for the total KLM fleet but there is for the 2 type of aircraft (wide body and narrow body). Figure 3-7 shows the number of total deferred defects for the wide body aircraft of KLM. It also depicts the target level of 500 deferred defects.

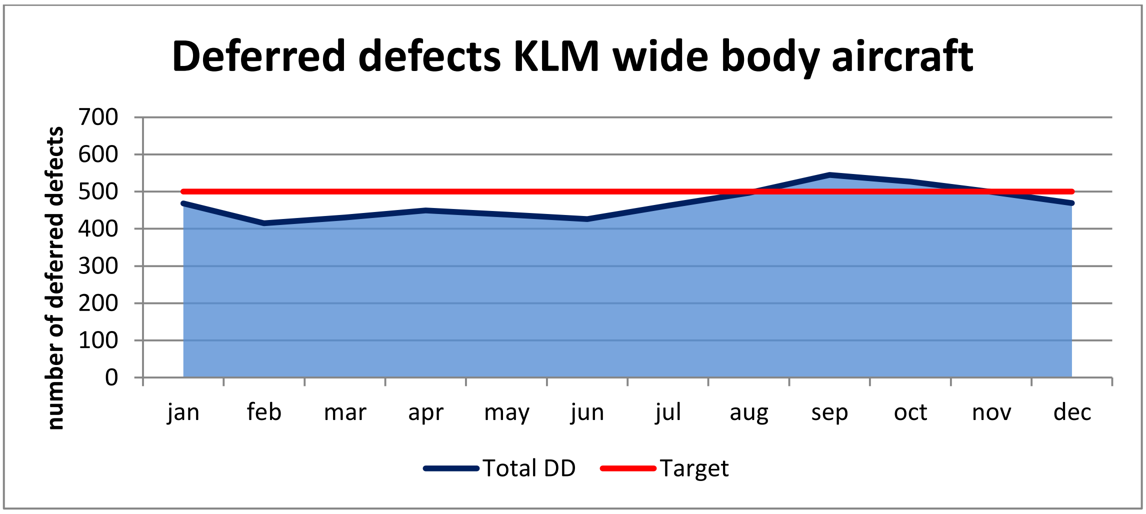


Figure 3-7: Deferred defects of KLM wide body aircraft in 2016

The same can be presented for the narrow body aircraft of KLM. Figure 3-8 shows the total deferred defects of the narrow body aircraft for the year 2016. The target level for narrow bodies is different from the wide bodies. The target level for the narrow body aircraft is set at 120 deferred defects.

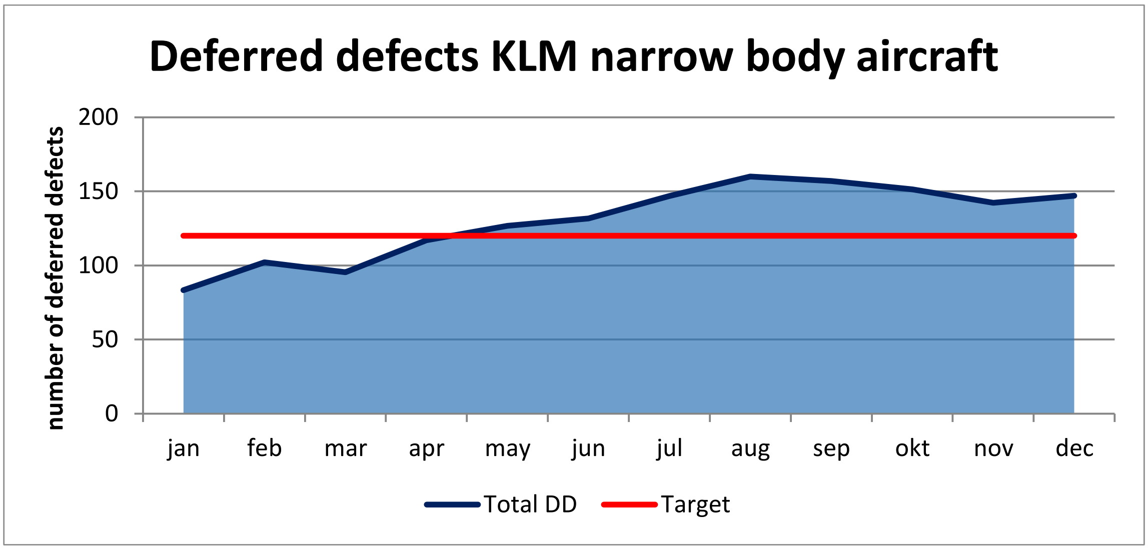


Figure 3-8: Deferred defects of KLM narrow body aircraft in 2016

The current performance of the airframe MRO chain of the other key performance indicators will not be presented for the entire airframe MRO chain, because of scoping of this research and data implications.

3.4.5 General observations airframe MRO chain

From interviews with different process managers and other employees at KLM E&M a number of observations were made. In order to control the airframe MRO processes, different handshakes must be in place and for the overall airframe MRO chain there is a clear lack of them. Also the targets for the deferred defects is a target for entire KLM E&M, but not for each type of check/location. Therefore, it is always possible to point to someone else when it comes to this subject. Furthermore, not all work that has to be performed is planned in advance for the check starts. The so called 'complaints' (section 1.3) from incoming flights are not planned, which results in deferred defects if only all the other work that was planned can be performed. Also not all deferred defects (so called 'can-do's) are taken into the work package and planned for the check. A GWK (ground engineer) decides which can-do's are solved if the time is available for solving them.

3.5 Research focus: wide body aircraft

This research will further focus on the wide body aircraft as the desire is to decrease the gap between the current performance and the desired performance as mentioned in section 1.4. The wide body aircraft underperforms more compared with the narrow body aircraft and therefore the focus will not be on the narrow body aircraft.

The quality of the airframe MRO chain for wide body aircraft is already described in the previous section (3.4.4). The other KPI's will be measured for the wide body aircraft, but only for the checks that are performed in hangar 11 as there are the most performed base maintenance checks and for further scoping of this research.

3.5.1 Currently measured output performance hangar 11

Also the performance of airframe MRO in hangar 11 is currently measured and monitored in a CBBSC. This can be seen in Figure 3-9 and shows the on time performance and occurrences of the different checks.

Figure 3-9: CBBSC KLM E&M airframe MRO hangar 11

Turnaround Time (TAT)

The turnaround time is as mentioned an important measure of MRO processes and therefore also for airframe MRO at KLM E&M. For this research it was desired to be able to measure the total airframe MRO chain, but due to (as mentioned) data implications and scope of this research it is chosen to focus only on the wide body aircraft checks that are performed in hangar 11.

First the most common planned check is the A-check; Figure 3-10 shows the probability plot of the performed A-checks in hangar 11. If a probability plot shows a skewered line and not a straight line than this means that the curve is not normally distributed and this is an indication of waste in the process (Van Blokland, De Waard, & Santema, 2008).

It can be seen that on average the A-check duration is 41.67 hours and has a large standard deviation of 25.7 hours. The desired TAT for an A-check is 24 hours for all wide body aircraft in hangar 11 except for the Boeing 747 (30 hours) and the Boeing 787 (not in hangar 11).

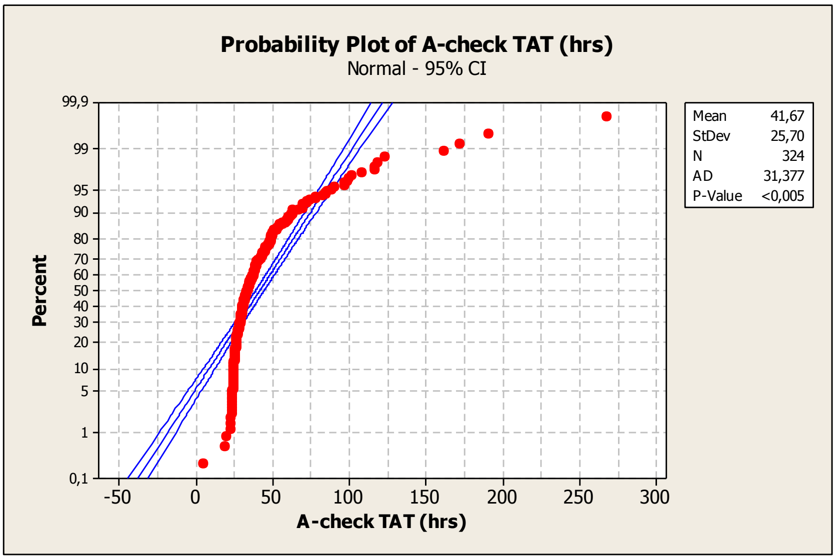


Figure 3-10: A-check TAT in 2016

The H-check is the check for the out-of-phase tasks that do not fit in the A-checks and for deferred tasks from an earlier A-check. The TAT performance is presented in Figure 3-11and it shows that the H-check has an average TAT of 33.56 hours with a standard deviation of 46.66 hours.

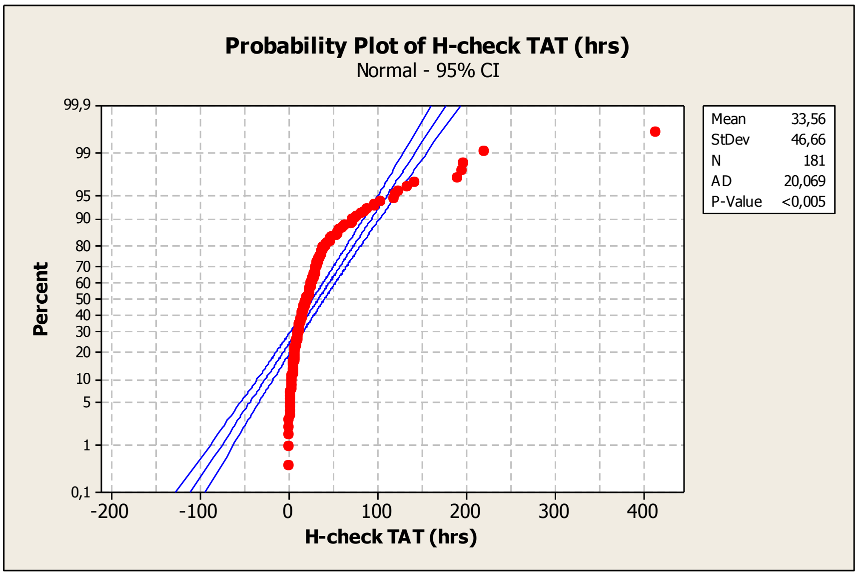


Figure 3-11: H-check TAT in 2016

The M-check is only for the Boeing 777 aircraft and falls between 2 A-checks of the aircraft. The average TAT of the M-check is 12.08 hours with a standard deviation of 9.8 hours.

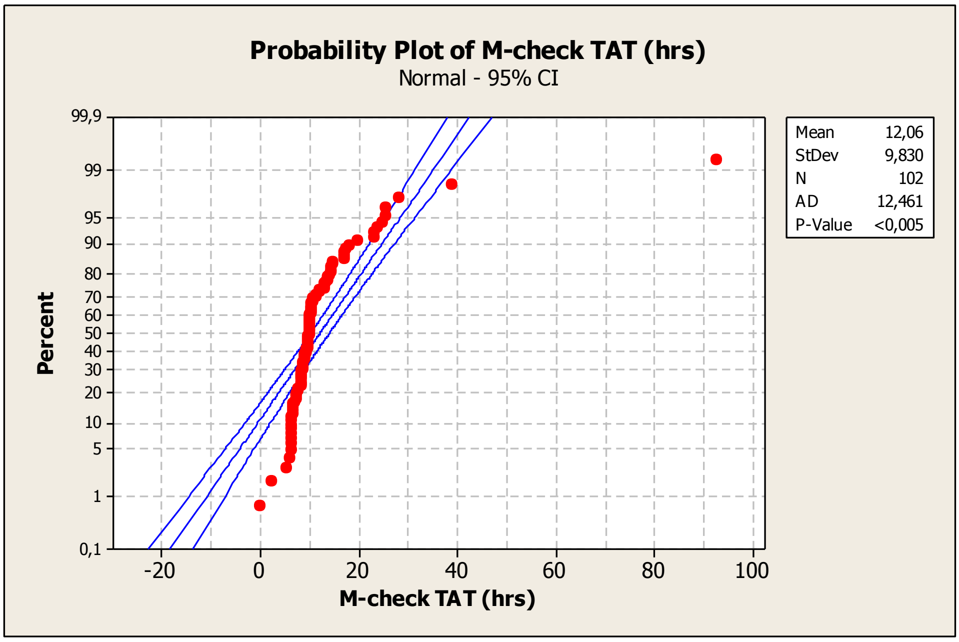


Figure 3-12: M-check TAT in 2016

The AOG-check is only for aircraft that have the status 'Aircraft On Ground'. This means that there is some trouble with the aircraft which has to be solved first before it can be put back into operation. The average time of the AOG-checks is 33.74 hours with a standard deviation of 44.8 hours.

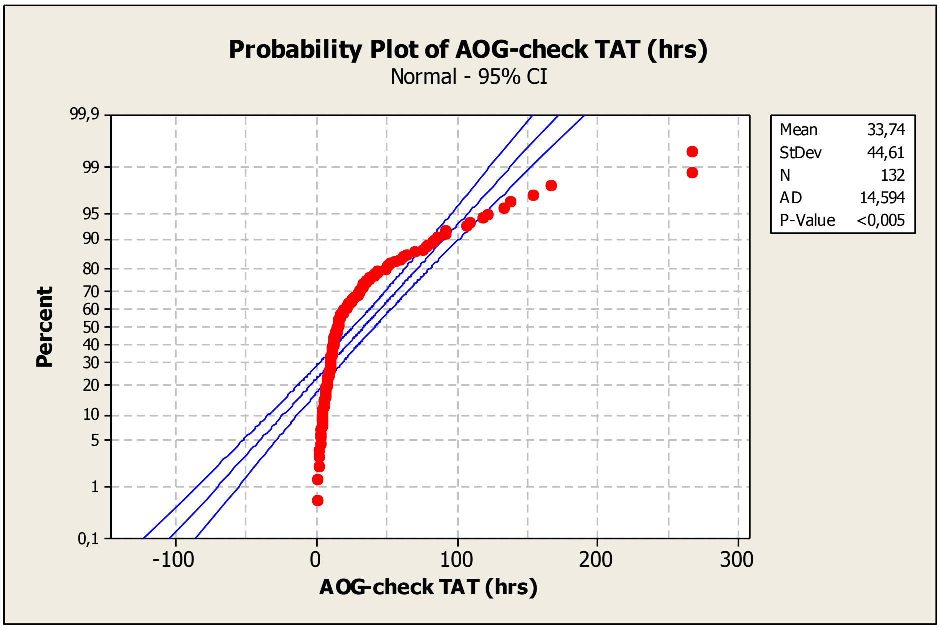


Figure 3-13: AOG-check TAT in 2016

The last type of check that is performed in hangar 11 is the TD-check. This is for complex problems/tasks that need to be performed and/or for reducing the WIP of the aircraft. The average time of a TD-check is 16.33 hours with a standard deviation of 18.46 hours.

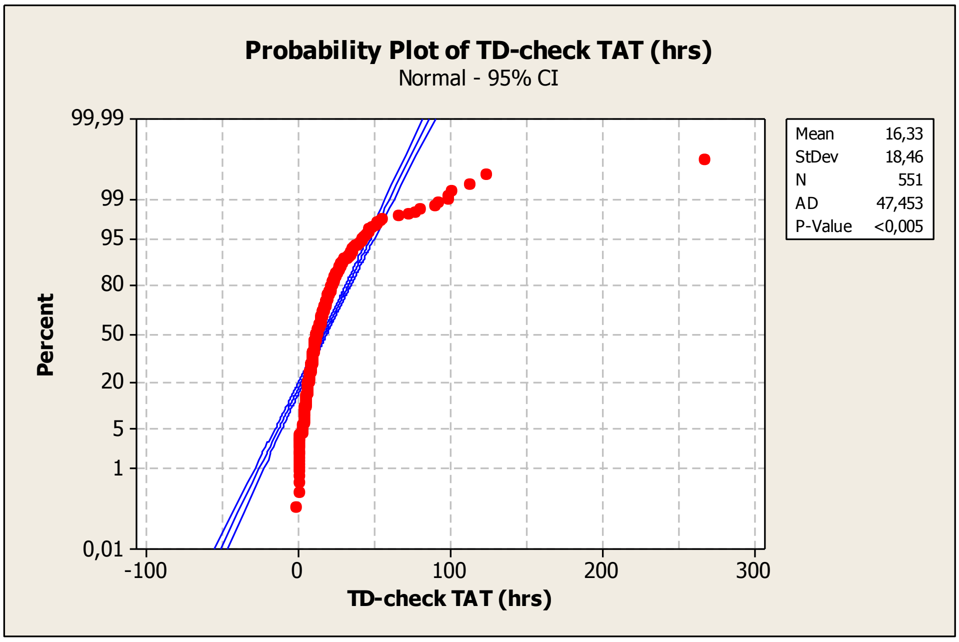


Figure 3-14: TD-check TAT in 2016

All the different checks are summarized in Table 3-2 where all the average turnaround times and standard deviations are showed.

