Implementing dynamic clustering of maintenance activities at AIS Airlines

MSc thesis – Niek Binnenmars
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AIS Airlines

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Management Summary

Problem Description

AIS Airlines is an airliner based in Lelystad with their own maintenance department. The maintenance department of AIS is responsible to have the 7 operational Jetstream 32 turbo-prop aircraft airworthy. As for now, the maintenance is solely planned on the expert knowledge of the maintenance planner. This causes inaccuracies to occur in the maintenance planning, especially when aircraft get swapped to other routes and therefore fly a different amount of flight hours or cycles than anticipated, which can mess up the maintenance planning.

AIS wants to start implement dynamic clustering to be able to quickly generate new maintenance schedules. Also, by making use of these scheduling methods, AIS will be able to quickly check what impact it will have when scheduling aircraft on other routes. When creating maintenance schedules, the planner has to take into consideration the initial due date of maintenance jobs, the maximum interval and what setup tasks might be necessary.

Research Objective

In this thesis we will have two objectives. The first objective is to find methods for dynamic clustering of maintenance activities and try to adapt the methods to fit the context of AIS Airlines. The second objective is to take these methods and find a way how to implement dynamic clustering of maintenance activities at AIS Airlines.

Method

In literature, we found multiple methods for clustering maintenance activities, for which a few were for multi-component systems. Most of these methods were static clustering methods, for which clusters are made at one moment in time and do not change. In the dynamic context of aviation, we need a dynamic clustering method that can make new maintenance clusters at any moment in time.

We used an adjusted MIP-model described by Budai (2005) to fit the maintenance structure at AIS Airlines. This meant we had to add the possibility of giving extension to a maintenance task to the model and the addition of multiple setups for a maintenance job. In the end, we modeled the MIP-model with and without the possibility of giving extension. After creating the MIP-model in AIMMS, we also programmed some heuristics to easily generate new maintenance schedules. We modelled a single-component heuristic, that schedules the individual maintenance tasks to optimality. Next, we modeled the opportunity-based heuristic. This heuristic clusters the maintenance activities based on the primary setup activity, flying to Lelystad. As an addition to this heuristic, we modeled an improvement heuristic to improve the schedule by also clustering the secondary setup activities.

Results

We experimented with all scheduling methods by letting all planning methods generate maintenance schedules for six of the aircraft because the other one is not allocated to a route. The other aircraft are allocated to the route they were flying at the moment the due lists of the maintenance jobs were generated.

As can be seen in the table below, the heuristics create feasible schedules with reasonable total maintenance costs. the opportunity list heuristic creates the same schedules as the

CAMO-manager does. The improvement heuristic does only improve the schedule when enough secondary setups are required which can be clustered. This is only the case for a few of these aircraft.

The MIP-model does generate significantly better schedules than the current scheduling, the MIP model without extension gives an improvement of €1113,74 per aircraft per year, which on a yearly basis will decrease the maintenance costs with €7796,18. When possible giving extension to maintenance tasks is taken into consideration by the MIP-model, a decrease of €1465,96 per aircraft per year can be realized. This will generate a decrease in yearly maintenance costs of €10261,72.

		BCI	DCI	FCI	HCI	NCI	OCI	AVERAGES
Heuristics	Single Component	€ 111,950.30	€ 140,541.02	€ 75,576.03	€ 92,061.75	€ 102,886.94	€ 102,833.24	€ 104,308.21
	Opportunity List	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59
	Opportunity List with improvement Heuristic	€ 34,537.77	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 30,288.61	€ 32,254.34	€ 32,146.62
Model	MIP (no extension)	€ 34,340.50	€ 42,673.02	€ 30,876.98	€ 20,557.61	€ 28,470.71	€ 31,289.09	€ 31,367.99
	MIP (with extension)	€ 33,992.99	€ 42,462.55	€ 30,498.13	€ 19,928.26	€ 28,246.53	€ 30,983.30	€ 31,018.63
CAMO	CAMO-planning	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59

Conclusion

Concluding, dynamic clustering of maintenance activities can be implemented at AIS Airlines and will most likely improve the scheduling of maintenance in comparison to the current situation.

If dynamic clustering of maintenance activities will be implemented, AIS has to make sure the maintenance management system can properly export the maintenance data. At the moment, the availability of data at AIS is very poor and makes it impossible to effectively implement dynamic clustering. It should be made possible to export the maintenance jobs with their corresponding interval, due date and maximum extension for each maintenance job as a usable format.

This being said, if AIS wishes to implement dynamic clustering of maintenance activities, some investments have to be made. First off, the maintenance management system has to be updated as is described above. Secondly, it is possible to improve the proposed heuristics to approach the solution of the MIP-model. For now, this is possibly the best option as AIS does not have the knowledge yet to implement optimization software. If AIS wants to implement this, staff has to be trained in how to use the software, and a license must be bought. For now, this will not be worthwhile, as the scheduling problem is not that difficult yet and it will take an investment of approximately €1000 for the license and employees will need training, which will offset the decrease in maintenance costs. If AIS grows, and its fleet becomes larger, or/and more secondary setups are identified, it might become more interesting to invest in optimization software as more costs can be saved.

AIS might research the possibilities to improve the heuristics. For now, the heuristics will improve the maintenance just slightly. If the heuristics are improved, the planned might be able to create easy-to-generate maintenance schedules with total costs that approach the optimal planning.

Preface

Before you lies the product of months of hard work that was written by me to graduate the master Industrial Engineering and Management – Production and Logistics. This was done by conducting research on dynamic clustering of maintenance at AIS Airlines, which is based at Lelystad Airport. I am proud to present to you the final product of months of blood, sweat and tears.

Before I started the master Industrial Engineering and Management, I finished the bachelor Industrial Design Engineering. I am very happy I finished my Bachelor in that direction and I have always enjoyed the combination between technology and creativity. I always had a thing with mathematics though. I loved solving puzzles and that is why I decided to continue with a master in Industrial Engineering and Management, which was the perfect continuation of my career as a student. I have always enjoyed the challenges that the master threw at me and I am happy to now graduate in this direction as well.

Before I go to the content of the thesis, I would like to take some time for expressing my gratitude to a few people for supporting me in the process of making this thesis:

First, I would like to especially thank Matthieu van der Heijden and Engin Topan for supervising the thesis from the University of Twente. With their support I found the right path to complete the thesis and when I needed guidance in which direction to go, they could always help me progress.

Secondly I would like to thank the people from AIS Airlines. I would like to thank Martin van der Meer for his supervision from the perspective of AIS Airlines. Also, I would like to thank Haidar Jabber as CAMO-manager for his expert opinion and providing the information necessary. Furthermore, I would like to thank the rest of my colleagues at the CAMO-department for the great working atmosphere in our small office and the very special CAMO-coffee, I enjoyed working with you all this time.

Last but not least I would like to thank my parents and my girlfriend for keeping up with me during these 'difficult times' of finishing a thesis. Returning to live with my parents was not always easy for them as well, I can imagine and I would thank them for the support they always gave me during these sometimes stressful months. Also, I would like to thank all the friends I made in Eanske the last couple of years that lead to this thesis, it was an amazing journey.

Niek Binnenmars

Table of Contents

List of figures

List of tables

List of abbreviations and glossary

Abbreviations

AD	: Airworthiness Directive
AFL	: Aircraft Flight Log
AIS	: Aeronautical Instruction Services
ALI	: Airworthiness Limitation Item
CAM	: Continuing Airworthiness Manager
CAMO	: Continuing Airworthiness Maintenance Organization
CPCP	: Corrosion Preventions and Control Program
EASA	: European Aviation Safety Agency
KPI	: Key Performance Indicator
MIP	: Mixed Integer Programming
NDI	: Non-destructive inspection
OH	: Overhaul
Ops	: Operations Airline
P-145	: Part-145 (EASA certified aeronautical repair station)
SB	: Service Bulletin
VBA	: Visual Basic for Applications

Glossary

AIS	: AIS Aviation group
AIS Flight Academy	: AIS Flight Academy – only flight academy
AIS Airlines	: AIS Airlines – only Airliner
Technics	: AIS Technics – maintenance department
Maintenance Package	: A set of maintenance jobs that are combined into a single maintenance package.
Major inspection	: A larger inspection package.
Job Order	: A set of maintenance jobs for a specific inspection of an aircraft.
Due List	: List of remaining flight hours, flight cycles or months for each job
Out-of-phase tasks	: The tasks not in a predetermined maintenance package
Raido	: Planning tool of AIS airlines used by operations
Set up task	: Preparatory task for a maintenance job
Maintenance job	: Task that has to be done for maintenance
Airworthiness	: The extent to which an aircraft is eligible to fly
Maintenance Management - System	: The maintenance database of AIS Airlines
Tasklist-creator	: The model that manipulates and extracts useful data from the due-lists.
CAMO-Manager	: The person responsible for maintenance planning
Maintenance Manager	: The person responsible for maintenance execution

1. Introduction

1.1. Company

AIS Airlines is an airliner based in Lelystad which provides flexible service for customers looking for scheduled flights, wet lease and full charter capacity. The company is unique because of its integrated maintenance department, development center and flight academy which are, together with the airline, all part of the AIS aviation group. The fleet consists of eight BAE Jetstream 32 turbo-props, and thirteen smaller aircraft used for training students of their flight academy. seven of the Jetstream 32 turbo-props are currently flying routes, one of the aircrafts is currently being cannibalized.

At this airliner, three departments are involved with planning of maintenance. Operations, Technics (P-145), and CAMO (Continuing Airworthiness Management Organization). Operations is in charge with the planning of flights and on-board personnel. This flight schedule is communicated to CAMO, which is responsible for the planning of base maintenance, which is done in Lelystad. Smaller line maintenance jobs can also be done at two line bases based in Sweden. CAMO plans the maintenance in a way that the due dates of the components of the aircraft are not exceeded. If a part has exceeded its maximum number of cycles/flight hours, it is not allowed to fly any further, which is something that must be avoided at all costs. It is the responsibility of CAMO to come up with a maintenance schedule that makes certain due dates are met with minimal costs. This maintenance schedule is passed down to the Technics department, which performs the actual maintenance. This maintenance is mainly done in the weekends, because the aircraft are flying their scheduled flights on the weekdays. In the ideal situation, seven aircraft are flying, and one spare-aircraft is left to cover for a defect one. CAMO also communicates with Operations to make sure the planes are at the right locations to execute the maintenance.

1.2. Problem

Most of the maintenance activities are done in-house by AIS at the maintenance facility at Lelystad Airport. The set of preventive maintenance jobs and their minimum frequencies are determined by an independent organization and strongly motivated by safety considerations. AIS cannot change these minimum frequencies. It is, of course, possible that AIS performs maintenance earlier than strictly necessary if that suits AIS better. This may be caused by time-consuming preparation activities needed for the maintenance job. For example, an aircraft first must fly to the maintenance facility at Lelystad Airport. Or: The interior of the aircraft must be removed to access the location of maintenance. Once such a preparation activity is executed, it may be economically justified to execute multiple maintenance jobs for which this preparation activity is needed, and the costs incurred by early maintenance may be easily compensated by a reduction in the costs of preparation activities. This is called clustering of maintenance activities.

The three departments (Operations, CAMO and Technics) communicate independently with each other, there is no central communication. Because of this, miscommunication happens quite often. If Operations and maintenance communicate about some maintenance job which must be done, and the CAMO department is not informed, there will be errors in the maintenance schedule. To make this work, improvements in maintenance planning will be necessary.

Earlier, a bachelor thesis was done at AIS to research the implementation of static clustering of maintenance jobs, this resulted in a clustering possibility which should lower the maintenance costs. AIS Airlines did not implement this way of clustering yet due to the model not being complete enough to directly implement, and the CAMO department not having enough personnel to focus on the implementation. Despite not being implemented, AIS would like to research the possibilities to improve this clustering method to a more dynamic way of clustering, possibly including corrective maintenance. Also, the model used in the bachelor thesis is not considering all the aspects of aircraft maintenance. Only one set up activity is considered, but, there are many more to be identified.

AIS wants to ensure that the result of the thesis is usable for them in the future. One of the main issues that AIS has identified is the communication between CAMO, Ops and Technics. To facilitate this, in the near future, a central planner will be employed. This planner will consider all the different information flows regarding maintenance. This includes the flight schedule and flight hours/cycles per aircraft from operations. The following maintenance schedule of CAMO, per week, for three months, and the corresponding tasks and items needed. Technics will provide the inventory position of spare parts and the possible list of items that must be ordered. These spare parts are not always available.

Because the central planner is a new position in the company, a lot of uncertainties are there on what information is available and how this information can be used and/or manipulated to organize a central planning system and overview for the central planner.

Also, the CAMO and Operations could benefit from such a system, as it may give them more insight on what consequences their decisions may have. For example, one of the current causes of imperfections in the maintenance planning is when Operations switches two aircraft in the flight schedule, without consulting CAMO whether this will have effect on the current maintenance schedule. This will result in two aircraft having different flight schedules and therefore different amount of flight hours and cycles then was considered by the CAMO department. One aircraft will fly more than anticipated and will therefore have to return to the maintenance base in Lelystad earlier. It might be that there is already another aircraft planned for maintenance that week, and then no maintenance can be performed on the incoming plane. This causes the aircraft to be out of order longer than necessary. The other way around, an aircraft might fly less than planned and come in for maintenance earlier than necessary, this increases the wasted lifetime of certain components as that could have been used longer.

1.3. Problem Cluster

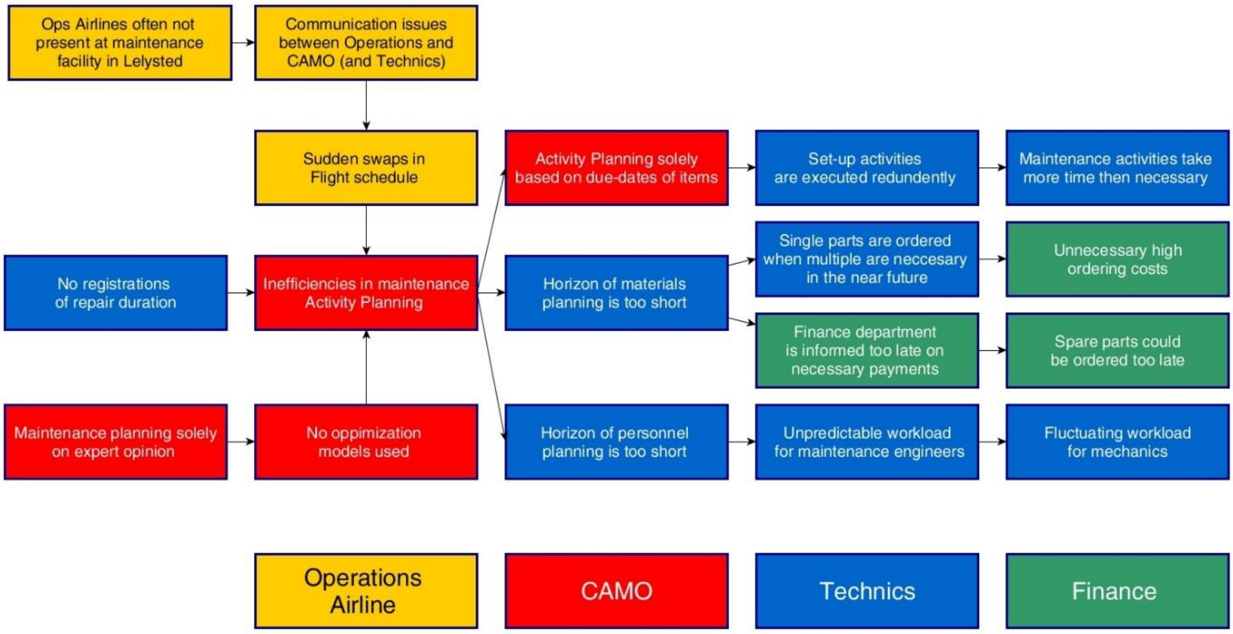

Figure 1: Problem Cluster AIS Airlines

In the problem cluster as can be seen in Figure 1, the core issue is the inefficiency in the maintenance planning of AIS Airlines. The planning is solely done on expert opinion and no optimizing models are used. This can be done with a small amount of aircraft, but in the last couple of years, the company has grown a lot. As of today, there are eight aircraft that are used by the airline and the planning department is under a lot of stress.

This is due to the person in charge of Operations being also a pilot for AIS. Therefore, he is not often present at the maintenance facility in Lelystad, which makes fast communications between the two departments difficult. When breakdowns occur, or maintenance must be performed that causes an aircraft to fly to a maintenance facility, aircraft will occasionally be swapped if this will create a more favorable situation. Due to bad communications, this might cause inefficiencies in the maintenance schedule as the CAMO department is informed too late.

Due to these uncertainties, the planning horizon can only be a few months. Planning attempts for a longer timespan are unnecessary, as it will always change due to swaps and breakdowns. Because of this relatively small planning horizon and the many sources of variability, the workload for mechanics is quite unpredictable, which causes fluctuating workloads. Because of the engineers preferring not to work after 5pm on the weekdays and not always on the weekends and surely want to know beforehand when they must work, the personnel planning is a tedious task.

The maintenance planning is scheduled solely on expert knowledge of the CAM (CAMO-manager). He has knowledge on the maintenance of the Jetstream 32's and knows exactly which jobs should be combined. When maintenance is planned, only the necessary setup tasks and due date of jobs is considered. The amount of time necessary to perform the maintenance is not, and this information is not available as this is data is not collected. Due to the CAM not using an optimization model to schedule the maintenance, taking capacities of engineers, duration of maintenance or costs into account, the maintenance is not optimal and changes in schedule are made quite often. All of this causes inefficiencies in the maintenance schedule and the performance of the maintenance department.

Due to the expertise of the CAM, some structural dependency is taken into consideration, but this can be optimized more. For example, at a 400-hours check, the floor of an aircraft must be removed, one check later, some cables must be checked for corrosion prevention and the floor must be removed again. These jobs should probably have been combined to only having the floor removed once.

Because of the short-term planning, the materials are also only ordered in the short-term. If the long-term planning could be considered more, materials could be ordered in larger batches and ordering costs can be saved. Also, the finance department can be notified earlier as the administration of orders can take a while and invoices are not always paid on time, which results in parts being delivered late.

In this thesis, we will focus on the development on an operational clustering method for maintenance. We will take in consideration the set-up tasks necessary to do certain maintenance jobs. This will be done dynamically, considering the most recent information on due dates, which are dependent on the flight schedule. The planning method will cluster the maintenance jobs into groups for which the maintenance costs will be as little as possible.

1.4. Goal

The goal of the thesis is to develop a new maintenance approach, using dynamic planning based on most recent information. To follow up on the earlier performed BSc-thesis, the clustering method will be extended and improved. The model will be improved to a more realistic representation, considering more set-up tasks that are required to perform certain maintenance jobs.

The system should be implemented in the context of AIS Airlines and employees should be able to implement the new scheduling method. A plan on how to implement the new maintenance approach will have to be written and the model should be appropriate for the employees to implement.

As for the implementation at AIS Airlines, a tool should be created to assist the central planner to get an overview of the maintenance activities and helps the planner make decisions regarding planning the maintenance for the different aircraft.

1.5. Scope

1.5.1. Flight schedule

The flight schedule is given by the operations department. The operations department determines to what destinations each aircraft will fly. The optimization of this flight schedule is not included in the scope of this thesis. Operations will communicate the flight hours/cycles with the maintenance planners and these hours are used to calculate the due date of the maintenance jobs.

Changes in the flight schedules might occur due to necessary maintenance. These swaps might result in a change in flight hours/cycles and will therefore have effect on the maintenance schedule. In the thesis, we will not take these changes into account and assume the flight schedule is fixed. If the resulting planning of the maintenance makes it useful to swap aircraft, a new maintenance planning should be created after.

1.5.2. Tree structure of maintenance jobs and setup tasks

The tree structure of maintenance jobs with their corresponding set-ups is not available yet. The maintenance tasks are known, but the corresponding set-up tasks are not defined as for now. This information is known by the maintenance experts from AIS technics and in the maintenance manual that is available from the BAE-website. BAE is the British Aerospace, the manufacturer of the Jetstream 23's. This information should be collected to create a sufficient model of the maintenance activities and the required setups for each maintenance job.

1.5.3. Minimal frequencies of maintenance jobs

The minimal frequency / maximum interval of each maintenance job is known in the maintenance management system of AIS Airlines. The due list of maintenance jobs can be exported from the system and the corresponding minimal frequencies, that are regulated by independent organizations to ensure safety. These minimal frequencies are given in number of flight hours, number of flight cycles or number of months. A flight cycle is the same as the combination of one takeoff and one landing.

1.5.4. Cost of maintenance jobs

The exact costs for each maintenance job is not known by AIS. Of course, for some maintenance activities, the price of components is known, but the time required for maintenance and the salary of the maintenance crew are not quantified yet. These costs, following from the manhours needed per maintenance job and the hourly/daily rate of engineers will have to be identified.

1.5.5. Inventory of spare parts

Inventory management of spare parts will partially follow from the maintenance schedule. Spare part management will not be considered in this thesis. The required materials should follow from the planning and will be done on expert opinion of the maintenance manager. In the planning of maintenance, we will assume all parts will be available when necessary.

1.5.6. Flight Academy

Besides being an airliner, AIS also has a flight academy. The students from the flight academy occasionally use the aircraft from the airliner as well and these flights also add up to the number of cycles and flight hours. This information is not readily available and thus the hours made by the flight academy is not taken into consideration.

1.6. Research questions

From the problem description and the scope, we can derive the main research question:

Main Research Question:

- *How can dynamic clustering of maintenance activities be implemented at AIS airlines to assist in maintenance planning?*

In order to answer the main research question, we will first need to answer some sub-questions subsequently to step-by-step get to an answer to the main research questions. We can formulate the following questions that first need to be answered:

Secondary Research Questions:

- *How is AIS Airlines currently planning their maintenance activities, how can we quantify its performance and what are the possibilities to improve this?*

- *How is (dynamic) planning and clustering in aviation described in literature?*

- *How can we use dynamic planning and clustering in the context of AIS Airlines to improve their processes?*

- *What is the added value of using dynamic clustering of maintenance activities in comparison to the current planning approach?*

- *How can we make the maintenance and the implementation of smart clustering visible to the central planner to support his decision making?*

The first two secondary questions are orientational, we need to answer these questions to understand the processes involved with maintenance planning at AIS Airlines and possible solutions to the maintenance scheduling problem need to be explored. After these questions are answered, we can pick an appropriate solution to the situation at AIS and manipulate the model such that it fits the processes at AIS Airlines. After the model is designed, the added value of using dynamic maintenance clustering should be made clear. If dynamic clustering of maintenance activities is beneficial to AIS, we should find how to implement dynamic clustering of maintenance activities at AIS. After answering all of these questions, we should be able to answer the main research question.

1.7.Approach

- First, we will try to identify the information flows regarding AIS Airlines' maintenance planning. The information sent from Operations to CAMO, CAMO to Technics and all other flows will be needed to create an appropriate maintenance planning.

- Secondly, a literature study on maintenance planning will be conducted, especially the literature on dynamic clustering and planning of maintenance jobs will be studied.

- Following, out of this literature, the useful methodologies that are identified will be extracted and should be adapted to the business processes of AIS Airlines.

- To construct an appropriate model of the processes, data will have to be gathered on the different maintenance jobs. Also, the necessary set-ups needed for all maintenance jobs will be required information. Due to the available information and the form which it is in, this will be a tedious task, that will take quite some work.

- Model the maintenance processes of AIS and develop a model that gives a viable maintenance schedule. The modelling should be done in an environment that employees of AIS will understand and are able to work with.

- Test the model and compare it to the current situation of maintenance scheduling.

- Give recommendations on how to implement the new approach in the business structure of AIS. What information is necessary? Who will be using the new approach? What will have to change to be able to use the new approach appropriately.

The aim of the research will be to find a solution for dynamic clustering of maintenance jobs. AIS Airlines want to be able to implement the result of this thesis in their company. The result should be simple and effective. Ultimately, a tool could be created to aid in the planning of maintenance jobs.

2. Context analysis

2.1. Introduction

In this chapter, we will discuss the current structure of AIS and its maintenance activities. In section 2.2 and 0 we will describe the structure of AIS as a company, with all its different departments related to maintenance and the fleet that AIS owns and for which it has to perform maintenance. In section 2.4 we will discuss the aircraft maintenance structure with its maintenance and setup tasks. Then, in section 2.5 we will discuss how the flight schedule and flight routes are currently set up. In section 2.6 we will describe the distinction between line and base maintenance. In section 2.7 we will discuss how, from and in combination with the flight schedule, the maintenance schedule is created.

2.2. Maintenance information flow

CAMO, Operations Airlines and AIS Technics are involved with the maintenance processes. Necessary information is sent between the different departments. The following figure represents the information flows between the departments regarding maintenance at AIS:

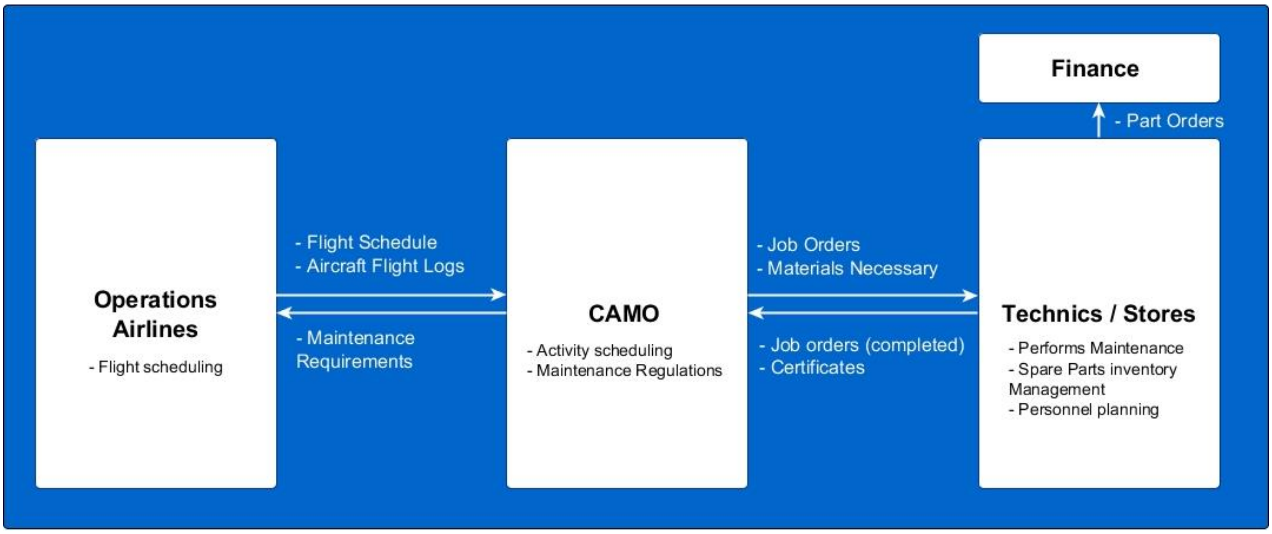

Figure 2: Information flow

The main business of AIS is the flying of different routes in Sweden, Germany and Croatia, although the Croatian route will be disbanded soon. AIS will have to make sure that the aircraft are in a good condition to be flying. This is where the maintenance organization at AIS comes in the picture. The maintenance organization, consisting mainly out of the CAMO and Technics department, is responsible to get the aircraft to be airworthy. An aircraft is airworthy when it complies with all maintenance regulations regarding the aircraft. The airworthiness of an aircraft is defined by AD's (Airworthiness Directives), which are leading in the planning of maintenance activities. Taking these directives into account, the priority of CAMO is to make sure the directives are satisfied, and the aircraft are able to fly, as an aircraft being grounded costs an approximate €10.000 each day due to missed revenue from ticket sales/refunds and possible penalties.

To make sure that the maintenance is organized adequately, the different departments of AIS must communicate with each other since they need the information from the other departments to be able to function.

2.2.1. CAMO (Continuing Airworthiness Maintenance Organization)

CAMO is the heart of the maintenance organization of AIS. In this department, all information about the flight schedule and corresponding flight hours/cycles, locations of maintenance bases, due dates of maintenance jobs and major inspections etc. are considered to create a feasible maintenance schedule. This maintenance schedule is then sent to operations airlines and AIS Technics. When necessary, feedback is given from the other departments and the maintenance schedule is adjusted appropriately. Due to the uncertainty in aviation, CAMO makes a maintenance schedule with a planning horizon of two to three months. This schedule might be changed later due to sudden failures or maintenance that is not finished on time. Scheduling is done on expert opinion, since AIS does not have planning software available. The several maintenance jobs are grouped in an appropriate way by common sense. The earliest due item with the current flight schedule is checked and then, the CAMO-manager (CAM) inspects the other items that are nearly due. There is no data on how long each job will take and how expensive it is. The CAM has experience in the maintenance of the Jetstream 32 aircraft and knows how long a job will take on average. The planning relies completely on the expertise of the CAM regarding maintenance duration, costs and required set-up tasks.