Table 3-2: Summary of TAT of checks in hangar 11

	A-check	H-check	M-check	AOG-check	TD-check
Average TAT (hours)	42.67	33.56	12.06	33.74	16.33
Standard deviation (hours)	25.70	46.66	9.83	44.61	18.46

3.6 A-check research focus

For this research a more focussed view will be on the A-check of the wide body aircraft in hangar 11, because this is the most frequent regular type of check in hangar 11 which has the most planned ground time (downtime) and the output of this check is the source for possible H- and TD-checks. Thus, the possible WIP left from the A-check is the input for H- and TD-checks. It is also expected that large improvements can be found for this check and get it more stable.

3.6.1 Current state of A-check

The TAT performance indicator is already presented in Figure 3-10 and the results is an average TAT of 41.67 hours with a standard deviation of 25.70 hours. Currently, the on time performance of the A-check is 42% (measured by KLM E&M), which is presented in Figure 3-5 (section 3.4.4.). All A-checks are on time if the check is performed within 24 hours and 30 for the Boeing 747 aircraft. However, from further investigation it was found that this 'on time performance' is not measured according to the composition rules set by KLM E&M. Another method is used to determine if the aircraft was delivered on time and this will be discussed below.

On time performance 2015 method

The '2015-method', as it is called, does not look if the aircraft was delivered within the 24 or 30 hours, but if the aircraft is delivered before the second last departure time of the same type of aircraft then it is measured as 'on time'. An example will be given with the help of Figure 3-15. For a Boeing 777-300 the A-check starts according to the composition rules at 8:45, local time (LT) and ends 24 hours later at 8:45 (LT, next day). The 2015 method works differently and is more practically explained. According to the flight plan (for this period in Figure 3-15) the Boeing 777-300 can be delivered to the hangar at 8:15 (LT), but the check is still on time, not only 24 hours later but 30 hours and 40 minutes later. This is explained as follow: the second last flight of the day with a Boeing 777-300 is too BKK (Bangkok International Airport) at 17:30 (LT), towing of the aircraft and handling of the aircraft before departure takes respectively 1 hour and 1:25 hours. The time for towing and handling is subtracted from the departure time which results in the 'Delivery moment Hangar' of 14:55 (LT) as presented in Figure 3-15. The aircraft is on time, because fleet services can usually shift different aircraft of the same type with each other. This is possible till the second last flight and therefore the delivery moment is calculated from this second last flight.

Although the aircraft is on time for fleet services, it was not on time delivered from the airframe MRO perspective. The aircraft was planned to finish within 24 hours and therefore all assets and resources were planned for this 24 hours.

W16	Period		Day	CR (LT)			INTEGRAL TAT				Towing	Departure	LUAM UTC	LUAM LT	FlightNo	Destination	Departure time (LT)
OP-A	From	Till		Start	end	TAT	Start	Deliverymoment Hangar (LT) - RFT	Integral TAT	LUAM IDLT			A-slot endtime	A-slot endtime			
747-400 combi	1-jan-17	25-mrt-17	3	7:45	13:45	30	7:45	**15:20**	**31:35**	**31:35**	1:00	1:25	14:45	15:45	KL887	HKG	17:45
	1-jan-17	25-mrt-17	7	7:45	13:45	30	7:45	**15:20**	**31:35**	**31:35**	1:00	1:25	14:45	15:45	KL887	HKG	17:45
777-300	1-jan-17	25-mrt-17	2	8:45	8:45	24	8:15	**14:55**	**30:40**	**30:10**	1:00	1:35	14:20	15:20	KL875	BKK	17:30
777-200	1-jan-17	25-mrt-17	3	8:45	8:45	24	8:15	**11:00**	**26:45**	**26:15**	1:00	1:30	10:20	11:20	KL641	JFK	13:30
	1-jan-17	25-mrt-17	6	8:45	8:45	24	8:15	**11:00**	**26:45**	**26:15**	1:00	1:30	10:20	11:20	KL641	JFK	13:30
A330-300	1-jan-17	25-mrt-17	2	8:45	8:45	24	8:15	**10:10**	**25:55**	**25:25**	1:00	1:25	9:35	10:35	KL765	AUA/BON	12:35
A330-200	1-jan-17	25-mrt-17	5	8:45	8:45	24	8:15	**12:00**	**27:45**	**27:15**	1:00	1:25	11:25	12:25	KL415	KWI/DMM	14:25

Figure 3-15: 2015 method A-check punctuality

In Figure 3-16 it can be seen that the average TAT of the on time delivered aircraft (according 2015 method) is 29,97 hours with a standard deviation of 8 hours.

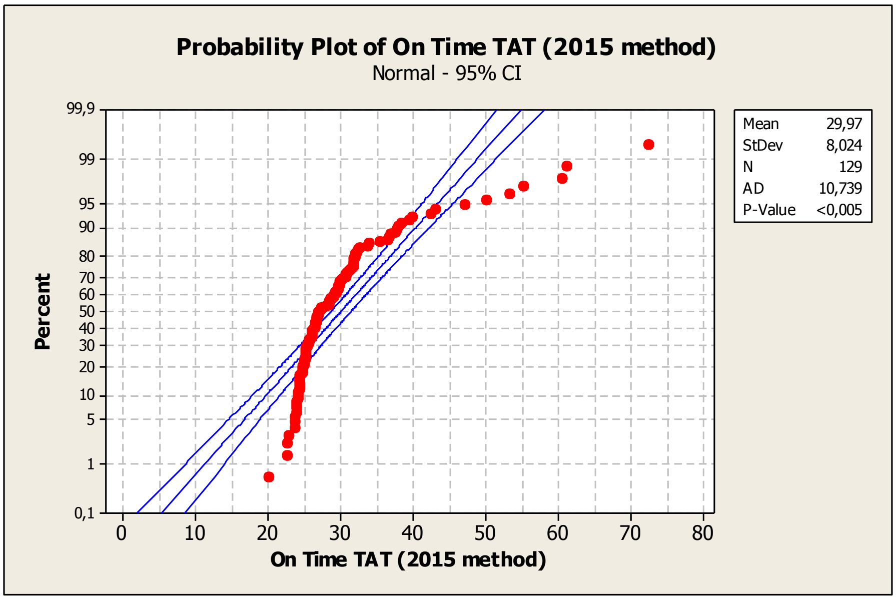


Figure 3-16: A-check TAT (OTP) 2015 method

In Figure 3-17 a histogram is showed of the on time TAT according to the 2015 method. Most of the time the aircraft was on time between 22.5 and 27.5 hours which is 51% of the total on time performances (2015 method).

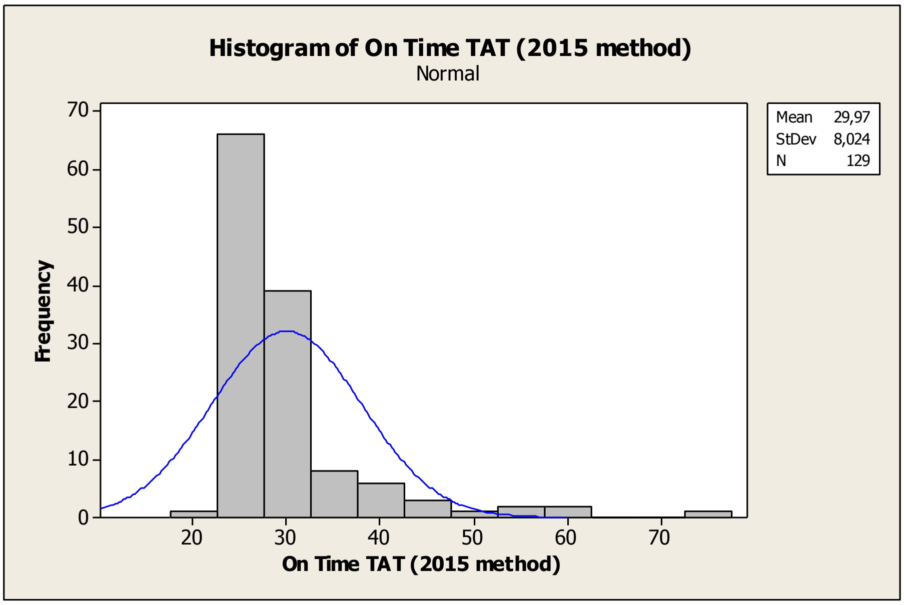


Figure 3-17: A-check TAT (OTP) histogram

On time performance TAT

At KLM E&M, the on time performance (OTP), according to the '2015 method', is the only KPI presented about the OTP of the wide body aircraft. Therefore, the management and everybody else thinks the OTP is 42%, for a TAT of 24 or 30 hours (depending on the aircraft). But in reality, the 2015 method does not measure according to the turnaround times of 24 and 30 hours. If the OTP is actually measured according to the 24 and 30 hours, the OTP performance will be 15% instead of the 42%.

A-check research limitations and complexity

Unfortunately there is no data available of the total WIP input and output of all the A-checks. From here on this research will focus on a single A-check, because of the extreme complexity and data limitations of the checks. In advance it was thought that there is sufficient data to analyse multiple checks, but during this research it was found that the data does not present the things that were needed in order to analyse multiple checks at once. Therefore, it was chosen with different stakeholders to scope this research further in order to first analyse one A-check.

A-check Boeing 777

The chosen A-check is first of all an A-check that is performed for a Boeing 777 (B777). This is because at KLM E&M they use the program 'Maintenix' (Mxi) for all the data of airframe MRO. Mxi is an aviation maintenance management software, which will be implemented for all aircraft at KLM E&M. However, for the wide body aircraft in hangar 11 this is already fully implemented for the Boeing 777 and the Boeing 747. Because KLM is phasing out (taking out of operation) the Boeing 747's, the choice was made to pick an A-check of the B777. More specifically, the check chosen to further analyse is the A-check on the 17th of January in 2017 for the B777 with registration number PH-BVC. This check was signed of as 'on time' delivered according to the 2015 method, but in reality it took 25.5 hours to complete the check and therefore was too late for the hangar. As presented in Figure 3-17, most of the checks that are on time according to the 2015 method, (but possible not on time according to the composition rule), have a duration between 22.5 and 25.5 hours. Therefore, the check of 17 January was also chosen because this check fits in this category and possibly represents the other checks as well in this category.

3.7 Current state A-check PH-BVC

3.7.1 Teams

The mechanics and GWK's (ground engineers) are currently divided into several teams. First there is the Cabin team. They perform all airframe MRO inside the cabin, but not in the cockpit (flight deck). The other teams are the 'lengthwise team' and 'crosswise team' which is also represented in Figure 3-18. The lengthwise team is responsible for all the tasks in- and outside in the longitudinal direction of the aircraft (except cabin), thus tasks for the flight deck is the responsibility of this team. The crosswise team is responsible for all the tasks on the wings which includes the engines. Although there are currently 3 different teams, the lengthwise and crosswise team switch from time to time and therefore can be seen as a single team ('Under the Wing'-team: they have the same skill sets together). All the different zones for which the team are responsible can be found in Appendix D.

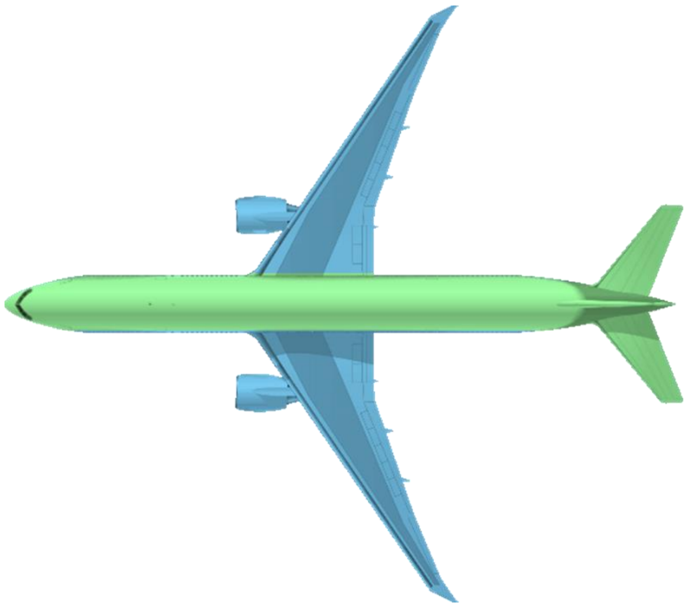


Figure 3-18: Lengthwise- (green) and crosswise (blue) team designated zones

3.7.2 A-check phases

The current A-check is divided into lot of different tasks for different zones of the aircraft. Each task is categorized in a 'phase'. The current phases are: general, preliminary, open/remove, inspect, work (component replacement, lubricate, service, modification), close/install, test and final/testrun. The downside of the current phases are that there is not a clear distinction between the task sequence, because for instance a task with a phase code 'open/remove' could happen before an inspection and another tasks with the same phase code could happen after an inspection. The first data implication arise due to this phenomenon and therefore each task was evaluated and categorised into new phases. This was checked with a project manager of hangar 11 to check if this was possible and was done properly (Prins, 2017). The new phases are:

- Hangar preparation
- Aircraft preparation
- Cabin preparation
- Preliminary work
- Inspect
- Work
- Corrective
- Test
- Final Work
- Preparation Final test

- Final Test
- Aircraft release

3.7.3 Turnaround time tasks

The A-check of PH-BVC on the 17th of January contained 518 single tasks to perform. The data unfortunately didn't provide the TAT of each single task, but it had to be calculated. The data only showed the completion date/time and the spent hours that was written. The spent hours does not represent the TAT of each single task, due to the amount of man that were needed for a task. Therefore, another data implication arise and it was needed to check by hand via Mxi for each single task what the TAT was. For most of the tasks it was possible to check how many men worked on a single task and then divide the spent hours by the amount of men, for the others it had to be looked up manually in Mxi. Start times were determined by subtracting the calculated TAT from the completion date/time. Figure 3-19 shows the current measured TAT for all the different teams and their working zones. It shows when work was performed and for how long, this can be any type of task of a different phase.

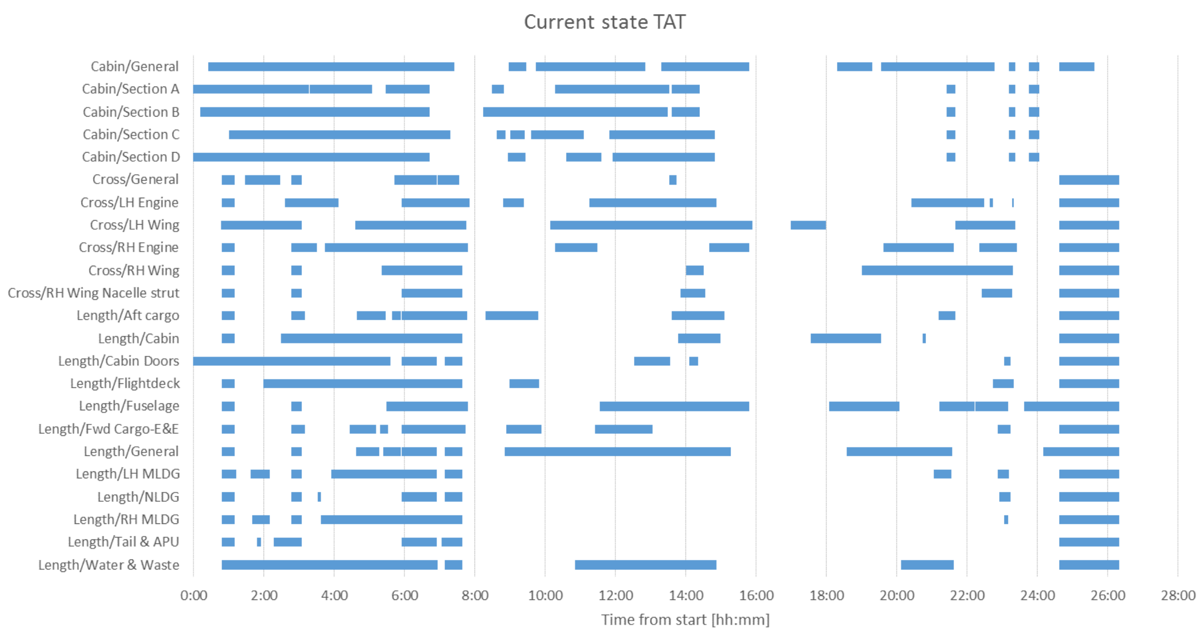


Figure 3-19: Current state TAT A-check PH-BVC

After assigning al the new phases and calculated TAT for each task, a new representation could be made of the current check. Figure 3-20 shows the current state TAT of the different phases for the Cabin team. Note that Cabin also is referred here as 'Above the wing'. This is because for this research the skill sets are categorized together, which results in an 'Above the wing' team and 'Under the Wing' team. The 'Under the Wing' team consists of the lengthwise- and crosswise team as it does not matter who does the task, because they have the same skillset.