2.2.2. Operations airline

The operations airline department has the responsibility to schedule the aircraft, whilst it meets the requirements of the maintenance schedule. Aircraft cannot be designated to a route if components are due and must be inspected. The task of operations is to make sure the aircraft have a determined schedule and are at the required locations in time. This means allocating an aircraft to a predetermined route or making sure an aircraft is at a maintenance location in time. The main challenge for operation is to make sure that the aircraft do not exceed the due dates of its components. Good communications with CAMO are key in scheduling the aircraft. Aircraft might fly more hours of make more cycles on different routes and might therefore need maintenance earlier than others. The art in planning is to make sure the maintenance schedule and the flight schedule are synchronized.

2.2.3. AIS Technics / Stores

AIS Technics is the department that carries out the maintenance. The job orders are sent from CAMO to Technics and there, the jobs on the job orders are carried out. The maintenance-manager makes the personnel schedule and makes sure that there are enough engineers to work on an aircraft. When there is not enough manpower available, this is communicated back to CAMO to adjust the maintenance schedule. AIS technics is also the department that takes care of the necessary parts that are needed for maintenance.

2.3. Fleet

As said before, the CAM creates an appropriate maintenance schedule with his expertise in maintenance for a Jetstream 32 Aircraft. AIS possesses 8 of these aircraft, for which maintenance must be planned. Besides the fleet of the airline, AIS Flight academy possesses 12 Socata TB-9 Tampico and one Cessna T303 Crusader. The maintenance of these aircraft is done in the same location and also by the technics department that also maintain the Jetstream 32 models. The aircraft from the airliner always have a priority to do maintenance. Since students can be rescheduled easily, but when flights are being cancelled due to a broken aircraft, income is missed and AIS might even get penalties. In this thesis we will only focus on the aircraft of the Airliner, the eight Jetstream 32's.

There are seven operational aircraft:

- PH-BCI
- PH-DCI
- PH-FCI
- PH-HCI
- PH-NCI
- PH-OCI
- PH-RCI

There is one aircraft that is currently being cannibalized:

- PH-CCI

Figure 3: An AIS-owned Jetstream 32 turbo-prop

2.4. Aircraft Maintenance Structure

2.4.1. Maintenance tasks

The Jetstream 32's have many maintenance jobs that have to be performed. These maintenance jobs can be divided into two types: major inspections and out-of-phase tasks. The major inspections are predetermined maintenance packages which must be executed after some interval, mostly based on flight hours. We can distinguish 7 different major inspections:

- 200 flight hours inspection
- 400 flight hours inspection
- 800 flight hours / 1-year inspection
- 2000 flight hours inspection
- 2400 flight hours inspection
- 4000 flight hours inspection
- 8000 flight hours inspection

Besides these major inspections, we have 300 out-of-phase tasks. These out-of-phase tasks are exactly what they are called. These tasks do not phase well with the predetermined major inspections and therefore must be planned individually around these major inspections. These tasks must be executed after some number of flight hours, flight cycles or at some monthly interval. In total, we have a list of 307 maintenance activities that must be planned.

2.4.2. Setup tasks

Maintenance tasks need preparatory setups. The first and main setup task that is necessary for every job is the flying to Lelystad. Flying to Lelystad does not immediately sound like a setup task, as it does not directly relate to a maintenance activity, but it is necessary before maintenance can be executed and thus can be seen as a setup. For every maintenance job, the exact steps that should be performed can be found in the maintenance manual. The maintenance manual is available to the engineers at AIS and is written by BAE-Systems, the manufacturer of the Jetstream 32. This maintenance manual is very extensive, and engineers only look up information on some specific task. For now, AIS does not have the major setup tasks distinguished yet. After interviews with the CAMO-manager and the maintenance manager, only 4 setups that are worthwhile can be connected to the maintenance jobs:

- Flying to Lelystad
- Non Destructive Inspections (NDI's)
- Access below floor area
- Open passenger door

There are many smaller setup activities, for which some jobs need the same setup. Unfortunately, AIS does not have these setups clearly distinguished and connected to the corresponding maintenance jobs. The setups can be found in the maintenance manual and in the future, more smaller setup tasks that can affect the maintenance planning should be identified. For example, a certain panel must be opened to reach some parts. If maintenance can be done for these parts, it might save a small amount of time. And many small-time savings can result in a significant decrease in maintenance costs.

2.5.Routing and flight schedule

AIS currently has six different routes its aircraft are flying. Five of these flights are in Sweden, one of them is in Germany. These different routes can be seen in Table 1 and Figure 4. The expected number of flight hours (FH) per route per week can also be seen in this table, and the expected number of flight cycles (FC) per week as well. The aircraft are allocated to one of these routes and there are no pre-designated combinations of route and aircraft. These aircraft are allocated to a route every few weeks and this is all subject to the maintenance schedule that is created before. This flight schedule is made by operations airline. There are some communication issues between CAMO and operations. This might result in unforeseen, sudden changes in flight schedule, might mess up the maintenance planning. When an aircraft gets transferred from the *Borlange Airport - Gotenburg-Landvetter Airport* route to the *Borlange Airport - Orebro Airport - Mora Airport* route for example, some tasks will be due way earlier than anticipated. In a situation like this, dynamic clustering of maintenance activities might be useful to create new maintenance schedules very quickly.

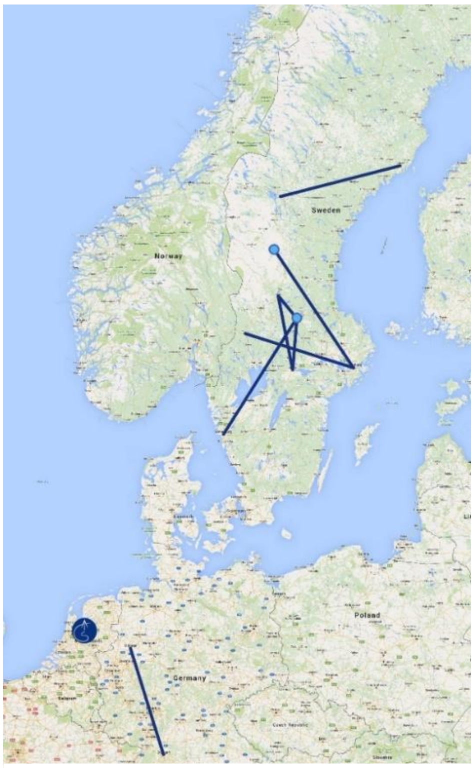

Figure 4: AIS routes and maintenance stations

Route	Hours per week	Landings per week (Cycles)
Borlange Airport - Gotenburg-Landvetter Airport	15:00	18
Borlange Airport – Orebro Airport - Mora Airport	24:00	36
Ostersund Airport – Umea Airport	13:20	20
Torsby Airport – Hagfors Airport - Stockholm Arlanda Airport	16:40	40
Munster Osnabrück Airport - Stuttgart Airport	21:00	18
SVEG Airport - Stockholm Arlanda Airport	22:00	24

Table 1: Routes of AIS Airlines

After a pilot finishes a flight, he or she always must fill in an AFL (Aircraft Flight Log). On this AFL the flight times are registered and added to the total time that the aircraft has flown. The AFL's are filled in by the pilot and checked by the operations department. The AFL is filled in by hand, which might cause an error as the handwriting might be unclear. It is quite important that these values are right, as the aviation authorities might check the correspondence between the number of flight hours in the maintenance system and the aircraft itself.

The flight schedule is made in RAIDO (Rule based Automated Integrated Dynamic Optimization), which is the airline management system AIS Airlines uses (Figure 5).

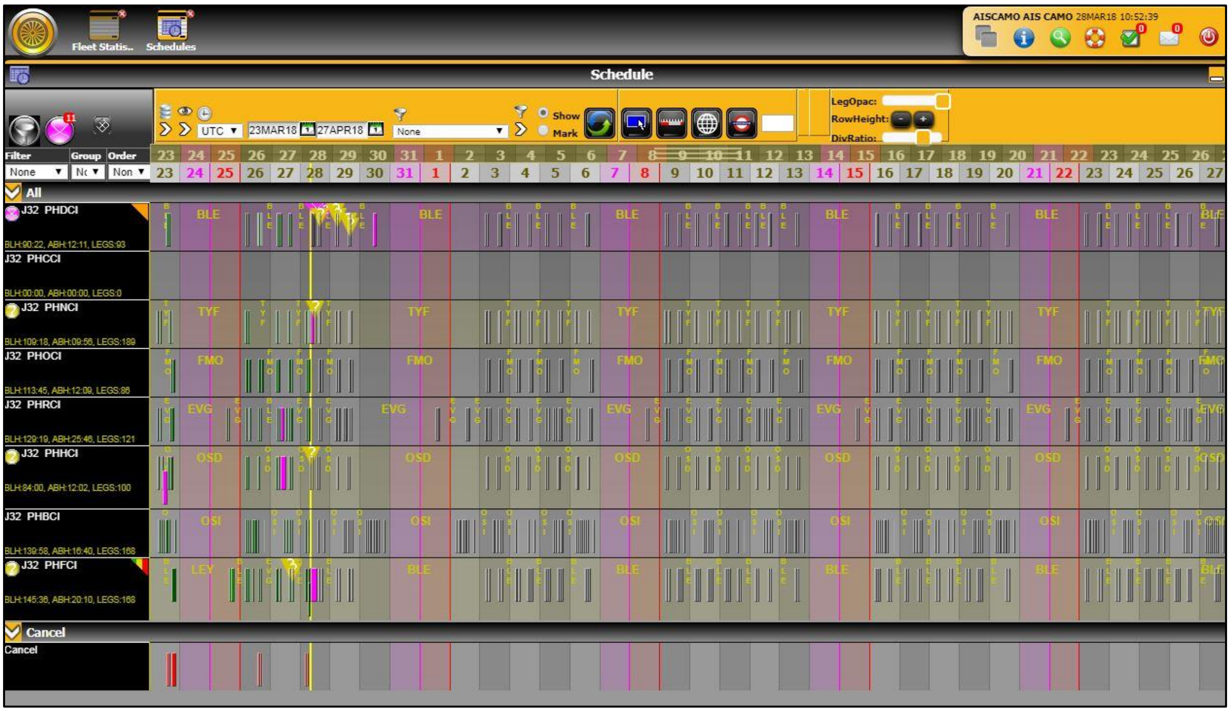

Figure 5: The dashboard of RAIDO, the routing software used by AIS Airlines

As can be seen in Figure 5, the 8 Jetstream 32's are on the left of the window. For the next couple of weeks, the flights can be seen for every aircraft as every bar represents one flight. On the bottom are the number of cancelled flights. These cancelled flights are due to necessary maintenance that causes an aircraft to be grounded. The goal of the flight- as well as the maintenance planning is to have this bar as empty as possible. One thing that should be noticed is that most flights are on the weekdays and there are almost no flights on the weekends.

The flight times are updated by operations after each day and RAIDO then creates a flight report per day. This way, the total flight hours and cycles can be extracted in the maintenance system by the CAMO-manager. The CAMO-manager will check Raido every day to check the flight schedule and in combination with the incoming AFL's the correct flight hours of flight cycles will be subtracted from the remaining time left on the maintenance jobs.

2.6. Line vs Base Maintenance

In aircraft maintenance, two types of maintenance can be distinguished: base maintenance and line maintenance. Line maintenance should be understood as any maintenance that is carried out before flight to ensure that the aircraft it fit for the intended flight. The most common maintenance jobs that are included in line maintenance are:

- Troubleshooting

- Defect rectification

- Component replacement with use of external test equipment, if required.

- Scheduled maintenance and/or checks including visual inspection that will detect obvious unsatisfactory conditions/discrepancies but do not require extensive in-depth inspection. It may also include internal structure, systems and powerplant items which are visible through quick opening access panels/doors.

- Minor repairs and modifications which do not require extensive disassembly and can be accomplished by simple means

- For temporary occasional cases (Airworthiness Directives (AD's), Service Bulletins (SB's)) the quality manager may accept base maintenance jobs to be performed by a line maintenance organization provided all requirements are fulfilled.

Every maintenance job falling outside the above criteria can be seen as base maintenance. Base maintenance is typically more extensive than line maintenance. Base maintenance is performed at a maintenance base and is always planned beforehand. Roughly said, base maintenance is all preventive maintenance done for the aircraft and line maintenance is all corrective maintenance. Due to the highly regulated maintenance for aircraft, the major components are checked very often, and high reliability of these components is ensured. Because of this, there is often no major corrective maintenance necessary and the smaller corrective maintenance can often be done pre-flight or at a nearby line maintenance base.

The base maintenance that is done for the aircraft of AIS is performed at Lelystad Airport, at the headquarters of AIS. The larger maintenance items are performed here and a part-145 certified maintenance hangar is available. Beside this facility, AIS has two bases for line maintenance, in Östersund and Borlange and there is a caddy available to go to Münster/Osnabrück for line maintenance.

2.7. Maintenance Planning

The maintenance that is planned for the aircraft are completely done on expert knowledge of the CAMO-manager and no planning methodologies are being used yet. The CAMO-manager does use software to keep track of the several maintenance jobs, for which the dashboard can be seen in Figure 6.

Figure 6: The maintenance management system of AIS Airlines

In this software package, the several aircraft can be seen on the left. In the main window, in the main window, the due list can be seen with all maintenance jobs for the selected aircraft. These jobs all have some minimal maintenance frequency in flight hours or cycle limit. As can be seen in Figure 6, as well as in Appendix 1, most items have one or the other. Some items do have both a minimal frequency in flight hours and a cycle limit as well though. From this maintenance management system, job orders can be created to be sent to technics. The completed job orders get processed by the software package and the remaining time will be updated. On the other hand, the flight hours and cycles are input for the software and are subtracted from the remaining time. The items that are due soon are in the top of the due list, and the less urgent the item is, the lower it is in the due list.

The maintenance jobs are all defined by an action-type. There are 14 different action-types to be identified, which can be seen in Table 2: The different action types

Action Type	Description
Adm	Administrative
ARC	Airworthiness Review Certificate
CHK	Check
CPCP	Corrosion preventive & control program
DVI	Detail Visual Inspection
FC	Functional Check
Hydro	Hydrostatic
INSP	Inspection
Life Limit	Life Limit
NDI	Non-Destructive Inspection
OH	Overhaul
REPL / Replace	Replace
SER	Service
W&B	Weight & Balance

Table 2: The different action types of the maintenance jobs

These codes are given by the manufacturer of the corresponding parts and are describing the general maintenance activities that should be performed on the components. AIS must describe these action types in their maintenance system and the action types give a very basic description of the maintenance job.

Depending on these basic descriptions, giving extension to a job might, or might not be allowed. Basic inspections can get extension which allows AIS to perform maintenance on a later moment. This might give more options to create an improved maintenance schedule. When an inspection is executed while given extension, the next execution of the inspection will not move to a later moment. Thus, giving extension to a certain maintenance job will not influence the next execution of the job. This can be seen as an example in Figure 7.

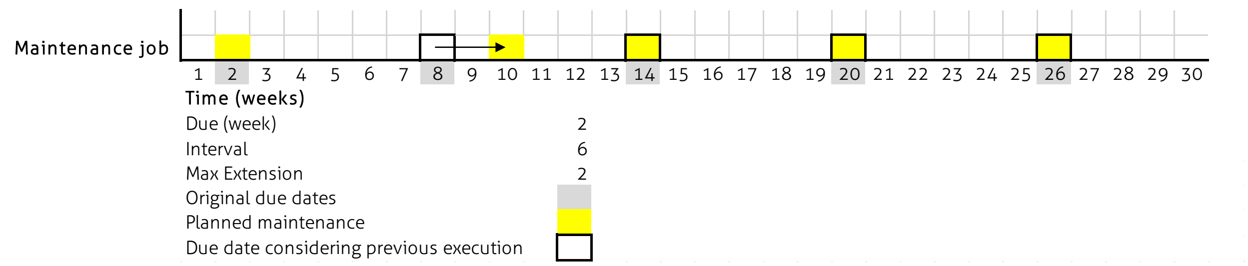

Figure 7: Example of due dates on extension given

From the due list, the CAMO-manager will create a maintenance schedule. Due to the earlier mentioned communication issues between CAMO and operations, planning maintenance in the long term is not effective, as too much will change in the flight schedule over time. As for now, the maintenance planning is made for two to three months and might still be subject to small changes in these months.

The CAMO-manager will check all the items that are due in this period. The major inspections like a 200-, 400- or 800-hour inspection will be taken as main indicator when maintenance for a certain aircraft has to be performed. Multiple other smaller checks might also be done in the time near to the larger checks. It is the CAMO-manager his job to cluster, with his expert opinion, the maintenance jobs into a package of maintenance jobs to be performed. The CAMO-manager will make the decision to bring jobs forward, wasting some lifetime of the component. The CAMO-manager also has the opportunity to give extension to some maintenance jobs, allowing them to be performed later in time. As for now, no specific methods are used to create optimal maintenance schedules. The CAMO-manager creates these schedules solely on his personal experience. When the CAMO-manager is finished clustering the maintenance activities, he hands over the schedule to operations airline and technics. An example of such a maintenance schedule can be seen in Figure 8. It can be seen that for each week, one or multiple aircraft are scheduled for maintenance. The aircraft registration-code can be seen, together with the larger checkups. For some aircraft, notes are added with additional maintenance jobs that must be performed next to these major checkups.

Upcoming Maintenance **16-4-2018**

Date	A/C	Maintenance Location	A/C	Maintenance Location	A/C	Maintenance Location	A/C	Maintenance Location
21-4-2018	PH-OCI 200+400+800+1200+1Y + Note 1	Lelystad	PH-BCI LH&RH Nozzles change	Lelystad				
5-5-2018	PH-NCI 200+400 + Note 2	Lelystad						
12-5-2018	PH-BCI (With Extension) 200 + Note 3	Lelystad						
19-5-2018	PH-FCI 200+400+800+1200+1Y + Note 4	Lelystad						
26-5-2018	PH-DCI 200+400 + Note 5	Lelystad						
2-6-2018	PH-HCI (With Extension) 200+ Note 6	Lelystad						

Figure 8: Example of a maintenance schedule

As the dates where maintenance should be performed get closer, the CAMO-manager will create job orders for the technics department with all jobs described that can also be found in the maintenance schedule. These job orders are usually more detailed than described in the schedule and include part numbers, serial numbers, parts and equipment necessary. Technics will then perform the maintenance as is described on the job order and will send the completed job order back to CAMO. After every job has been checked, the aircraft may be released. The flowchart of maintenance activities can be seen in Figure 9.

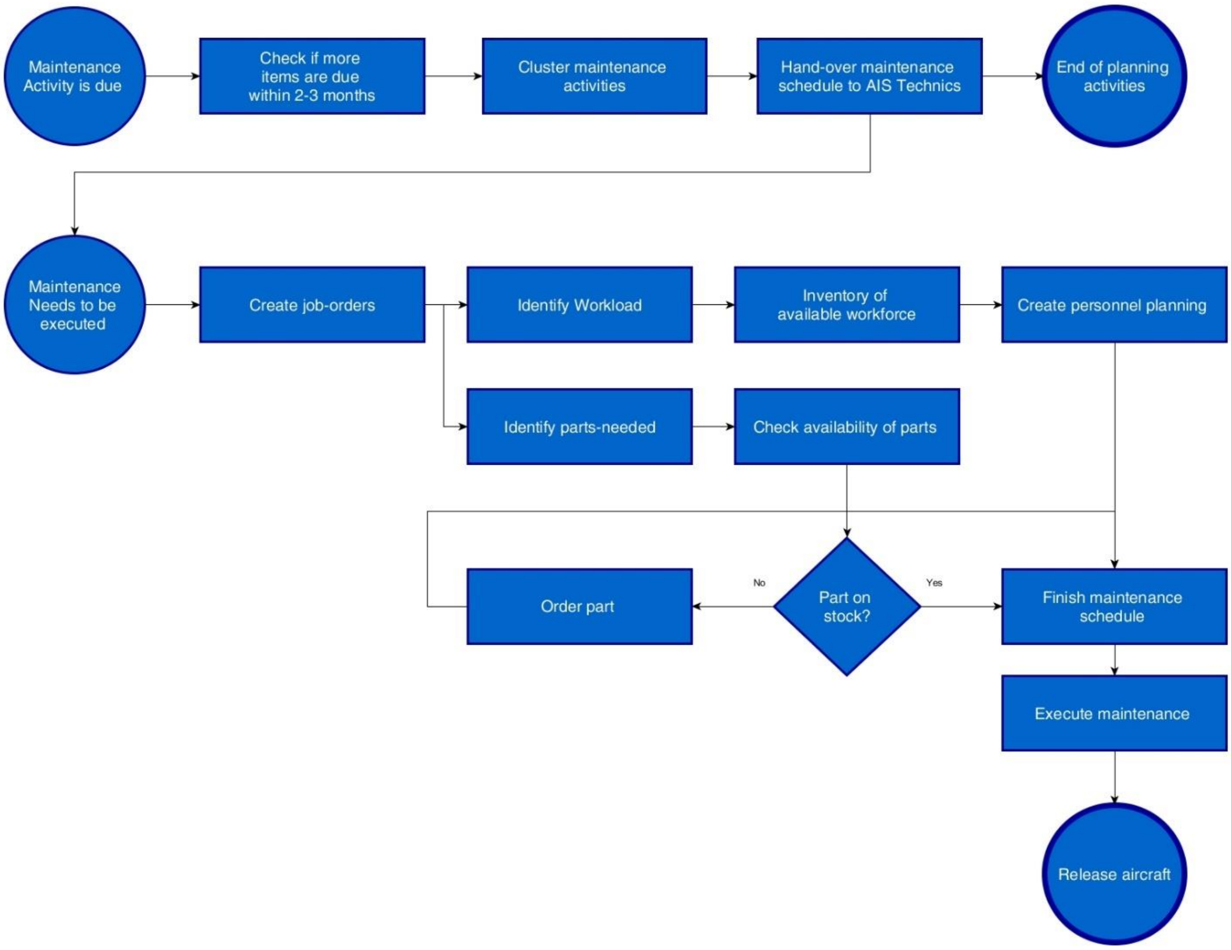

Figure 9: Flowchart of maintenance activities

2.8. Conclusion

In this chapter, we gave an overview of the current situation regarding maintenance at AIS Airlines. After analyzing the current maintenance activities, we can answer the first sub-question that is described in 1.6.

There are three departments involved with the maintenance of aircrafts at AIS Airlines. The main department is the CAMO-department, which creates the maintenance schedule. Next, we have the Technics department, which actually performs the maintenance. Finally, we have the Operations department, which creates the flight schedule. This flight schedule affects the maintenance planning.

The fleet of AIS Airlines consists of eight Jetstream 32 turbo-props. One of these aircraft is currently being cannibalized and is completely out of the picture. Still, seven of the aircraft are operational, for which maintenance has to be planned. The maintenance jobs consist of seven major inspections and around 300 out-of-phase tasks. The main setup task is flying the aircraft to Lelystad and there are three other secondary setup tasks identified: Non-destructive inspections, access below floor area and open the passenger door.

These maintenance tasks all have an initial due date, maintenance interval and maximum extension that characterize the maintenance planning for each individual task. All of these characteristics are influenced by the flight schedule as they depend on the number of flight hours/cycles that have been flown.

The CAMO-manager plans all of the maintenance activities around the major inspections. Normally, the 200-hours inspection is done every 2-3 months and all the out-of-phase tasks are planned around these inspections.

3. Literature Review

3.1. Introduction

In this chapter we will discuss the relevant literature and we will give a short review of what was found. We mainly used Google Scholar to find appropriate literature and started out with the SPICE methodology. The Setting, Perspective, Intervention Comparison and Evaluation were considered to search for the first articles. This first step resulted in multiple articles on multi-component maintenance methods and other literature reviews. From these articles, references were also used to find other useful articles. There are a lot of articles found on general creation of maintenance models, which is beyond the scope of this research. Instead, we try to focus on the literature on multi-component maintenance systems that are related to aircraft maintenance and can be applied to the situation of AIS. The research on multi-component maintenance systems is unfortunately not very extensive and only a few articles were found that addressed this. Kobbacy et. al. (2008) stated in reference to models that consider multiple set-up activities over a finite horizon: "We have found one article in this category… this is the first attempt to model a maintenance problem with hierarchical set-up structure." This is the article of van Dijkhuizen et al. (1997). where these models are discussed for multi-component maintenance models for common set-ups and shared set-ups. We will first discuss general maintenance models and maintenance model development, then we will discuss several models that were found that help model the maintenance activities mathematically. Finally, we will link the literature to the rest of the thesis.

3.2. Overall Maintenance Concepts

Essentially, the maintenance concept of a technical system is the set of directives describing maintenance to be carried out (Gits, 1992). In the early days, maintenance was not something that needed much attention. Maintenance was a necessary evil and was only necessary as a breakdown occurred. The consequences of maintenance were not that impactful, and repairs were relatively simple. Nowadays, systems got way more complex and the impact of breakdown much greater. For example, an aircraft that is grounded due to a breakdown may cost the airliner tens of thousands of euros per day. The maintenance itself got more complicated as well and had to be planned very well and complex models have been developed for this purpose. In the field of operations research, maintenance models mainly aim at optimal decisions on activating maintenance demand (Gits, 1992).

3.3.Maintenance Concept Development

A maintenance concept can be defined as the set of various maintenance interventions (corrective, preventive, condition based, etc.) and the general structure in which these interventions are foreseen (Pintelon and Waeyenbergh, 1999) Gits (1992) and Waeyenbergh and Pintelon (2002) discuss the design of maintenance concepts.

Gits describes maintenance as the total of activities required to retain the systems in, or restore them to the state necessary for fulfilment of the production function. (Gits, 1992) Retaining corresponds to preventive maintenance and restoring to corrective maintenance.

In the development stage of a maintenance plan, data is one of the most important requirements, and gathering it is one of the most difficult jobs (Pintelon and Waeyenbergh, 1999). Two types of data are distinguished here: First level data and second level data. Pintelon et. al describe first level data as data recorded as part of the system installation and second level data as data recorded during the chain of normal work. The first level data is usually quite easy to obtain from the supplier. Second level data is more difficult to obtain, as it comes from experience and databases. This kind of information is difficult to gather, structure and analyze.

Gits describes 5 requirements of a maintenance concept:

3.3.1. Effectivity

The effectivity of a maintenance concept is measured by the correctness at the time (potential effectivity) and its physical effectiveness (technical effectivity).

potential effectivity is the link between the failure behavior of a system and the start of maintenance activities. In more simple terms, it is when maintenance should be initiated, depending on the state of the system. There are three types of maintenance initiation to be distinguished, namely failure-based maintenance, use-based maintenance and condition-based maintenance.

Technical effectivity is the physical result of a maintenance activity, where two types of maintenance activities are distinguished, namely inspection and repair. Where inspection is defined as assessing the value of a prognostic characteristic and comparing the assessed value with a predetermined one. Repair is defined as the altering of an existing state of the technical system to the original one.

3.3.2. Efficiency

There are two types of efficiency to be distinguished:

3.3.2.1.Individual Efficiency

Individual efficiency relates to the reduction of failure consequences against the cost of maintenance in accordance to a certain maintenance rule. This means that maintenance rules might lower the number of occurring failures, but this will require more inspections, which will cost more money. In failure-based maintenance, there is no tradeoff as all maintenance is corrective. Use- and condition-based maintenance will have to set a certain norm when maintenance will be initiated, the setting of this norm will be the tradeoff between failure reduction and maintenance costs.

3.3.2.2. Combinatorial efficiency

Combinatorial efficiency relates to the trading off of benefits accruing from simultaneous execution of individual maintenance operations against increased frequency of demand for some of these operations. This means that multiple maintenance operations could be exceeded together in order to only having to do the mutual set-up activity once. This will reduce the number of times the set-ups have to be performed, but results in a higher frequency of which a component will be inspected/repaired.

Overall, the final efficiency of a maintenance concept results from the tradeoff between the maintenance effort and the reduction of failures

3.3.3. Safety

Governments and Insurance companies often induce safety regulations to systems with very hazardous consequences on failure. The reliability of these systems should be very high to ensure failures will occur as little as possible. Certain failures will have to be considered when setting up the maintenance concept. It also dominates the decision of the minimal frequencies of certain maintenance jobs in use-based and condition-based maintenance.

3.3.4. Continuity

The systems that must be maintained should be interrupted as little as possible to ensure maximum availability. It follows that continuity of a system requires preventive maintenance to ensure the minimization of failure occurrences. Furthermore, preventive maintenance should be done during the nonproductive periods in the production pattern (Gits, 1992).

3.3.5. Controllability

The controllability of maintenance follows on the regularity of maintenance demand. The more regular the demand for maintenance is, the easier it is to control the maintenance activities. It implies a preference for preventive maintenance, as preventive maintenance can be planned. Corrective maintenance is only conducted at a system failure. Regularity of preventive maintenance demand refers to the activation of the maintenance demand and the capacity requirements. There are two types of maintenance that can be distinguished in this aspect.

Fist, periodic maintenance refers to maintenance jobs carried out at the same intervals (or periods) of time. It requires the intervals to be at integer times the period. Cyclic maintenance is when groups of maintenance jobs are carried out at equidistant times.

3.4. Optimal clustering of maintenance operations

In literature, much attention has been paid to the planning of preventive maintenance jobs, where correlation between various jobs is essential in view of set-up avoidance. The whole maintenance system, with all correlations between maintenance jobs have to be identified (van Dijkhuizen et. al., 1997). To cluster the maintenance jobs optimally, mathematical models are applied create sufficient solutions. One of the problems encountered in practice,

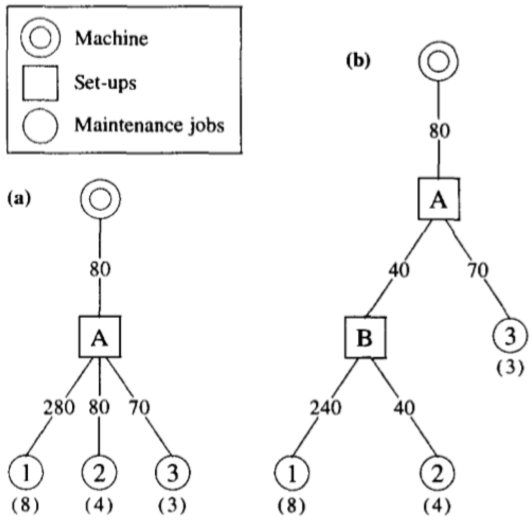

Figure 10: Common- and shared setups

is that for large numbers of components, mathematical models are difficult to analyze (Vanneste, 1992). These optimal models are often too difficult to implement in real-life. Therefore, a decomposition of the problem is necessary, where the outcome of simpler models is used as inputs for more comprehensive models.

There are two types of maintenance systems that can be distinguished, namely maintenance for a system with identical set-ups (common set-ups) and systems for which not all operations share the same set-up activities (shared set-ups). An example can be seen in Figure 10. These partially identical set-up activities are called shared set-ups. Nowadays, systems get more and more complex. Systems consist of subsystems, which consist of assemblies, which consist of several parts. This means that maintenance operations of certain parts do not have the same set-up activities. The assumption that modern, complex systems have common set-ups is therefore incorrect in most cases. Van Dijkhuizen states that the assumption of common set-ups cannot sustained, as production systems become more and more complicated.

Van Dijkhuizen et. al propose models to create appropriate clustering solutions for common- and shared set-up maintenance systems. First, he describes a dynamic programming algorithm for common set-up problems and a greedy heuristic and a branch and bound algorithm is presented for a clustering problem with shared set-ups.

In the case of common set up, the best clustering solution is computed by evaluating all clustering possibilities with the lowest frequencies and then adding the next lowest operation with the lowest frequency to the evaluation. First, the maintenance operations are sorted by frequency, and the operations with the same minimal frequency are added together, because the operations have to be performed equally often. When first considering the first operation, the best cluster is easily found, because it can only contain operation 1.

The next iteration, the next operation is added to the evaluation and with the output of the earlier done iteration, a new clustering iteration is made. This continues until all maintenance operations are taken into consideration. In the case of a shared set-up structure, a similar way of clustering is described. Also, a branch and bound algorithm is described to come to a sufficient clustering of maintenance operations

In this brand and bound approach, first, an initial solution is created with each job in a separate cluster. Then, in each iteration of the heuristic, the two clusters that reduce the total costs the most when combined, are united. Then, the next node is selected. The selection rule, which dictates on what node to iterate next, tells us to select the node with the best lower bound at the deepest level of the branch and bound tree. Several dominance rules are described as well to, as Jouglet et al. (2011) describes: to reduce, either statically or dynamically, the search space of combinatorial problems which are in the process of being solved.

3.5. The Cycle Rounding Algorithm

Levi (Levi et. al., 2014) discuss two maintenance management models for modular systems. The components have respective cycle limits and must be maintained before this limit is exceeded. The goal of the two models is to minimize the preventive maintenance cost of multi-component systems.

First, they discuss a cycle rounding algorithm, that generate easy-to-compute cyclic policies. The system first is described in a dependency tree model which describes all system components and modules, up to the root node which is the entire system. Each leaf of the dependency tree corresponds to a component and each node is a module. The dependency path P_i of each component corresponds to the shortest path connecting the component to the root. The residual path R_i consists of all modules that are on the dependency path, excluding those that are on a dependency path of lower indexed component $1, \dots, i-1$. Sort all components $i \in C$ on their cycle limits $f_1 \leq \cdots \leq f_{|c|}$. Then calculate the cycle rounded frequency f_i^{CR} by applying the cycle rounding algorithm:

$$f_i^{CR} = \left\lfloor \frac{f_i}{f_{m(i)}^{CR}} \right\rfloor \cdot 3.5. f_{m(i)}^{CR} \quad (1)$$

Where $m(i)$ is the predecessor of i. You start with the first component for which $f_1^{CR} = f_1$, the cycle rounded maintenance cycles of the next components can be calculated with formula 1.

3.6. Shifted Power-Of-Two Policies

Next to the Cycle rounded algorithm, Levi et. al describe a shifted power-of-two policy that schedules the maintenance job at a power-of-two times a base value $\delta \in [1, 2)$. This causes the schedule to become nested. For a given value of δ, a rounded cycle limit $f_i^{\delta} = \delta \cdot 2^k$, for which k is a positive integer for which $\delta \cdot 2^k \leq f_i < \delta \cdot 2^{k+1}$. For a δ of 1 for example, the rounded cycle limits can only be at 1, 2, 4, 8 etc. Each maintenance job has its own k_i for which the above inequalities counts. The value of this integer will depend on the minimal frequency of the individual maintenance job.

This algorithm is guaranteed to give solutions to have a cost of $1/\ln(2) \approx 1{,}44$ of optimal for infinite horizon instances. The δ can be incrementally increased sufficiently small that the new cycle limits are still feasible until one f_i^{δ} equals an f_i. This way, the maintenance policy is shifted towards the largest possible cycle time possible with the maximum cycle times given.

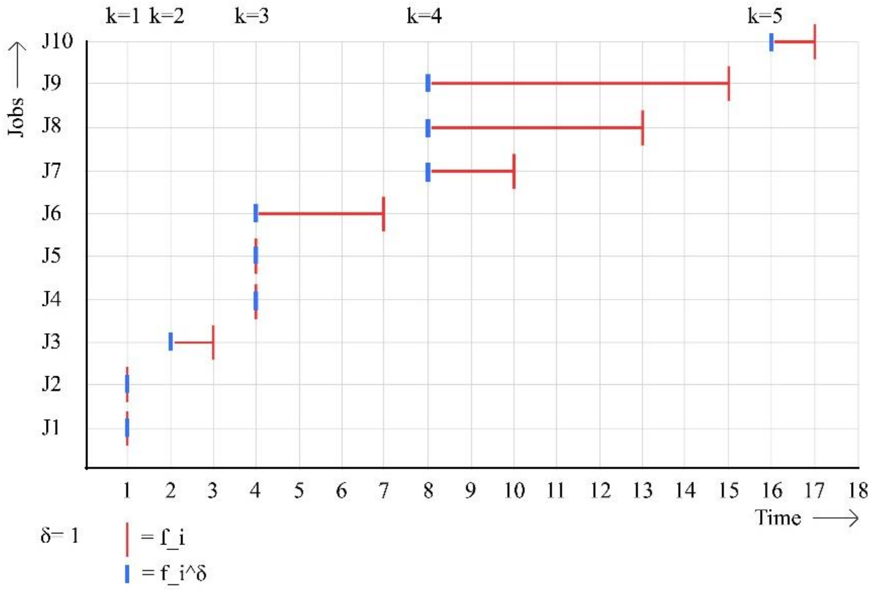

Figure 4: Example power-of-two policy

Note, that the cycle times found by this algorithm may result in fractional cycle times which can be used only in continuous time. In real-life, these cycles will not work due to the fractional nature of the cycle time. Maintenance will be performed only at integer times a period, for example each day, or each week, not every 1,234... weeks Levi also describes an easy rounding procedure to convert the continuous time cycle times to discrete time periods.

3.7. The preventive maintenance scheduling problem

Budai (Budai et.al., 2006) developed a model to schedule preventive railway maintenance. The situation in railway maintenance is similar to the performance of maintenance at AIS. In this article, the PMSP (preventive maintenance scheduling problem) is introduced. In contrast to the models described before, this model considers not only cyclic policies, but also non-cyclic policies. Budai describes the PMSP as follows: Given a set of routine activities and projects, we like to schedule them such that the track possession costs and maintenance costs are minimized. Some routine works and projects may be combined to reduce the possession time, but others may exclude each other. On first sight, the model looks similar to the machine scheduling problem or multi-project scheduling. The difference between these models is that the jobs in the PMSP is that they have a repetitive character.

The model considers a set of projects and routine maintenance works. It is defined which maintenance tasks can be combined and which tasks cannot be combined. For each Job, the cycle length is known, and the frequency can be calculated. An ILP model is created that schedules the maintenance jobs accordingly. The cost function reviews the solution by three terms: The maintenance costs, the possession costs (cost of using a track for maintenance) and the end-of-horizon effect.

3.8. PMSM and RPMSM Heuristics

Budai et al. (2005) describes four different heuristics regarding the PMSP (preventive maintenance scheduling problem) and the RPMSP (restricted preventive maintenance problem).
The RPMSP is basically the PMSP with the difference that all executions of maintenance for all jobs is exactly the maintenance cycle length, these executions cannot be moved forward. The other difference is that in the first planning cycle (before d_j) the number of executions for job j is exactly 1.

Budai describes four heuristics, for which the first two are to solve the RPMSP and the last two are to solve the PMSP. I'll shortly describe the four heuristics that are described using the following notation:

We are given a set of maintenance jobs $J\ (j_1, \dots, j_n)$ with a certain planning cycle f_j and frequency $F_j\ \forall j \in J$. At the start of planning horizon T there are g_j periods elapsed since maintenance job j was executed in the past. $e_{j,k}$ denotes the kth execution of job j and pc_t is the possession cost for using a track to perform maintenance. This could also be seen as some setup cost that is required to do maintenance. Every job j also has some maintenance cost m_j. In the article of Budai, some jobs cannot be scheduled together. There are also some projects that should be scheduled. To simplify the explanation of the heuristics, we will remove the scheduling parts of these projects, as these are separate from the maintenance jobs.

3.8.1. Single Component strategy

Step 0: For every job, make an individual schedule such that the sum of the possession cost, maintenance cost and penalty paid for late execution per time horizon T is minimized. There is not being looked at the reduction of costs by combining maintenance executions and thus reducing possession costs. In the article of Budai, some jobs cannot be combined and thus might not be scheduled together.

Step 1: The scheduling of projects, with the earliest possible starting time. We will not elaborate any further on the scheduling of these projects.

Step 2: Calculate the overall costs resulting step 1 and 2.

3.8.2. Most Frequent Work First Heuristic (MFWFH)

Step 0: Order the set of jobs such that the planning cycles are in increasing order: $f_1 \leq f_2 \leq \dots \leq f_3$.
Schedule job 1 at its maximum interval, that is, in periods $1, 1 + f_j, 1 + 2f_j, 1 + 3f_j, \dots$

Step 1: (For $j = 2, \dots, n$) schedule the maintenance jobs such that the sum of all costs is minimal. The first execution of job j should be in the period $[1, f_j - g_j]$. In the article of budai, some maintenance jobs are not allowed to be scheduled together. This should be taken into consideration when scheduling the jobs.

Step 2: The allocation of projects, as soon as possible, as much together as possible with already planned maintenance jobs.

Step 3: Repeat step 1 and 2 for all values where job 1 can be carried out for the first time, namely in the period $[1, f_1 - g_1]$. The schedule with the minimal costs is chosen.

3.8.3. Opportunity Based Heuristic (OBH)

Step 0: Order the set of jobs such that the planning cycles are in increasing order: $f_1 \leq f_2 \leq \dots \leq f_3$.
The execution times of the most frequent job give the initial values of the opportunities' list, $Opp = \{e_{1,1}, e_{1,2}, \dots, e_{1,F_1}\}$.

Step 1: (For $j = 2, \dots, n$ and for all execution times of job k) If a given execution time of job j, $e_{j,k}$, is not yet in the Opp list, then a consideration has to be made whether it is cheaper to move the execution forward to the closest possible opportunity is cheaper than the cost of a new possession (moment of maintenance execution).

If $\frac{m_j S}{f_j} > pc_j$,where S is the number of periods between the current execution time and the closest earlier possibility, then a new opportunity is created and $e_{j,k}$ is added to the opportunity list.

If $pc_j \geq \frac{m_j S}{f_j}$, then it is cheaper to move the execution of the maintenance job to the closest earlier opportunity.

A few things have to be taken into consideration at this point. When a job is moved to an earlier moment, as more executions might fit in the planning horizon at this point and these should be added to the schedule. Also, if there are more than two executions in $f_j + 1$ consecutive periods, the middle execution can be deleted.

Step 2: Scheduling of projects.

3.8.4. Most Costly Work First Heuristic (MCWFH)

Step 0: Order the set of jobs such that their maintenance cost per planning horizon are in decreasing order, that is $m_1F_1 \geq m_2F_2 \geq \ldots \geq m_nF_n$.

Step 1: Schedule these jobs together with projects, using MFWF heuristic.

Step 2: Execution times of the most costly job and the rounded-down value of the average of its two consecutive execution times give the initial values of the opportunities list, $Opp = \{\left\lfloor\frac{t_{1,1}}{2}\right\rfloor, t_{1,1}, \left\lfloor\frac{t_{1,1}+t_{1,2}}{2}\right\rfloor, t_{1,2}, \ldots, t_{1,F_1}\}$

Step 3: (For $j = 2, \ldots, n$ and for all execution times of job k) If a given execution time of job j is not in the Opportunity-list then $t_{j,k}$ is shifted forward to the closest earlier opportunity even if this leads to a higher overall cost. Sometimes this might not be possible due to a combination which is not allowed. In this case the execution is shifted one opportunity further back if it does not coincide with $t_{j,k-1}$. Again, if there are more than two executions in $f_j + 1$ consecutive periods, the middle one can be deleted.

Step 4: Rescheduling of projects

3.9. Planning Horizon

In his review article on optimal maintenance of multi-component systems, Nicolai et al. (2006) noticed the majority of articles on multi-component maintenance systems assume an infinite horizon. Dekker et.al. (1997) state that models of this kind often consider static rules for maintenance which do not change over time. Often, long-term maintenance frequencies for groups of related activities. In these more static models, there is more focus on preventive maintenance as this can be more easily planned than corrective maintenance. For corrective maintenance, clear rules are set on to handle this.

The more dynamic maintenance models can be divided into two groups: models with a finite horizon and models with a rolling horizon. In finite horizon models, time is discrete and is set for a certain amount, and decision variables are parametrized with time. These models are able to consider more detailed recent information but are not able to look further than the set horizon. Something one can do to still take the future after this planning horizon into account is to incorporate some residual value that describes the quality of the system at the end of the finite horizon.

A combination of a finite and an infinite planning horizon is called a rolling horizon. A rolling horizon is actually a finite horizon, but when implementing a rolling horizon, repeatedly, a schedule will be produced. This happens when new information becomes available that influences the maintenance planning. A new planning horizon will be considered each time. This way, every significant moment that should be considered will cause the planning to look a small amount more into the future. You could say the maintenance schedule is rolling on time.

3.10. Conclusions

In this chapter, we tried to present the current methods on dynamic clustering of multi-component maintenance systems as described in literature. Unfortunately, the amount of literature that describes this subject is not very extensive. Not much literature can be found on maintenance for multi-component systems and much of the described models are static.

Van Dijkhuizen proposes a static clustering heuristic for multi-component systems. Two scheduling methods are presented for common- and shared setups. With these methods, preventive maintenance jobs can be clustered into maintenance packages. These maintenance packages are static and thus will not change with time.

Levi et al. describe two basic scheduling heuristics: the cycle rounding algorithm and the shifted power-of-two policies. Both of these policies generate easy-to-compute maintenance schedules based on the frequency of a maintenance job. These scheduling methods do to consider the maintenance structure of a component, but do not consider the multiple possible setups that might be necessary. Both methods create schedules for an infinite horizon.

Budai et. al. presents the preventive maintenance scheduling problem. She presents a MIP-model to schedule preventive maintenance in railway maintenance. The context of the problem that is presented in the paper is quite similar to that of AIS Airlines. The MIP-model can generate maintenance schedules that do not necessarily have to be cyclic in comparison to the earlier proposed models. In a dynamic environment as the aviation industry, this more dynamic way of scheduling is better suited. The model can be run whenever wanted and thus, schedules can be made on a rolling horizon.

Next to the MIP-model, Budai also proposes four heuristics to create similar maintenance schedules: the single component strategy, the most frequent work first heuristic, the opportunity-based heuristic and the costliest work first heuristic. The single component strategy gives a solution without clustering which plans all maintenance jobs as late as possible. The other three heuristics create proper schedules where clustering is applied.

The models that are described by Budai closely resemble the situation at AIS and we choose to implement and adjust the MIP model to the context of AIS. The model has to be adjusted in a way that possible extension can be given to maintenance tasks. Also, the MIP model as described by Budai only considers a single setup activity (possession cost) and we want to consider multiple setup activities while dynamically clustering maintenance activities. Next, we will implement the single component heuristic and the opportunity-based heuristic to create easy-to-compute schedules with reasonable maintenance costs.

4. Modelling approach

4.1. Introduction

In chapter 3 we discussed several models for clustering maintenance activities. The first models are used for static clustering of maintenance activities and give us an idea of what to look for in a clustering method. Next, we discuss models of Budai (Budai et al.,2005) which describe dynamic modeling of maintenance activities in railway systems. These models describe a similar situation as AIS Airlines has with aircraft maintenance. We will take these models and make some alterations to make it fit the situation at AIS Airlines. Next, we will develop some heuristics to get some easy-to-generate maintenance schedules. In Section 4.2. we will discuss the model sets, parameters and decision variables that are used in the MIP model. In Section 4.3 we will then discuss the MIP-model which describes the scheduling of maintenance activities for one aircraft. In Section 4.4, we will discuss the MIP model which takes all of the aircraft into account, with added capacity restrictions. Then, in Section 4.5 we will describe several heuristics to create quick solutions.

4.2. Model sets, parameters and decision variables

First, we will try to model the maintenance activities of AIS as an MIP model. AIS does not have the software to run the MIP model though. Because of that, the model will be used mostly to benchmark the heuristics that will be described later.

Indices

$a = \{1, \dots, A\}$ $\quad = Set\ of\ aircraft$

$i = \{1, \dots, I\}$ $\quad = \ Set\ of\ preparatory\ set - up\ tasks$

$j = \{1, \dots, J\}$ $\quad = \ Set\ of\ frequency\ constrained\ maintenance\ jobs$

$t = \{1, \dots, T\}$ $\quad = \ Discrete\ time\ periods\ in\ week(end)s\ with\ planning\ horizon\ T$

$nj = \{1, \dots, N_j\}$ $\quad = \left(N_j = \frac{T}{f_j}\right) minimal\ set\ of\ cycles\ that\ fit\ in\ planning\ horizon$

Data

s_i $\quad = setup\ costs\ of\ setup\ i\ \in I$

f_j $\quad = cycle\ time\ of\ maintenance\ job\ j\ \in J$

m_j $\quad = \ costs\ of\ maintenance\ job\ j$

d_{ja} $\quad = \ due\ date\ of\ maintenance\ job\ j \in J\ of\ aircraft\ a\ \in A$

g_{ja} $\quad = \ f_j - d_{ja} =$
$time\ of\ cycle\ already\ passed\ at\ start\ of\ planning\ horizon$

r_j $\quad = duration\ of\ job\ j\ in\ hours$

Z_{ij} $\quad = \begin{cases} 1, & if\ set - up\ task\ i\ is\ necessary\ for\ job\ j \\ 0, & otherwise \end{cases}$

e_j $\quad = max\ allowed\ extention\ given\ for\ maintenance\ job\ j$

b_{ajt} $= \frac{T-t}{f_j}$ = *length of the remaining interval until the end of planning horizon divided by the length of the planning cycle for maintenance job j*

LC_j $= \{t \in T | 1 + |T| - f_j \leq t \leq |T|\} \subseteq T$ *set of time periods from last planning cycle for maintenance job j*

C = *Capacity in number of hours of maintenance that can be planned in a weekend*

K = *Capacity in number of aircraft that can be maintained per weekend*

Decision variables

$$X_{ajt} = \begin{cases} 1, & if\ job\ j\ of\ aircraft\ a\ is\ scheduled\ at\ time\ t \\ 0, & otherwise \end{cases}$$

$$Y_{ait} = \begin{cases} 1, & if\ setup\ activity\ i\ \ t\ is\ planned\ on\ day\ t\ for\ aircraft\ a \\ 0, & otherwise \end{cases}$$

$$W_{ajt} = \begin{cases} 1, & if\ job\ j\ of\ aircraft\ a\ is\ performed\ for\ the\ last\ time\ at\ time\ t \\ 0, & otherwise \end{cases}$$

4.3. Planning per aircraft

To create a solution per aircraft, we will initially not consider the capacity constraints for maintenance planning. By doing this, the individual planning of maintenance for the several aircraft does not influence each other. For each individual aircraft, we will determine when maintenance should be performed to minimize the total costs of maintenance. To create a feasible schedule, we propose the following model:

Cost function

$$Min\ z\ = \sum_{j=1}^{J}\sum_{t=1}^{T} X_{jt} \cdot m_j + \sum_{i=1}^{I}\sum_{t=1}^{T} Y_{it} \cdot s_i + \sum_{j=1}^{J}\sum_{t \in LC_j} m_j\, b_{jt} W_{jt}$$

s.t.

$$\sum_{t=1}^{f_j - g_j + e_j} X_{jt} \geq 1, \qquad \forall\, j \in J \qquad (1)$$

$$\sum_{s=0}^{nf_j - 1 + e_j} X_{j(t+s)} \geq n, \qquad \forall j \in J, n \in N_j, 1 \leq t \leq |T| - f_j + 1 \qquad (2)$$

$$Z_{ij} \cdot X_{jt} \leq Y_{it}, \qquad \forall\, i \in I, j \in J, t \in T \qquad (3)$$

$$\sum_{t \in LC_j} W_{jt} \geq 1 \qquad \forall j \in J,\, t \in T \qquad (4)$$

$$W_{jt} \leq X_{jt} \qquad \forall j \in J, t \in LC_j \qquad (5)$$

$$X_{jt}, Y_{it}, W_{jt}, Z_j \in \{1,0\} \qquad \forall\, i \in I, j \in J, t \in T \qquad (6)$$

Assumptions

The reality of planning maintenance is really complex, too complex to

- *Costs of aircraft returning to Lelystad is not depending on location of aircraft.* In reality, the costs of returning to Lelystad might differ due to longer or shorter distances the aircraft has to fly. The costs might therefore be slightly different. To simplify the model, we assume that the costs of flying to Lelystad is always the same.
- *Maintenance will not be planned on weekdays.* In general, maintenance is always planned in the weekends. On a rare occasion, it might be possible to plan maintenance on a weekday as well, if the aircraft does not have flights scheduled for that day. We will not take these exceptions into consideration.
- *Aircraft have scheduled flights from Monday until Friday.* In reality, flights might be cancelled for some reason, having the aircraft not flying as many hours or cycles. For simplification, we will assume the aircraft fly from Monday until Friday.
- *Flight schedule is fixed.* Aircraft might be swapped to different routes. This could for example be to take over a route of another aircraft because the other aircraft is defect. We will not take these swaps into consideration. If these swaps occur, a new schedule will have to be generated.
- *Maintenance jobs cost the same for each aircraft.* In reality, the aircraft might slightly differ in structure, due to repairs or parts being in other conditions. Because we cannot know beforehand what the differences are for each aircraft, we will assume that every task will take the same amount of time for each aircraft.

Limitations

- *Maintenance cannot be planned on the weekdays.* In reality, aircraft maintenance might be planned on the weekdays following a weekend (for example maintenance is planned Saturday to Monday), if necessary.
- *Capacity restrictions are not taken into consideration.* Due to planning for one aircraft only, the sum of maintenance activities summed over all aircraft might become very high if all maintenance is planned in one weekend. The model does not take into consideration the maintenance planning of other aircraft and thus might plan a lot of maintenance executions on one weekend.

4.3.1. Constraints

Planning interval and Extension

As can be read in section 2.6, there are two types of maintenance tasks to be distinguished. First, we have the visual inspections and checks. For these tasks, no components must be replaced or repaired, no alterations are initially being made to the aircraft. Secondly, we have the maintenance tasks where alterations must be made. The main difference between those two types is that inspections and checks do not have a strict due date and overhauls, CPCP's and other tasks where physical alterations must be made do have a strict due date. These tasks must be performed before the due date is expired, otherwise the aircraft must be grounded until the maintenance task has been performed, also if the aircraft is not at the main maintenance facility in Lelystad. Flying with due items can result in the loss of airline licenses for AIS by the government and thus must be prevented at all costs. The inspections and checks do not have such a strict deadline and might be given extension on their due date.

We will discuss both of the two maintenance types and how to mathematically formulate this regarding scheduling the executions of maintenance.

Type 1 maintenance jobs: overhauls, replacements etc.

We can summarize the characteristics of the type 1 maintenance job as follows:

- Have a hard deadline
- Cannot be given extension
- Can be planned earlier, next maintenance occasion should be planned earlier as well.

Regarding the scheduling of maintenance executions, we can formulate the following two constraints:

$$\sum_{t=1}^{f_j-g_j} X_{jt} \geq 1, \qquad \forall j \in J \qquad (7)$$

$$\sum_{s=0}^{f_j-1} X_{j(t+s)} \geq 1, \qquad \forall j \in J, t = 1 \ldots T - f_j + 1 \qquad (8)$$

In equation 7, X_{jt} is 1 if maintenance job j of aircraft a is planned on time t, f_j denotes the cycle time of maintenance job j. In this equation, maintenance job j should be planned at least once between t=1 and its current due date (maintenance cycle time f_j – cycle time that is already passed g_j). Furthermore, equation 8 describes that for each range of f_j periods, at least one maintenance occasion must be planned for maintenance job j. For example, if $f_j =$ 4, there should be at least one execution in every range of 4 periods. This can be for example the range [1,4] or [13,16] up to $[\mathrm{T} - f_j + 1, \mathrm{T}]$. As can be seen in the figure below, this will cause the maintenance occasions not to be too much apart.

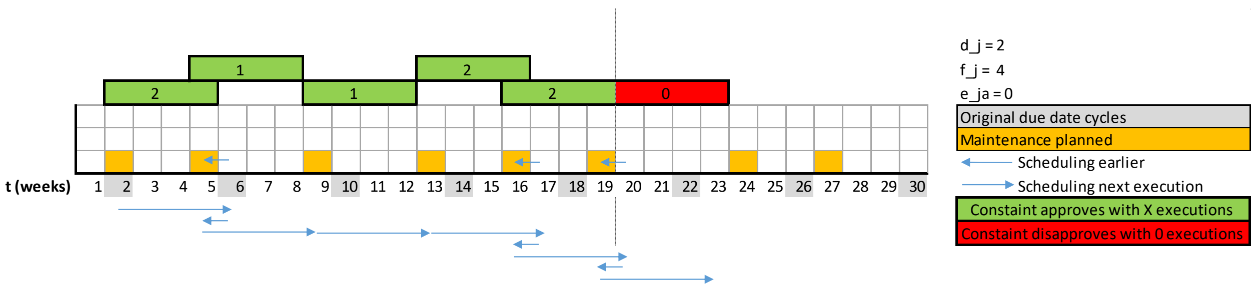

Figure 11: Example of constraint 7

Type 2, inspections and checks

For the inspections and checks, a more difficult situation is at hand. The maintenance jobs not only might be planned earlier then necessary, but these jobs can also be given extension. The deadline of the next maintenance task will stay the same however. Extension might be given again and again, but all deadlines will not move.

We can formulate the type 2 maintenance jobs as follows:

- Have a soft deadline.
- Can be given extension up till some limit.
    - Does not affect next maintenance instance.
- Can be planned earlier, next maintenance occasion should be planned earlier as well, or given extension.