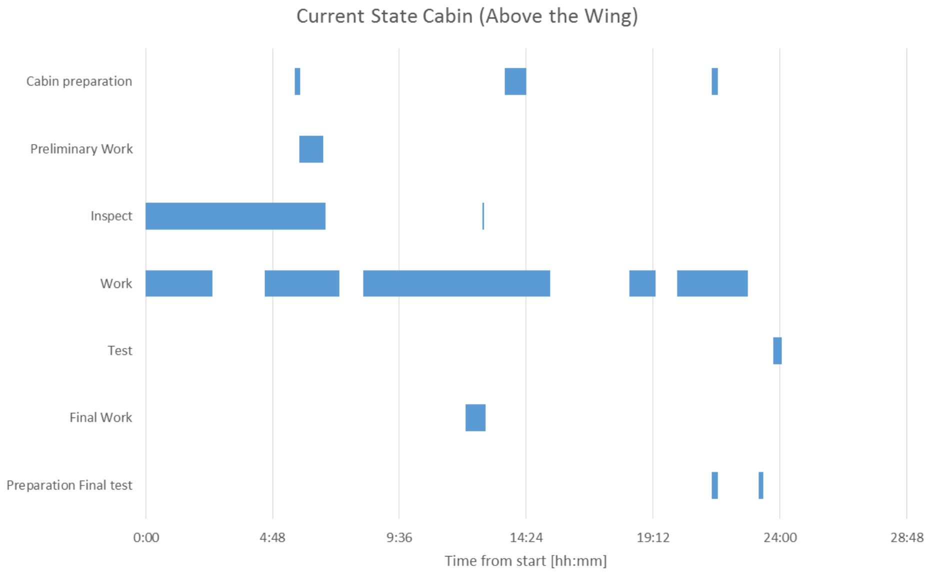


Figure 3-20: Current state TAT A-check 'Above the Wing' team

The same representation can be made of the Under the Wing team (Figure 3-21). It can be seen that tasks are signed off at times much later than they should have occurred. For example, the hangar preparation tasks are tasks that happen before all other tasks. However, the data shows that this is signed off about 7 hours after the check started.

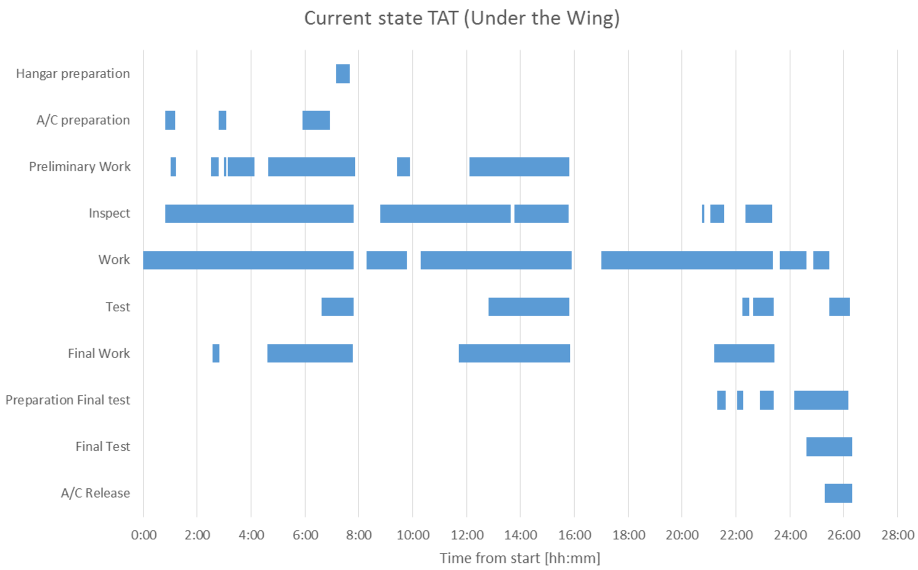


Figure 3-21: Current state TAT A-check 'Under the Wing' team

3.7.4 Observations A-check

From observations during several A-checks some explanations can be given for the strange sign off dates/time and overlap of tasks that should happen in sequence. Each mechanic/GWK has a set of tasks to do when he starts his work. The mechanic/GWK often get to work and knows what to do, but when a task is completed he does not sign it off immediately. Therefore, tasks can be signed off at times that are strange. Also the mechanic batches tasks, this means he performs a set of tasks and after completing all of them he signs them all off at the same time. This creates overlap of tasks that should be performed in sequence, however the data does not show the sequences unfortunately.

3.8 Theoretical preliminary model

From the current state with the current data it is not possible to point out what the constraint is of the output performance of the airframe MRO. In order to analyse what is constraining the output and from the found literature to implement Phase-Gate and concentrate resources, a new theoretical preliminary model is developed and this is also used later on to evaluate the potential of the current A-check. This section will discuss the theoretical preliminary model that will be used for the rest of this research.

3.8.1 Zone and teams

As mentioned in section 3.7.1 there are different teams performing airframe MRO. From the Theory of Constraints and Critical Chain, it is stated that not only the duration and sequences of tasks can constrain the output of a project, but the resources assigned to the tasks as well (Steyn, 2001). Therefore, for the model a distinction is made of 2 teams where the skillsets of the resources determined the 2 teams, namely as mentioned earlier the 'Above the Wing' and 'Under the Wing' team. The teams can work independently from each other, although there are some phases where they are depended of each other but this will be discussed in the next section.

3.8.2 Phase Sequence

Each task was already assigned to a new phase (section 3.7.2) but as shown, the phase sequence is not followed at check level but at task level. For instance, a main task is to inspect a component. First all tasks (opening panels) are performed before this inspection can be done, after the inspection, the work is completed by closing the panels. Then the same sequence is followed for another main task. With this type of sequence cycles it is possible that an inspection is done and a problem is found at the end of a check. This means extra work that was not planned for (typical for MRO) and if a part has to be ordered it can delay the check, because this problem was not found earlier.

From interviews with different stakeholders and from literature it is wanted to perform all inspections as soon as possible, so there is still enough time to order all the parts and possibly easier to adapt to the situation. From literature it was found that by implementing Phase-Gate it can improve the output performance of airframe MRO processes which led to the developed phase sequence in Figure 3-22.

Developed phase sequences

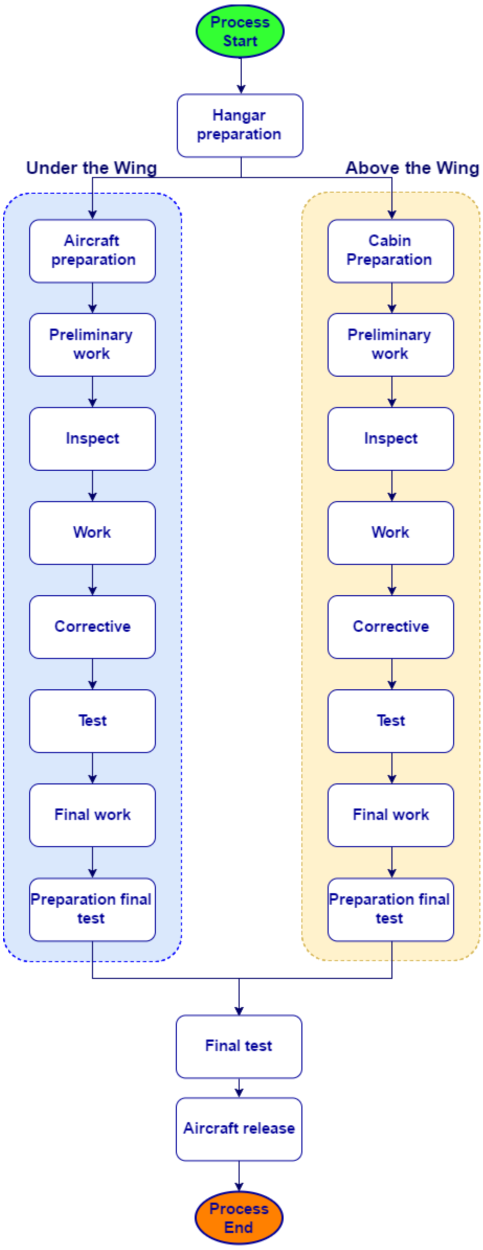


Figure 3-22: Developed phase sequence for preliminary model

The developed phase sequence for the entire A-check can be seen in Figure 3-22. The check start with the 'hangar preparation' phase and then splits up for the 2 teams. After both teams are finished with their phases, the final test and aircraft release will follow.

3.9 Conclusions current state

This section gives the main conclusions of the Measurement phase of this research. This phase and chapter was dedicated to answer the sub question:

"What is the current state of the Airframe MRO process at KLM E&M Airframe Services?"

This question can be answered from multiple perspectives. First the overall current state of airframe MRO at KLM E&M will be answered, secondly the current state of the checks in hangar 11 will be answered and lastly the current state of the focus for this research will be answered, which is the A-check.

Overall airframe MRO chain

The current performance of the overall airframe MRO chain is hard to measure, because of many different processes at different location, however the process quality (WIP) is measured for the year 2016. For wide body and narrow body aircraft the amount of deferred defects was higher than the desired target. The TAT performance of the overall airframe MRO is currently only measured for the A-checks and C-checks. The wide body aircraft had an on time performance of 42% (according 2015 method) and the narrow body aircraft 72%. The performance of the C-checks was 99% and 98% for respectively wide – and narrow body aircraft. It can be concluded that the current control of the overall airframe MRO is insufficient, because there is a clear lack on handshakes and agreements between all process steps within the overall chain.

Hangar 11

The performance of hangar 11 was measured for each type of check. This is shown below in Table 3-3. Unfortunately there is no data available to measure the WIP performance of each check.

Table 3-3: Summary of TAT of checks in hangar 11

	A-check	H-check	M-check	AOG-check	TD-check
Average TAT (hours)	42.67	33.56	12.06	33.74	16.33
Standard deviation (hours)	25.70	46.66	9.83	44.61	18.46

Research focus: A-check (wide body)

The on time TAT performance of the A-check is in reality different than currently is measured. At KLM E&M the performance is measured as 42%, but in reality this is 15%. The hangar (process managers) thinks the 42% is measured according to the composition rules but in reality this is measured according the ‘2015 method’. The 2015 method does not measure the TAT performance, but only checks if the aircraft is delivered before a ‘delivery moment’ that is determined by subtracting towing- and handling time from the second last departure time of the same type of aircraft.

A-check process

Currently there are 3 teams working during an A-check, namely cabin-, lengthwise and crosswise team. Although, lengthwise and crosswise team can be seen as a single team due to the same skillsets. The A-check is currently performed on task level, when it is desired to perform more on a phase level. For this research a phase-gate approach is chosen which results in performing the A-check in phases and concentrating resources per phase. Each phase has to be completed before the next phase can start.

Analyse Phase

4 Constraint identification for an A-check

This chapter is dedicated to answer the following sub question of this research:

> "What constraints are limiting the turnaround time and quality output of the Airframe MRO process at KLM E&M Airframe Services?"

First the methods that are used for the identification of constraints of the A-check output performance is described in section 4.1. Secondly, in section 4.2 the data is verified for usability as input for the preliminary model. After some correction of some data, an analysis was made with the model to identify what is constraining the output (section 4.3). Finally, the root cause of constraining the process is discussed in section 4.4 and the chapter is concluded in section 4.5, which is dedicated to summarize and answer the above sub question.

4.1 Methods used for constraint identification

There are various tools and methods available to identify constraints in the airframe MRO processes. A constraint is something that limits the output of a process from its potential. This section describes which tools and methods are used for identifying the constraints for airframe MRO and more specifically, the A-check.

Gantt chart

A Gantt chart is a graphic representation to show activities in a process to a time scale (section 2.3.1). For the A-check, each phase can be related to its TAT and to the time scale of the project. For the representation of the preliminary model, the Gantt chart will show each phase in sequence for each team.

Constraint types

There are many drivers possible which can constrain a process. During literature review different drivers were found and they are depicted in Figure 4-1. It shows the drivers that are based on Lean Six Sigma and Total Quality Management.

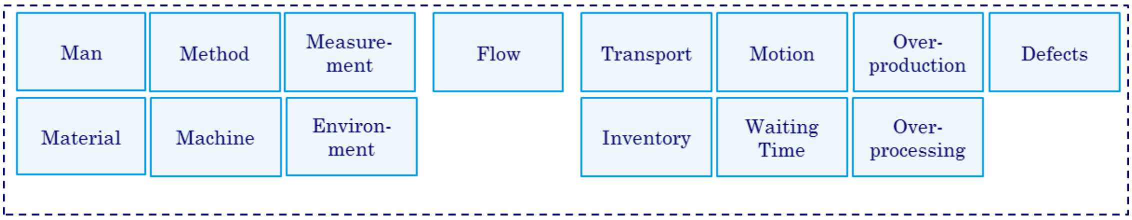


Figure 4-1: Possible drivers for constraining a process. (Rozenberg, 2016)

4.2 Data verification

The data is checked for accuracy and furthermore if it is usable for implementation in the preliminary model. The current sign off date/time is firstly checked to see how many men worked at the same time according to the data. This is first done for the Under the Wing team and depicted in Figure 4-2.

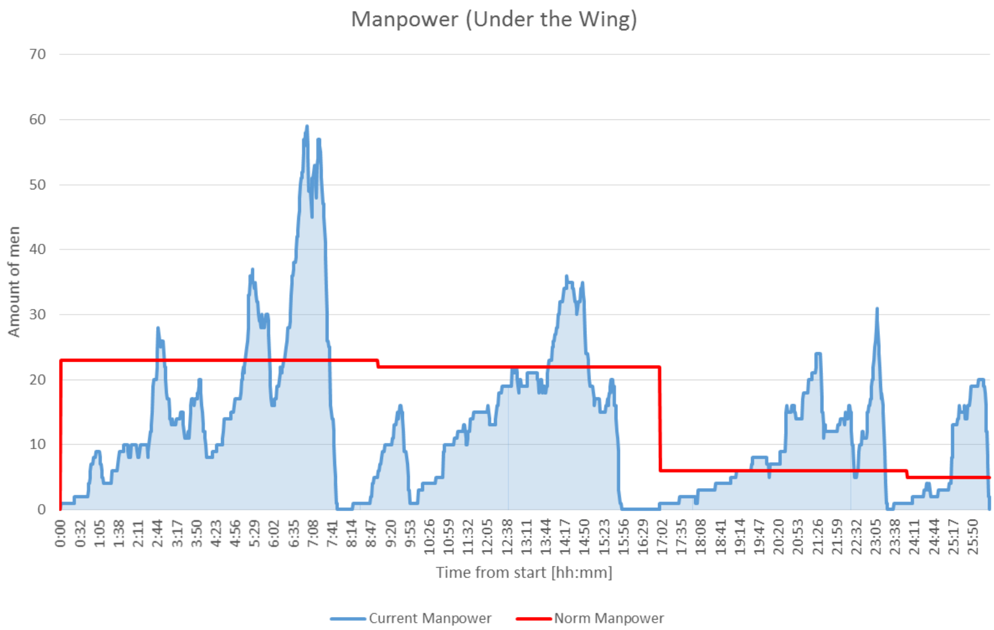


Figure 4-2: Current manpower according to data versus norm of manpower (Under the Wing)

From Figure 4-2 can be seen that data shows more men working than there was available (norm). The red line represents the amount of men that could have worked at the same time according to the norm. The drops in the red line represents the shift changes of the work teams which consists of a different amount. The first shift has 23, second has 22, the third has 6 and the last shift has 5 men. The blue line should not peak above the norm in reality, but clearly with this data this is the case. From observations (section 3.7.4) an explanation became clear for those peaks. The mechanic/GWK batches his tasks and signs them all off at the same time, this happens usually at the end of a shift. Because the data cannot show the performed sequence of the tasks, it currently shows that they were performed at the same time. Therefore, to check the data further, the possible written hours of the men and available working hours were compared which each other. The norm for the amount of men for each shift and team is showed in Table 4-1.

Table 4-1: Manpower according to norm

Norm Manpower	Shift 1 (7:00-16:00)	Shift 2 (15:30-24:00)	Shift 3 (23:30-07:00)	Shift 4 (07:00-end)
Above the wing	8	6	0	0
Under the wing	23	22	6	5

The available working hours is calculated by taking the available presence hours minus all the time for breaks etc. This leaves 372 hours and 45 minutes available work hours from the Under the Wing team. In reality they had (written) spent 328 hours and 51 minutes. This means an efficiency of 88%. Thus, looking at possible workhours and amount of men all the work could have performed according the manpower norm. Therefore, the written TAT for each check is kept and used for the model.

The same steps are followed for the Above the Wing team. The current manpower according to the data versus the norm is depicted in Figure 4-3. Also in this figure there are peaks visible that are above the norm. When calculating the available work hours possible, a result of 102 hours is possible. But the written spent hours by the men is 151 hours and 57 minutes. This is a lot more than possibly could, which results in efficiency of 149% of the mechanics/GWK's. Further investigation explained how this could have happened. For 'Above the Wing'-work there is no time reserved for solving 'correctives/findings' (Prins, 2017). The amount of work for those findings/correctives was 52 hours. Thus the mechanics/GWK had written in total about 100 hours for their planned work which is pretty much the same as the norm. From observations this is also explainable; the mechanics/GWK often does not change the norm time to actual spent times, which Mxi will take by default if the actual spent is not filed.