A planning of an inspection with a maintenance cycle of 4 weeks and a maximum extension of 2 weeks might look as follows:

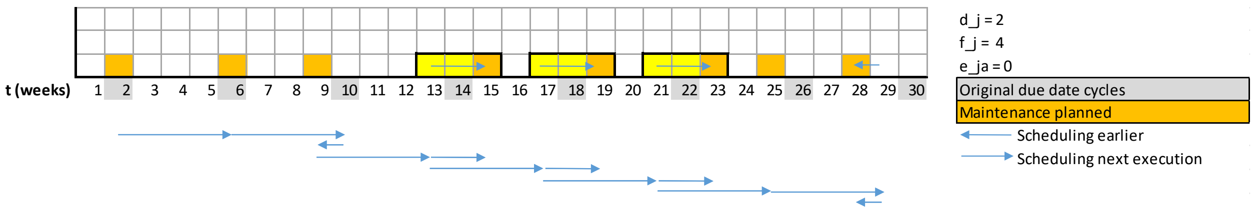

Figure 12: Example of a schedule with extension given

To take the possibility of extension into account, we will alter the first two constraints (7) and (8) by adding the maximum amount of extension e_j of job j. This addition of e_j will work for the maintenance jobs of type 1 as well when setting the maximum allowed extension to 0. For multiple extensions we need another alteration of constraint (8) to consider multiple following extensions.

$$\sum_{t=1}^{f_j-g_j+e_j} X_{jt} \geq 1, \qquad \forall j \in J \qquad (1)$$

$$\sum_{s=0}^{f_j-1+e_j} X_{j(t+s)} \geq 1, \qquad \forall\, j \in J, 1 \leq t \leq |T| - f_j + 1 \qquad (9)$$

To make sure not too much extension is given to a task, the first constraint determines that there must be at least 1 maintenance execution in its cycle f_j plus the maximum amount of extension e_j that is allowed. The next execution however might be given extension as well, and thus there also must be at least two maintenance occasions in the first two cycles plus possible extension. This goes on for as many cycles fit in the planning horizon.

$$\sum_{s=0}^{1f_j-1+e_j} X_{j(t+s)} \geq 1 + \sum_{s=0}^{2f_j-1+e_j} X_{j(t+s)} \geq 2 + \sum_{s=0}^{3f_j-1+e_j} X_{j(t+s)} \geq 3 + \cdots \rightarrow \sum_{s=0}^{n_j f_j-1+e_j} X_{j(t+s)} \geq n$$

$$\sum_{s=0}^{nf_j-1+e_j} X_{j(t+s)} \geq n, \qquad \forall j \in J, n \in N_j, 1 \leq t \leq |T| - nf_j + 1 \qquad (2)$$

Where N_j is the number of cycles of job j that fit in the planning horizon.

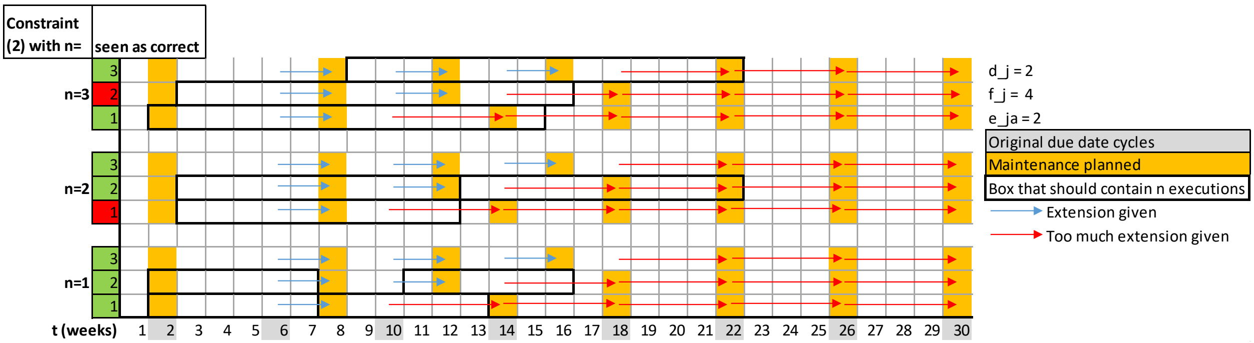

Figure 13: Constraint 2 on wrong schedules

To illustrate this, we will look at Figure 13. The same job with a cycle of 4 weeks with a maximum of 2 weeks extension is planned in 3 different ways, which are all wrong due to excessive extension given to maintenance tasks. As can be seen, when taking constraint 3 with n=1, all three instances are seen as correct, while too much extension is given. This constraint only makes sure that two consecutive maintenance instances are not more than $f_j + e_j$ periods apart from each other. It does not remember whether or not extension is given before. To make sure it remembers whether too much extension is given for two maintenance executions, the constraint with n=2 is necessary. With an n=2, the first instance is deemed wrong, as it should. If one instance of maintenance with the allowed amount of extension is planned after the first extension given, the constraint does not work anymore. Thus, we add another constraint with n=3. This constraint will check if not too much extension is given in the second situation. Overall, we need the full combination of constraints and ranges to check whether or not the schedule is feasible.

Maintenance tasks and set-up tasks

$$Z_{ij} \cdot X_{jt} \leq Y_{it}, \qquad \forall i \in I, j \in J, t \in T \qquad (4)$$

To ensure that the right set-up tasks are done for all maintenance tasks that are planned on period t, constraint 4 will be used. It makes sure that for every maintenance task, the necessary set-up task(s) will be planned that weekend as well. Z_{ij} denotes whether setup i is necessary for job j as the value will then be equal to 1, otherwise 0. X_{jt} is 1 if job j is planned on period t, Y_{it} denotes whether setup i is planned on period t. Constraint 4 makes sure that when job j is planned on period t ($X_{jt} = 1$), and setup i is necessary for job j ($Z_{ij} = 1$), then setup i will also be planned on period t ($Y_{it} = 1$). If either X_{jt} or Z_{ij} are 0, then Y_{it} will also become 0 due to the minimizing objective function.

End of horizon effect

$$z = \sum_{j=1}^{J} \sum_{t \in LC_j} m_j \, b_{ajt} W_{ajt}$$

$$\sum_{t \in LC_j} W_{jt} \geq 1 \qquad \forall j \in J \qquad (5)$$

$$W_{jt} \leq X_{jt} \qquad \forall j \in J, t \in LC_j \qquad (6)$$

Constraints 5 and 6, together with an addition to the goal function, the end of horizon effect can be considered. Which is the sum over all aircraft, all jobs and all periods from last planning cycle to the end of the planning horizon multiplied by a fraction of the maintenance costs corresponding to the job. This fraction is the remaining periods / cycle time of maintenance job j. The end-of-horizon effect is important as this will give an indication of the future effects of the schedule. It encourages the model to plan the jobs as late as possible, which results in less end-of-horizon costs. When not considering the end-of-horizon effect, the model is indifferent to where plan the executions, as planning earlier does not result in more costs, as long as the due dates are met.

The end-of-horizon effect is not only applicable to maintenance costs, but setup costs should be considered as well, especially when the setup costs are relatively large in comparison to the maintenance costs. The end-of horizon effect of setup costs is more difficult to predict though, as multiple maintenance jobs might need the same setup, the execution of setup activities is not cyclical. For example, a setup activity might be necessary in week 10, 26 and 50. It is difficult to predict when the next setup activity is needed. Because of this, these end-of-horizon costs are not included in the models yet.

Planning Horizon

This dynamic clustering of maintenance activities will be planned on a rolling horizon. This means that we will plan repeatedly, for some planning horizon. When sudden changes occur, we will create a new schedule with the changes in input taken into consideration. We will make a planning up until some planning horizon T. Due to possible switches in routes, it does not make sense to plan too much more in the future. Currently, the CAM schedules the maintenance not more than 2 or 3 months in advance. If planning for a longer period, there will be changes such that the planning will have to altered. Therefore, it does not make sense to make a schedule for a longer period.

4.4. Planning for all aircraft

Considering the earlier proposed model for a single aircraft, an easy switch can be made to model the maintenance of all aircraft. This should be done when capacity restrictions are to be implemented in the model to make sure not too much maintenance is planned in a weekend. The earlier found constraints will be quite similar, but for some parameters and variables, an aircraft index should be added. These constraints can be found below. Additionally, capacity restrictions should be added as this is the reason we are planning over all aircraft.

Cost function

$$Min\ z\ =\ \sum_{a=1}^{A}\sum_{j=1}^{J}\sum_{t=1}^{T} X_{ajt}\cdot m_j\ +\sum_{a=1}^{A}\sum_{i=1}^{I}\sum_{t=1}^{T} Y_{ait}\cdot s_i\ +\sum_{a=1}^{A}\sum_{j=1}^{J}\sum_{t\in LC_j} m_j\, b_{ajt} W_{ajt}$$

s.t.

$$\sum_{t=1}^{f_j-g_j+e_j} X_{ajt}\ \geq 1, \qquad \forall a\in A, j\in J \tag{10}$$

$$\sum_{s=0}^{nf_j-1+e_j} X_{aj(t+s)}\ \geq n, \qquad \forall a\in A, j\in J, n\in N_j, 1\leq t\leq |T|-f_j+1 \tag{11}$$

$$Z_{ij}\cdot X_{ajt}\leq Y_{ait}, \qquad \forall a\in A, i\in I, j\in J, t\in T \tag{12}$$

$$\sum_{t\in LC_j} W_{ajt}\geq 1 \qquad \forall a\in A, j\in J \tag{13}$$

$$W_{ajt}\leq X_{ajt} \qquad \forall a\in A\ , j\in J, t\in LC_j \tag{14}$$

$$\sum_{a=1}^{A}\sum_{j=1}^{J} X_{ajt}\cdot\ r_j\ \leq C, \qquad \forall t\in T \tag{15}$$

$$\sum_{a=1}^{A} Y_{a1t}\ \leq K \qquad \forall t\in T \tag{16}$$

$$X_{ajt}, Y_{ait}, W_{jt}, Z_j \in \{1,0\} \qquad \forall a \in A, i \in I, j \in J, t \in T \qquad (17)$$

4.4.1. Extension: Capacity restrictions

Capacity restrictions will make sure that not too many hours of maintenance are planned in one weekend (15) and not too many aircraft are flown to Lelystad (16). Constraint 15 will sum up all the maintenance activities in one particular period, over all aircraft and make sure the amount of manhours does not exceed the capacity of the maintenance department. Constraint 16 can be used to set the maximum amount of aircraft that fly to Lelystad for maintenance. In reality, there is enough space in the hangar to store all of the aircraft, but it might not be desired to let all aircraft fly to Lelystad for maintenance. The first reason for this is that there are a limited number of engineers that can work on the aircraft and not all aircraft can be worked on at the same time. The second reason are the costs of flying the aircraft to Lelystad. The costs of letting the aircraft fly to Lelystad are quite high and it is likely to be better to limit the amount of aircraft that fly to Lelystad for one weekend. To make this constraint work, i=1 should be the first setup task, flying the aircraft to Lelystad.

$$\sum_{a=1}^{A}\sum_{j=1}^{J} X_{ajt} \cdot r_j \leq C, \qquad \forall t \in T \qquad (15)$$

$$\sum_{a=1}^{A} Y_{a1t} \leq K \qquad \forall t \in T \qquad (16)$$

4.5. Proposed Heuristics

To make a feasible schedule, a few heuristics are designed. First off, we created two heuristics based on the article of Budai (Budai et al.,2005). The other heuristic follows from the results of the MIP-model, which tries to find a solution close to the one found by the model. We will show how the heuristics work by a small problem instance. The parameters of the problem instance can be seen in Table 3. For every job, the first due date, the maintenance interval, the required setups and the cost of maintenance is known. The costs of setups 1, 2 and 3 are respectively 3000, 1000 and 500 euros.

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs
J1	4	5	1			1200
J2	2	6	1			1400
J3	5	10	1	1	1	400
J4	2	12	1			100
J5	10	13	1	1		50
J6	3	27	1			50
J7	3	30	1		1	100
J8	15	32	1	1		20
J9	3	40	1			2500
J10	20	100	1	1		250

Table 3: Input example

4.5.1. Single-component strategy

This heuristic is based on the first heuristic described in the article of Budai, this heuristic does create a feasible solution, but not an optimal one. The heuristic works as follows:

Step 1: For every job, make an individual schedule such that the sum of the setup costs, maintenance cost and penalty paid for late execution per time horizon T is minimized. The reduction of costs by combining maintenance executions and thus reducing setup costs is not taken into consideration in this heuristic.

Step 2: Calculate the overall costs resulting step 1

As the combination of maintenance executions is not taken into consideration, a far from optimal schedule is created. The use of this heuristic is mainly to show how much a proper heuristic can improve the schedule.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1				1					1					1					1					1					1	
J2		1						1						1						1						1				
J3					1										1										1					
J4		1												1												1				
J5										1													1							
J6			1																											1
J7			1																											
J8															1															
J9			1																											
J10																				1										

Time (weeks)

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs	COSTS Maintenance costs	End of horizon effect
J1	4	5	1			1200	7200	480
J2	2	6	1			1400	7000	1166.666667
J3	5	10	1	1	1	400	1200	240
J4	2	12	1			100	300	41.66666667
J5	10	13	1	1		50	100	30.76923077
J6	3	27	1			50	100	1.851851852
J7	3	30	1		1	100	100	93.33333333
J8	15	32	1	1		20	20	10
J9	3	40	1			2500	2500	1750
J10	20	100	1	1		250	250	27.5
Setup costs						TOTALS	18770	3841.787749

Setup costs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
3000	Setup 1		1	1	1	1			1	1	1				1	1				1	1			1	1	1	1			1	1	
1000	Setup 2					1					1					1					1			1		1						
500	Setup 3			1		1										1										1						TOTAL
Setup costs		0	3000	3500	3000	4500	0	0	3000	3000	4000	0	0	0	3000	4500	0	0	0	3000	4000	0	0	4000	3000	4500	3000	0	0	3000	3000	59000

TOTAL COSTS	81611.79

Figure 14: Example of the single-component strategy on a simple instance

4.5.2. Opportunity-based

This heuristic is based on a combination of two heuristics that are described by Budai, the MFWF (Most Frequent Work First Heuristic) and the OBH (Opportunity Based Heuristic). Due to the costs of flying the aircraft to Lelystad outweighs the maintenance costs of almost all jobs, it does not make sense to compare the loss of lifetime for a job to the setup costs of creating a new maintenance execution. It is always, or as far as the current data indicates, better to have as little setups as possible.

The heuristic works as follows:

Step 1: Order the set of jobs such that the planning cycles are in increasing order: $f_1 \leq f_2 \leq \cdots \leq f_3$. Schedule job 1 at its maximum interval, that is, in periods $1, 1+f_j, 1+2f_j, 1+3f_j$. The execution times of the most frequent job give the initial values of the opportunities' list, $Opp = \{e_{1,1}, e_{1,2}, \ldots, e_{1,F_1}\}$.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1	1					1					1					1					1					1				
J2		1						1						1						1						1				
J3					1										1										1					
J4		1												1												1				
J5										1													1							
J6			1																											1
J7			1																											
J8															1															
J9			1																											
J10																				1										

Time (weeks)

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	Setup S2	Setup S3	Maintenance Job costs	COSTS: Maintenance costs	COSTS: End of horizon effect
J1	4	5	1			1200	7200	1200
J2	2	6	1			1400	7000	1166.666667
J3	5	10	1	1	1	400	1200	240
J4	2	12	1			100	300	41.66666667
J5	10	13	1	1		50	100	30.76923077
J6	3	27	1			50	100	1.851851852
J7	3	30	1		1	100	100	93.33333333
J8	15	32	1	1		20	20	10
J9	3	40	1			2500	2500	1750
J10	20	100	1	1		250	250	27.5
Setup costs						TOTALS	18770	4561.787749

Setup costs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	Setup 1	1	1	1		1	1		1		1	1			1	1	1				1	1		1		1	1				1	
1000	Setup 2					1					1					1					1			1		1						
500	Setup 3			1		1										1										1						
Setup costs		3000	3000	3500	0	4500	3000	0	3000	0	4000	3000	0	0	3000	4500	3000	0	0	0	4000	3000	0	4000	0	4500	3000	0	0	0	3000	59000

TOTAL COSTS	82331.79

Figure 15: Opportunity based Heuristic step 1

Step 2: (For $j=2,\ldots,n$) plan the first execution at the earliest opportunity possible. The earliest opportunity possible is the due date minus the smallest due date of all jobs, in this case 2. This is because we will later shift the entire schedule to this period. If we do not subtract the smallest due date, the execution might eventually be planned after its due date, which is of course not allowed. Do this for every following execution in the planning horizon if necessary.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1	1					1					1					1					1					1				
J2	1					1					1					1					1					1				
J3	1										1										1									
J4	1										1										1									
J5						1										1										1				
J6	1																									1				
J7	1																													
J8											1																			
J9	1																													
J10																1														

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	Setup S2	Setup S3	Maintenance Job costs	COSTS: Maintenance costs	COSTS: End of horizon effect
J1	4	5	1			1200	7200	1200
J2	2	6	1			1400	8400	1166.666667
J3	5	10	1	1	1	400	1200	400
J4	2	12	1			100	300	83.33333333
J5	10	13	1	1		50	150	19.23076923
J6	3	27	1			50	100	9.259259259
J7	3	30	1		1	100	100	100
J8	15	32	1	1		20	20	12.5
J9	3	40	1			2500	2500	1875
J10	20	100	1	1		250	250	37.5
	Setup costs					TOTALS	20220	4903.490028

Setup costs	Time (weeks)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
3000	Setup 1	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	
1000	Setup 2	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	
500	Setup 3	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	TOTAL
Setup costs		4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	0	25500

TOTAL COSTS	50623.49

Figure 16: Opportunity based Heuristic step 2

Step 3: Shift the entire schedule to the earliest due date of all jobs, this will be the first-time maintenance has to be performed.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1										1										1			
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10																	1													

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	Setup S2	Setup S3	Maintenance Job costs	COSTS: Maintenance costs	COSTS: End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1	1	1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	15.38461538
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1		250	250	35
						TOTALS	20220	4307.167023

Setup costs	Time (weeks)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
3000	Setup 1		1					1					1					1					1					1				
1000	Setup 2		1					1					1					1					1					1				
500	Setup 3		1										1										1									TOTAL
Setup costs		0	4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	25500

TOTAL COSTS	50027.17

Figure 17: Opportunity based Heuristic step 3

Step 4: Calculate the overall costs resulting step 1, 2 and 3.

4.5.3. Improvement Heuristic

This heuristic can be seen as an addition to the Opportunity-based heuristic but we will describe it separately. As can be noticed in the previous heuristic, only flying to Lelystad is taken into consideration (as this has to be done every time maintenance is planned).

The secondary setup(s) are not considered yet, but it might be profitable to cluster some tasks if a setup execution can be prevented. The heuristic works as follows:

Step 1: Create a feasible schedule (with the opportunity-based heuristic)

Step 2: Order the set of setups such that the setup costs are in decreasing order: $s_1 \geq s_2 \geq \cdots \geq s_n$. The execution times of the setups give the initial values of the opportunities' list $Opp_i = \{e_{i,1}, e_{i,2}, \ldots, e_{i,m}\}$ where m is the last execution of setup i.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1										1										1			
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10																	1													

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs	COSTS Maintenance costs	End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1		1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	15.38461538
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1	1	250	250	35
						TOTALS	20220	4307.167023

Setup costs	Time (weeks)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	S1		1					1					1					1					1					1				
1000	S2							1					1					1										1				
500	S3		1										1					1					1									
Setup costs		0	3500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4500	0	0	0	0	3500	0	0	0	0	4000	0	0	0	24000

Opportunity list

TOTAL COSTS	48527.17

Figure 18: Improvement heuristic - step 2

Step 3: (For every execution of setup i, starting with the last one $\{e_{i,m} \rightarrow e_{i,m-1} \rightarrow \cdots \rightarrow e_{i,1}\}$) find all tasks in that weekend that need setup i. for each of these tasks, find out if in the previous weekend where setup i is necessary, none of the tasks are executed. If this is the case, we are allowed to shove the tasks to the previous weekend. Otherwise, we cannot move the tasks to the previous weekend.

Move the selected tasks to the previous weekend if possible and compare the total costs before and after the switch. If there is a reduction in costs, move the maintenance jobs. Otherwise, move the tasks back and move to the next execution.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1										1										1			
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10																	1													

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs	COSTS Maintenance costs	End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1		1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	15.38461538
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1	1	250	250	35
						TOTALS	20220	4307.167023

Setup costs	Time (weeks)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	S1		1					1					1					1					1					1				
1000	S2							1					1					1										1				
500	S3		1										1					1					1									
Setup costs		0	3500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4500	0	0	0	0	3500	0	0	0	0	4000	0	0	0	24000

TOTAL COSTS	48527.17

Figure 19: Improvement heuristic - step 3 - Iteration 1

The first iteration can be seen in Figure 19. The secondary setup that has the highest cost is setup 2, for which the last execution is done at time=27, regarding job 5. Now, we will check if we can move job 5 to the period of the previous execution of setup 2, if possible, we will save us one execution of setup 2. Unfortunately, there is already an execution of job 5 in this period, so we cannot shift the execution back in time.

Now, we will go on to the second iteration of the improvement heuristic. Since we cannot shift the last execution of setup 2 back in time, we will try to shift the second-to-last execution back in time. As can be seen in Figure 20, this execution is on period 17. In this case, it involves two maintenance jobs: job 5 and job 10. Fortunately, this time, we can move the two jobs to the previous execution of setup 2, as both jobs are not executed in this period.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1										1										1			
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10																	1													

Time (weeks)

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs	COSTS Maintenance costs	End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1		1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	15.38461538
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1	1	250	250	35
TOTALS							20220	4307.167023

Setup costs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	S1		1					1					1					1					1					1				
1000	S2							1					1					1										1				
500	S3		1										1					1					1									
Setup costs		0	3500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4500	0	0	0	0	3500	0	0	0	0	4000	0	0	0	24000

TOTAL COSTS 48527.17

Figure 20: Improvement heuristic - step 3 - Iteration 2

After having determined that we can shift the two jobs to the previous execution of setup 2, we can actually shift the two jobs. When shifting a maintenance job, the following executions of the job have to be shifted forward in time as well, otherwise the interval between two executions might become too large and the minimal interval might be violated. In last execution of job 5 has to be shifted forward as well. If necessary, another execution might need to be added if the minimal interval requires it.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1					1										1								
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10												1																		

Time (weeks)

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	S2	S3	Maintenance Job costs	COSTS Maintenance costs	End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1		1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	34.61538462
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1	1	250	250	47.5
TOTALS							20220	4338.897792

Setup costs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	S1		1					1					1					1					1					1				
1000	S2							1					1										1									
500	S3		1										1										1									
Setup costs		0	3500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	3000	0	0	0	0	4500	0	0	0	0	3000	0	0	0	22500

TOTAL COSTS 47058.90

Figure 21: Improvement heuristic - step 3 - Iteration 2 – Executed

After the jobs have been shifted, we can calculate the new total costs. As can be seen in Figure 21, the total costs have decreased. If this was not the case, we should shift the jobs back to its original executions.

4.5.4. Restrictions

No extension has been taken into consideration. This is to keep the heuristics relatively simple. Also, in reality, extension is only given to a maintenance job if really necessary. Giving extension to tasks might improve the schedule though, and the MIP-model shows that this can result in a less costly schedule.

4.6. Conclusion

From the literature, we took the preventive maintenance scheduling problem of Budai and adjusted the model to fit the context of AIS. First, we proposed a model for scheduling maintenance for one aircraft. A few adjustments have been made in comparison to the MIP-model that was proposed by Budai.

The first adjustment that had to be made was the addition of the possibility to give extension to a specific maintenance execution. Modeling this characteristic was not easy as the amount of extension has to be measured over the entire schedule. Secondly, the model of Budai only considered one setup and in the adjusted model, multiple setups can be considered.

The model considering only one aircraft does not consider capacity restrictions of the Technics department. Capacity restrictions only make sense when considering a model with all the aircraft. The earlier proposed model can easily be adjusted to consider all aircraft. Some of the constraints have to be adjusted by adding an index a that corresponds to a specific aircraft. Then, two capacity constraints are proposed, one to make sure not too much manpower is used, the second to make sure not too many aircraft are present in Lelystad.

Then, three heuristics are presented: The single-component strategy, the opportunity-based and the improvement heuristic. The single-component strategy schedules the individual tasks without looking at clustering the setup activities. The opportunity-based heuristic creates a fairly simple, but feasible schedule, only taking into consideration the primary setup, flying to Lelystad. The Improvement heuristic builds further on the opportunity-based heuristic (or any other schedule) and tries to improve the schedule by clustering the secondary setup activities.

5. Experiments

5.1. Introduction

In order to test the proposed models and heuristics in Chapter 4, we will model and test them on a real-life situation at AIS Airlines. We took the due-lists from the maintenance management system at AIS on the 11th of June 2018. We took the due lists from the maintenance management system and connected the aircraft to the current routes. In Section 5.2 we will describe how we got the necessary input for the several models. In Section 5.3 we will describe how we conducted the several experiments. Section 5.4 will describe the results from the experiments. In Section 5.5 we will try to link the results from the experiments to the current situation at AIS Airlines. In Section 0 we will present some final conclusions regarding the experiments.

5.2. Data preparation

To create a maintenance model for AIS, several types of data are needed. First off, we need a set of maintenance jobs and possible corresponding setup tasks that are necessary to perform these jobs. Furthermore, we need several types of information from these jobs:

- The maintenance interval, the maximum time there can be between maintenance occasions
- The maximum amount of extension that can be given to the maintenance task
- The time that is already spent of the interval / the first time the job is due
- The cost of performing this maintenance task

From the setup tasks, we need some information as well:

- Which setup tasks are necessary for each maintenance job
- The cost of the setup times

At AIS, most information can be found in the maintenance management system, in this database every maintenance job is being tracked. The interval is known, the number of months, flight cycles or flight hours left for each maintenance job can be found. This information is stored in a due list.

These due lists can be exported to a pdf-file and it is therefore not easy to manipulate/manage the data. When converting the data from pdf to an excel-file, with which we can manipulate the data better, the data gets messed up in multiple ways:

- Some inputs get converted to an image in jpeg-format
- Multiple types of data get put in the same cell
- Some types of data get split into multiple cells
- Data types are not in the same column, but sometimes in 2, 3 of even 4 different ones
- Multiple task-specific errors

Overall, the data of AIS is very hard to work with. To make the data of AIS somewhat useful as input for a mathematical model or heuristic, we'll have to find a way to correct the above errors. To do this, we created a macro-enabled workbook in Excel, which uses VBA (Visual Basic for Applications) to manipulate the data to correct the above errors. Because of the errors in the data due to the conversion from pdf to excel, this is for some tasks quite specific. From now on, we will refer to this program as the tasklist-creator.

With the current format of the pdf-files that get exported from the maintenance management system, we can extract the useful data into a readable format and for each due list per aircraft. we can extract the maintenance jobs, with the corresponding job number and description. We can also extract the maintenance interval in months, flight cycles or flight hours. Next, we can find the initial due date in months, flight cycles or flight hours.

From the intervals of the maintenance jobs, we can calculate the maximum extension we can give to a task, if we are allowed to give extension to such a task. The amount of extension that is allowed to be given to a maintenance task relies on two things:

- The action type of maintenance task
- The interval of the maintenance task

Firstly, the action type of the maintenance task defines whether a maintenance task can be given extension or not. The inspections and checks do not have a strict deadline. These tasks can be given extension up to a predetermined number of weeks. Jobs with an action type like an overhaul or a CPCP may not be given extension. These type of maintenance jobs are more crucial and if not performed on time undermines the reliability of an aircraft. Therefore, it is not allowed to perform these tasks later than the predetermined maximum interval.

Secondly, the maximum interval of the maintenance task influences the maximum extension that might be given to a maintenance task. Table 4 indicates the amount of extension a maintenance task might be given. A further explanation on extension can be read in section 2.7.

(a) Tasks controlled by flight hours up to 5000FH (a) Tasks controlled by 5000FH or more	10% 500FH
(b) Tasks controlled by calendar time, with an interval of: - 1 year or less - More than 1 year, but not exceeding 3 years - More than 3 years	 10% or 1 month, whichever is the lesser 2 months 3 months
(c)Tasks controlled by landings/cycles	10%, with a maximum of 250 landings/cycles

Table 4: The maximum allowed amount of extension

With the help of this table, we can calculate the maximum amount of extension that might be given to a maintenance job.

The information we need next are the costs of maintenance and setups. The cost of performing maintenance is twofold: Primarily, you have the costs of the engineers that perform the maintenance jobs. AIS has its own maintenance organization and the costs of engineers is therefore only have to pay the salaries of the engineers. An engineer at AIS costs approximately 100 euros per day and we assume that one workday consists of 8 hours of labor. The costs of maintenance per maintenance job can therefore be calculated from the number of man-hours necessary for a maintenance job:

$$costs_1 = \frac{manhours}{8} * €100$$

At the one hand you have the costs of materials or the possible necessity to hire third parties, which are the additional costs of a maintenance job.