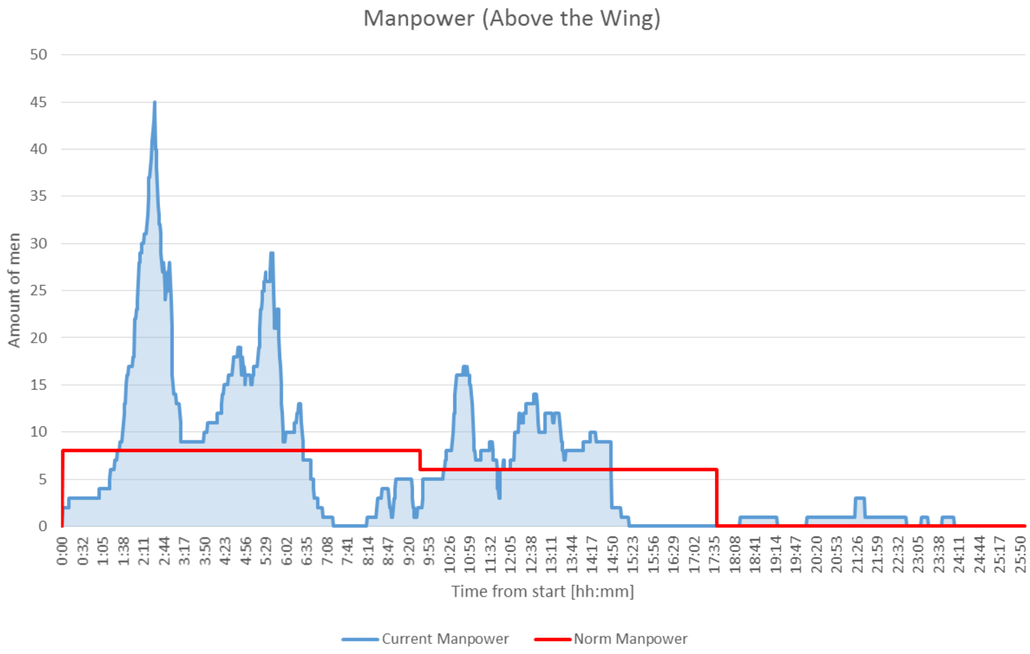


Figure 4-3: Current manpower according to data versus norm of manpower (Above the Wing)

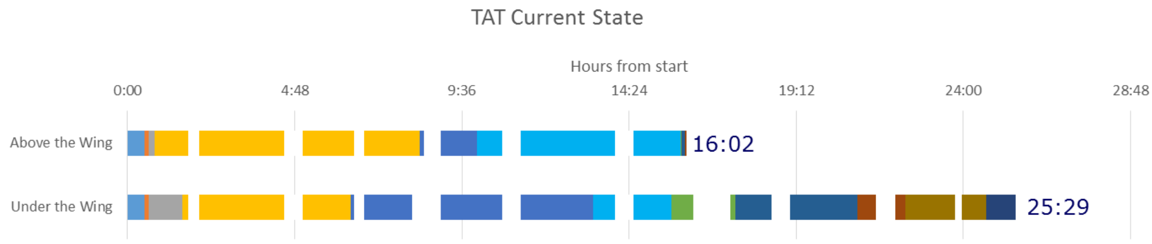
Correction factor

In order to have a model that represents the reality as much as possible. The data for the Above the Wing team is adapted by a correction factor. With this correction factor the data is adapted to the norm of possible working hours by the men. The possible working hours was 102 hours, therefore each data entry was divided by 1.49 (the efficiency). The 'over efficiency' is then divided over all the tasks for the Above the Wing team.

Now with the data and theoretical preliminary model an analysis can be done for identifying constraints within the A-check. This will be explained in the next section.

4.3 Analysis of airframe MRO – A-check

For analysis of the current A-check and subsequently identifying the constraint in this process, the theoretical preliminary model is used as discussed in section 3.8. The check is divided in different phases which follow in sequence. A distinction is made for the 2 teams: Above the Wing (Cabin) and Under the Wing (lengthwise & crosswise). With the data implemented into the model a Gantt chart could be made of the current state of the A-check (Figure 4-4).



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:56	0:09
Inspect	4:50	7:37
Work	6:56	1:38
Corrective	2:15	5:49
Test	1:50	0:02
Final Work	3:29	0:05
Preparation Final test	1:22	0:02
Final Test	2:19	
A/C Release	0:50	

Figure 4-4: Current State Gantt chart of A-check

First of all, it can be seen that the model is a fairly good representation of the current state as the check had a duration of 25.5 hours in reality and the model shows 25 hours and 29 minutes. The work for Above the Wing was finished after 16 hours, which is explainable, because the data was adjusted to the norm and the team only works for 2 shifts. The Gantt chart also shows the time when work is not performed due to breaks and times the mechanics did not worked (according to the data). The time they did not worked are just before or after breaks/shift changes and this is also observed in real life.

Constraint

From this current state it can be seen that Under the Wing is constraining the turnaround time of the check. For finding out why 'Under the Wing is constraining the performance of the A-check, the root cause need to be identified. By identifying the root cause(s), improvement plans can be made in order to improve the output performance.

4.4 Root cause analysis

In this section a root cause analysis will be performed in order to identify the root cause(s) for constraining the output performance of the A-check. The constraint was identified as 'Under the Wing' section. The root cause analysis will be done on basis of the 4M method as those are known as drivers which can constrain a process.

Machine

As mentioned in section 3.4.3 the 'Machine' is divided into 'Machine: equipment' and 'Machine: aircraft'. Both are not the root cause for constraining Under the Wing performance.

In fact, the aircraft was delivered on time to the hangar, so all the tasks could start according to plan. For 'Machine: equipment', all tools/equipment was available for performing airframe MRO.

Material

To check if Material could have been the root cause of constraining the process is hard to identify. The data cannot show if material was not available at the moment it was needed. The only thing that can be determined is that for all the tasks that were completed, the availability of material was in the end not the issue. However, it could be that there is still WIP due to unavailable material. Although, data shows that 5 of 6 tasks that were deferred, were planned tasks. Therefore it can be assumed that for those tasks the material was in order before the check started. Thus, material was not the issue for constraining Under the Wing and keeping WIP.

Method

To identify if the method of performing the tasks was constraining the performance cannot be determined from the data. It is possible that tasks could be done quicker, but for this research it is assumed that the way they perform the tasks is how they should do it, therefore this is not the root cause of the constraint. The Method of performing airframe MRO on check-level could be a root cause, currently they do not work according the phases sequence that is used for the model. The model therefore also shows the potential of performing airframe MRO by phase implementation.

Man

The current manpower can be checked with the needed men per phase for this model. Currently the first shift of the check starts at 07:00 (LTC) and all the men of the first shift are present. However, the aircraft usually arrives not at this time but later. From observations it became clear that the men are performing nothing and are just waiting for the aircraft to arrive.

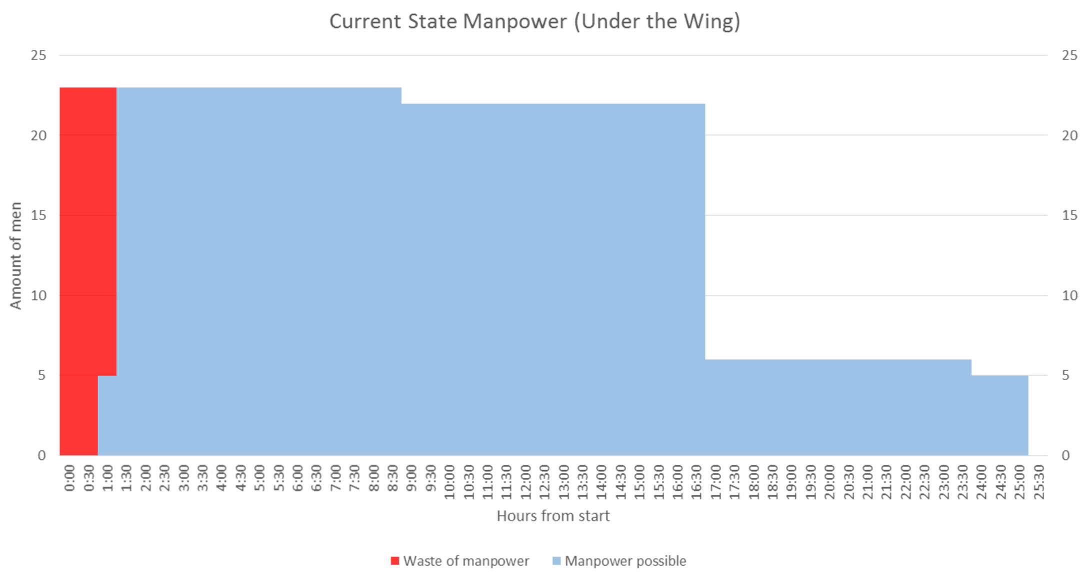


Figure 4-5: Current state manpower efficiency

Figure 4-5 shows the present amount of men and also shows the waste of men (in red) because there is no work for them to do. The first hour all the men wait for the aircraft to arrive and secondly the first half hour when the aircraft has arrived, not all men are needed for the 'hangar preparation'-phase which consists of assisting the aircraft into the hangar and ground the aircraft. Thus a lot of available man hours is not used, because the shift is not aligned with the needed work. Therefore, the planning of the manpower is a root cause for constraining the output performance.

4.5 Conclusions of constraint identification

This chapter aimed to answer the following sub question:

"What constraints are limiting the turnaround time and quality output of the Airframe MRO process at KLM E&M Airframe Services?"

Firstly, to identify the constraint, the different used methodologies were outlined. Secondly the data was checked and adapted if necessary for implementation of the model. It was found that the data for Above the Wing needed a correction.

The model showed a good approximation of the current check and it clearly showed that 'Under the Wing' was constraining the output performance. A root cause analysis was performed based on the 4M method. The main root cause for constraining the output performance was mainly the misaligned of man and work. It was analysed and from observations clearly identified that the first one and a half hour the available manpower could not be utilized. Also there is a possibility that the current method of performing MRO could be constraining the output. Therefore the model also shows the potential of performing airframe MRO in phase sequence.

Design Phase

5 Design of solution alternatives

After the identification of the constraint and root causes different solutions alternatives should be made, by focussing on the root cause. Therefore, this chapter aims to answer the following sub question:

> "What solutions alternatives can improve the turnaround time and quality output of the Airframe MRO process?"

First the used methods are discussed for creating the solution alternatives in section 5.1 where it will become clear which steps were taken. After this the different designed solutions alternatives will be outlined in section 5.2 and finally this all will be concluded and summarized in section 5.3.

5.1 Methods used for creating solutions

Different solutions can be created for improving the output performance of airframe MRO. Previous chapter showed the constraints and therefore the solutions will focus on improving the performance of the constraint. The solutions are thus created by using the 'Theory of Constraints'-methodology (TOC) and the use of Lean tools. An example of such tool is Just-In-Time, in this case the solutions are created by focussing on letting the right people work at the right time.

Exploiting the constraint

From the 'TOC'-methodology follows several steps to take for improving a process. First the system constraint must be identified, then this constraint must be exploited. Therefore the first solution is exploiting the constraint, which in this case is the manpower of the 'Under the Wing'- team.

Elevating the constraint

After exploiting the constraint, the next step is to elevate the constraint. For this case it means have the capacity of extra manpower. Therefore, this solution is performing the check with extra manpower.

Ideal world

From the lean methodology, the theoretical optimal performance should be determined. However, in order to determine this optimal performance it is needed to know all waste in the process and maximum output. This is unfortunately not possible with the current data and therefore it is chosen not to model the ideal world but the 'desired world' for hangar 11.

5.2 Solutions for the check

In this section the designed solutions alternatives are discussed. The previous section (5.1) briefly described the methods used for creating the solutions and therefore the first solution will be outlined (exploiting the constraint)

5.2.1 Exploiting the manpower constraint

As described in section 4.4, the root cause for constraining the output performance of the check was the manpower. There are several ways for exploiting the current manpower and this section will be dedicated to outline the different solution alternatives for exploiting the current manpower.

Exploit 1: Norm

The first solution is to exploit the manpower, so let them work the time they are available. Therefore, let them work according to the norm times and not always send them home early (from observations and interviews).

Exploit 2: Later start of shifts

The second solution for exploiting the manpower is to eliminate the first hour of waste of available manpower during this time. Therefore, not changing anything to the norm, but just let everybody start at a later time.

Exploit 3: Core shift

The third solution alternative for exploiting the manpower is to implement a so called core shift within a 24 hours availability for the check. From the previous solution there is still waste of manpower in the beginning of the check and eventually also at the end. Therefore, to utilize those men, a core shift solution alternative is designed. This means to assign the men to the work when they are most needed. Therefore, a small group starts the check and when this is done the core shift starts.

5.2.2 Elevate the manpower constraint

As mentioned, to elevate the current manpower, more men are needed. When looking at the available resources in hangar 11, there are possible multiple checks performed at the same time. There is in hangar 11 a dedicated team for the AOG-check, but not all the time there is an AOG-check, so this solution alternative is badding the men of the AOG-check to the A-check, which consist of 4 extra man for 'Under the Wing'. In 2016 this was possible for a minimal of 60% of the total performed A-checks.

5.2.3 Desired world

The last solution alternative is more a scenario to check what is needed for the desired world. The desired world is in this case performing the A-check within 2 shifts. This means that the check must be performed within 16.5 hours, because the average service length of the men must be 8 hours according the collective agreement (Slobbe, 2017). Each shift has one half hour paid permission and therefore the men are present for 8.5 hours. Also the shifts have one half hour overlap which in total results in 16.5 hours for the two shifts together.

5.3 Conclusions and overview of solutions alternatives

This chapter was dedicated for answering the following sub question:

"What solutions alternatives can improve the turnaround time and quality output of the Airframe MRO process?"

First the method used for designing the solution alternatives was discussed which resulted in first exploiting the manpower in several ways:

Exploit:

- Norm: utilize the available manpower according to the norm; do not allow early end of shift
- Later start of shifts: Let the current men start later, therefore eliminating the first hour of manpower waste
- Core shift: Better utilize the available man, by starting the check with a small amount of men and then let the core shift(s) start.

The next steps is to design a solution alternative by elevating the constraint:

Elevate

- Extra men: Adding of extra men from other checks when there is no check to perform for this extra men.

Lastly, the 'desired world' solution alternative was discussed:

Desired World

- A-check within 2 shifts: For hangar 11 it is desired to perform the A-check within 2 shifts. This scenario is dedicated to identify what is needed in terms of recourses to perform the check within the 2 shifts.

Control Phase

6 Modelling and results of the solution alternatives

This chapter is dedicated to answer the following sub question:

"What is the impact of these improvements on the aircraft availability (for uptime) and assets/resources at KLM E&M Airframe Services?"

The designed solution alternatives (chapter 5) are tested and their impact on the assets and resources will be shown in this chapter. First the methods used are briefly discussed in section 6.1, then the modelling of the current state and the solution alternatives will be explained in section 6.2, and also the results of the model is described in this section. Finally, the chapter is concluded by presenting an overview of all the results in section 6.3.

6.1 Methods used for modelling

The theoretical preliminary model is already discussed in section 3.8. It shows the model follows a phase sequence for 'Above the Wing'- and 'Under the Wing'-teams. To represent the output of the airframe MRO process, a Gantt chart is used. A Gantt chart is a graphic representation to show activities in a process to a time scale (section 2.3.1). It is a static, deterministic model to show the turnaround time for each phase during the check and subsequently show the turnaround time of the overall check.

6.2 Modelling of the current state and solution alternatives

The current and corrected data need to be implemented into the theoretical preliminary model. In this section the specifications of the model will be discussed by explaining what equations were used. The used dataset is described in Appendix C. From there on the results of the current state and other designed alternatives will be discussed. For all solution alternatives, the manpower is presented in Appendix E. Furthermore, all graphical result representations of the modelled solution alternatives can be found in Appendix F.

6.2.1 Model specification and assumptions

To model the current state of the performed A-check, the turnaround time for each phase for each team (if applicable) is determined by the following equation:

$$TAT_{phase} = \frac{\sum spent\_hours_{phase}}{Available\ men} + TAT_{break} \qquad (7.1)$$

Where,

TAT_{phase} is the turnaround time for each phase, $\sum spent\_hours_{phase}$ is the sum of the spent hours, TAT_{break} is the time spent for a break or shift change during the phase. The available men are the amount of men that are able to work during this phase.

It depends how many men there are available at the time of the different phases. So if a phase starts for example at 08:00 and at 09:00 a shift change occurred, the time for the shift change is added to the TAT of the phase (equation 7.1, TAT_{break}) and if the amount of men changes in the meantime, this is also taken into account for calculating the TAT_{phase}.

Now for each phase and for the different teams (above- and under the wing) the turnaround times are calculated. The total turnaround time of the check is determined by the following equation:

$$\boldsymbol{TAT_{check}} = \boldsymbol{TAT_{hangar\ preparation}} + \max\left(\boldsymbol{TAT_{Above\ the\ Wing}}, \boldsymbol{TAT_{Under\ the\ Wing}}\right) + \boldsymbol{TAT_{final\ test}} + \boldsymbol{TAT_{aircraft\ release}} \quad \textbf{(7.2)}$$

Where,

$TAT_{Above\ the\ Wing}$ and $TAT_{Under\ the\ Wing}$ are the sum of all turnaround times of each phase for the different teams. An assumption is made that all the men during a phase can contribute to the needed work. However, there is an exception for the following phases: hangar preparation, final test and aircraft release, as there is a maximum amount of men that can perform tasks during those phases; this is set at 5 men.

6.2.2 Current state model results

Applying equation 7.1 and 7.2 and implement the results into the preliminary model, the current state model was developed. This can be seen in Figure 6-1, were each phase is indicated by a different colour and the distinction of the two teams is shown. The gaps within and between the phases indicate the time when there is not work performed. This could have different reasons such as the coffee breaks, lunch, diner, shift changes but also the time when there was not work performed due to a different reason. The model, as mentioned earlier in section 4.3, shows a fairly good representation of the overall check.

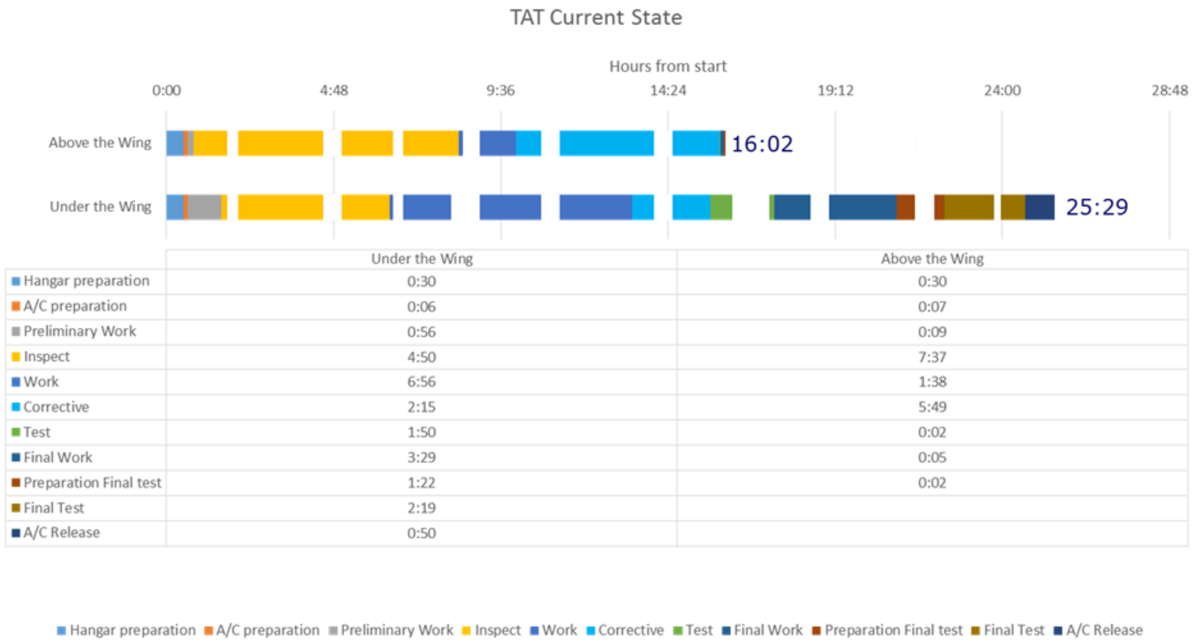


Figure 6-1: Current state model A-check

Impact on assets and resources current state

With the current state model a turnaround time was achieved of 25 hours and 29 minutes. However not all work was performed, the WIP was for the current state 4 hours and 17 minutes of work. Also not the total amount of manpower was used for the current state, a waste of 60 available man-hours and 9 minutes was the result of the current state. This all is summarized in Table 6-1

Table 6-1: Current state impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Current state	25:29	4:17	60:09

6.2.3 Modelling of solution alternatives

The different solution alternatives are applied to the model for 2 different cases. The first is applying the solutions with the same amount of work as for the current state. However, there was still WIP after the current state and therefore the second case is applying the solutions alternatives for all the work, thus including the WIP. This is done to see what the impact is on the TAT and resources for delivering a ‘clean’ aircraft, in other words deliver an aircraft without WIP.

6.2.4 Results of solution alternatives

The results of all the different solution alternatives are described here. As mentioned each solution alternative is applied for 2 cases, first with the current work package and secondly a work package resulting in no WIP after the check.

Exploit: Norm

With this solution alternative the available manpower is utilized according to the norm. The men are working for the time they are planned. The results for this solution alternative is summarized in Table 6-2.

Table 6-2: Exploit: Norm impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Exploit: Norm	23:05	4:17	46:12
Exploit: Norm (clean)	23:54	0:00	45:23

Exploit: Later start of shifts

The results of exploiting the manpower according to the norm shows still a large amount of waste of resources (man-hours). For this solution alternative, the shifts start at a later time in order to eliminate most of this waste at the beginning of the check. The results are shown in Table 6-3

Table 6-3: Exploit: Later start of shifts impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Exploit: Later start of shifts	21:15	4:17	23:04
Exploit: Later start of shifts (clean)	22:20	0:00	22:55

Exploit: Core shift

The last solution alternative which focus on exploiting the current available manpower of Under the Wing team, achieves even a better utilization of the current manpower. By starting the shift later, still waste of resources occur for the phase (Hangar preparation). Therefore, those resources are assigned to a core shift. This results in even better turnaround time and less waste of resources (Table 6-4).

Table 6-4: Exploit: Core shift impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Exploit: Core shift	20:25	4:17	28:46
Exploit: Core shift (clean)	20:35	0:00	25:38

Elevate: Extra men

For elevating the constraint, it was determined that extra men could be used from other checks when there is no check to perform for those extra men. For 2016 a minimum of 60% of the times, the AOG team could be used for the A-check. Which results in 4 extra men for the 'Under the Wing'-team. When modelling with the extra men. The performance became limited due to 'Above the Wing'-work. Therefore, this team needed elevation as well (2 man extra in the second shift), because exploiting 'Above the Wing' was not enough. The end results of elevating the constraint is showed in Table 6-5.

Table 6-5: Elevate: Extra men impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Elevate: Extra men	18:04	4:17	86:01
Elevate: Extra men (clean)	18:10	0:00	83:45

Desired world: 2 shifts

By elevating the constraint as previously described, it showed it is not enough for completing the check in 2 shifts. This 'Desired world' solution aims to complete the check within 2 shifts (16:30). In order to accomplish this, a team size of 31 man (both shifts) was needed for Under the Wing. In order to deliver a 'clean' aircraft, the second shift needed one man more, thus 32 men instead of 31.

The needed team size for Above the Wing is 9 man in the first shift and 10 for the second shift. By increasing the team sizes it also can be seen in Table 6-6 that a lot of waste of resources is formed. This is because for 2 shifts all the man are present, but a lot of the time not all men are needed. Mostly at the end of the check during the 'final test'- and 'aircraft release'-phase.

Table 6-6: Desired world: 2 shifts impact

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Desired world: 2 shifts	16:28	4:17	116:20
Desired world: 2 shifts	16:28	0:00	120:08

(clean)

6.3 Conclusions and overview of results

This chapter was dedicated to answer the following sub question:

> "What is the impact of these improvements on the aircraft availability (for uptime) and assets/resources at KLM E&M Airframe Services?"

The aircraft availability increases with a shorter turnaround time of the check and reducing the WIP. Table 6-7 shows all the results of the model by first modelling the current state and subsequently modelling the designed solution alternatives.

Table 6-7: Overview of all results from the model

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Current state	25:29	4:17	60:09
Exploit: Norm	23:05	4:17	46:12
Exploit: Norm (clean)	23:54	0:00	45:23
Exploit: Later start of shifts	21:15	4:17	23:04
Exploit: Later start of shifts (clean)	22:20	0:00	22:55
Exploit: Core shift	20:25	4:17	28:46
Exploit: Core shift (clean)	20:35	0:00	25:38
Elevate: Extra men	18:04	4:17	86:01
Elevate: Extra men (clean)	18:10	0:00	83:45
Desired world: 2 shifts	16:28	4:17	116:20
Desired world: 2 shifts (clean)	16:28	0:00	120:08

7 Solution evaluation

This chapter is dedicated to answer the following sub question:

"What is the best solution alternative from the designed alternatives to be implemented for KLM E&M Airframe Services?"

First the methods that are used for the solution evaluation are described in section 7.1. Secondly the evaluation of the solutions is done in section 7.2. The chosen solution from the evaluations is discussed in section 7.3 and in section 7.4 the desired control will be evaluated. The chapter is concluded by answering the above sub question in section 7.5.

7.1 Methods used for solution evaluation

For this research a Multi Criteria Analysis (MCA) (Valiris, Chytas, & Glykas, 2005) is used to evaluate the solution results described in the previous chapter. Therefore, weights are needed for the different criteria after which the alternatives will be assessed on by using the Analytical Hierarchy Process.

7.2 Evaluation of solutions

7.2.1 Criteria

The criteria that are used for evaluate the different solution alternatives are already defined in section 2.4.5. The defined criteria are as follow:

- Turnaround Time
- Process Cost – expressed in man-hours
- Product Quality – expressed in airworthiness
- Process Quality – expressed in WIP

7.2.2 Determine weights of the criteria

To determine the importance between the different criteria, an Analytic Hierarchy Process (AHP) is followed (Saaty, 2003). A pairwise comparison between the different criteria is performed with different stakeholders. Between each criteria a choice is made which is more important. Then the comparison is scored on a 1-9 scale, 1 for equal importance and 9 for extremely more important. The columns of the matrix with all the criteria-scores are then normalized and subsequently the average normalized score is computed per row. The weight factors are now computed, but can only be accepted if the matrix has a consistency ratio lower than 0.1 (Russo & Camanho, 2015).

As mentioned in section 2.4.3, the product quality is expressed in airworthiness. The result of the check is always an airworthy aircraft, otherwise the check is not completed. If for this criteria also a weight is giving, it would be for all the different solution alternatives be the same. Therefore, there is chosen to not determine a weight for this criteria as it will not be used for the multi-criteria analysis further on, because it is constant for all the solutions.

From the AHP the weights of the other criteria are determined. The matrices used to score the criteria and determine the weights can be found in Appendix G. The results of the AHP are formed from the perspective of KLM E&M (hangar 11) and can be seen in Table 7-1. Different perspectives will be used for the sensitivity analysis.

Table 7-1: Criteria Weights Process Owner

Criterion	Weight Factor
Turnaround Time (TAT)	0.64
Process Quality (WIP)	0.23
Process Cost (man-hours)	0.12

7.2.3 Multi-Criteria analysis and results

Before performing the multi-criteria analysis (MCA) the quantitative results found for each solution alternative (section 6.2.4) is normalized to values between 0 and 1 (Valiris et al., 2005). This is done in order to enable a fair comparison between the different results. The worst result for each criteria has a value of 0 and the best results a 1. The normalized results are shown in Table 7-2.

Table 7-2: Normalized results of solutions alternatives

Solution	TAT	WIP	Resources
Current state	0,00	0,00	0,62
Exploit: Norm	0,27	0,00	0,76
Exploit: Norm (clean)	0,18	1,00	0,77
Exploit: Later shifts	0,47	0,00	1,00
Exploit: Later shifts (clean)	0,35	1,00	1,00
Exploit: Core shift	0,56	0,00	0,94
Exploit: Core shift (clean)	0,54	1,00	0,97
Elevate: Extra men	0,82	0,00	0,35
Elevate: Extra men (clean)	0,81	1,00	0,37
Desired world: 2 shifts	1,00	0,00	0,04
Desired world: 2 shifts (clean)	1,00	1,00	0,00

Now the different solutions can be ranked by multiplying each normalized results (Table 7-2) with their weight factor (Table 7-1) and then adding those values up to determine the total score for each solution. The results of the MCA and ranking of the solutions is shown in Table 7-3.

Table 7-3: MCA results of solutions (KLM E&M perspective)

Solution	Total score	Rank
Desired world: 2 shifts (clean)	0,88	1
Elevate: Extra men (clean)	0,80	2
Exploit: Core shift (clean)	0,70	3
Desired world: 2 shifts	0,65	4
Exploit: Later shifts (clean)	0,58	5
Elevate: Extra men	0,57	6
Exploit: Core shift	0,48	7
Exploit: Norm (clean)	0,44	8
Exploit: Later shifts	0,42	9
Exploit: Norm	0,26	10
Current state	0,08	11

The table shows a most favourable solution, which is in this case ‘Desired world: 2 shifts (clean)’. This is as expected the most favourable, because the analysis is currently performed from the perspective of KLM E&M (hangar 11). The desired world solution also was designed from this perspective, so it is logical this resulted in the most favourable solution.

A sensitivity analysis is needed, because this ranking is a result from a subjective weight-set determined by KLM E&M. The next section shows the results for the analysis from different perspective and therefore testing the sensitivity of the MCA.

7.2.4 Multi-Criteria analysis sensitivity test

For the sensitivity testing of the performed MCA, different set of weights are used. First the weights are determined from a client perspective and secondly, all the weights are set equally.

A client highly values a short TAT of a check with all the work done and does not matter how many and/or how efficient the resources are used. The criteria weight determination from a client perspective can be found in Appendix G. The results of the MCA from a client’s perspective is depicted in Table 7-4.

Table 7-4: MCA results of solutions (Client's perspective)

Solution	Total score	Rank
Desired world: 2 shifts (clean)	0,93	1

Elevate: Extra men (clean)	0,81	2
Desired world: 2 shifts	0,75	3
Exploit: Core shift (clean)	0,65	4
Elevate: Extra men	0,64	5
Exploit: Later shifts (clean)	0,51	6
Exploit: Core shift	0,49	7
Exploit: Later shifts	0,42	8
Exploit: Norm (clean)	0,36	9
Exploit: Norm	0,25	10
Current state	0,04	11

As expected, the 'desired world: 2 shifts (clean)' is the most favourable as this solution results in the shortest turnaround time (higher uptime availability) and delivers a 'clean' aircraft. It is remarkable that for the client and process owner the same solution is favourable. This can be explained by the high importance of the turnaround time in both perspectives. Therefore it is checked what the results are when all weights are equal.

The ranking of the solutions when all criteria have an equal weight is shown in Table 7-5. Now the most favourable solution becomes 'Exploit: Core shift (clean)'

Table 7-5: MCA results of solutions (Equal weights)

Solution	Total score	Rank
Exploit: Core shift (clean)	0,84	1
Exploit: Later shifts (clean)	0,78	2
Elevate: Extra men (clean)	0,73	3
Desired world: 2 shifts (clean)	0,67	4
Exploit: Norm (clean)	0,65	5
Exploit: Core shift	0,50	6
Exploit: Later shifts	0,49	7
Elevate: Extra men	0,39	8
Desired world: 2 shifts	0,35	9
Exploit: Norm	0,34	10
Current state	0,21	11

The overall highest scoring solution alternative on the three sets of criteria weights are calculated. The top 3 is shown in Table 7-6 and the total overall ranking can be found in Appendix G.

Table 7-6: Overall ranking of solution alternatives (3 sets of criteria weights)

Solution	Total score	Rank
Desired world: 2 shifts (clean)	2,47	1
Elevate: Extra men (clean)	2,34	2
Exploit: Core shift (clean)	2,20	3

7.3 Chosen solution

From the multi criteria analysis and the sensitivity tests it became clear that overall the Desired world (clean) scored the best, followed by Elevate: extra men (clean) and Exploit: Core shift (clean). It is noticeable that for all solutions a clean aircraft policy is followed. A description of the solution alternatives will be repeated from section 5.2.

Exploit: Core shift

This alternative focus on exploiting the manpower (constraint) by implementing a so called core shift within a 24 hours availability for the check. Currently the teams are present at 07:00 (LTC) but the aircraft arrives about an hour later and even then not all the men are needed at the beginning of the check (Hangar preparation phase). Therefore, for this solutions a small team is present when the aircraft arrives and after this the core-shift is presents and also starts with the check.

The core-shift is divided into 2 shifts and when this is finished a small team is still present to perform the last tasks. By implementing the core shift the desired workload is much better in tune with the available resources at that time as most of the workload occurs during the inspection- and work phase.

Implementing the core shift results in a turnaround time of 20 hours and 35 minutes with a clean aircraft policy. This is a reduction of 4 hours and 54 minutes compared to the current state, just by getting the resources much better in tune with the demanded workload of the check.

Elevate: Extra men

As mentioned, to elevate the current manpower, more men are needed. When looking at the available resources in hangar 11, there are possibly multiple checks performed at the same time. There is in hangar 11 a dedicated team for the AOG-check, but not all the time there is an AOG-check, so this solution alternative is adding the men of the AOG-check to the A-check, which consist of 4 extra man for 'Under the Wing'. In 2016 this was possible for a minimal of 60% of the total performed A-checks. Compared to the Core shift alternative, the thing differently is just extra men. The main principle and basis for this solution is therefore also a core shift, but this time with more available resources.

By implementing extra men from other checks, such as the AOG-check, the resulting turnaround time will be 18 hours and 10 minutes with also a clean aircraft policy. A decrease of 7 hours and 19 minutes is achieved, but it is not always possible to use other resources from the hangar.

Desired world: 2 shifts

This solution alternative is more a scenario to check what is needed for the desired world. The desired world is in this case performing the A-check within 2 shifts. This means that the check must be performed within 16.5 hours, because the average service length of the men must be 8 hours according the collective agreement (Slobbe, 2017). Each shift has one half hour paid permission and therefore the men are present for 8.5 hours. Also the shifts have one half hour overlap which in total results in 16.5 hours for the two shifts together. Also for this solution the resources are more in tune with the workload demand of the check.

This solution results in a turnaround time of the desired 16.5 hours, but extra men are needed. This could come from other checks such as for the previous described solution or an investment is needed in resources.

Concluding chosen solution

Concluding the overall best solutions, it became clear that KLM E&M can choose between different solutions. The first thing noticeable is that a solution with a clean aircraft policy overall scores the best, therefore a clean aircraft policy should be followed. The most favourable and highest scoring solution alternative is the 'Desired world' alternative. Therefore, this solution should be chosen, but it is advisable to start with implementing a core shift. The core shift alternative is the basis for the other (overall better) solutions and it is logical that those solutions scored better, because more resources are available during a core shift. Thus the main conclusion is that the resources should be better in tune with the demanded workload first.