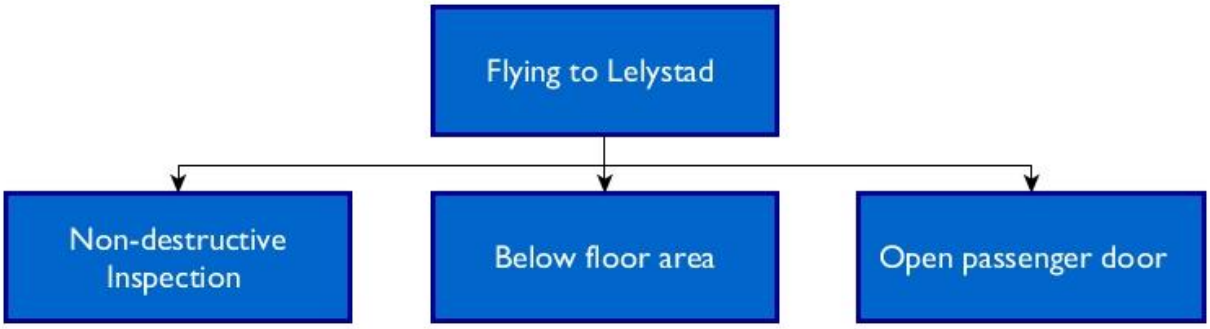

Figure 22: Setup structure

These number of man-hours needed for each maintenance job and the additional costs that might be there are not explicitly known at AIS. The maintenance- and CAMO manager roughly know how long each job will take and what costs are involved. To quantify this information, interviews with the CAM and the maintenance manager were conducted and for each task, for every aircraft, that has to be executed in the next year, the manhours, additional costs and thus the total costs are identified. Also, the possible necessity of setup activities are found, which can be seen in

Figure 22. Flying to Lelystad is the primary setup activity, the other three are the secondary setup activities. Now we have all the information necessary to begin experimenting on a few due lists.

5.3. Experimentation

To create different schedules, different models have been programmed. First, a model has been made to create an exact solution. This is done with the MIP-model described in Section 4.3. The model is programmed in AIMMS, which is software for operation research and analytics and has the possibility to solve linear programming models with CPLEX 12.8. Afterwards, the heuristics are built in Microsoft Excel with Visual Basic for Applications.

5.3.1. MIP-Model

As said before, the MIP-model is built in AIMMS. AIS Airlines is not yet able to use this software itself and the results of the MIP model will be used as a benchmark for the following heuristics. The input for the model can be retrieved from the tasklist-creator that is described in section 5.2. There are six different types of input that are necessary for the model and will be extracted by the tasklist-creator:

- The interval of job j
- The initial due date of job j
- The maximum amount of extension that might be given to job j
- The maintenance cost of job j
- The setup cost of setup i
- The required setups i per maintenance job j

The planning horizon of the model is set to 52 weeks and thus, only the tasks with an initial due date less than 52 are taken into consideration. This causes the jobs taken into consideration to be different per aircraft, as other maintenance jobs might be due in comparison between the different aircraft. Because of this, the set declaration of the model has to be altered to accommodate the appropriate number of maintenance jobs that should be taken into consideration. An overview of the number of maintenance jobs and setup tasks can be seen inTable 5.

52 weeks	# Maintenance jobs	# Setup 1: Flying to Lelystad	# Setup 2: NDI	# Setup 3: Access below floor area	# Setup 4: Open passenger door
Costs		€ 3,000.00	€ 1,000.00	€ 100.00	€ 12.50
PH-BCI	64	64	5	1	0
PH-DCI	87	87	8	4	3
PH-FCI	48	48	1	1	1
PH-HCI	59	59	2	1	0
PH-NCI	62	62	6	1	4
PH-OCI	77	77	9	1	0

Table 5: Input data for experiments

For every aircraft, we take the input data that follows from the flight schedule and calculate the optimal schedule with the MIP-model. The text representation of the MIP-model can be seen in Appendix 2.

5.3.2. Heuristics

The heuristics have been modelled in VBA. As with the MIP-model, the input data comes from the tasklist-creator. This has to be done manually and if necessary, could be easily edited. For the same combinations of aircraft and flight schedule, we will create a schedule with the heuristics described in Section 4.5. With VBA, we can create the schedules for a single-component strategy and an opportunity-based strategy in a few seconds. The code that is used to model the three heuristics can be found in Appendix 4, 5 and 6.

5.3.3. Schedule generation

We created six different maintenance schedules, of the six aircraft that can be seen in Table 6. Only schedules were created for the first six aircraft, as the RCI was not allocated to a route at this particular moment. With these settings, we created six schedules for every model or heuristic: The MIP-model with extension, the MIP-model without extension, the Single-component scheduling heuristic, the opportunity-list heuristic and the opportunity-list with improvement heuristic. We can use the MIP-model without extension to benchmark the opportunity-list heuristics and with the MIP-model with extension, we can show what the added value is of giving possible extension to certain tasks to lower maintenance costs.

Aircraft	Route	Hours/Week	Cycles/week
PH-HCI	Borlange Airport - Gotenburg-Landvetter Airport	15:00	18
PH-DCI	Borlange Airport – Orebro Airport - Mora Airport	24:00	36
PH-FCI	Ostersund Airport – Umea Airport	13:20	20
PH-BCI	Torsby Airport – Hagfors Airport - Stockholm Arlanda Airport	16:40	40
PH-OCI	Munster Osnabrück Airport - Stuttgart Airport	21:00	18
PH-NCI	SVEG Airport - Stockholm Arlanda Airport	22:00	24
PH-RCI	-	-	-

Table 6: Allocation of aircraft and routes

5.3.4. Planning Horizon

We only have data about the costs of the maintenance jobs for the first year. Therefore, we cannot have a longer planning horizon than 52 weeks, which is rolling, so we will plan again and again for a year. In reality, the planner only makes a planning for the first 2 or 3 months though. Only taking into consideration the jobs in these few months is not very interesting for this research. As can be seen in Table 5, just a few secondary setup tasks are already taken into account in the first year, and already so much clustering can be done. Taking a longer planning horizon, with considering more maintenance jobs can improve the clustering as more jobs can be considered and potentially clustered, although, due to the initial due date being so far away from the moment of planning, these jobs will most likely be planned at the end of the horizon. Before these jobs will have an effect, a new schedule will most likely be created.

5.4. Results

5.4.1. Cost comparison

With the MIP-model, we created the maintenance schedules for the six aircraft. First, we would like to see what the optimal schedule is when extension might be given to maintenance tasks to create a cheaper maintenance schedule. Secondly, we will also make a schedule with the MIP-model where it is not allowed to give extension to any task. This is because of the fact that in reality, extension is mostly given when it is really necessary and not to optimize the maintenance schedule. Also, we can use this solution as a benchmark as well, as the heuristics also do not take into consideration giving extension. After running the models with AIMMS, we get the following results that can be seen in Table 7:

	BCI	DCI	FCI	HCI	NCI	OCI	AVERAGE
MIP (no extension)	€ 34,340.50	€ 42,673.02	€ 30,876.98	€ 20,557.61	€ 28,470.71	€ 31,289.09	€ 31,370.85
MIP (with extension)	€ 33,992.99	€ 42,462.55	€ 30,498.13	€ 20,557.61	€ 28,246.53	€ 30,983.30	€ 31,018.63
Difference (absolute)	€ 347.51	€ 210.47	€ 378.85	€ 646.57	€ 224.18	€ 305.79	€ 352.23
Difference (percentage)	1.01%	0.49%	1.23%	3.14%	0.79%	0.98%	1.27%

Table 7: MIP-results

As can be seen in Table 7, giving extension to maintenance tasks will most likely result in slightly lower maintenance costs. The average difference between the six schedules with or without extension is €352,23 for this year, which is a difference of on average 1,27%. If all aircraft are operational, this could add up to €352,23 * 7 = € 2465,61 of decreased maintenance costs per year.

After the MIP-model was run for all the aircraft, we tested the heuristics whether or not feasible schedules can be created that come close to the results of the MIP-model. First, we tested the single-component schedule. This created a very bad schedule where setups are not considered, and all jobs are executed as late as possible. Secondly, we tested the opportunity-list heuristic, which creates a very basic schedule that only clusters the primary setup, Flying to Lelystad. Then, we ran both the opportunity-list heuristic and the improvement heuristic. This improvement heuristic only has use when sufficient secondary setups are necessary for the maintenance jobs that are taken into consideration when making a maintenance schedule for an aircraft. The results can be seen in Table 8.

	BCI	DCI	FCI	HCI	NCI	OCI	AVERAGES
Single Component	€ 111,950.30	€ 140,541.02	€ 75,576.03	€ 92,061.75	€ 102,886.94	€ 102,833.24	€ 104,308.21
Opportunity List	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59
Opportunity List with improvement Heuristic	€ 34,537.77	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 30,288.61	€ 32,254.34	€ 32,146.62
MIP (no extension)	€ 34,340.50	€ 42,673.02	€ 30,876.98	€ 20,557.61	€ 28,470.71	€ 31,289.09	€ 31,367.99

Table 8: Heuristics and MIP-results

A more extensive overview and comparison between the several planning methods can be seen in Appendix 7. As can be seen, the opportunity list itself does not create a very good schedule in comparison to the MIP-model with no extension. On average over the six schedules, we can see an absolute difference of €1113,74, which is a 3,55% decrease in costs in comparison to the MIP model without extension.

When we run the improvement heuristic after the opportunity list heuristic, for some schedules, we get an improvement, for others not. As can be seen in Appendix 3, on the schedules where no improvements are made, not many secondary setups are necessary, and thus the improvement heuristic cannot find any improvements when trying to cluster the secondary setups. For these six schedules, two of them are improved by the improvement heuristic, namely the BCI and the NCI. These improvements still account for an average absolute improvement of €337,97, which is a 1,04% decrease in costs in comparison to the opportunity list heuristic on its own. Still, the MIP-model without extension creates a schedule which is way better, with a decrease in costs of €775,77 which is a 2,41% decrease in costs in comparison to the opportunity list heuristic on its own. An overview of the total maintenance costs can be seen in Figure 23.

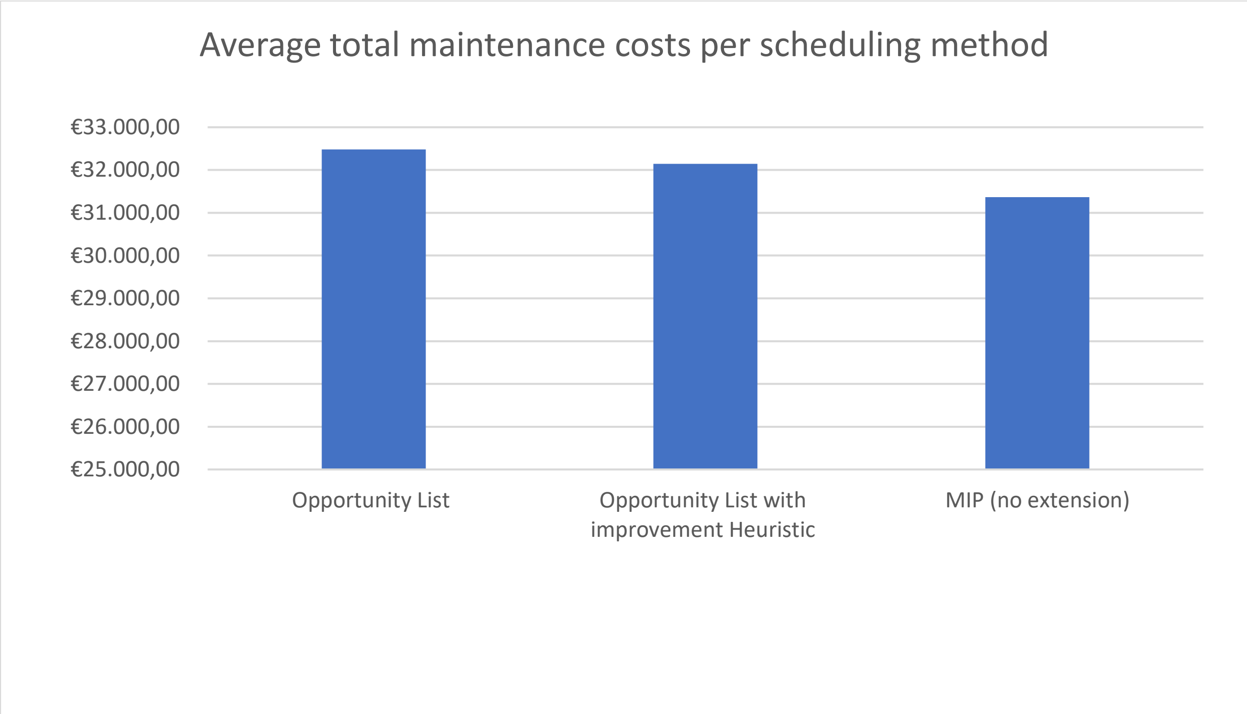

Figure 23: Bar chart of total maintenance costs for the different models

In conclusion, we can say that the opportunity list in combination with the improvement heuristic creates a feasible schedule, which does not differ than much from the optimal MIP-solution. When more secondary setup tasks will be identified by AIS, this heuristic will make more of a difference as more setup costs can be saved by clustering these secondary setups.
While the heuristics create reasonable schedules, the MIP-model still shows a relatively large improvement in comparison to the heuristics.

5.4.2. Weekly maintenance occupation

We individually scheduled the maintenance for each aircraft. Because of this, we did not take into consideration the capacity of the maintenance organization. Multiple aircraft could be planned on the same weekends and this might be problematic as Technics cannot handle an infinity amount of work.

For the six aircraft, maintenance is planned by the MIP-model with extension on the following weekends, that can be seen in Figure 24:

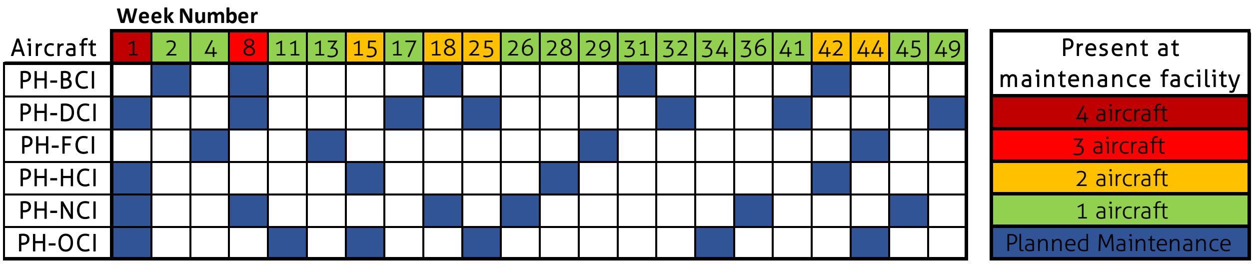

Figure 24: Weekly occupancy of the maintenance facility – MIP with Extension

As can be seen, there are a few weekends for which multiple aircraft come to Lelystad. First, on week number 1, four aircraft have to get to Lelystad, this is because there are a few aircraft for which some maintenance task was already due in the database and this maintenance should be done as soon as possible. Furthermore, there are three aircraft that have to come to Lelystad on week 8. This is not desirable as this will most likely, if many jobs have to be done per aircraft, surpass the capacity of the maintenance department. For a few other weeks, two aircraft are planned for maintenance. As the maintenance department rather has one aircraft to perform maintenance on (two is acceptable, but not desirable), the CAMO-manager should shift some of the maintenance to an earlier week if necessary, in this case, maintenance that is planned on week 8 should be shifted to week 7 for example. In Figure 25, we can see the same situation for the schedules created by the opportunity based heuristic in combination with the improvement Heuristics. We will not focus any further on what maintenance should be shifted.

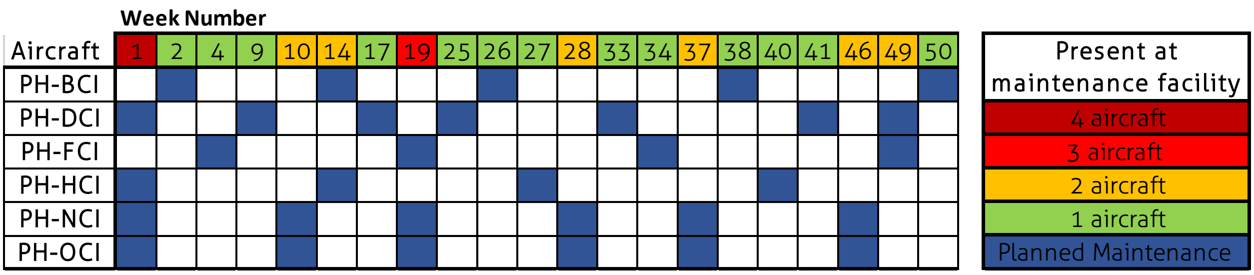

Figure 25: Weekly occupancy of the maintenance facility – Opportunity-based heuristic with improvement heuristic

5.4.3. Differences in scheduling MIP and Heuristics

There are small differences in schedules between the MIP-model and the heuristics. We will point out the differences and the possibilities for improvement of the heuristics. In Figure 26 and Figure 27 we can see the first 16 jobs for the PH-BCI as scheduled by the heuristics and the MIP-model.

The first thing that can be noticed is that the heuristics schedule the maintenance jobs with a fixed interval that is equal to the smallest interval of the maintenance jobs. The MIP-model however shows that it is not always most profitable to schedule in this fixed intervals. It sometimes might be more profitable to schedule maintenance one or two weeks earlier if there are some maintenance tasks due in this week. If not planned earlier, these maintenance jobs have to be executed weeks earlier, which throws away some of the lifetime.

The second thing that can be noticed that in the MIP-model, the 200-hours inspection sometimes is not executed in the first cluster (this is the case is most of the schedules). The heuristics do not consider this possibility while it can reduce the maintenance costs. It must be said that if the planning of was done properly, this situation would not be possible, as everything is planned around the 200-hours inspections. The data from the maintenance management system does show that some maintenance jobs are due before the 200-hour inspection. In this case, it might be good to consider planning a separate maintenance cluster for these earlier due jobs.

		Week number										TOTAL COSTS
Jobs	Costs	2	14	26	38	50	Maintenance Costs	End of Horizon Effect	Due Date	Interval	Max Extension	34562.4078
Perform 200 hours Inspection	250	1	1	1	1	1	1250.0	41.7	7.6	12.0	1.2	
Perform 400 hours Inspection	400	1		1		1	1200.0	33.3	7.6	24.0	2.4	
LH main battery Concorde CAP check Lead ac	6.25	1		1		1	18.8	0.5	13.0	26.0	2.6	
Pilot and Co-pillot restraint harness F/C -DVI	6.25	1		1		1	18.8	0.5	13.0	26.0	2.6	
RH main battery Concorde CAP check Lead ac	6.25	1		1		1	18.8	0.5	13.0	26.0	2.6	
F/C & clean Fuel manifold & nozzle assy LH	75		1		1		150.0	38.9	19.7	27.0		
F/C & clean Fuel manifold & nozzle assy RH	75		1		1		150.0	38.9	19.7	27.0		
Visually inspect LH combustion case assy iaw	6.25		1		1		12.5	3.2	19.7	27.0		
Visually inspect RH combustion case assy iav	6.25		1		1		12.5	3.2	19.7	27.0		
MLG LH Pintle to Cylinder interface NDT Insp	12.5	1		1			25.0	10.8	12.1	30.0		
MLG RH Pintle to Cylinder interface NDT Insp	12.5	1		1			25.0	10.8	12.1	30.0		
Detailed visual inspection of the aileron upp	12.5		1				12.5	11.9	22.1	40.0		
FIRST AID KIT DVI contents and reseal Ref MI	6.25	1					6.3	6.0	7.6	52.0		
Weight check of the cabin portable fire extir	6.25	1					6.3	6.0	8.7	52.0		
Weight check of the flight deck portable fire	6.25	1					6.3	6.0	8.7	52.0	4.3	
Perform 800FH/1200FH/1 YR Inspection	725		1				725.0	529.8	14.2	52.0	4.3	

Figure 26: Scheduling first 16 jobs heuristics

		Week number										TOTAL COSTS
Jobs	Maintenance Costs (job)	2	8	18	31	42	Maintenance Costs	End of Horizon Effect	Due	Interval	Max Extention	33992.99156
Perform 200 hours Inspection	250		1	1	1	1	1000.0	208.3	7.6	12.0	1.2	653.7113761
Perform 400 hours Inspection	400		1		1		800.0	350.0	7.6	24.0	2.4	
LH main battery Concorde CAP check Lead ac	6.25		1		1		12.5	5.0	13.0	26.0	2.6	
Pilot and Co-pillot restraint harness F/C -DVI	6.25		1		1		12.5	5.0	13.0	26.0	2.6	
RH main battery Concorde CAP check Lead ac	6.25		1		1		12.5	5.0	13.0	26.0	2.6	
F/C & clean Fuel manifold & nozzle assy LH	75			1		1	150.0	27.8	19.7	27.0		
F/C & clean Fuel manifold & nozzle assy RH	75			1		1	150.0	27.8	19.7	27.0		
Visually inspect LH combustion case assy iaw	6.25			1		1	12.5	2.3	19.7	27.0		
Visually inspect RH combustion case assy iav	6.25			1		1	12.5	2.3	19.7	27.0		
MLG LH Pintle to Cylinder interface NDT Insp	12.5	1			1		25.0	8.8	12.1	30.0		
MLG RH Pintle to Cylinder interface NDT Insp	12.5	1			1		25.0	8.8	12.1	30.0		
Detailed visual inspection of the aileron upp	12.5			1			12.5	10.6	22.1	40.0		
FIRST AID KIT DVI contents and reseal Ref MI	6.25	1					6.3	6.0	7.6	52.0		
Weight check of the cabin portable fire extir	6.25		1				6.3	5.3	8.7	52.0		
Weight check of the flight deck portable fire	6.25		1				6.3	5.3	8.7	52.0	4.3	
Perform 800FH/1200FH/1 YR Inspection	725			1			725.0	474.0	14.2	52.0	4.3	

Figure 27: Scheduling first 16 jobs MIP

5.5. Comparison to Current Situation

To say something about the solutions of the MIP-model and the heuristics, we need to compare the created schedules to the current planning method at AIS. AIS unfortunately does not have historical data recorded. In the maintenance management system, there can be seen what maintenance is done at what time. This data is not exportable from the system however. Therefore, we cannot easily find how the maintenance has been planned in the past.

To make a comparison to the current planning methods and the newly proposed ones, we interviewed the CAMO-manager on the manner he schedules the maintenance and what he takes into consideration. The CAMO-manager makes a planning for the next 2-3 months. As said before, this is because of the uncertainty in aircraft schedules and due to changes, the planning will most likely be altered if a longer planning horizon is used.

As for now, the CAMO-manager schedules all maintenance activities around the 200-hours inspection. This inspection has to be performed every 200 flight hours, which usually runs out in 8-13 weeks, depending on the flight schedule of the aircraft. This inspection is the most frequent one and therefore sets the maximum number of weeks the aircraft can be operational if the other maintenance tasks are planned simultaneously.

The maintenance manager first checks when the first maintenance job is due. If the scheduling is done right, this should be the 200-hours inspection. In reality, this is not always the case, as can be seen in the input files for the models. At the period where maintenance should be performed first, the 200-hours inspection is executed as well. All jobs between this 200-hours inspection and the next 200-inspection, so all jobs for the next 8-13 weeks, are also executed at this moment. This would normally make sure that the aircraft does not have to return to Lelystad before the next 200-hours inspection.

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	due (week)	Maintenance Interval (weeks)	Setup S1	Setup S2	Setup S3	Maintenance Job costs	COSTS: Maintenance costs	COSTS: End of horizon effect
J1		1 ←					1 ←					1 ←					1 ←					1 ←					1 ←				4	5	1			1200	7200	960
J2		1						1						1						1						1					2	6	1			1400	7000	1166.666667
J3					1										1										1						5	10	1	1	1	400	1200	240
J4		1												1												1					2	12	1			100	300	41.66666667
J5										1													1								10	13	1	1		50	100	30.76923077
J6			1																											1	3	27	1			50	100	1.851851852
J7			1																												3	30	1		1	100	100	93.33333333
J8															1																15	32	1	1		20	20	10
J9			1																												3	40	1			2500	2500	1750
J10																				1											20	100	1	1		250	250	27.5
																																Setup costs				TOTALS	18770	4321.787749

Setup costs	Time (weeks)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	TOTAL
3000	Setup 1		1	1	1	1			1	1	1				1	1				1	1			1	1	1	1			1	1	
1000	Setup 2					1					1					1					1			1		1						
500	Setup 3			1		1										1										1						
Setup costs		0	3000	3500	3000	4500	0	0	3000	3000	4000	0	0	0	3000	4500	0	0	0	3000	4000	0	0	4000	3000	4500	3000	0	0	3000	3000	59000

TOTAL COSTS	82091.79

Figure 28: CAMO-planning step 1

Jobs	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
J1		1					1					1					1					1					1			
J2		1					1					1					1					1					1			
J3		1										1										1								
J4		1										1										1								
J5							1										1										1			
J6		1																									1			
J7		1																												
J8												1																		
J9		1																												
J10																	1													

Jobs	due (week)	Maintenance Interval (weeks)	Setup S1	Setup S2	Setup S3	Maintenance Job costs	COSTS Maintenance costs	COSTS End of horizon effect
J1	4	5	1			1200	7200	960
J2	2	6	1			1400	8400	933.3333333
J3	5	10	1	1	1	400	1200	360
J4	2	12	1			100	300	75
J5	10	13	1	1		50	150	15.38461538
J6	3	27	1			50	100	7.407407407
J7	3	30	1		1	100	100	96.66666667
J8	15	32	1	1		20	20	11.875
J9	3	40	1			2500	2500	1812.5
J10	20	100	1	1		250	250	35
		Setup costs				TOTALS	20220	4307.167023

Time (weeks)

Setup costs		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	
3000	Setup 1		1					1					1					1					1					1				
1000	Setup 2		1					1					1					1					1					1				
500	Setup 3		1										1										1									TOTAL
Setup costs		0	4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	0	4500	0	0	0	0	4000	0	0	0	25500

TOTAL COSTS	50027.17

Figure 29: CAMO-planning step 2

It can be noticed that this is exactly the same schedule as the opportunity-list heuristic. The logic is exactly the same as is the outcome of the scheduling. There has to be said that the CAMO-manager plans the maintenance tasks on his expert opinion and once in a while might cluster some tasks together, which should improve the schedule. In reality, the schedule created by the CAMO-manager should be a bit better than the opportunity-list heuristic.

This way of planning has been done for the six aircraft for which the MIP-model and the heuristics also have generated a schedule. The outcomes of the total costs can be seen in Table 9.

	BCI	DCI	FCI	HCI	NCI	OCI	AVERAGES
Single Component	€ 111,950.30	€ 140,541.02	€ 75,576.03	€ 92,061.75	€ 102,886.94	€ 102,833.24	€ 104,308.21
Opportunity List	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59
Opportunity List with improvement Heuristic	€ 34,537.77	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 30,288.61	€ 32,254.34	€ 32,146.62
MIP (no extension)	€ 34,340.50	€ 42,673.02	€ 30,876.98	€ 20,557.61	€ 28,470.71	€ 31,289.09	€ 31,367.99
CAMO-planning	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59

Table 9: Total costs of CAMO-planning on the six aircraft

5.6. Conclusions

Overall, we can conclude that the current scheduling can be improved by dynamic clustering of maintenance activities. The proposed heuristics give feasible solutions with relatively good costs on average, the combination of both heuristics create schedules that are €337,97 cheaper per aircraft per year. These calculations are done for six of the aircraft on the different routes. At the moment there is one new route, and all seven aircraft are flying. When all aircraft are operational, this might result in 7x €337,97 = €2365,79 as savings in maintenance costs.

As for the MIP-model, schedules can be created that do not allow extension to be given. These schedules are on average €775,77 cheaper per aircraft per year than the schedules that are created with the heuristics. When all aircraft are operational, this might result in 7x €775,77 = €5430,39 as savings in maintenance costs. As for now, AIS does not give extension to maintenance activities for the sake of creating a better maintenance schedule with less costs. The MIP-model that is allowed to give extension shows that this might be a good thing to take into consideration. Giving extension to maintenance tasks might be beneficial as a reduction in costs of €352,02 per aircraft per year in comparison to the model that is not allowed to give extension can be attained.

As for now, not many setup tasks are taken into consideration, because of the little data available at AIS. In the future, it might be beneficial for AIS to identify more of the maintenance jobs that should be clustered together if possible. Creating a planning that considers only flying to Lelystad is done quite well by the CAMO-manager as this can be quite straightforward. The CAMO-manager plans the maintenance activities in an effective way, but not as efficient as it could be.