7.4 Control

The provided solution alternatives are a good first step to increase the airframe MRO output. Next to the solutions, there is also a change needed in the current control of the airframe MRO chain. As earlier mentioned in section 3.4.3 there is currently a clear lack of handshakes, which are essential for managing and controlling the entire airframe MRO chain. They all should be focussing on the main goal, namely increasing uptime availability, and not only on local optimums.

During this research, only one analysis of a check could be done. Therefore, the designed solutions should also be tested for more checks. The main principles of the developed model (work in phases and rearrange the resources) should be used and stakeholders confirmed that those principles are also currently desired.

This concludes the case study at KLM E&M Airframe Services; the next and final chapter consist the total conclusions for this research and discusses further recommendations.

7.5 Conclusions

This chapter was dedicated to answer the following sub question:

> "What is the best solution alternative from the designed alternatives to be implemented for KLM E&M Airframe Services?"

By using a multi criteria analysis after the weights of the criteria was determined, it can be concluded that the most best solution is the 'Desired world' alternative with achieving a clean aircraft policy. However, other solution alternative also have a high overall score and they all follow the same principle. Namely, get the resources in tune with the demanded workload by implementing a core shift. Therefore, KLM E&M should begin with implementing a core shift and if possible increase resources from other checks or investment in resources.

Furthermore, to achieve a better control of the overall Airframe MRO chain, the lack of handshakes must be dealt with. All 'eyes' should be focussing on the main goal, uptime availability, and not on local optimums.

8 Conclusions and recommendations

This chapter will first answer the main research question followed by the answers to the research sub questions in section 8.1. The recommendations and research limitations will respectively be described in section 8.2 and 8.3.

8.1 Research questions - answers

The main research question:

> "How can the output of airframe Maintenance, Repair and Overhaul processes be improved from an uptime perspective?"

Can be answered by following a good structured framework. By first defining the case and measuring, it ensured a good analysis for identifying the main constraint in the process. Different solution alternatives can then be created that focusses on the constraints. The constraints can then be exploited or elevated in order to improve the output of the process. It was found from literature and tested in this research that airframe MRO can be improved by implementing Phase-Gate methodology and concentrating resources within the phases.

This answer was formed by answering the research sub questions and will now be briefly outlined.

What framework and methodologies can be used from literature to find and evaluate solutions for improving the output of Airframe MRO?

An approach for this research has been used following 5 main steps, first defining the research problem and defining evaluation criteria's for the case study, secondly the current state is measured which resulted in a development of a theoretical preliminary model. Thirdly, this model is checked and used to analyse the system constraints. Next [4], solution alternatives were designed and lastly [5] the designed solution alternatives are tested and the results are evaluated to find the best solution.

What criteria can be used to assess the different solution alternatives for KLM E&M Airframe Services?

Different criteria's were found from literature and practice in order to evaluate several solution alternatives. For the case study at KLM E&M Airframe Services, four different criteria were determined, namely: Turnaround time, Process cost, Product quality and Process quality.

What is the current state of the Airframe MRO process at KLM E&M Airframe Services?

The current state of the Airframe MRO is measured on different levels and performances. First the Process quality is measured for the deferred defects (WIP) for the overall KLM E&M Airframe MRO chain. The deferred defects had a total average of 599/day which resulted in exceeding the target level. The research then focused on the checks for wide body aircraft in hangar 11 and the average turnaround time for those checks are:

	A-check	H-check	M-check	AOG-check	TD-check
Average TAT (hours)	42.67	33.56	12.06	33.74	16.33

A more in-depth focus for this research has been done for the A-check. It was measured that the on time performance of the check is not 42% (measured by KLM E&M), but 15%.

What constraints are limiting the turnaround time and quality output of the Airframe MRO process at KLM E&M Airframe Services?

For the overall Airframe MRO chain it was found that current control lacked consistent handshakes/agreements. As this research then focused on the A-check and specifically of a Boeing 777-300. It was found that 'Under the Wing' (lengthwise- and crosswise-section) activities was constraining the output of the airframe MRO process. The main constraint was formed by misaligning resources with the demanded workload of the check.

What solutions alternatives can improve the turnaround time and quality output of the Airframe MRO process?

Different solution alternatives were designed based on first exploiting the constraint, then elevating the constraint and finally the creation of the desired world solution. Resulting in five solution alternatives: exploit (norm), exploit (later shift), exploit (core shift), elevate (extra men) and desired world (2 shifts).

What is the impact of these improvements on the aircraft availability (for uptime) and assets/resources at KLM E&M Airframe Services?

The designed solution alternatives are then implemented in the theoretical preliminary model and the results are shown below. Each solution alternative was also tested for a clean aircraft policy.

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Current state	25:29	4:17	60:09
Exploit: Norm	23:05	4:17	46:12

Exploit: Norm (clean)	23:54	0:00	45:23
Exploit: Later start of shifts	21:15	4:17	23:04
Exploit: Later start of shifts (clean)	22:20	0:00	22:55
Exploit: Core shift	20:25	4:17	28:46
Exploit: Core shift (clean)	20:35	0:00	25:38
Elevate: Extra men	18:04	4:17	86:01
Elevate: Extra men (clean)	18:10	0:00	83:45
Desired world: 2 shifts	16:28	4:17	116:20
Desired world: 2 shifts (clean)	16:28	0:00	120:08

What is the best solution alternative from the designed alternatives to be implemented for KLM E&M Airframe Services?

The best solution alternative is found by using a Multi Criteria Analysis combined with the Analytical Hierarchy Process. The previously determined criteria are used for this analysis and after the analysis and sensitivity test the best solution could be determined.

The most favourable and overall best solution from the analysis is the 'Desired world' alternative with following a clean aircraft policy (no WIP after the check). However, other solution alternative also have a high overall score and they all follow the same principle. Namely, get the resources in tune with the demanded workload by implementing a core shift. Therefore, KLM E&M should begin with implementing a core shift and if possible increase resources from other checks or investment in resources.

8.2 Recommendations and further research

First it is recommended to implement phases within a check where all resources are working on the same goal, namely finish all the tasks of the phase before working on tasks of another phase (so called Phase-Gate).

Then it is recommended for KLM E&M Airframe Services to plan the available resources (man) in tune with the workload by implementing a core shift and follow a clean aircraft policy. It is advised to start the check with a small group of men and then the core shift should be present when the aircraft is inside the hangar and grounded. Also, it is essential that clear handshakes/agreements are in place between all process steps within the overall airframe MRO chain.

Furthermore, it is advised for KLM E&M Airframe Services that further improvements are made for the current way of writing and signing off tasks during a check. Currently there is no control how this happens and therefore resulting in unreliable data or not complete data. It is advisable that the data really shows when and for how long the mechanics/GWK's worked on each task. This only can improve future analyses and gives the opportunity for continuous improvements. Another data improvement is to determine which task belongs to the different phases, as now they already have a 'phase-code', but the current 'phase-codes' are too broad.

This analysis should be done on multiple A-checks in order to have a better analysis and a more robust conclusion of the analysis. A good way is by simulating the checks in order to test the impact of implementing Phase-Gate within the checks. Also, a recommendation is performing an analysis for determining which tasks are critical within a phase, so the resources are well appointed to those tasks.

Another recommendation is that the mechanics/GWK's can see the progress of the check and easily know where the focus of resources should be so they could help one another.

From a scientific aspect, it is advised to use the theoretical model at different airframe MRO processes to test if it can improve the output performance. The theoretical model could easily be adapted to any airframe MRO process as the phases could be changed.

8.3 Research limitations

The main limitation of this research is the useable data. There is a lot of data available but the data do not provide instantly the needed things. A lot of manual checks had to be done in order to perform an analysis. This resulted in the next limitation, namely the focus of the research is only based on a single A-check. This limits the robustness of the made conclusions and recommendations.

This research is limited by the focus on only the main constraint, but other smaller constraint were neglected. All the solution alternatives are focussed on this main constraint but it is possible that other solutions could be better than some of the designed solutions. Also the modelling of the different solution are limited by made assumptions as earlier described in the specifications of the model.

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Appendices

A. Research Paper

-Research paper can be found on the next page-

Redesign of airframe MRO processes at KLM E&M from an uptime perspective

J.D. Hockers, dr. W.W.A. Beelaerts van Blokland, dr. ir. D.L. Schott

1

Abstract—**This paper addresses a problem at KLM E&M, where a gap exist between the desired performance and current performance of airframe MRO. This research is performed to find solutions within the A-check for wide body aircraft by identifying the constraint in the A-check and subsequently develop solution alternatives by first exploiting the constraint, then elevating and finally develop a 'desired world' alternative. For the A-check a theoretical preliminary model was developed which tests Phase-Gate methodology and concentrating resources within the phases during the check. It was found that applying Phase-Gate and aligning the available manpower to the workload could improve the output performance of the A-check. The best of the designed solution alternatives all consists an implementation of a core shift, which focus of aligning and full concentration of available manpower to the workload.**

***Index Terms* — airframe MRO, KLM, Phase-Gate, A-check, Turnaround time, low WIP**

I. Introduction

An airline is able to achieve more profit (from an operational perspective) by increasing their amount of flights with the means of increasing its fleet size or achieve a better aircraft utilization or by decreasing their costs. This research focused on achieving a better utilization of the aircraft.

The utilization of the aircraft depends on different factors. In general, the flight plan determines the aircraft utilization. Although the utilization of the aircraft can be increased by demanding more flights due to changes of the flight plan, it is depended of the maintenance plan of the aircraft. Both the flight plan and the maintenance plan has big influence on each other and for both it means the aircraft must be available for any of the plans. In order to achieve more uptime availability, maintenance should be done as quick as possible and without leaving open work.

This research is conducted at KLM Engineering & Maintenance (KLM E&M) located at Schiphol Airport, which is an airline third party MRO provider and a division of the Air-France KLM holding. Currently, there is gap between the desired performance of airframe MRO at KLM E&M and the current performance. This research aims to contribute to improving the output performance of airframe MRO (A-check) for wide body aircraft.

II. Method

A. Research approach

The research approach is based upon the DMAIC cycle – Define, Measure, Analyse, Improve, Control [1]. The DMAIC approach is a known method from the Six Sigma methodology and consists of a study phase (Define, Measure, Analyse) and an improve phase (Improve, Control). However, a real implementation of the improve phase is not part of this research. Instead of "Improve and Control" steps, is the 'Improve' phase replaced by a so called 'Design' phase, where future state scenarios are developed for improvements and also tested. During the 'Control' phase, the impact of the different scenarios on assets and resources for improvement are evaluated.

B. Theory of Constraints

The main principle of Theory of Constraints (TOC) is to find the constraints of a systems outcome and then to solve those constraints [2]. By solving the constraints, the outcome of the whole system improves and not only locally. There are five steps defined to find and eliminate the constraint:

1. *Identify the constraint*
2. *Exploit the constraint*
3. *Subordinate other activities to the constraint*
4. *Elevate the constraint*
5. *Prevent inertia from becoming the constraint*

These main principles are used throughout this research to develop solution alternatives that could improve airframe MRO.

C. Phase-Gate

The methodology of Phase-Gate is to divide each project into large subprojects called 'stages' or 'phases'. The phases are separated by the so called 'gates' or 'milestones'. Furthermore, the phases are typically defined to be the same for every project and therefore the main activities can also be defined for all projects as well [3]. The four main advantages of Phase-Gate project management are:

1. *Common activities for all projects.*
2. *Standardizing approval processes*
3. *Opportunities for continuous improvement*
4. *Provide a common framework for portfolio management*

As the A-check is each time unique at task level, the same phases can be defined. Therefore, Phase-Gate will be used for improving the performance of the A-check.

D. Critical Chain

The critical chain methodology is based on TOC and also find the constraint of a system [4]. It states that the primary measure of project management effectiveness is schedule. For this measurement, the constraint is the path through the project network that has a longer durations than all the others and by avoiding conflicts of resources.

1) Low Work in Progress

Critical chain methodology holds the principle of low Work In Progress (WIP). When WIP increases, more distractions are caused to the teams due to conflicting priorities and multitasking. Eventually, this will lead to longer project durations and longer project queues. Low WIP can be achieved by concentrating the resources on the scheduled work and not allowing to start with other work when the previous work is not finished. This has proven to work for airframe MRO in order to improve the performance of airframe MRO processes [5].

2) Full Kitting

'Full kitting' is the practice of ensuring that everything is needed for a task, project or phase. It ensures that when a project/task is started it can proceed at full speed to completion. This avoids the waste incurred when a project starts and then stops or proceeds with partial effort.

Airframe MRO has high uncertainties, because the main activities consists of inspections and therefore unscheduled arisings are common practice. It is hard to predict those unscheduled arisings (findings from inspections) and it is wanted to know all possible arisings as soon as possible. If an inspection is performed somewhere at the end of the airframe MRO process, the chance exist that from the inspection something is found that needs repair. This is unwanted, because possible parts need to be ordered and there is less time available to solve the issue [5]. Therefore, 'Full kitting' ensures that all inspections are first performed before continuing with other tasks.

E. Combination of Phase-Gate and Critical Chain

The Full Kitting principle from the Critical Chain methodology is much built into Phase-Gate projects. As stated in [4], multitasking is inefficient, therefore a combination of phase-gate and avoiding multitasking can be made. As for airframe MRO it is wanted to have all inspections completed as soon as possible, thus all available resources should focus on the same phase during the project in order to complete the phase as fast as possible. All resources can only focus on the tasks within the phase they are working in. Fig. 1 shows the benefit of Phase-Gate and not multitasking/multi-phasing. It shows clearly that each (total) phase is finished earlier without time-slicing and just focus on a single tasks, or in this case, a phase.

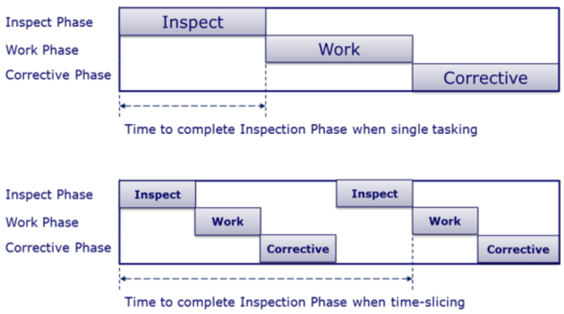

Fig. 1: Inefficiency of multitasking/multi-phasing.

F. Key Performance Indicators

Most maintenance providers, including KLM E&M, are focused on their most important key performance indicators (KPI) which are typically the quality, the turnaround time (TAT) and the costs [6]. Those factors are interrelated outputs of the MRO process and the main goal of the MRO process is to achieve a low TAT with a high quality and for low costs. For airframe MRO those KPI's can be expressed as:

- Turnaround Time
- Process Cost – expressed in man-hours
- Product Quality – expressed in airworthiness
- Process Quality – expressed in WIP

From an uptime perspective the aircraft is airworthy after each check, otherwise the check is not finished. This results in an interrelation of the KPI's for airframe MRO as presented in Fig. 2.

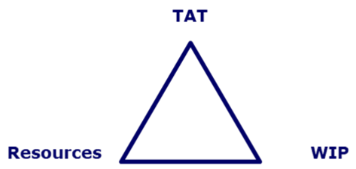

Fig. 2: Airframe MRO process key performance indicators.

G. *Theoretical preliminary model*

A new theoretical preliminary model is developed and this is also used later on to evaluate the potential of the current A-check.

1) *Zones and teams*

There are different teams performing airframe MRO. From TOC and Critical Chain, it is stated that not only the duration and sequences of tasks can constrain the output of a project, but the resources assigned to the tasks as well. Therefore, for the model a distinction is made of 2 teams where the skillsets of the resources determined the 2 teams. This results in an 'Above the Wing' and 'Under the Wing' team. The teams can work independently from each other, although there are some phases during the A-check where they are depended of each other.

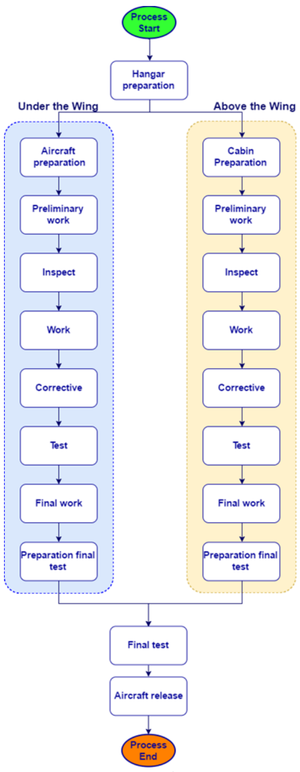

Fig. 3: Developed phase sequence for preliminary model.

2) *Phase sequence*

From interviews with different stakeholders and from literature it is wanted to perform all inspections as soon as possible, so there is still enough time to order all the parts and possibly easier to adapt to the situation. From literature it was found that by implementing Phase-Gate it can improve the output performance of airframe MRO processes which led to the developed phase sequence in Fig. 3. The check start with the 'hangar preparation'-phase and then splits up for the 2 teams. After both teams are finished with their phases, the final test and aircraft release will follow.

III. Results

A. *Current state measurements*

The current state of the Airframe MRO is measured on different levels and performances. First the Process quality is measured for the deferred defects (WIP) for the overall KLM E&M Airframe MRO chain. The deferred defects had a total average of 599/day which resulted in exceeding the target level. The research then focused on the checks for wide body aircraft in hangar 11 and the average turnaround time for those checks are presented in Table 1.

Table 1: Average TAT checks in hangar 11.

	A-check	H-check	M-check	AOG-check	TD-check
Average TAT (hrs)	42.67	33.56	12.06	33.74	16.33

B. *Analyse system constraints*

For the overall Airframe MRO chain it was found that current control lacked consistent handshakes/agreements. As this research then focused on the A-check and specifically of a Boeing 777-300. It was found that 'Under the Wing' activities was constraining the output of the airframe MRO process (A-check). The main constraint was formed by misaligning resources (manpower) with the demanded workload of the check.

C. *Design of solution alternatives*

Different solution alternatives were designed based on TOC; first exploiting the constraint, then elevating the constraint and finally the creation of the desired world solution. Resulting in five solution alternatives: exploit (norm), exploit (later shift), exploit (core shift), elevate (extra men) and desired world (2 shifts).

1) *Exploit (norm):*

The first solution is to exploit the manpower, so let them work the time they are available. Therefore, let them work according to the norm times and not sending them home early.

2) *Exploit (Later start of shifts):*

The second solution for exploiting the manpower is to eliminate the first hour of waste of available manpower during this time. Therefore, not changing anything to the norm, but just let everybody start with work one hour later.

3) Exploit (Core shift):

The third solution alternative for exploiting the manpower is to implement a so called 'core shift' within a 24 hours availability for the check. From the previous solution there is still waste of manpower in the beginning of the check and eventually also at the end. Therefore, to utilize those men, a core shift solution alternative is designed. This means to assign the men to the work when they are most needed. Therefore, a small group starts the check and when this is done the core shift starts.

4) Elevate (Extra men):

When looking at the available resources in hangar 11, there are possible multiple checks performed at the same time. There is in hangar 11 a dedicated team for the AOG-check, but not all the time there is an AOG-check, so this solution alternative is by adding the men of the AOG-check to the A-check, which consist of 4 extra men for 'Under the Wing'. In 2016 this was possible for a minimal of 60% of the total performed A-checks.

5) Desired World (2 shifts):

The last solution alternative is more a scenario to check what is needed for the desired world. The desired world is in this case performing the A-check within 2 shifts. This means that the check must be performed within 16.5 hours, because the average service length of the men must be 8 hours according the collective agreement. Each shift has one half hour paid permission and therefore the men are present for 8.5 hours. Also the shifts have one half hour overlap which in total results in 16.5 hours for the two shifts together.

D. Impact of solution alternatives on assets and resources

The designed solution alternatives are then implemented in the theoretical preliminary model and the results are shown in Table 2 Each solution alternative was also tested for a clean aircraft policy (no WIP after the check). The TAT represents the time needed for the A-check, 'WIP' is the amount of work (in workhours) that is not completed and therefore deferred to a later check. The resource KPI is expressed as the waste of available man-hours (there is no work available but men are available to work).

Table 2: Overview of all impact on assets and resources per alternative.

	TAT (hh:mm)	WIP (work-hours)	Waste of resources (man-hours)
Current state	25:29	4:17	60:09
Exploit: Norm	23:05	4:17	46:12
Exploit: Norm (clean)	23:54	0:00	45:23
Exploit: Later start of shifts	21:15	4:17	23:04
Exploit: Later start of shifts (clean)	22:20	0:00	22:55
Exploit: Core shift	20:25	4:17	28:46
Exploit: Core shift (clean)	20:35	0:00	25:38
Elevate: Extra men	18:04	4:17	86:01
Elevate: Extra men (clean)	18:10	0:00	83:45
Desired world: 2 shifts	16:28	4:17	116:20
Desired world: 2 shifts (clean)	16:28	0:00	120:08

E. Evaluation of solutions

A Multi Criteria Analysis (MCA) [7] is used to evaluate the solution results. Therefore, criteria weights are determined for the different criteria (TAT, WIP, Resources) after which the alternatives are assessed on by using the Analytical Hierarchy Process (AHP) [8].

1) Analytical Hierarchy Process

The results of the AHP are formed from the perspective of KLM E&M (hangar 11) and can be seen in Table 3.

Table 3: Criteria Weights from KLM E&M perspective.

Criterion	Weight Factor
Turnaround Time (TAT)	0.64
Process Quality (WIP)	0.23
Process Cost (man-hours)	0.12

2) Multi Criteria Analysis

After determining the criteria weights, the MCA was performed and the results are presented in Table 4.

Table 4: MCA results of solutions (KLM E&M perspective).

Solution	Total score	Rank
Desired world: 2 shifts (clean)	0,88	1
Elevate: Extra men (clean)	0,80	2
Exploit: Core shift (clean)	0,70	3
Desired world: 2 shifts	0,65	4
Exploit: Later shifts (clean)	0,58	5
Elevate: Extra men	0,57	6
Exploit: Core shift	0,48	7
Exploit: Norm (clean)	0,44	8
Exploit: Later shifts	0,42	9
Exploit: Norm	0,26	10
Current state	0,08	11

IV. CONCLUSIONS

The most favorable and best solution from the analysis is the 'Desired world' alternative with following a clean aircraft policy (no WIP after the check). However, other solution alternative also have a high overall score and they all follow the same principle. Namely, get the resources in tune with the demanded workload by implementing a core shift.

From this research it is concluded that by implementing Phase-Gate within the A-check and aligning the resources better with the workload can improve the output of the A-check. Therefore, first it is recommended to implement phases within a check where all resources are working on the same goal, namely finish all the tasks of the phase before working on tasks of another phase. Then it is recommended for KLM E&M Airframe Services to plan the available resources (man) in tune with the workload by implementing a core shift and follow a clean aircraft policy. It is advised to start the check with a small group of men and then the core shift should be present when the aircraft is inside the hangar and grounded. Also, it is essential that clear handshakes/agreements are in place between all process steps within the overall airframe MRO chain.

This analysis should be done on multiple A-checks in order to have a better analysis and a more robust conclusion of the analysis. A good way is by simulating the checks in order to test the impact of implementing Phase-Gate within the checks. Also, a recommendation is performing an analysis for determining which tasks are critical within a phase, so the resources are well appointed to those tasks.

From a scientific aspect, it is advised to use the theoretical model at different airframe MRO processes to test if it can improve the output performance. The theoretical model could easily be adapted to any airframe MRO process as the phases could be changed.

A. Research limitations

The main limitation of this research is the useable data. There is a lot of data available but the data do not provide instantly the needed things. A lot of manual checks had to be done in order to perform an analysis. This resulted in the next limitation, namely the focus of the research is only based on a single A-check. This limits the robustness of the made conclusions and recommendations.

This research is limited by the focus on only the main constraint, but other smaller constraint were neglected. All the solution alternatives are focused on this main constraint but it is possible that other solutions could be better than some of the designed solutions.

V. REFERENCES

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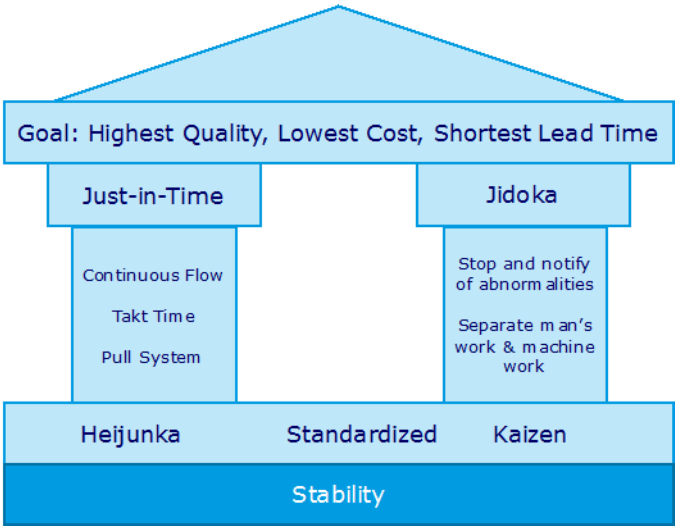
B. Process improvement methodologies

Lean

The Toyota Production System developed the so called TPS House. This 'Toyota Production House', depicted in the figure below represents the basic principles of Lean thinking. In order to have a stable house, it needs a strong foundation. The strong foundation is represented by Standardization and Stability and without this the whole system would fail. The two pillars of the house are formed by Just-In-Time (JIT) and Jidoka. Just-In-Time means that the right materials are at the right place and at the right moment. Jidoka, also referred as 'build-in-quality', means that detection of defects and repairing of them must be occur early in the process. The roof of the TPS House is obviously carried by the pillars and the pillars are supported by the strong foundations. The roof represents the goal of lean manufacturing, namely: highest quality, shortest lead time and lowest costs by continuous improvement.



Total Quality Management

TQM can be defined as the management of initiatives and procedures that are aimed at achieving the delivery of quality products and services. A number of key principles can be identified in defining TQM, including:

- Total employee involvement - All employees participate in working toward common goals
- Customer focus – Improvements on quality should improve customer satisfaction
- Continuous improvement – always work toward quality improvements
- Use of quality tools – usage of the right quality tools to measure quality

- Fact - based decision making – Quality decisions should be made on data of performance measures
- Executive Management – Top management should act as the main driver for TQM and create an environment that ensures its success

Object oriented methods

Object orientation methods are defined as: "*methods to model and programme a process described as objects, which are transformed by activities along the process*" (Aguilar-savén, 2004). The 'object' combines operations (behaviour) and data structure (attributes) in a single entity.

IDEF

The Integrated Definition for Function Modelling (IDEF) is a group of methods for modelling a process. The most important parts of the IDEF group are: IDEF0, IDEF1, IDEF1X, IDEF2, IDEF3, IDEF4 and IDEF5, but for process modelling, the most useful versions are IDEF0 and IDEF3.

IDEF0 is used for developing a structural graphical representation of a process. It specify function models, which are "*What do I do?*" models. IDEF3 is used to capture behavioural aspects of a process. It is used to show how different things work within an organisation and is developed to explicit describe process.

C. Used datasets

Various datasets are used for measuring the current state of the airframe MRO processes at KLM E&M.

Deferred defects (WIP) dataset

The data used in order to measure the amount of deferred defects origins from the so called 'Peter Schluter-portal'. This is a dashboard used at KLM E&M for presenting the measurements of different processes within KLM E&M. Also it presents the total amount of deferred defects per month for each category of aircraft (narrow- and wide- body aircraft). Also the dataset of the incoming complaints are used for measuring the amount of deferred defects. This data is provided by the 'Reliability'-department at KLM E&M (van de Werken, 2017). All data of the complaints per aircraft can be found in this dataset. The data from the year 2016 is used for the complaints as well as the already measurements from the 'Peter Schluter-portal'.

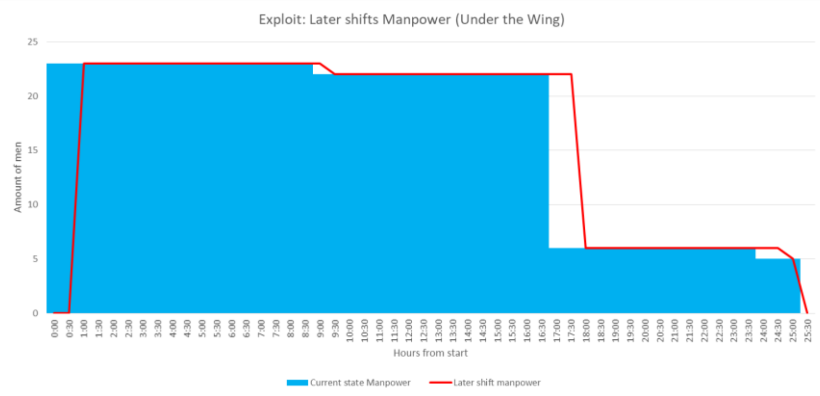
Turnaround times and on time performances

The data used for measuring the turnaround times and on time performances for the different checks in hangar 11 was retrieved from the Qlikview system used at KLM E&M (Gortenmulder, 2017). As this research focussed more into the A-checks, the data used for more detail of the A-check was retrieved from Maintenix (Mxi). All check details for the Boeing 777 series can be retrieved and the dataset consist all turnaround times and other details of the work packages.

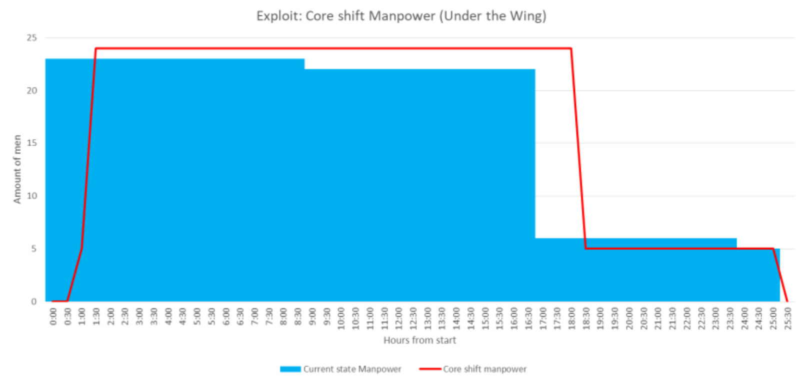
D. Aircraft work zones

Aircraft Work zones
Cabin/General
Cabin/Section A
Cabin/Section B
Cabin/Section C
Cabin/Section D
Crosswise/LH Engine
Crosswise/LH Wing
Crosswise/LH Wing Nacelle strut
Crosswise/RH Engine
Crosswise/RH Wing
Crosswise/RH Wing Nacelle strut
Lengthwise/Aft cargo
Lengthwise/Apu
Lengthwise/Cabin
Lengthwise/Cabin Doors
Lengthwise/Flightdeck
Lengthwise/ECS Bay
Lengthwise/Fuselage
Lengthwise/Fwd Cargo-E&E
Lengthwise/LH MLDG
Lengthwise/NLDG
Lengthwise/RH MLDG
Lengthwise/Tail & APU
Lengthwise/Water & Waste

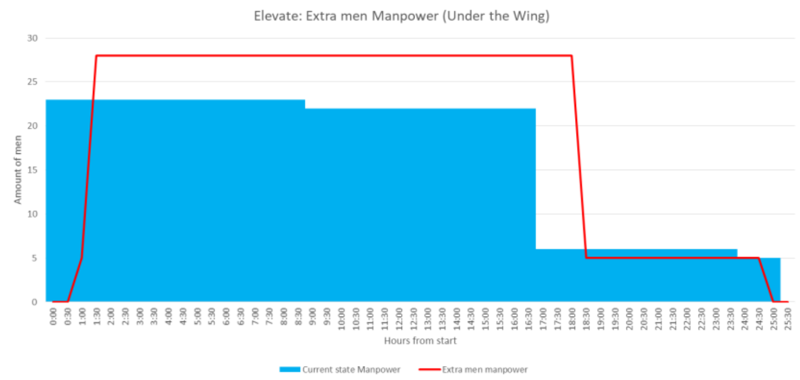
Manpower for Exploit: later start of shifts solution



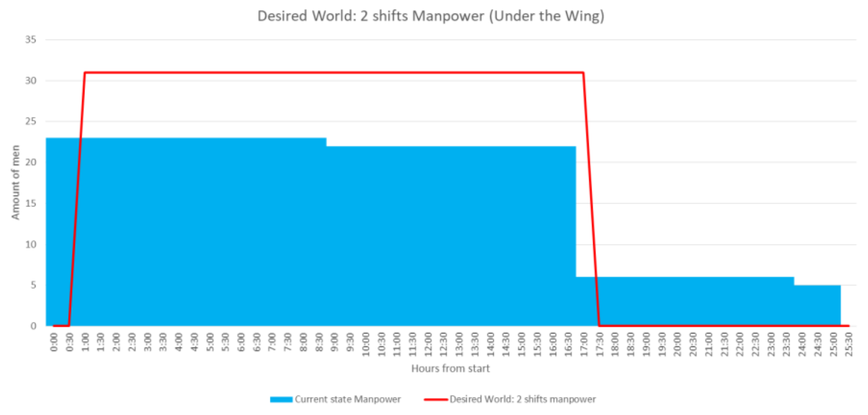
Manpower for Exploit: Core shift solution



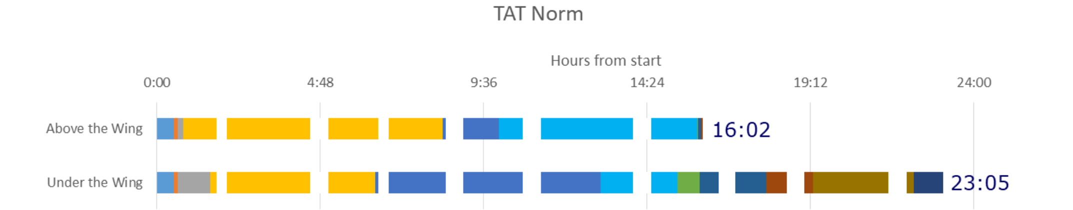
Manpower for Elevate: Extra men solution