It might be worthwhile for AIS to invest in optimization software to be able to run the maintenance optimization models and create optimal schedules with or without extension. This, in combination with the addition of more setups, will result in a reduction of about €5432 in maintenance costs, while the license for such a software package is about €1000 euros per year. Then again, personnel is also needed that know how to utilize the software which will also bring some more costs.

6. Implementation at AIS Airlines

6.1. Introduction

After the MIP-model and the heuristics have been tested, we found that implementing dynamic clustering of maintenance activities will be beneficial for AIS as this will ultimately reduce the costs of maintenance activities for the maintenance of the Jetstream 32's. At this moment, AIS does not have the personnel and the tools yet to implement dynamic clustering of maintenance activities. To make this possible in the future, we will discuss the several steps that have to be taken by AIS to implement dynamic clustering. In section 6.2 we will discuss what AIS would have to do in order to get the right inputs to implement dynamic clustering. In section 6.3 we will discuss what AIS should do to make it possible to create improved maintenance schedules that will reduce costs of maintenance activities.

6.2. Data gathering

One of the main issues at AIS is the limited availability of data. There is some data available in the maintenance management system, but this data is not exportable to an easy-to-use format like Excel. This makes it very difficult to gather the right inputs for potential scheduling models. Exporting the data from the maintenance management system can only be done to pdf, which is a really non-flexible format. Data can be copied to Microsoft Excel or Microsoft Word, but this messes up a lot of the data. Without the possibility to easily gather the necessary data into some format that can be manipulated, dynamic scheduling of the maintenance activities becomes quite a challenge. It is of the utmost importance that if AIS wants to implement dynamic clustering, that the maintenance management system gets upgraded so that it at least is able to export the data to an Excel-format.

Now, a lot of information comes from the expertise of the CAMO-manager regarding the combination of maintenance activities through common setups. All of the setups for maintenance jobs can be found in the maintenance manual. This maintenance manual consists of thousands of pages in pdf that are online available. This manual describes step-by-step the activities (setup and maintenance) that have to be performed for each maintenance job. This is the only concrete information available considering setup activities and also this is not easily retrievable. With the help of the camo manager, we identified some of the setups. If more can be identified, this could be beneficial to the maintenance schedule due to possible combination of the setups. AIS should try to make clear what setup tasks are necessary for each maintenance job. Even adding some smaller setup tasks, which are not necessary for many tasks, small improvements can be made. Take a few of these smaller improvements and it might become a significant reduction is costs. AIS should therefore try to identify more significant setup activities. This could be done by the maintenance manager.

For now, we constructed a tasklist-creator in Excel that can extract the data from due lists that are exported from the maintenance management system. For every aircraft, a due list can be exported. This is in a pdf-format though, and should first be exported as an Excel-file by, for example Adobe Acrobat Pro. As said before, this messes up the data somewhat and makes the file difficult to use. The tasklist-creator is developed to fix most of the issues in the file, and uses VBA to extract the task number, description, interval and due date from the due lists. Afterwards, the maximum allowed extension can be calculated, and the total costs and necessary setups should be added. As already described in section 5.2, the VBA model now solves very specific errors in the model. When exporting data in the future fist to pdf and then to Excel, other errors might occur that the model not yet can handle. It is therefore highly recommended that AIS updates the maintenance management system so, that data from the system can properly be exported.

6.3.Maintenance schedule generation

For now, the maintenance schedules are created by hand, by the CAMO-manager. No software is used to find an optimal schedule and it all depends on the capabilities of the CAMO-manager. In Chapter 0, we showed that the use of an optimization model or heuristic should improve the maintenance schedules and will reduce the total maintenance costs. In order to use dynamic clustering of maintenance activities, AIS could use the models that are described in chapter 4. To use the models, the data has to be put in the Excel sheet in a particular way so that the model can find the right inputs.

AIS does not yet have the appropriate software to run optimization models as an MIP yet. AIS does have Microsoft Excel available, so the heuristics that are programmed in VBA can be used to create maintenance schedules can be used by AIS. These heuristics will not only create feasible schedules with decent maintenance costs but will also reduce the amount of time necessary for the CAMO-manager to create the maintenance schedules.

Still, the heuristics do not generate the best schedules, as the MIP-model does generate better ones. The amount of reduced costs of maintenance activities per aircraft per year is more than the costs of the license for optimization software. It might therefore be beneficial for AIS to invest in optimization software.

6.4. Step-by-step guide for CAMO

The CAMO-manager can use the models that were created to find feasible schedules quickly. Before this can be done, the CAMO manager has to perform a few tasks. The tools that the CAMO-manager can use are the tasklist-creator and the Heuristics. If AIS decides to buy a license for the optimization software, the MIP model can be used as well.

Step 1: The CAMO-manager should update the routes that the aircraft are currently flying, with the corresponding flight-hours and flight-cycles per week. These routes are needed to later convert the due date and intervals from hours and cycles to weeks.

Step 2: Due lists of all the aircraft should be exported from the maintenance management system. Subsequently, the due lists should be converted to Excel. This should be done with Adobe Acrobat Pro, then, the due list should be in the right format to be handled by the tasklist-creator. After conversion to Excel, the data should be copied to the tasklist-creator and put in the corresponding tab.

Step 3: On the dashboard of the tasklist-creator, click the button 'create tasklists'. All due lists will then be processed, and the useful information will be extracted.

Step 4: In the 'heuristics' workbook, set the desired planning horizon. We chose a planning horizon of 52 weeks, which is more than enough, but every desired planning horizon can be chosen.

Step 5: Copy all the relevant data, for all maintenance jobs with the initial due date inside the planning horizon into the 'heuristics' workbook. Order the data on increasing maintenance interval.

Step 6: On the dashboard of the 'heuristics' workbook, click the button 'Opportunity + Improvement'. Now, the heuristic will create a feasible schedule.

6.5. Conclusions

The main issue with implementing the proposed scheduling methods is the availability of data. Input data has to be gathered, especially from the maintenance management system. Currently, the maintenance management system is not able to export the required data in a useable way. It is clear that if in the future, AIS wants to implement dynamic clustering of maintenance activities, the maintenance management system has to be updated to be able to export the data into a useful format.

For now, a macro-enabled workbook in Excel is created to manipulate the data that is exported from the maintenance management system. For now, this method can extract the necessary information, but is quite error-prone and is not sustainable for the future.

Furthermore, the heuristics that are discussed in Section 4.5 are also programmed in a macro-enabled workbook. With the output of the tasklist-generator, which can be used as the input of these heuristics. When the input is properly entered, the workbook can generate feasible schedules in a few seconds.

Still, it is preferable to use the MIP-model to generate maintenance schedules as this will still generate schedules with lower total costs. If AIS aims to implement dynamic clustering of maintenance, it would be a good idea to buy a license for optimization software.

7. Conclusions, Recommendations and Further Research

In this chapter we will give the conclusions and provide answers on the research questions that were presented in section 1.6. In Section 7.1 we will give the conclusions of the thesis and provide answers to the research questions. In Section 7.2 we will give recommendations to AIS Airlines regarding the maintenance planning. in Section 7.3 we will give suggestions on which topics further research had to be done and in Section 7.4 we will discuss the limitations of the performed research.

7.1. Conclusions

As the conclusion of the thesis, we will try to answer all of the beforementioned research question that were presented in section 1.6. We will first answer all of the secondary research question and finally we will answer the main research question.

> *How is AIS Airlines currently planning their maintenance activities, how can we quantify its performance and what are the possibilities to improve this?*

Currently, AIS is planning its maintenance solely on the expert knowledge of the CAMO-manager. At the moment, no optimization software is used, and the CAMO-manager uses his own methodology on how to schedule maintenance. At the moment, the maintenance is planned around the major inspections, particularly the 200-hours inspection as this is the inspection with the highest frequency. All tasks between two executions of the 200-hours inspection are planned simultaneously with the first execution of the 200-hours inspection. The CAMO-manager sometimes clusters some tasks when he thinks this to be more favorable.

> *How is (dynamic) planning and clustering in aviation described in literature?*

In literature, dynamic clustering of maintenance in multi-component system is not extensively reviewed. Most models found in literature review static clustering of maintenance. The most notable models found were optimal clustering of maintenance operations model of van Dijkhuizen (1997), the cycle rounding algorithm and the shifted power-of-two policies of Levi (2014) and the preventive maintenance scheduling problem of Budai (2006). The MIP-model of Budai and the following heuristics came closest to the context of AIS Airlines and are further built upon.

> *How can we use dynamic planning and clustering in the context of AIS Airlines to improve their processes?*

Following up on the model of Budai, the MIP-model was adapted to fit the context of AIS Airlines. Most notably the possibility of giving extension to maintenance jobs is added and the addition of multiple setup activities is now possible. The model was programmed in AIMMS and can generate optimal maintenance scheduled per aircraft in a few seconds.

Three heuristics were also modelled and can be run in Excel, the single-component heuristic, the opportunity-based heuristic and an improvement heuristic can be run when the proper input is given to the model. The input-data is still a big issue for AIS, as the maintenance management system cannot properly export the data. If dynamic planning and clustering of maintenance is to be implemented in the future, this system should be updated to make this possible.

What is the added value of using dynamic clustering of maintenance activities in comparison to the current planning approach?

In the table below, we can see the costs of each of the scheduling methods and respective costs for each of the aircraft for one moment in time. As can be seen, the improvement heuristic will generate schedules that have a decrease in costs of €338,33, this is a yearly improvement of 7x €338,33 = €2368,31 in comparison to the opportunity list heuristic on its own and the CAMO-planning.

	BCI	DCI	FCI	HCI	NCI	OCI	AVERAGES
Single Component	€ 111,950.30	€ 140,541.02	€ 75,576.03	€ 92,061.75	€ 102,886.94	€ 102,833.24	€ 104,308.21
Opportunity List	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59
Opportunity List with improvement Heuristic	€ 34,537.77	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 30,288.61	€ 32,254.34	€ 32,146.62
MIP (no extension)	€ 34,340.50	€ 42,673.02	€ 30,876.98	€ 20,574.82	€ 28,470.71	€ 31,289.09	€ 31,370.85
MIP (with extension)	€ 33,992.99	€ 42,462.55	€ 30,498.13	€ 19,928.26	€ 28,246.53	€ 30,983.30	€ 31,018.63
CAMO-planning	€ 35,555.74	€ 44,056.43	€ 31,184.92	€ 20,557.61	€ 31,298.50	€ 32,254.34	€ 32,484.59

Table 10: Comparison between all planning methods for the different aircraft.

Still, the MIP model without extension, just as the heuristics, creates schedules with on average a €776 decrease in costs on a yearly base per aircraft, which if summed up over all aircraft will result in an improvement of 7x €776 = € 5432. When extension is taken into consideration, an additional €352,02 per aircraft can be saved on a yearly basis, which is a €1465,96 improvement in comparison to the CAMO-planning. Summed up over all seven aircraft a decrease of €10.261,72 in total maintenance costs can be attained.

How can we make the maintenance and the implementation of smart clustering visible to the central planner to support his decision making?

At the start of the thesis, it was said a central planner would be employed, which unfortunately has not happened as of yet. The implementation of dynamic clustering of maintenance is made visible though. The heuristics that are described are programmed in VBA and when the proper input is given to the model, the heuristics will create a feasible schedule, and this is being visualized in the spreadsheet.

How can dynamic clustering of maintenance activities be implemented at AIS airlines to assist in maintenance planning?

Dynamic clustering of maintenance activities can be implemented at AIS Airlines and will most likely improve the scheduling of maintenance in comparison to the current situation. If dynamic clustering of maintenance activities will be implemented though, AIS has to make sure the maintenance management system can properly export the maintenance data. It should be possible to export the maintenance jobs with their corresponding interval, due date and maximum extension for each maintenance job. At this moment, AIS does not have sufficient data available to properly use optimization methods.

The heuristics are modelled in Microsoft Excel and when the right input is given, maintenance schedules can be generated in just a few seconds. Better schedules can be generated with optimization software which is not yet available to AIS. The MIP-model as described in section 4.3 can then be implemented and optimal schedules can be created very quickly. Every time there is a change in the flight- of maintenance schedule, a new schedule can be created very quickly.

7.2. Recommendations

The first recommendation would be for AIS to update their maintenance management system. For now, the information that is needed for the models cannot be exported properly from the system. If optimization software is going to be implemented at AIS, it should be made easier to gain access to the necessary inputs for such an optimization model. As the data can exported to pdf, it should not be a large update to also export the data into a more useful format.

Secondly, I would suggest AIS to invest time and money into the implementation of dynamic clustering of maintenance activities. As is shown in section 5.4 and 0, a few thousand euros can be saved by implementation of dynamic clustering methods. Of course, it will also require some investment due to the necessary update of the maintenance management system, the possible license for optimization software and learning the employees on how to use these models. It might even be possible to employ someone that has the knowledge on how to implement these optimization models and can even make improvements in the future. For now, because of the lack of information on setups, scheduling is not as difficult as when more setups will be taken into consideration. For now, the heuristics will suffice in making a feasible schedule and small improvements in the heuristics might approach the solution of the MIP-model. As for now, it is not necessary to invest in a license for optimization software. AIS does not have employees that know how to implement this software and AIS must buy a license and educate the employees, which takes too much effort. As small improvements in the heuristics might result in approximately the same results as the MIP-model, it would be better to first develop improved heuristics that are easy to use. If the fleet of AIS grows, and more secondary setups can be implemented, the problem will grow more difficult. The use of optimization software might result in a further decrease in costs, at that point, it might be worthwhile to consider using this software.

Not only will the implementation of dynamic clustering of maintenance activities result in better maintenance schedules, it will also take some load of the CAMO-manager as schedules can easily be created. The CAMO-manager only has to verify is the schedules are actually viable, as the CAMO-manager will always be responsible.

The third recommendation would be to collect more information on secondary setups that are required for maintenance tasks. For now, only three secondary setups are taken into consideration and the addition of more secondary setups will improve the dynamic clustering of maintenance activities even more. Even small setup tasks can make a difference if a lot of them are clustered appropriately. As the English say: ‘pennies make pounds, and pounds make profits’.

Another recommendation is to check if planning a major inspection earlier might result in a more profitable maintenance schedule. Now, the 200-hours inspections are just planned as far as possible from each other, what sounds logical to do, as the aircraft will have to return to Lelystad as little as possible. As dynamic clustering will sometimes suggest, if there are a lot of other maintenance jobs are due just before a 200-hours inspection, it might be better to shift the 200-hours inspection a little bit forward in time.

7.3. Further research

To fully benefit from dynamic clustering of maintenance activities, some further research should be conducted to gain the full potential of dynamic clustering.

First off, the current models that are experimented with, consider single aircraft scheduling. Because of this, it might happen that aircraft maintenance is scheduled on the same day for a couple of aircraft. This might cause the capacity of the maintenance department to be exceeded. In section 4.4 we have proposed an MIP-model that takes into consideration the full fleet of AIS and with the addition of capacity restrictions.

Secondly, a next step after implementing dynamic clustering of maintenance activities might be to optimize the flight schedule and thus the allocation of aircraft over the routes. Allocating the aircraft to certain routes will impact the maintenance schedule and it might be preferable to have some aircraft fly on longer or shorter routes to optimize the maintenance planning.

Another thing that needs more further research are the end-of-horizon costs of the setup activities. In the models that are described in chapter 4 the end-of-horizon costs of maintenance jobs are considered when scheduling the maintenance activities. The end-of-horizon costs of setups activities is not taken into consideration yet. This is because it is very difficult to predict when a certain setup will be necessary after the planning horizon. This could be right after the planning horizon or could be 3 weeks later for example. To add these costs to the model, a certain predictive model should be used to calculate the end-of-horizon costs of setup tasks.

Finally, AIS should perform more research in quantifying and allocating more secondary setup activities to the maintenance jobs. If this is done, the maintenance costs can be decreased even more by clustering these secondary maintenance activities. In the most ideal situation, a tree structure should be created with all maintenance activities and their necessary setup tasks.

7.4. Discussion

This research still has its limitations as we will discuss in this paragraph. Aviation is a very complex industry that can never be modelled 100% as the real-life situation. Also, the data availability of AIS was not very good, and thus not too many experiments have been conducted. We generated six schedules of six of their aircraft. Optimally, we would have generated way more schedules to gain some more statistical substantiation.

Also, the way the CAMO-department currently plans the maintenance is not too clear. The process as described in Section 5.5 has been used to calculate the current performance of the AIS maintenance planning, which is the same process as the opportunity-based heuristic. In real-life the CAMO-manager clusters some tasks when he thinks this would be beneficial. Not a very clear method of planning is used, and the real performance is therefore difficult to model. Also, no historical data is recorded and thus also cannot be used to compare to the heuristics and MIP-model.

As said before, the addition of end-of-horizon costs for setups should be added to the models to create a situation that represents the reality better. Still, these end-of-horizon costs affect the schedule more at the end of the horizon. Because we plan on a rolling horizon, which should be done every few weeks, a new schedule is constantly generated, and new tasks would be added at the end of the horizon. The addition of end-of-horizon setup costs would not affect the earlier planned maintenance jobs and therefore might not affect the scheduling that much.

Currently, giving extension to maintenance tasks only is used when really necessary. This is because of two reasons: the CAMO-manager does not actively try to optimize the planning by giving extension to some tasks and also because giving extension comes with a risk. When giving the full extension to a maintenance task, you are not that flexible anymore, once the extension is also expired, the aircraft must be grounded, therefore you must be sure that the maintenance can be finished on time. This could be a reason to not consider the MIP-model that could give extension when implementing dynamic clustering at AIS.

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Appendix 1 – Due List (first 2/5 pages)

Task No.	Description	Action	Int.	Rem.	Due
08-20-001	Weight and balance	W&B	48M	40M	11-08-2021
100/110/IN/02 C1	Inspection of aft wing root fairing internal area for corrosion	CPCP	96M	95M	09-03-2026
120/IN/03 C1	Inspection of front pressure bulkhead fwd face for corrosion	CPCP	24M	23M	09-03-2020
130/EX/01 C1	Inspection of external skin including horizontal lap joints and vertical butt joints at Stn 57-130	CPCP	48M	43M	13-11-2021
130/EX/01 C2	Inspection of windshield frames external surface for corrosion	CPCP	48M	43M	13-11-2021
130/EX/01 C3	Inspection of skin under antenna external area for corrosion	CPCP	48M	17M	13-09-2019
130/IN/02 C1	Inspection of below floor area Stn 57 to 130 for corrosion , SB 53- JM5284	CPCP	48M	1M	23-05-2018
130/IN/03 C1	Inspection of above floor area Stn 57 to 130 for corrosion	CPCP	96M	15M	23-07-2019
130/IN/03 C2	Inspection of internal area of windshield frames for corrosion, SB 53-JM7331	CPCP	48M	19M	01-11-2019
140/EX/01 C1	Inspection of external skin includig horizontal lap joints, vertical butt joints and window cut-outs at Stn 130-328 for corrosion	CPCP	48M	43M	13-11-2021
140/EX/01 C2	Inspection of external area of skin under antenna for corrosion (with antenna removed)	CPCP	48M	43M	13-11-2021
140/IN/02 C1	Inspection of below floor area Stn 130 to 328 for corrosion, SB 53-JM7520 & SB 53-JM7389	CPCP	48M	1M	23-05-2018
140/IN/02 C2	Inspection of above floor area Stn 130 to 328 for corrosion, SB 53-JM7520 & SB 53-JM7389	CPCP	96M	15M	22-07-2019
150/EX/01 C1	Inspection of external skin including horizontal lap joints and vertical butt joints at Stn 328-421 for corrosion	CPCP	48M	43M	13-11-2021
150/EX/01 C2	Inspection of external skin under antennas for corrosion (Antenna Removed)	CPCP	48M	19M	01-11-2019
150/IN/02 C1	Inspection of below floor Stn 328-421 for corrosion Ref SB 53- JA880545	CPCP	48M	19M	01-11-2019
150/IN/02 C2	Inspection of above floor area Stn 328-421 for corrosion	CPCP	96M	15M	22-07-2019
160/EX/01 C1	Inspection of external skin including lap joints Stn 421 to 463 for corrosion	CPCP	48M	43M	13-11-2021
160/IN/01 C1	Inspection of internal area Stn 421 to 463 for corrosion	CPCP	48M	1M	23-05-2018
170/EX/01 C1	Inspection of external skin Stn 463 to 511 for corrosion Ref SB 53-JM5245	CPCP	48M	2M	20-06-2018
170/IN/01 C1	Inspection of internal area Stn 463 to 511 for corrosion	CPCP	48M	2M	20-06-2018
200/EX/01 C1	Inspection of external skin of vertical and horizontal stabilizers, SB 55-JM5278	CPCP	48M	2M	20-06-2018
200/EX/01 C2	Inspection of vertical stabiliser rear spar attach, including upper & center rudder hinge fitting & vertical stab lower rear spar fitting	CPCP	24M	16M	11-08-2019
21-20-001	Perform Recirculation Fan bearing change and brush check Ref MM 21-20-11	Replace	1200FH	466,29FH	21.818,50FH
21-30-011	Operational check of the Altitude pressure switch	DVI	15000FH / 72M	11.616,39FH / 23M	32.969,00FH / 29-03-2020
21-50-010A	Detailled visual inspection of the pipelines of the vapour cycle cooling system	DVI			
21-50-010B	Vapour cycle cooling system (Var) system pressure check	DVI			
21-50-011A	Vapour cycle compressor drive belt tension check	CHK			
21-50-011B	Vapour cycle compressor overhaul	OH			
21-60-001E	Clean the LH Heat Exchanger of the refrigeration unit.Ref MM 21- 50-00	SER	6000FH	3.326,47FH	24.679,08FH
21-60-001E	Clean the RH Heat Exchanger of the refrigeration unit.Ref MM 21-50-00	SER	6000FH	3.326,47FH	24.679,08FH
22-10-005	Autopilot pitch up and pitch down relays 1CA36 and 1CA38 fitted to SPZ 500 autopilot systems only (PRE MOD 2628 every 800hrs , post mod.2628 is OC) Autopilot pitch up and pitch down relays 1CA36 and 1CA38 fitted to SPZ 500 autopilot systems only (				
23-10-023	HF aerial cable	DVI			
23-20-000	Emergency V.H.F F/C	FC			
23-70-003B	CVR underwater locator battery change Ref MM 23-70-00	Replace	72M	65M	21-09-2023
24-00-000A	LH main battery Concorde CAP check Lead acid batteries Ref MM 24-30-71	FC	6M	5M	30-09-2018
24-00-000A	RH main battery Concorde CAP check Lead acid batteries Ref MM 24-30-71	FC	6M	0M	11-04-2018
24-20-101	Overhaul LH AC inverter	OH			
24-20-101	Overhaul RH AC inverter	OH			
24-30-001C	Replace/Overhaul pre LH starter generator bearings pre LAPEC only pre mod	OH			
24-30-001C	Replace/Overhaul pre RH starter generator bearings pre LAPEC only pre mod	OH			
24-30-001D	LH Starter generator Replace/Overhaul bearings Post mod G Ref CMM 24-30-001	OH	1500FH	314,50FH	21.667,11FH
24-30-001D	RH Starter generator Replace/Overhaul bearings Post mod G Ref CMM 24-30-001	OH	1500FH	1.325,35FH	22.677,56FH
24-30-001E	LH Starter Generator Brush Change Ref MM24-30-03	Replace	1200FH	14,50FH	21.367,11FH
24-30-001E	RH Starter Generator Brush Change Ref MM24-30-03	Replace	1200FH	1.025,35FH	22.377,56FH
25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref MM 25-10-05	FC	1200FH / 6M	787,33FH / 1M	22.139,54FH / 13-05-2018
25-20-011	Overhaul life jacket crew 1	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket crew 2	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket infant 1	OH	72M	9M	31-01-2019
25-20-011	Overhaul life jacket infant 2	OH	72M	9M	31-01-2019
25-20-011	Overhaul life jacket infant 3	OH	72M	32M	31-12-2020
25-20-011	Overhaul life jacket seat 1A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 1B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 1C	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 2A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 2B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 2C	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 3A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 3B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 3C	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 4A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 4B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 4C	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 5A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 5B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 5C	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 6A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 6B	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket seat 6C	OH	72M	59M	01-03-2023
25-20-011	Overhaul life jacket seat 7A	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket spare 1	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket spare 2	OH	72M	23M	31-03-2020
25-20-011	Overhaul life jacket spare 3	OH	72M	23M	31-03-2020
25-60-000	PBE replacement	Replace	120M	43M	30-11-2021
25-60-001B	ELT Artex battery change Ref MM 25-60-05 or -10 or -15	Replace	60M	2M	09-06-2018
25-60-011	FIRST AID KIT DVI contents and reseal Ref MM 25-60-00/only if seal broken perform the content check	CHK	400FH / 12M	-12,26FH / 7M	21.339,54FH / 13-11-2018
25-60-011	First aid kit Replacement		72M	-1M	31-03-2018
25-60-030B	Weight check of the cabin portable fire extinguisher Ref MM26- 22-00	CHK	12M	11M	05-03-2019
25-60-030B	Weight check of the flight deck portable fire extinguisher Ref MM26-22-00		12M	11M	05-03-2019
25-60-030C	Overhaul of the portable cabin fire extinguisher Ref MM26-22-00	OH	120M	35M	16-03-2021
25-60-030C	Overhaul of the portable flight deck fire extinguisher Ref MM26- 22-00	OH	120M	35M	16-03-2021
25-62-21	Perform ELT Reset check ref MM ARTEX 570-5012 Rev.K SUBTASK 25-62-21-750-010	FC	1M	0M	07-04-2018
26-20-000	Fire extinguisher system F/C Firing circuits with bottles disconnected. Check continuity of duplicate supply & E Ref MM 26-21-00	FC	48M	19M	01-11-2019
26-20-001A	Replace Fire extinguisher cartridges LH IB Ref MM 26-21-11	Replace	72M	71M	09-03-2024
26-20-001A	Replace Fire extinguisher cartridges LH O/B Ref MM 26-21-11	Replace	72M	71M	09-03-2024
26-20-001A	Replace Fire extinguisher cartridges RH IB Ref MM 26-21-11	Replace	72M	71M	09-03-2024
26-20-001A	Replace Fire extinguisher cartridges RH OB Ref MM 26-21-11	Replace	72M	71M	09-03-2024
26-20-001B	Hydrostatic test of the fire extinguisher bottle LH I/B	Hydro	60M	13M	20-05-2019
26-20-001B	Hydrostatic test of the fire extinguisher bottle LH O/B	Hydro	60M	13M	20-05-2019
26-20-001B	Hydrostatic test of the fire extinguisher bottle RH I/B	Hydro	60M	23M	25-03-2020
26-20-001B	Hydrostatic test of the fire extinguisher bottle RH O/B	Hydro	60M	23M	25-03-2020
26-20-004A	Replace fire extinguisher flex hoses LH I/B Ref MM26-21-19	Replace	96M	61M	26-05-2023
26-20-004B	Replace fire extinguisher flex hoses RH O/B Ref MM26-21-19	Replace	96M	61M	26-05-2023
26-20-004C	Replace fire extinguisher flex hoses LH O/B Ref MM26-21-19	Replace	96M	61M	26-05-2023

26-20-004D	Replace fire extinguisher flex hoses RH I/B Ref MM26-21-19	Replace	96M	40M	01-08-2021
26-20-004E	Replace fire extinguisher flex hoses	Replace			
26-20-004F	Replace fire extinguisher flex hoses	Replace			
26-20-004G	Replace fire extinguisher flex hoses	Replace			
26-20-004H	Replace fire extinguisher flex hoses	Replace			
27-20-010	Rudder pedal Brake cylinder attachment Bracket	DVI			
27-50-005	Flap acutator overhaul	OH	10000FC / 72M	5144FC /12M	31952FC / 11-04-2019
27-50-008A	Flap torque shaft universal joints Type F	Replace			
27-50-008B	Flap torque shaft universal joints Type M	Replace			
29-20-003	Hydraulic power emergency selector valve - introduction of an inspection Check operating load ref SB29-JA901242	CHK	1800FH / 24M	1.028,18FH / 13M	22.380,39FH / 10-05-2019
29-20-003C	Hydraulic power emergency selector valve Seal change Ref MM29-10-32	FC	24M	13M	10-05-2019
3/400/EX/01 C1	Inspection of external area of wing main structure (Jet pipe removed)	CPCP	48M	1M	30-05-2018
3/400/IN/01 C1	Inspection of internal area of wing main structure (JSNL 28-030)	CPCP	48M	19M	01-11-2019
3/400/IN/01 C2	Inspection of Stns 36, 51, 83 including surrounding skins for corrosion (Ensure drainage paths are clear and any excessive sealant removed)	CPCP	48M	19M	01-11-2019
3/410/EX/01 C1	Inspection of external area of wing leading edge for corrosion. Areas of skin exposed during de-ice boot removal must be inspected for corrosion (Note4, AMM 30-10-17,page block 401)	CPCP	48M	2M	19-06-2018
3/410/IN/01 C1	Inspection of internal area of wing leading edge incl. fwd face of wing front spar for corrosion	CPCP	96M	1M	14-05-2018
3/420/EX/01 C1	Inspection of external area of the wing trailing edge including flaps and ailerons for corrosion	CPCP	48M	1M	30-05-2018
3/420/IN/01 C1	Inspection of internal area of the wing trailing edge for corrosion	CPCP	96M	67M	01-11-2023
3/430/IN/01 C1	Inspection of internal area of the MLG bay for corrosion	CPCP	48M	2M	18-06-2018
30-42-002-ALI	Windshield wiper LH arm assy DVI Ref MM 30-42-02, SB 30- JA950641	DVI	48M	43M	13-11-2021
30-42-002-ALI	Windshield wiper RH arm assy DVI Ref MM 30-42-02, SB 30- JA950641	DVI	48M	43M	13-11-2021
30-42-003B	Replacement of the LH wiper attachment bolts, SB 30-JA950641	Replace	96M	25M	06-05-2020
30-42-003B	Replacement of the RH wiper attachment bolts, SB 30-JA950641	Replace	96M	25M	06-05-2020
30-42-004	Replace windshield wiper LH arm assy, SB 30-JA950641	Replace	96M	38M	17-06-2021
30-42-004	Replace windshield wiper RH arm assy, SB 30-JA950641	Replace	96M	38M	17-06-2021
31-20-001	Replace LH panel clock battery Ref MM 31-25-00.	Replace	36M	13M	26-05-2019
31-20-001	Replace RH panel clock battery Ref MM 31-25-00.	Replace	36M	24M	28-04-2020
31-30-000	Flight Data |Recorder (FDR) system functional check. Note: including parameter read out Ref MM 31-35-00, 31-37-00, 31-38-00	FC	24M	0M	01-04-2018
31-30-003B	Replace FDR ULB Battery Ref MM 31-35-07/ 31-38-05	REPL	72M	15M	31-07-2019
32-00	LH Landing gear inspect radius rod spherical bearing LH, SB 32- JA030340	INSP	5000FC	3318FC	30126FC
32-00	RH Landing gear inspect radius rod spherical bearing RH, SB 32- JA030340	INSP	5000FC	3318FC	30126FC
32-00A	LH MLG radius rod inspection for cracks NDI, SB 32-JA060741	INSP	12M	-17M	13-11-2016
32-00A	RH MLG radius rod inspection for cracks NDI, SB 32-JA060741	INSP	12M	-17M	13-11-2016
32-00B	Landing gear LH MLG to wing fitting insp/repair/replace, SB 32- JA090240	INSP	27000FC	20566FC	47374FC
32-00B	Landing gear RH MLG to wing fitting insp/repair/replace, SB 32- JA090240	INSP	27000FC	20566FC	47374FC
32-00C	NDI Radius rod cylinder LH, AD 2012-0212	NDI	6000FC	410FC	27218FC
32-00C	NDI Radius rod cylinder RH, AD 2012-0212	NDI	6000FC	410FC	27218FC
32-00D	Crack check LH MLG Cylinder, SB 32-JA-860812	NDI			
32-00D	Crack check RH MLG Cylinder, SB 32-JA-860812	NDI			
32-10-001C	Replace LH MLG hydraulic fluid Ref MM 32-10-11	Replace	4000FC / 18M	2733FC / 13M	29541FC / 13-05-2019
32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	Replace	4000FC / 18M	3389FC / 13M	30197FC / 13-05-2019
32-10-001D	MLG LH Pintle to Cylinder interface NDT Inspection, SB 32- JA960142R4/AD2017-0053	NDI	1200FC	589FC	27397FC
32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspection, SB 32- JA960142R4/AD2017-0053	NDI	1200FC	589FC	27397FC
32-10-001E	Overhaul LH MLG assy (including yoke bearings) Ref MM 32-10- 11	OH	10000FC / 72M	8733FC / 61M	35541FC / 04-05-2023
32-10-001E	Overhaul RH MLG assy (including yoke bearings) Ref MM 32-10- 11	OH	10000FC / 72M	9389FC / 67M	36197FC / 13-11-2023
32-10-002	Overhaul LH Radius rod & actuator Ref MM 32-10-31	OH	10000FC / 72M	4410FC / 3M	31218FC / 14-07-2018
32-10-002	Overhaul RH Radius rod & actuator Ref MM 32-10-31	OH	10000FC / 72M	4410FC / 3M	31218FC / 18-07-2018
32-10-005	Overhaul LH up-lock actuator Ref MM 32-10-51	OH	10000FC / 72M	4410FC / 1M	31218FC / 25-05-2018
32-10-005	Overhaul RH up-lock actuator Ref MM 32-10-51	OH	10000FC / 72M	9061FC / 9M	35869FC / 11-01-2019
32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	Replace	4000FC /18M	2994FC / 8M	29802FC / 18-12-2018
32-20-001D	Torque Check NLG top cap bolt, SB 32-JA840827	CHK			
32-20-001E	NLG overhaul Ref MM 32-20-11	OH	10000FC /72M	8994FC / 62M	35802FC / 18-06-2023
32-20-005	NLG down-lock overhaul Ref MM 32-20-71	OH	8500FC	4727FC	31535FC
32-20-008	Nose uplock actuator overhaul Ref MM 32-20-61	OH	10000FC /72M	8994FC / 58M	35802FC / 22-02-2023
32-20-009	Nose retraction jack overhaul recommended (Pre Mod JM5387 only)	OH	n/a		
32-40-216	LH Time limit and maintenance check MLG radius rod mounting shaft assy, SB 05-JA090143	Life Limit	31038FC	4230FC	31038FC
32-40-216	RH Time limit and maintenance check MLG radius rod mounting shaft assy, SB 05-JA090143	Life Limit	31038FC	4230FC	31038FC
32-50-003B	Nose landing gear steering jack overhaul Ref MM 32-50-13	OH	10000FC / 72M	4995FC / 11M	31803FC / 13-03-2019
32-50-004	Steering selector valve overhaul NLG Ref MM32-50-11	OH	10000FC / 72M	9925FC / 66M	36733FC / 03-10-2023
33-20-000	Inspect cabin lights, check SB 33-A-JA891240 for applicibility	INSP			
33-50-002	Emergency lights power unit No1 & No2 battery cap check Ref MM 33-50-10	FC	64M	1M	13-05-2018
34-20-004	Perform Compass Swing of Standby Compass System Ref MM34-21-31	CHK	24M	11M	12-03-2019
34-20-010	Perform Compass Swing of Gyromagnetic Compass System Ref MM34-21-31	CHK	24M	11M	12-03-2019
34-44-00	TAWS software update	CHK	4M	0M	01-04-2018
34-54-01A	DVI of antenna installation of TCAS	DVI	48M	19M	01-11-2019
35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) Ref MM35-10-05	FC	36M	3M	23-07-2018
35-00-001B	Replace Oxygen bottle fixed (storage cylinder) Ref MM35-10-05	Replace	288M	220M	31-08-2036
35-10-003A	Hydrostatic test Pilot portable oxygen bottle	Hydro	60M	38M	30-06-2021
35-10-003B	Hydrostatic test co- Pilot portable oxygen bottle	Hydro	60M	19M	30-11-2019
35-30-001C	Hydrostatic test Passenger oxygen bottle Therapeutic portable	FC	n/a		
500/IN/02 C1	Inspect Spar/Fuselage Fitting Bolt Bore at Stn. 223 ref NDI Manual part 5, 53-40-05 & AMM 53-40-05	NDI	72M	-24135M	01-01-0007
51-00-200-ALI	Engine mount structure life limit	Life Limit	53000FC	26192FC	53000FC
51-00-200-ALI	Fuselage Life limit	Life Limit	46200FC	19392FC	46200FC
51-00-200-ALI	Horizontal stabiliser life limit	Life Limit	45000FC	18192FC	45000FC

Appendix 2 - Text representation of AIMMS model

```
Model Main_AISMaintenanceClustering {
    DeclarationSection sets {
        Set Jobs {
            Index: j;
            Definition: ElementRange(1,59);
        }
        Set Setups {
            Index: i;
            Definition: ElementRange(1,4);
        }
        Set Time {
            Index: t;
            Definition: elementrange(1,52);
        }
        Set Integersz {
            Index: int;
            Definition: elementrange(0,ord(last(t)));
        }
        Set Num {
            Index: n;
            Definition: elementrange(1,20);
        }
    }
    DeclarationSection InputData {
        Parameter f {
            IndexDomain: j;
        }
        Parameter s {
            IndexDomain: i;
        }
        Parameter m {
            IndexDomain: j;
        }
        Parameter d {
            IndexDomain: j;
        }
        Parameter e {
            IndexDomain: j;
        }
        Parameter AllocationSetMaint {
            IndexDomain: (i,j);
            Range: binary;
        }
    }
    Parameter g {
        IndexDomain: j;
        Definition: f(j)-d(j);
    }
    Parameter MinNumCyclHor {
        IndexDomain: j;
        Definition: Ord(Last(Time),Time)/f(j);
    }
    Parameter IntervalFraction {
        IndexDomain: (j,t);
        Definition: (Ord(Last(time),time)-ord(t))/f(j);
    }
    Set q {
        IndexDomain: j;
        SubsetOf: Integersz;
        Definition: {
            {int|ord(int)<= ord(last(t))/f(j)}
        }
    }
```

```
    Set LC {
        IndexDomain: j;
        SubsetOf: Integersz;
        Definition: {
            {Int|1 + ord(last(t))- f(j) <= ord(Int) <= ord(last(t))}
        }
    }
    Variable X {
        IndexDomain: (j,t);
        Range: binary;
    }
    Variable Y {
        IndexDomain: (i,t);
        Range: binary;
    }
    Variable W {
        IndexDomain: (j,t);
        Range: binary;
    }
    Variable EndCost {
        IndexDomain: j;
        Range: free;
        Definition: Sum((t)|((1+ord(last(Time))-
f(j))<=ord(t))and(ord(t)<=ord(last(time))),m(j)*IntervalFraction(j,t)*W(j,t));
    }
    Variable MaintCost {
        Range: free;
        Definition: SUM((j,t),X(j,t)*m(j));
    }
    Variable SetUpCost {
        Range: free;
        Definition: SUM((i,t),Y(i,t)*s(i));
    }
    Variable EndofHorCost {
        Range: free;
        Definition: Sum((j,t)|((1+ord(last(Time))-
f(j))<=ord(t))and(ord(t)<=ord(last(time))),m(j)*IntervalFraction(j,t)*W(j,t));
    }
    Variable MaintenanceCost {
        Range: free;
        Definition: {

SUM((j,t),X(j,t)*m(j))+SUM((i,t),Y(i,t)*s(i))+Sum((j,t)|((1+ord(last(Time))-
f(j))<=ord(t))and(ord(t)<=ord(last(time))),m(j)*IntervalFraction(j,t)*W(j,t))
            /*SUM((j,t),X(j,t)*m(j))+SUM((i,t),Y(i,t)*s(i))*/
        }
    }
    Constraint Ontime {
        IndexDomain: j;
        Definition: Sum(t|ord(t)<=(d(j)+e(j)),X(j,t))>=1;
    }
    Constraint NotTooMuchExtention {
        IndexDomain: (j,n,t)|(ord(t)>=1)and(ord(t)<=(ord(last(time))-
ord(n)*f(j)+1))and(ord(n)<=(ord(last(Time))/f(j)));
        Definition: {
            sum(int|(ord(int)<=ord(n)*f(j)+e(j)),X(j,ord(t)+ord(int)))>=ord(n)
            /*sum(int|(ord(int)<=f(j)-1),X(j,ord(t)+ord(int)))>=1*/

            /*sum(int|(ord(int)<=ord(n)*f(j)-
1+e(j)),X(j,ord(t)+ord(int)))>=ord(n)*/
        }
    }
    Constraint SetupNeccecity {
        IndexDomain: (i,j,t);
        Definition: AllocationSetMaint(i,j)*X(j,t)<=Y(i,t);
    }
    Constraint EndOfHorizon1 {
        IndexDomain: j;
```

```
        Definition: sum(t|((1+ord(last(Time))-
f(j))<=ord(t))and(ord(t)<=ord(last(time))),W(j,t))>=1;
    }
    Constraint EndOfHorizon2 {
        IndexDomain: (j,t)|((1+ord(last(Time))-
f(j))<=ord(t))and(ord(t)<=ord(last(time)));
        Definition: W(j,t)<=X(j,t);
    }
    Set PMSP {
        SubsetOf: AllConstraints;
    }
    Set RPMSP {
        SubsetOf: AllConstraints;
    }
    MathematicalProgram DescisionModel {
        Objective: MaintenanceCost;
        Direction: minimize;
        Constraints: AllConstraints;
        Variables: AllVariables;
        Type: Automatic;
    }
    Procedure MainInitialization {
        Comment: "Add initialization statements here that do NOT require any
library being initialized already.";
    }
    Procedure PostMainInitialization {
        Comment: {
            "Add initialization statements here that require that the libraries are
already initialized properly,
            or add statements that require the Data Management module to be
initialized."
        }
    }
    Procedure MainExecution {
        Body: {
            Solve DescisionModel;
        }
    }
```

Appendix 3 – Model Inputs AIS

BCI								SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
	Column2	Column3	Column4	Colu	Column1	Column15	Column16	Column17	3000	1000	100	12.5
0	Job No.	Descrbition	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column22	Column3
1	AMP-AIS/JS-PHIssue1 Rev1	Perform 200 hours Inspection	12.00	7.58	1.20	16.00	50.00	250.00	1			
2	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	24.00	7.58	2.40	24.00	100.00	400.00	1			
3	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.00	13.00	2.60	0.50		6.25	1			
4	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref M	26.00	13.00	2.60	0.50		6.25	1			
5	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.00	13.00	2.60	0.50		6.25	1			
6	73-10-09	F/C & clean Fuel manifold & nozzle assy LH	27.00	19.69		6.00		75.00	1			
7	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	27.00	19.69		6.00		75.00	1			
8	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	27.00	19.69		0.50		6.25	1			
9	72-40-01	Visually inspect RH combustion case assy iaw AD 2	27.00	19.69		0.50		6.25	1			
10	32-10-001D (1)	MLG LH Pintle to Cylinder interface NDT Inspectio	30.00	12.10		1.00		12.50	1	1		
11	32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspectio	30.00	12.10		1.00		12.50	1	1		
12	57-50-023-ALI	Detailed visual inspection of the aileron upper an	40.00	22.10		1.00		12.50	1			
13	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.00	7.58		0.50		6.25	1			
14	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.00	8.67		0.50		6.25	1			
15	25-60-030B	Weight check of the flight deck portable fire extin	52.00	8.67	4.33	0.50		6.25	1			
16	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.00	14.17	4.33	48.00	125.00	725.00	1			
17	53-11-011-ALI	Detailed visual inspection of the RPB fwd face, ho	60.00	29.45		6.00		75.00	1			
18	53-10-063-ALI	DVI of windscreen frame attachment fittings at fra	62.50	31.95		2.00		25.00	1			
19	53-10-067-ALI	Detailed visual inspection of the coaming at frame	62.50	44.60		4.00		50.00	1			
20	53-10-065-ALI	Torque check of the canopy attachment bolts at fr	62.50	44.60		8.00		100.00	1			
21	53-10-069-ALI	Torque check of the coaming attachment bolts at f	62.50	44.60		7.00		87.50	1			
22	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-0	72.00	8.22		1.00		12.50	1			
23	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-0	72.00	46.47		1.00		12.50	1			
24	57-10-024-ALI	Internal Detailed visual inspection of LH/RH wing	75.00	8.28		1.00		12.50	1			
25	57-30-004-ALI	NDI inspection of wing lower skin LH/RH wing Stn	75.00	28.98		1.00		12.50	1	1		
26	32-10-001C (1)	Replace LH MLG hydraulic fluid Ref MM 32-10-11	78.00	13.00	8.67	2.00		25.00	1			
27	32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	78.00	13.00	8.67	2.00		25.00	1			
28	32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	78.00	13.00	8.67	2.00		25.00	1			
29	57-10-213-ALI	NDI inspection of the leading edge attachment rib	90.00	51.55		2.00		25.00	1	1		
30	57-30-003	Inspection of LH/RH wing lower skin Stn 36-83. Ins	104.00	4.33	8.67	4.00		50.00	1			
31	53-10-083-ALI	Detailed visual inspection of intercostals at passe	104.00	8.67		16.00		200.00	1			
32	120/IN/03 C1	Inspection of front pressure bulkhead fwd face fo	104.00	21.67		8.00		100.00	1			
33	34-20-010	Perform Compass Swing of Gyromagnetic Compas	104.00	30.33	8.67	1.00		12.50	1			
34	34-20-004	Perform Compass Swing of Standby Compass Syst	104.00	30.33	8.67	1.00		12.50	1			
35	29-20-003	Hydraulic power emergency selector valve - intro	104.00	41.66		1.00		12.50	1			
36	29-20-003C	Hydraulic power emergency selector valve Seal ch	104.00	43.33		6.00		75.00	1			
37	AMP-AIS/JS-PH Issue1 Rev	Perform 2000 hours Inspection	120.00	30.67	12.00	78.00	125.00	1100.00	1		1	
38	53-11-004-ALI	Detailed visual inspection of passenger door surro	120.00	32.13		3.00		37.50	1			
39	53-10-001-ALI	DVI of the front pressure bulkhead FWD face inter	145.00	18.95		2.00		25.00	1			
40	57-40-006-ALI (1)	Detailed visual inspection of LH engine mount att	145.00	27.13		2.00		25.00	1			
41	57-40-006-ALI	Detailed visual inspection of RH engine mount att	145.00	27.13		2.00		25.00	1			
42	57-30-005-ALI	NDI inspection of wing lower skin at Stn 115-151 a	150.00	2.08		4.00		50.00	1	1		
43	57-10-030-ALI	Internal detailed visual inspection of attachment	150.00	13.23		3.00		37.50	1			
44	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) R	156.00	8.67		1.00	300.00	312.50	1			
45	31-20-001 (1)	Replace LH panel clock battery Ref MM 31-25-00.	156.00	26.00		2.00		25.00	1			
46	31-20-001	Replace RH panel clock battery Ref MM 31-25-00.	156.00	26.00		2.00		25.00	1			
47	57-50-021-ALI.	Detailed visual inspection of the aileron upper an	187.50	22.75		1.00		12.50	1			
48	57-40-008-ALI (1)	Inspection and torque check LH inboard flap hinge	200.00	35.25		2.00		25.00	1			
49	57-40-008-ALI	Inspection and torque check RH inboard flap hinge	200.00	35.25		2.00		25.00	1			
50	3/400/EX/01 C1	Inspection of external area of wing main structure	208.00	8.67		2.00		25.00	1			
51	32-20-005	NLG down-lock overhaul Ref MM 32-20-71	212.50	41.08		3.00		37.50	1			
52	AMP-AIS/JS-PH Issue1 Rev	Perform 4000 hours Inspection	240.00	30.33	24.00	65.00	125.00	937.50	1			
53	35-10-003B	Hydrostatic test co- Pilot portable oxygen bottle	260.00	4.33		1.00	300.00	312.50	1			
54	35-10-003A	Hydrostatic test Pilot portable oxygen bottle	260.00	34.67		1.00	300.00	312.50	1			
55	26-20-001B (1)	Hydrostatic test of the fire extinguisher bottle LH	260.00	52.00		1.00	300.00	312.50	1			
56	26-20-001B (2)	Hydrostatic test of the fire extinguisher bottle LH	260.00	52.00		1.00	300.00	312.50	1			
57	26-20-001B (3)	Hydrostatic test of the fire extinguisher bottle RH	260.00	52.00		1.00	300.00	312.50	1			
58	26-20-001B	Hydrostatic test of the fire extinguisher bottle RH	260.00	52.00		1.00	300.00	312.50	1			
59	32-20-008	Nose uplock actuator overhaul Ref MM 32-20-61	312.00	26.00		2.00		25.00	1			
60	25-60-011	First aid kit Replacement	312.00	43.33		0.25		3.13	1			
61	32-10-002	Overhaul RH Radius rod & actuator Ref MM 32-10-	312.00	47.67		6.00	6000.00	6075.00	1			
62	72-10-005 (1)	LH Propeller Governor OH	426.00	22.54		8.00		100.00	1			
63	32-40-216 (1)	LH Time limit and maintenance check MLG radius	775.95	48.05		3.00		37.50	1			
64	32-40-216	RH Time limit and maintenance check MLG radius	775.95	48.05		3.00		37.50	1			

	DCI							SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
									3000	1000	100	12.5
	Job No.	Describtion	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column2	Column3
1	AMP-AIS/JS-PHIssue1 Rev1	Perform 200 hours Inspection	8.33	8.30	0.83	16.00	50.00	250.00	1			
2	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	16.67	1.00	1.67	24.00	100.00	400.00	1			
3	72-40-01	Visually inspect RH combustion case assy iaw AD 2	18.75	1.00		0.50	0.00	6.25	1			
4	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	18.75	1.00		6.00	0.00	75.00	1			
5	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	18.75	11.18		0.50	0.00	6.25	1			
6	73-10-09	F/C & clean Fuel manifold & nozzle assy LH	18.75	11.18		6.00	0.00	75.00	1			
7	33-50-002	Emergency lights power unit No1 & No2 battery ca	26.00	1.00	2.60	0.50	0.00	6.25	1			
8	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.00	17.33	2.60	0.50	0.00	6.25	1			
9	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.00	17.33	2.60	0.50	0.00	6.25	1			
10	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref N	26.00	17.33	2.60	0.50	0.00	6.25	1			
11	32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspectio	33.33	10.39		1.00	0.00	12.50	1	1		
12	32-10-001D (1)	MLG LH Pintle to Cylinder interface NDT Inspectio	33.33	10.39		1.00	0.00	12.50	1	1		
13	57-50-023-ALI	Detailed visual inspection of the aileron upper an	44.44	36.39		1.00	0.00	12.50	1			
14	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-(	50.00	8.35		1.00	0.00	12.50	1			
15	21-20-001	Perform Recirculation Fan bearing change and bru	50.00	12.59		2.00	0.00	25.00	1			
16	57-10-006-ALI	Detailed visual inspection of flap and aileron hing	50.00	18.38		1.00	0.00	12.50	1			
17	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-(	50.00	35.88		1.00	0.00	12.50	1			
18	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.00	9.09		0.50	0.00	6.25	1			
19	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.00	9.30	4.33	48.00	125.00	725.00	1			
20	25-60-030B	Weight check of the flight deck portable fire extin	52.00	39.00	4.33	0.50	0.00	6.25	1			
21	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.00	39.00		0.50	0.00	6.25	1			
22	24-30-001D (1)	LH Starter generator Replace/Overhaul bearings P	62.50	8.35		0.50	0.00	6.25	1			
23	53-11-011-ALI	Detailed visual inspection of the RPB fwd face, ho	66.67	12.17		6.00	0.00	75.00	1			
24	53-10-065-ALI	Torque check of the canopy attachment bolts at fr	69.44	43.81		8.00	0.00	100.00	1			
25	53-10-067-ALI	Detailed visual inspection of the coaming at frame	69.44	43.81		4.00	0.00	50.00	1			
26	53-10-069-ALI	Torque check of the coaming attachment bolts at f	69.44	43.81		7.00	0.00	87.50	1			
27	52-10-001D	Passenger/crew door Inspect for evidence of exce	75.00	43.38	7.50	1.00	0.00	12.50	1			1
28	52-10-004	F/C & Lubricate door warning Circuit Function test	75.00	43.38	7.50	1.00	0.00	12.50	1			1
29	52-11-001B-ALI	Detailed visual inspection of passenger door struc	75.00	43.38		1.00	0.00	12.50	1			1
30	32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	78.00	26.00	8.67	2.00	0.00	25.00	1			
31	32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	78.00	47.67	8.67	2.00	0.00	25.00	1			
32	32-10-001C (1)	Replace LH MLG hydraulic fluid Ref MM 32-10-11	78.00	47.67	8.67	2.00	0.00	25.00	1			
33	57-30-004-ALI	NDI inspection of wing lower skin LH/RH wing Stn	83.33	14.06		1.00	0.00	12.50	1	1		
34	AMP-AIS/JS-PH Issue1 Rev	Perform 2000 hours Inspection	83.33	24.59	8.33	78.00	125.00	1100.00	1		1	
35	57-10-024-ALI	Internal Detailed visual inspection of LH/RH wing	83.33	30.64		1.00	0.00	12.50	1			
36	53-11-028-ALI	Detailed visual inspection of vertical stabilizer att	83.33	51.28		2.00	0.00	25.00	1			
37	AMP-AIS/JS-PH Issue1 Rev	Perform 2400 hours Inspection	100.00	6.14	10.00	36.00	0.00	450.00	1		1	
38	57-10-213-ALI	NDI inspection of the leading edge attachment rib	100.00	47.31		2.00	0.00	25.00	1	1		
39	57-30-003	Inspection of LH/RH wing lower skin Stn 36-83. Ins	104.00	30.33	8.67	4.00	0.00	50.00	1			
40	29-20-003	Hydraulic power emergency selector valve - introd	104.00	36.00		1.00	0.00	12.50	1			
41	34-20-004	Perform Compass Swing of Standby Compass Syst	104.00	39.00	8.67	1.00	0.00	12.50	1			
42	34-20-010	Perform Compass Swing of Gyromagnetic Compas	104.00	39.00	8.67	1.00	0.00	12.50	1			
43	AMP-AIS/JS-PH Issue1 Rev	Perform Avionics Check	104.00	39.00	10.00	4.00	0.00	50.00	1			
44	29-20-003C	Hydraulic power emergency selector valve Seal ch	104.00	47.67		6.00	0.00	75.00	1			
45	72-00-000B	RH Engine hotsection	150.00	17.84		50.00	0.00	625.00	1			
46	72-00-000B (1)	LH Engine hotsection	150.00	19.44		50.00	0.00	625.00	1			
47	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) R	156.00	8.67		1.00	300.00	312.50	1			
48	53-30-001 C1	Inspect for corrosion LH/RH Area fuselage skin ice	156.00	30.33		4.00	0.00	50.00	1			
49	31-20-001 (1)	Replace LH panel clock battery Ref MM 31-25-00.	156.00	47.67		2.00	0.00	25.00	1			
50	53-10-001-ALI	DVI of the front pressure bulkhead FWD face inter	161.11	20.25		2.00	0.00	25.00	1			
51	57-40-007-ALI	Detailed visual inspection of RH engine mount top	161.11	41.39		0.50	0.00	6.25	1			
52	57-40-007-ALI (1)	Detailed visual inspection of LH engine mount top	161.11	41.39		0.50	0.00	6.25	1			
53	32-00C	NDI Radius rod cylinder RH, AD 2012-0212	166.67	5.42		1.00	0.00	12.50	1	1		
54	32-00C (1)	NDI Radius rod cylinder LH, AD 2012-0212	166.67	5.42		1.00	0.00	12.50	1	1		
55	57-30-005-ALI	NDI inspection of wing lower skin at Stn 115-151 a	166.67	44.53		4.00	0.00	50.00	1	1		
56	53-11-012-ALI	Detailed visual inspection of fuselage stringer cle	202.78	49.36		4.00	0.00	50.00	1			
57	130/IN/02 C1	Inspection of below floor area Stn 57 to 130 for co	208.00	1.00		8.00	0.00	100.00	1		1	
58	140/IN/02 C1	Inspection of below floor area Stn 130 to 328 for c	208.00	1.00		8.00	0.00	100.00	1		1	
59	160/IN/01 C1	Inspection of internal area Stn 421 to 463 for corro	208.00	1.00		2.00	0.00	25.00	1			
60	170/EX/01 C1	Inspection of external skin Stn 463 to 511 for corro	208.00	1.00		1.00	0.00	12.50	1			
61	170/IN/01 C1	Inspection of internal area Stn 463 to 511 for corro	208.00	1.00		2.00	0.00	25.00	1			
62	200/EX/01 C1	Inspection of external skin of vertical and horizon	208.00	1.00		1.00	0.00	12.50	1			
63	3/400/EX/01 C1	Inspection of external area of wing main structure	208.00	1.00		2.00	0.00	25.00	1			
64	3/410/EX/01 C1	Inspection of external area of wing leading edge f	208.00	1.00		0.50	0.00	6.25	1			
65	3/420/EX/01 C1	Inspection of external area of the wing trailing ed	208.00	1.00		0.50	0.00	6.25	1			
66	3/430/IN/01 C1	Inspection of internal area of the MLG bay for corr	208.00	1.00		1.00	0.00	12.50	1			
67	72-10-06 (1)	NTS Valve LH	212.50	9.42		2.00	0.00	25.00	1			
68	53-10-013-ALI	Detailed visual inspection of front pressure bulkh	219.44	34.75		1.00	0.00	12.50	1			
69	26-20-001B (1)	Hydrostatic test of the fire extinguisher bottle LH	260.00	47.67		1.00	300.00	312.50	1			
70	26-20-001B (2)	Hydrostatic test of the fire extinguisher bottle LH	260.00	47.67		1.00	300.00	312.50	1			
71	57-30-215	NDI LH & RH wings bottom skin LG bay Eddy curren	277.78	4.53		1.00	0.00	12.50	1	1		
72	72-00-79S	RH Torque temp limiter bypass valve	295.83	18.14		1.00	0.00	12.50	1			
73	72-00-79S (1)	LH Torque temp limiter bypass valve	295.83	37.50		1.00	0.00	12.50	1			
74	73-20-001 (1)	LH Fuel control unit OH	295.83	37.50		4.00	0.00	50.00	1			
75	73-10	RH Fuel Pump OH	295.83	42.94		4.00	0.00	50.00	1			
76	32-10-002	Overhaul RH Radius rod & actuator Ref MM 32-10-	312.00	8.67		6.00	6000.00	6075.00	1			
77	32-10-002 (1)	Overhaul LH Radius rod & actuator Ref MM 32-10-3	312.00	8.67		3.00	0.00	37.50	1			
78	32-10-005 (1)	Overhaul LH up-lock actuator Ref MM 32-10-51	312.00	8.67		2.00	0.00	25.00	1			
79	61-00-001A	McCauley Propeller RH OH	312.00	21.26		4.00	0.00	50.00	1			
80	32-10-005	Overhaul RH up-lock actuator Ref MM 32-10-51	312.00	30.33		2.00	0.00	25.00	1			
81	32-50-003B	Nose landing gear steering jack overhaul Ref MM	312.00	39.00		8.00	0.00	100.00	1			
82	27-50-005	Flap acutator overhaul	312.00	43.33		2.00	0.00	25.00	1			
83	25-60-011	First aid kit Replacement	312.00	52.00		0.25	0.00	3.13	1			
84	3/410/IN/01 C1	Inspection of internal area of wing leading edge i	416.00	1.00		0.50	0.00	6.25	1			
85	55-10-011 C1	Inspection of horizontal stabilizer attach bolts for	416.00	1.00		8.00	0.00	100.00	1			
86	55-10-010-ALI	Detailed visual inspection of attachments and fitt	416.00	18.84		1.00	0.00	12.50	1			
87	55-30-001-ALI	Detailed visual inspection of attachment fittings v	416.00	18.84		1.00	0.00	12.50	1			