Manpower for Desired World: 2 shifts solution



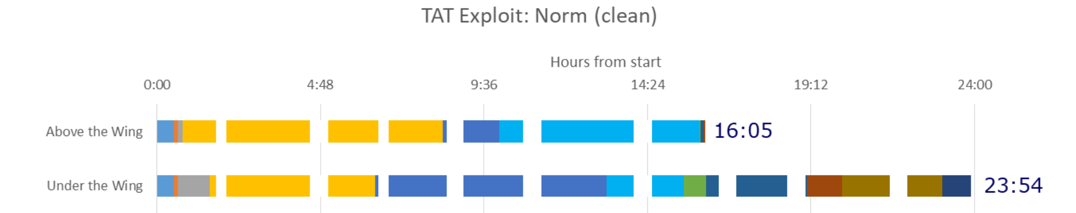
Results Exploit: Norm alternative



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:56	0:09
Inspect	4:50	7:37
Work	6:36	1:38
Corrective	2:15	5:49
Test	0:39	0:02
Final Work	1:58	0:05
Preparation Final test	1:22	0:02
Final Test	2:57	
A/C Release	0:50	

Hangar preparation A/C preparation Preliminary Work Inspect Work Corrective Test Final Work Preparation Final test Final Test A/C Release

Results Exploit: Norm (clean) alternative

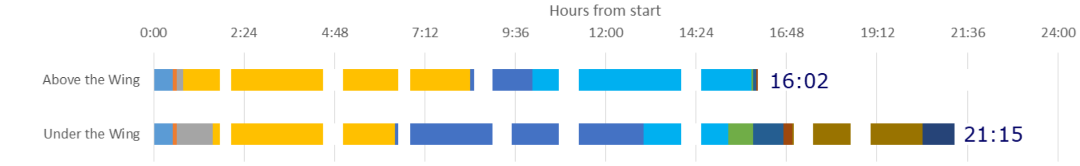


	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:56	0:09
Inspect	4:50	7:37
Work	6:47	1:38
Corrective	2:15	5:53
Test	0:39	0:02
Final Work	2:57	0:05
Preparation Final test	1:00	0:02
Final Test	2:57	
A/C Release	0:50	

Hangar preparation A/C preparation Preliminary Work Inspect Work Corrective Test Final Work Preparation Final test Final Test A/C Release

Results Exploit: Later shift

TAT Exploit: Later shift

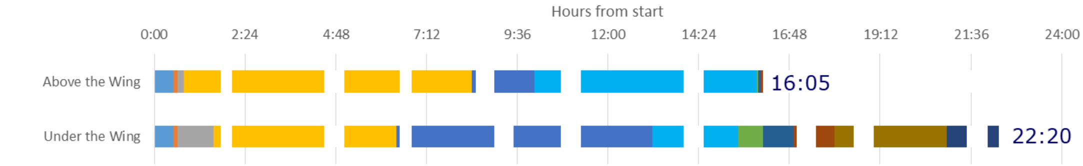


	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:56	0:09
Inspect	4:50	7:37
Work	6:35	1:38
Corrective	2:15	5:49
Test	0:39	0:02
Final Work	0:48	0:05
Preparation Final test	0:13	0:02
Final Test	3:27	
A/C Release	0:50	

Hangar preparation, A/C preparation, Preliminary Work, Inspect, Work, Corrective, Test, Final Work, Preparation Final test, Final Test, A/C Release

Results Exploit: Later shift (clean)

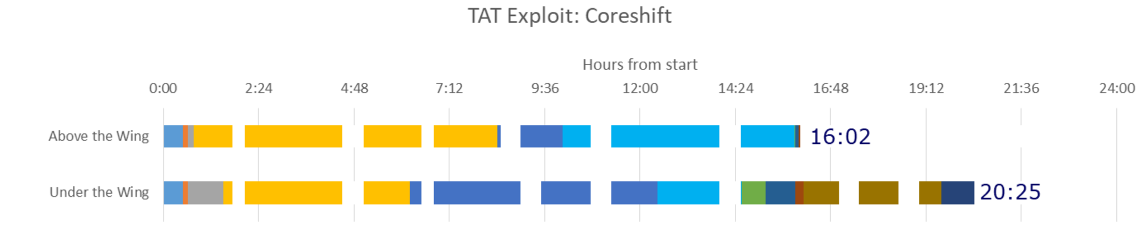
TAT Exploit: Later shift (clean)



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:56	0:09
Inspect	4:50	7:37
Work	6:46	1:38
Corrective	2:15	5:53
Test	0:39	0:02
Final Work	0:48	0:05
Preparation Final test	1:05	0:02
Final Test	2:57	
A/C Release	1:22	

Hangar preparation, A/C preparation, Preliminary Work, Inspect, Work, Corrective, Test, Final Work, Preparation Final test, Final Test, A/C Release

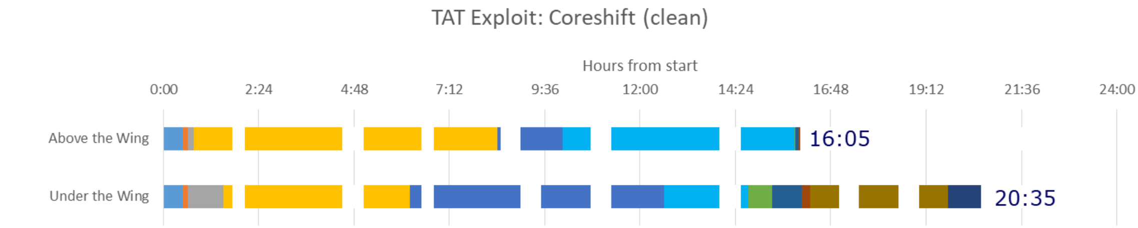
Results Exploit: Core shift



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:54	0:09
Inspect	4:40	7:37
Work	6:14	1:38
Corrective	2:07	5:49
Test	0:35	0:02
Final Work	0:44	0:05
Preparation Final test	0:12	0:02
Final Test	3:27	
A/C Release	0:50	

Hangar preparation ■ A/C preparation ■ Preliminary Work ■ Inspect ■ Work ■ Corrective ■ Test ■ Final Work ■ Preparation Final test ■ Final Test ■ A/C Release

Results Exploit: Core shift (clean)

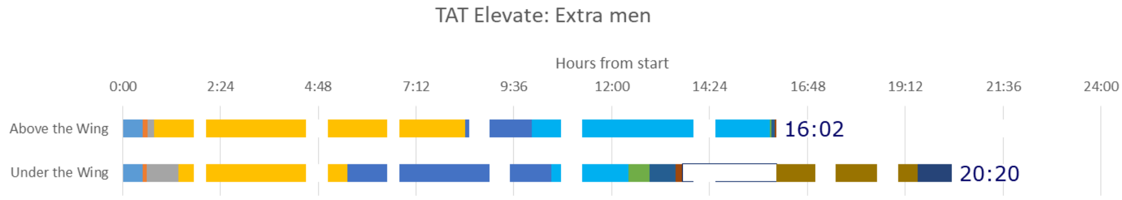


	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:06	0:07
Preliminary Work	0:54	0:09
Inspect	4:40	7:37
Work	6:24	1:38
Corrective	2:07	5:49
Test	0:35	0:02
Final Work	0:44	0:05
Preparation Final test	0:12	0:02
Final Test	3:27	
A/C Release	0:50	

Hangar preparation ■ A/C preparation ■ Preliminary Work ■ Inspect ■ Work ■ Corrective ■ Test ■ Final Work ■ Preparation Final test ■ Final Test ■ A/C Release

Results Elevate: Extra men (Above the wing becoming constraint)

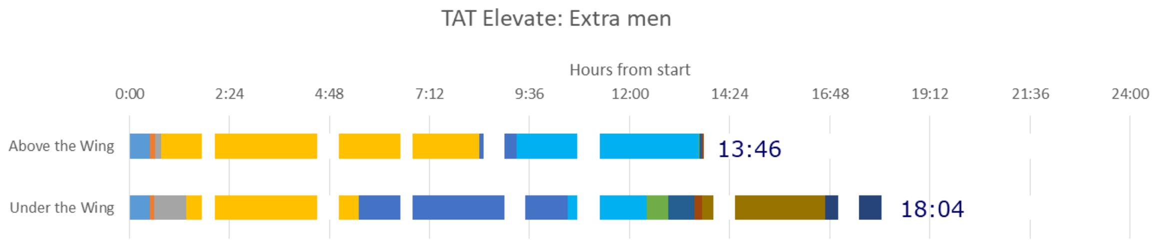
By just elevating the resources for the Under the Wing-team, the Above the Wing team will constrain the turnaround time of the check. The Under the Wing team needs to wait for the Above the Wing is finished with all its tasks.



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:05	0:07
Preliminary Work	0:46	0:09
Inspect	4:07	7:37
Work	5:00	1:38
Corrective	1:53	5:49
Test	0:30	0:02
Final Work	0:38	0:05
Preparation Final test	0:10	0:02
Waiting for final test	2:18	0:00
Final Test	3:27	
A/C Release	0:50	

Hangar preparation, A/C preparation, Preliminary Work, Inspect, Work, Corrective, Test, Final Work, Preparation Final test, Waiting for final test, Final Test, A/C Release

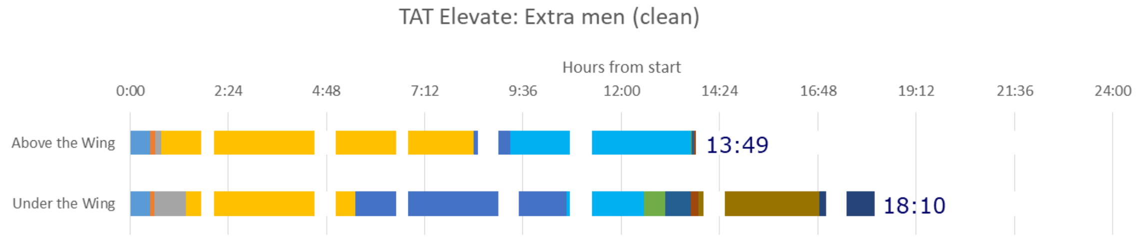
Results Elevate: Extra men



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:05	0:07
Preliminary Work	0:46	0:09
Inspect	4:07	7:37
Work	5:00	0:52
Corrective	1:53	4:22
Test	0:30	0:01
Final Work	0:38	0:03
Preparation Final test	0:10	0:02
Final Test	2:57	
A/C Release	1:20	

Hangar preparation, A/C preparation, Preliminary Work, Inspect, Work, Corrective, Test, Final Work, Preparation Final test, Final Test, A/C Release

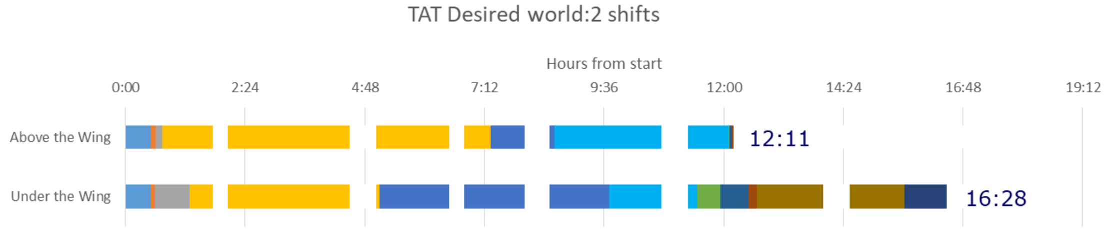
Results Elevate: Extra men (clean)



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:05	0:07
Preliminary Work	0:46	0:09
Inspect	4:07	7:37
Work	5:09	0:52
Corrective	1:53	4:24
Test	0:30	0:01
Final Work	0:38	0:03
Preparation Final test	0:10	0:02
Final Test	2:57	
A/C Release	1:20	

Hangar preparation ■ A/C preparation ■ Preliminary Work ■ Inspect ■ Work ■ Corrective ■ Test ■ Final Work ■ Preparation Final test ■ Final Test ■ A/C Release

Results Desired World: 2 shifts

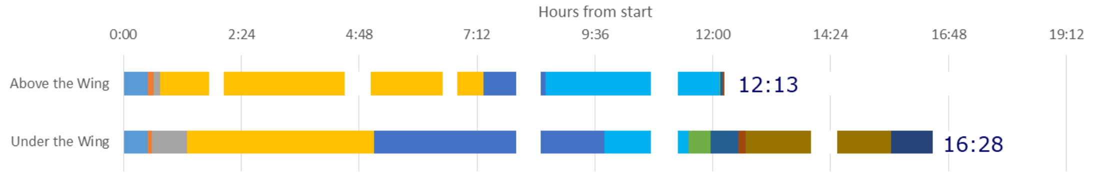


	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:05	0:06
Preliminary Work	0:42	0:08
Inspect	3:48	6:35
Work	4:36	1:16
Corrective	1:45	3:30
Test	0:27	0:01
Final Work	0:34	0:03
Preparation Final test	0:09	0:01
Final Test	2:57	
A/C Release	0:50	

Hangar preparation ■ A/C preparation ■ Preliminary Work ■ Inspect ■ Work ■ Corrective ■ Test ■ Final Work ■ Preparation Final test ■ Final Test ■ A/C Release

Results Desired World: 2 shifts (clean)

TAT Desired World: 2 shifts (clean)



	Under the Wing	Above the Wing
Hangar preparation	0:30	0:30
A/C preparation	0:05	0:06
Preliminary Work	0:42	0:08
Inspect	3:48	6:35
Work	4:41	1:16
Corrective	1:43	3:31
Test	0:26	0:01
Final Work	0:33	0:03
Preparation Final test	0:09	0:01
Final Test	2:57	
A/C Release	0:50	

Hangar preparation, A/C preparation, Preliminary Work, Inspect, Work, Corrective, Test, Final Work, Preparation Final test, Final Test, A/C Release

G. Solution evaluation

G.1 Criteria weight determination

Process manager's perspective:

	TAT	WIP	Waste of resources	Normalized principal eigenvector	consistency ratio (CR limit = 10%)	consistent?
TAT	-	3,30	4,31	64,20%	3,70%	yes
WIP	0,30	-	2,29	23,45%		
Waste of resources	0,23	0,44	-	12,35%		

Client's perspective:

	TAT	WIP	Waste of resources	Normalized principal eigenvector	consistency ratio (CR limit = 10%)	consistent?
TAT	-	5,00	9,00	75,14%	3,00%	yes
WIP	0,20	-	3,00	17,82%		
Waste of resources	0,11	0,33	-	7,04%		

G.2 Multi Criteria Analysis results

Process manager's perspective:

	TAT	WIP	Waste of resources		
	64,2%	23,4%	12,4%	Sum	rank
Current state	0,00	0,00	0,62	0,08	11
Exploit: Norm	0,27	0,00	0,76	0,26	10
Exploit: Norm (clean)	0,18	1,00	0,77	0,44	8
Exploit: Later shifts	0,47	0,00	1,00	0,42	9
Exploit: Later shifts (clean)	0,35	1,00	1,00	0,58	5
Exploit: Core shift	0,56	0,00	0,94	0,48	7
Exploit: Core shift (clean)	0,54	1,00	0,97	0,70	3
Elevate: Extra men	0,82	0,00	0,35	0,57	6
Elevate: Extra men (clean)	0,81	1,00	0,37	0,80	2
Desired world: 2 shifts	1,00	0,00	0,04	0,65	4
Desired world: 2 shifts (clean)	1,00	1,00	0,00	0,88	1

Client's perspective:

	TAT	WIP	Waste of resources		
	75,1%	17,8%	7,0%	Sum	rank
Current state	0,00	0,00	0,62	0,04	11
Exploit: Norm	0,27	0,00	0,76	0,25	10
Exploit: Norm (clean)	0,18	1,00	0,77	0,36	9
Exploit: Later shifts	0,47	0,00	1,00	0,42	8
Exploit: Later shifts (clean)	0,35	1,00	1,00	0,51	6
Exploit: Core shift	0,56	0,00	0,94	0,49	7
Exploit: Core shift (clean)	0,54	1,00	0,97	0,65	4
Elevate: Extra men	0,82	0,00	0,35	0,64	5
Elevate: Extra men (clean)	0,81	1,00	0,37	0,81	2
Desired world: 2 shifts	1,00	0,00	0,04	0,75	3
Desired world: 2 shifts (clean)	1,00	1,00	0,00	0,93	1

Equal weigths

	TAT	WIP	Waste of resources		
	33,3%	33,3%	33,3%	Sum	rank
Current state	0,00	0,00	0,62	0,21	11
Exploit: Norm	0,27	0,00	0,76	0,34	10
Exploit: Norm (clean)	0,18	1,00	0,77	0,65	5
Exploit: Later shifts	0,47	0,00	1,00	0,49	7
Exploit: Later shifts (clean)	0,35	1,00	1,00	0,78	2
Exploit: Core shift	0,56	0,00	0,94	0,50	6
Exploit: Core shift (clean)	0,54	1,00	0,97	0,84	1
Elevate: Extra men	0,82	0,00	0,35	0,39	8
Elevate: Extra men (clean)	0,81	1,00	0,37	0,73	3
Desired world: 2 shifts	1,00	0,00	0,04	0,35	9
Desired world: 2 shifts (clean)	1,00	1,00	0,00	0,67	4

Total overall ranking

	Score	rank
Desired world: 2 shifts (clean)	2,47	1
Elevate: Extra men (clean)	2,34	2
Exploit: Core shift (clean)	2,20	3
Exploit: Later shifts (clean)	1,88	4
Desired world: 2 shifts	1,75	5
Elevate: Extra men	1,61	6
Exploit: Core shift	1,47	7
Exploit: Norm (clean)	1,45	8
Exploit: Later shifts	1,34	9
Exploit: Norm	0,86	10
Current state	0,33	11