	FCI							SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
									3000	1000	100	12.5
0	Job No.	Describtion	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column2	Column3
1	AMP-AIS/JS-PHIssue1 Rev1	Perform 200 hours Inspection	15.00	11.88	1.50	16.00	50.00	250.00	1			
2	33-50-002	Emergency lights power unit No1 & No2 battery ca	26.00	13.00	2.60	0.50	0.00	6.25	1			
3	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.00	13.00	2.60	0.50	0.00	6.25	1			
4	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.00	13.00	2.60	0.50	0.00	6.25	1			
5	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref M	26.00	13.00	2.60	0.50	0.00	6.25	1			
6	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	30.00	26.89	3.00	24.00	100.00	400.00	1			
7	72-40-01	Visually inspect RH combustion case assy iaw AD 2	33.75	9.01		0.50	0.00	6.25	1			
8	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	33.75	9.01		6.00	0.00	75.00	1			
9	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	33.75	9.01		0.50	0.00	6.25	1			
10	73-10-09	F/C & clean Fuel manifold & nozzle assy LH	33.75	9.01		6.00	0.00	75.00	1			
11	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.00	14.93		0.50	0.00	6.25	1			
12	25-60-030B	Weight check of the flight deck portable fire extin	52.00	30.33	4.33	0.50	0.00	6.25	1			
13	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.00	30.33		0.50	0.00	6.25	1			
14	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.00	47.67	4.33	48.00	125.00	725.00	1			
15	32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	78.00	26.00	8.67	2.00	0.00	25.00	1			
16	32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	78.00	26.00	8.67	2.00	0.00	25.00	1			
17	32-10-001C (1)	Replace LH MLG hydraulic fluid Ref MM 32-10-11	78.00	26.00	8.67	2.00	0.00	25.00	1			
18	57-10-006-ALI	Detailed visual inspection of flap and aileron hing	90.00	12.34		1.00	0.00	12.50	1			
19	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-(	90.00	33.30		1.00	0.00	12.50	1			
20	21-20-001	Perform Recirculation Fan bearing change and bru	90.00	33.30		2.00	0.00	25.00	1			
21	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-(	90.00	33.30		1.00	0.00	12.50	1			
22	31-30-000	Flight Data |Recorder (FDR) system functional che	104.00	17.33	8.67	1.00	0.00	12.50	1			
23	34-20-004	Perform Compass Swing of Standby Compass Syst	104.00	47.67	8.67	1.00	0.00	12.50	1			
24	34-20-010	Perform Compass Swing of Gyromagnetic Compas	104.00	47.67	8.67	1.00	0.00	12.50	1			
25	57-30-003	Inspection of LH/RH wing lower skin Stn 36-83. Ins	104.00	52.00	8.67	4.00	0.00	50.00	1			
26	29-20-003	Hydraulic power emergency selector valve - introd	104.00	52.00		1.00	0.00	12.50	1			
27	AMP-AIS/JS-PH Issue1 Rev	Perform Avionics Check	104.00	52.00	18.00	4.00	0.00	50.00	1			
28	29-20-003C	Hydraulic power emergency selector valve Seal ch	104.00	52.00		6.00	0.00	75.00	1			
29	200/EX/01 C2	Inspection of vertical stabiliser rear spar attach, in	104.00	52.00		2.00	0.00	25.00	1			
30	52-11-002 C1	Passenger/Crew Door Hinge and Support Structure	104.00	52.00		1.00	0.00	12.50	1			1
31	120/IN/03 C1	Inspection of front pressure bulkhead fwd face fo	104.00	52.00		8.00	0.00	100.00	1			
32	53-10-063-ALI	DVI of windscreen frame attachment fittings at fra	125.00	47.40		2.00	0.00	25.00	1			
33	AMP-AIS/JS-PH Issue1 Rev	Perform 2000 hours Inspection	150.00	11.03	15.00	78.00	125.00	1100.00	1		1	
34	57-30-004-ALI	NDI inspection of wing lower skin LH/RH wing Stn	150.00	30.20		1.00	0.00	12.50	1	1		
35	53-30-001 C1	Inspect for corrosion LH/RH Area fuselage skin ice	156.00	17.33		4.00	0.00	50.00	1			
36	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) F	156.00	43.33		1.00	300.00	312.50	1			
37	32-00	RH Landing gear inspect radius rod spherical beari	250.00	29.65	12.50	0.50	0.00	6.25	1			
38	32-00 (1)	LH Landing gear inspect radius rod spherical beari	250.00	29.65	12.50	0.50	0.00	6.25	1			
39	35-10-003A	Hydrostatic test Pilot portable oxygen bottle	260.00	39.00		1.00	300.00	312.50	1			
40	72-00-000B	RH Engine hotsection	270.00	49.61		50.00	0.00	625.00	1			
41	57-40-007-ALI	Detailed visual inspection of RH engine mount top	290.00	43.30		0.50	0.00	6.25	1			
42	57-40-007-ALI (1)	Detailed visual inspection of LH engine mount top	290.00	43.30		0.50	0.00	6.25	1			
43	AMP-AIS/JS-PH Issue1 Rev	Perform 4000 hours Inspection	300.00	8.64	15.00	65.00	125.00	937.50	1			
44	32-10-002	Overhaul RH Radius rod & actuator Ref MM 32-10-	312.00	4.33		6.00	6000.00	6075.00	1			
45	32-10-001E (1)	Overhaul LH MLG assy (including yoke bearings) R	312.00	4.33		8.00	0.00	100.00	1			
46	32-50-003B	Nose landing gear steering jack overhaul Ref MM	312.00	8.67		8.00	0.00	100.00	1			
47	32-10-005 (1)	Overhaul LH up-lock actuator Ref MM 32-10-51	312.00	26.00		2.00	0.00	25.00	1			
48	AMP-AIS/JS-PH Issue1 Rev	Perform 8000 hours Inspection	600.00	8.74	37.50	210.00	0.00	2625.00	1			

	HCI							SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
									3000	1000	100	12.5
0	Job No.	Description	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column2	Column3
1	AMP-AIS/JS-PHIssue1 Rev1	Perform 200 hours Inspection	13.33	1.00	1.33	16.00	50.00	250.00	1			
2	33-50-002	Emergency lights power unit No1 & No2 battery ca	26.00	13.00	2.60	0.50	0.00	6.25	1			
3	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.00	13.00	2.60	0.50	0.00	6.25	1			
4	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.00	13.00	2.60	0.50	0.00	6.25	1			
5	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref M	26.00	13.00	2.60	0.50	0.00	6.25	1			
6	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	26.67	12.77	2.67	24.00	100.00	400.00	1			
7	72-40-01	Visually inspect RH combustion case assy iaw AD 2	30.00	16.10		0.50	0.00	6.25	1			
8	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	30.00	16.10		6.00	0.00	75.00	1			
9	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	30.00	16.10		0.50	0.00	6.25	1			
10	73-10-09	F/C & clean Fuel manifold & nozzle assy LH	30.00	16.10		6.00	0.00	75.00	1			
11	25-60-030B	Weight check of the flight deck portable fire extin	52.00	8.67	4.33	0.50	0.00	6.25	1			
12	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.00	8.67		0.50	0.00	6.25	1			
13	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.00	12.77		0.50	0.00	6.25	1			
14	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.00	39.00	4.33	48.00	125.00	725.00	1			
15	32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspectio	66.67	51.28		1.00	0.00	12.50	1	1		
16	32-10-001D (1)	MLG LH Pintle to Cylinder interface NDT Inspectio	66.67	51.28		1.00	0.00	12.50	1	1		
17	32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	78.00	21.67	8.67	2.00	0.00	25.00	1			
18	32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	78.00	21.67	8.67	2.00	0.00	25.00	1			
19	32-10-001C (1)	Replace LH MLG hydraulic fluid Ref MM 32-10-11	78.00	21.67	8.67	2.00	0.00	25.00	1			
20	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-0	80.00	11.08		1.00	0.00	12.50	1			
21	21-20-001	Perform Recirculation Fan bearing change and bru	80.00	20.50		2.00	0.00	25.00	1			
22	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-0	80.00	35.23		1.00	0.00	12.50	1			
23	57-10-006-ALI	Detailed visual inspection of flap and aileron hing	80.00	40.17		1.00	0.00	12.50	1			
24	57-50-023-ALI	Detailed visual inspection of the aileron upper an	88.89	45.00		1.00	0.00	12.50	1			
25	24-30-001D (1)	LH Starter generator Replace/Overhaul bearings P	100.00	31.08		0.50	0.00	6.25	1			
26	31-30-000	Flight Data |Recorder (FDR) system functional che	104.00	1.00	8.67	1.00	0.00	12.50	1			
27	AMP-AIS/JS-PH Issue1 Rev	Perform 2000 hours Inspection	133.33	22.97	13.33	78.00	125.00	1100.00	1		1	
28	53-10-063-ALI	DVI of windscreen frame attachment fittings at fra	138.89	28.00		2.00	0.00	25.00	1			
29	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) R	156.00	17.33		1.00	300.00	312.50	1			
30	53-11-024B-ALI	Detailed visual inspection and torque check of fw	166.67	37.50		2.00	0.00	25.00	1			
31	6/700/IN/01 C1	Internal area of RH Power Plant fire zone 1	208.00	1.00		0.50	0.00	6.25	1			
32	6/700/IN/01 C1 (1)	Internal area of LH Power Plant fire zone 1	208.00	1.00		0.50	0.00	6.25	1			
33	6/700/IN/02 C1	Internal area of RH Power Plant fire zone 2	208.00	1.00		0.50	0.00	6.25	1			
34	6/700/IN/02 C1 (1)	Internal area of LH Power Plant fire zone 2	208.00	1.00		0.50	0.00	6.25	1			
35	6/700/IN/03 C1	Internal area of RH Power Plant fire zone 3	208.00	1.00		0.50	0.00	6.25	1			
36	6/700/IN/03 C1 (1)	Internal area of LH Power Plant fire zone 3	208.00	1.00		0.50	0.00	6.25	1			
37	200/EX/01 C1	Inspection of external skin of vertical and horizon	208.00	4.33		1.00	0.00	12.50	1			
38	3/410/EX/01 C1	Inspection of external area of wing leading edge f	208.00	4.33		0.50	0.00	6.25	1			
39	3/420/EX/01 C1	Inspection of external area of the wing trailing ed	208.00	4.33		0.50	0.00	6.25	1			
40	3/430/IN/01 C1	Inspection of internal area of the MLG bay for corr	208.00	4.33		1.00	0.00	12.50	1			
41	3/400/IN/01 C1	Inspection of internal area of wing main structure	208.00	4.33		3.00	0.00	37.50	1			
42	3/400/EX/01 C1	Inspection of external area of wing main structure	208.00	4.33		2.00	0.00	25.00	1			
43	26-20-001B (3)	Hydrostatic test of the fire extinguisher bottle RH	260.00	8.67		1.00	300.00	312.50	1			
44	35-10-003A	Hydrostatic test Pilot portable oxygen bottle	260.00	21.67		1.00	300.00	312.50	1			
45	32-00	RH Landing gear inspect radius rod spherical beari	277.78	33.39	13.89	0.50	0.00	6.25	1			
46	32-00 (1)	LH Landing gear inspect radius rod spherical bearin	277.78	33.39	13.89	0.50	0.00	6.25	1			
47	32-10-001E	Overhaul RH MLG assy (including yoke bearings) R	312.00	30.33		8.00	0.00	100.00	1			
48	32-10-001E (1)	Overhaul LH MLG assy (including yoke bearings) R	312.00	39.00		8.00	0.00	100.00	1			
49	32-10-002 (1)	Overhaul LH Radius rod & actuator Ref MM 32-10-3	312.00	39.00		3.00	0.00	37.50	1			
50	26-20-001A (1)	Replace Fire extinguisher cartridges LH IB Ref MM	312.00	43.33		2.00	0.00	25.00	1			
51	25-60-011	First aid kit Replacement	312.00	43.33		0.25	0.00	3.13	1			
52	21-60-001E	Clean the RH Heat Exchanger of the refrigeration u	400.00	2.36	33.33	1.50	0.00	18.75	1			
53	21-60-001E (1)	Clean the LH Heat Exchanger of the refrigeration u	400.00	2.36	33.33	1.50	0.00	18.75	1			
54	55-10-010-ALI	Detailed visual inspection of attachments and fitti	416.00	10.84		1.00	0.00	12.50	1			
55	55-30-001-ALI	Detailed visual inspection of attachment fittings v	416.00	10.84		1.00	0.00	12.50	1			
56	57-40-008-ALI	Inspection and torque check RH inboard flap hinge	444.44	30.56		2.00	0.00	25.00	1			
57	57-40-008-ALI (1)	Inspection and torque check LH inboard flap hinge	444.44	30.56		2.00	0.00	25.00	1			
58	73-10-002	RH Fuel shut off valve OH	473.33	1.00		1.00	0.00	12.50	1			
59	72-10-005	RH Propeller Governor OH	473.33	38.89		1.00	0.00	12.50	1			

	NCI							SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
								Setup Costs ->	3000	1000	100	12.5
0	Job No.	Describtion	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column2	Column3
1	AMP-AIS/JS-PHIssue1 Rev1	Perform 200 hours Inspection	9.1	5.0	0.9	16.00	50.00	250.00	1			
2	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	18.2	14.5	1.8	24.00	100.00	400.00	1			
3	72-40-01	Visually inspect RH combustion case assy iaw AD 2	20.5	1.0		0.50	0.00	6.25	1			
4	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	20.5	1.0		6.00	0.00	75.00	1			
5	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	20.5	1.0		0.50	0.00	6.25	1			
6	73-10-09	F/C & clean Fuel manifold & nozzle assy LH	20.5	1.0		6.00	0.00	75.00	1			
7	33-50-002	Emergency lights power unit No1 & No2 battery ca	26.0	21.7	2.6	0.50	0.00	6.25	1			
8	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.0	21.7	2.6	0.50	0.00	6.25	1			
9	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.0	21.7	2.6	0.50	0.00	6.25	1			
10	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref M	26.0	21.7	2.6	0.50	0.00	6.25	1			
11	32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspectio	50.0	42.2		1.00	0.00	12.50	1	1		
12	32-10-001D (1)	MLG LH Pintle to Cylinder interface NDT Inspectio	50.0	42.2		1.00	0.00	12.50	1	1		
13	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.0	5.1		0.50	0.00	6.25	1			
14	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.0	16.9	4.3	48.00	125.00	725.00	1			
15	25-60-030B	Weight check of the flight deck portable fire extin	52.0	47.7	4.3	0.50	0.00	6.25	1			
16	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.0	47.7		0.50	0.00	6.25	1			
17	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-0	54.5	8.1		1.00	0.00	12.50	1			
18	21-20-001	Perform Recirculation Fan bearing change and bru	54.5	35.8		2.00	0.00	25.00	1			
19	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-0	54.5	43.2		1.00	0.00	12.50	1			
20	24-30-001D (1)	LH Starter generator Replace/Overhaul bearings P	68.2	22.4		0.50	0.00	6.25	1			
21	52-10-001D	Passenger/crew door Inspect for evidence of exce	81.8	29.2	8.2	1.00	0.00	12.50	1			1
22	52-10-004	F/C & Lubricate door warning Circuit Function test	81.8	29.2	8.2	1.00	0.00	12.50	1			1
23	52-11-001B-ALI	Detailed visual inspection of passenger door struc	81.8	29.2		1.00	0.00	12.50	1			1
24	AMP-AIS/JS-PH Issue1 Rev	Perform 2000 hours Inspection	90.9	52.0	9.1	78.00	125.00	1100.00	1		1	
25	53-11-011-ALI	Detailed visual inspection of the RPB fwd face, ho	100.0	19.6		6.00	0.00	75.00	1			
26	57-30-003	Inspection of LH/RH wing lower skin Stn 36-83. Ins	104.0	13.0	8.7	4.00	0.00	50.00	1			
27	53-10-083-ALI	Detailed visual inspection of intercostals at passe	104.0	13.0		16.00	0.00	200.00	1			
28	53-10-080-ALI	Eddy Current Inspection NDI of fuselage skin at pa	104.0	30.3		0.50	0.00	6.25	1	1		
29	53-10-081-ALI	NDI of all window pans LH and RH side Ref SB 51-J	104.0	30.3		1.00	0.00	12.50	1	1		
30	34-20-004	Perform Compass Swing of Standby Compass Syst	104.0	39.0	8.7	1.00	0.00	12.50	1			
31	34-20-010	Perform Compass Swing of Gyromagnetic Compas	104.0	39.0	8.7	1.00	0.00	12.50	1			
32	57-10-213-ALI	NDI inspection of the leading edge attachment rib	150.0	20.2		2.00	0.00	25.00	1	1		
33	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) R	156.0	8.7		1.00	300.00	312.50	1			
34	53-30-001 C1	Inspect for corrosion LH/RH Area fuselage skin ice	156.0	17.3		4.00	0.00	50.00	1			
35	31-20-001 (1)	Replace LH panel clock battery Ref MM 31-25-00.	156.0	34.7		2.00	0.00	25.00	1			
36	31-20-001	Replace RH panel clock battery Ref MM 31-25-00.	156.0	34.7		2.00	0.00	25.00	1			
37	3/430/IN/01 C1	Inspection of internal area of the MLG bay for corr	208.0	21.7		1.00	0.00	12.50	1			
38	3/400/EX/01 C1	Inspection of external area of wing main structure	208.0	21.7		2.00	0.00	25.00	1			
39	160/IN/01 C1	Inspection of internal area Stn 421 to 463 for corro	208.0	21.7		2.00	0.00	25.00	1			
40	170/EX/01 C1	Inspection of external skin Stn 463 to 511 for corro	208.0	21.7		1.00	0.00	12.50	1			
41	130/EX/01 C2	Inspection of windshield frames external surface	208.0	21.7		2.00	0.00	25.00	1			
42	200/EX/01 C1	Inspection of external skin of vertical and horizon	208.0	26.0		1.00	0.00	12.50	1			
43	55-10-012 C1	Perform int. Corr. Inspection of internal area of ho	208.0	47.7		2.00	0.00	25.00	1			
44	52-20-001 C1	Inspect the exit(s) internal area for corrosion	208.0	47.7		2.00	0.00	25.00	1			1
45	72-10-06	NTS Valve RH	231.8	12.2		2.00	0.00	25.00	1			
46	32-00C (1)	NDI Radius rod cylinder LH, AD 2012-0212	250.0	46.9		1.00	0.00	12.50	1	1		
47	26-20-001B (3)	Hydrostatic test of the fire extinguisher bottle RH	260.0	21.7		1.00	300.00	312.50	1			
48	26-20-001B	Hydrostatic test of the fire extinguisher bottle RH	260.0	26.0		1.00	300.00	312.50	1			
49	35-10-003B	Hydrostatic test co- Pilot portable oxygen bottle	260.0	39.0		1.00	300.00	312.50	1			
50	32-10-002 (1)	Overhaul LH Radius rod & actuator Ref MM 32-10-3	312.0	21.7		3.00	0.00	37.50	1			
51	32-20-001E	NLG overhaul Ref MM 32-20-11	312.0	21.7		12.00	0.00	150.00	1			
52	26-20-001A	Replace Fire extinguisher cartridges RH OB Ref MM	312.0	21.7		2.00	0.00	25.00	1			
53	61-00-001A (1)	McCauley Propeller LH OH	312.0	32.6		4.00	0.00	50.00	1			
54	25-60-011	First aid kit Replacement	312.0	43.3		0.25	0.00	3.13	1			
55	61-00-001A	McCauley Propeller RH OH	312.0	47.1		4.00	0.00	50.00	1			
56	27-50-005	Flap acutator overhaul	312.0	47.7		2.00	0.00	25.00	1			
57	53-10-013-ALI	Detailed visual inspection of front pressure bulkh	329.2	20.7		1.00	0.00	12.50	1			
58	8/900/IN/01 C1	Inspection of internal area of forward wing root fa	416.0	26.0		6.00	0.00	75.00	1			
59	57-10-005 C1	Inspect internal area of LH flap and aileron for cor	416.0	30.3		0.50	0.00	6.25	1			
60	57-10-005 C2	Inspect internal area of RH flap and aileron for cor	416.0	30.3		0.50	0.00	6.25	1			
61	55-10-010-ALI	Detailed visual inspection of attachments and fitti	416.0	50.3		1.00	0.00	12.50	1			
62	55-30-001-ALI	Detailed visual inspection of attachment fittings v	416.0	50.3		1.00	0.00	12.50	1			

OCI								SETUPS	Flying to Lelystad	NDI	Below Floor	Open Door
									3000	1000	100	12.5
0	Job No.	Description	Interval	Due	MaxExt	Man Hours	Additional Costs	Costs	Column1	Column2	Column2	Column3
1	AMP-AIS/JS-PHIssue1 Rev:	Perform 200 hours Inspection	9.52	4.37	0.95	16.00	50.00	250.00	1			
2	AMP-AIS/JS-PH Issue1 Rev	Perform 400 hours Inspection	19.05	13.47	1.90	24.00	100.00	400.00	1			
3	72-40-01	Visually inspect RH combustion case assy iaw AD 2	21.43	1.38		0.50	0.00	6.25	1			
4	73-10-09	F/C & clean Fuel manifold & nozzle assy RH	21.43	1.38		6.00	0.00	75.00	1			
5	72-40-01 (1)	Visually inspect LH combustion case assy iaw AD 2	21.43	11.69		0.50	0.00	6.25	1			
6	33-50-002	Emergency lights power unit No1 & No2 battery ca	26.00	13.00	2.60	0.50	0.00	6.25	1			
7	24-00-000A	RH main battery Concorde CAP check Lead acid ba	26.00	13.00	2.60	0.50	0.00	6.25	1			
8	24-00-000A (1)	LH main battery Concorde CAP check Lead acid bat	26.00	13.00	2.60	0.50	0.00	6.25	1			
9	25-10-004A	Pilot and Co-pillot restraint harness F/C -DVI Ref N	26.00	17.33	2.60	0.50	0.00	6.25	1			
10	25-60-011 (1)	FIRST AID KIT DVI contents and reseal Ref MM 25-6	52.00	13.47		0.50	0.00	6.25	1			
11	AMP-AIS/JS-PH Issue1 Rev	Perform 800FH/1200FH/1 YR Inspection	52.00	31.65	4.33	48.00	125.00	725.00	1			
12	25-60-030B	Weight check of the flight deck portable fire extin	52.00	39.00	4.33	0.50	0.00	6.25	1			
13	25-60-030B (1)	Weight check of the cabin portable fire extinguish	52.00	39.00		0.50	0.00	6.25	1			
14	21-20-001	Perform Recirculation Fan bearing change and bru	57.14	15.77		2.00	0.00	25.00	1			
15	57-10-006-ALI	Detailed visual inspection of flap and aileron hing	57.14	36.61		1.00	0.00	12.50	1			
16	24-30-001E (1)	LH Starter Generator Brush Change Ref MM24-30-(	57.14	45.78		1.00	0.00	12.50	1			
17	24-30-001E	RH Starter Generator Brush Change Ref MM24-30-(	57.14	45.78		1.00	0.00	12.50	1			
18	32-10-001D	MLG RH Pintle to Cylinder interface NDT Inspectio	66.67	17.13		1.00	0.00	12.50	1	1		
19	32-10-001D (1)	MLG LH Pintle to Cylinder interface NDT Inspectio	66.67	17.13		1.00	0.00	12.50	1	1		
20	32-20-001C	Replace NLG hydraulic fluid Ref MM 32-20-11	78.00	4.33	8.67	2.00	0.00	25.00	1			
21	32-10-001C	Replace RH MLG hydraulic fluid Ref MM 32-10-11	78.00	4.33	8.67	2.00	0.00	25.00	1			
22	32-10-001C (1)	Replace LH MLG hydraulic fluid Ref MM 32-10-11	78.00	4.33	8.67	2.00	0.00	25.00	1			
23	57-50-023-ALI	Detailed visual inspection of the aileron upper an	88.89	45.00		1.00	0.00	12.50	1			
24	31-30-000	Flight Data |Recorder (FDR) system functional che	104.00	4.33	8.67	1.00	0.00	12.50	1			
25	34-20-004	Perform Compass Swing of Standby Compass Syst	104.00	13.00	8.67	1.00	0.00	12.50	1			
26	34-20-010	Perform Compass Swing of Gyromagnetic Compas	104.00	13.00	8.67	1.00	0.00	12.50	1			
27	200/EX/01 C2	Inspection of vertical stabiliser rear spar attach, in	104.00	13.00		2.00	0.00	25.00	1			
28	29-20-003	Hydraulic power emergency selector valve - introd	104.00	26.00		1.00	0.00	12.50	1			
29	29-20-003C	Hydraulic power emergency selector valve Seal ch	104.00	26.00		6.00	0.00	75.00	1			
30	53-10-083-ALI	Detailed visual inspection of intercostals at passe	104.00	43.33		16.00	0.00	200.00	1			
31	53-10-080-ALI	Eddy Current Inspection NDI of fuselage skin at pa	104.00	43.33		0.50	0.00	6.25	1	1		
32	53-10-081-ALI	NDI of all window pans LH and RH side Ref SB 51-J	104.00	43.33		1.00	0.00	12.50	1	1		
33	AMP-AIS/JS-PH Issue1 Rev	Perform 2400 hours Inspection	114.29	36.34	11.43	36.00	0.00	450.00	1		1	
34	53-11-011-ALI	Detailed visual inspection of the RPB fwd face, ho	133.33	27.13		6.00	0.00	75.00	1			
35	35-00-001A	Hydrostatic test oxygen bottle (storage cylinder) F	156.00	52.00		1.00	300.00	312.50	1			
36	53-11-024B-ALI	Detailed visual inspection and torque check of fw	166.67	20.21		2.00	0.00	25.00	1			
37	53-11-028-ALI	Detailed visual inspection of vertical stabilizer att	166.67	20.21		2.00	0.00	25.00	1			
38	72-00-000B	RH Engine hotsection	171.43	45.66		50.00	0.00	625.00	1			
39	AMP-AIS/JS-PH Issue1 Rev	Perform 4000 hours Inspection	190.48	5.89	9.52	65.00	125.00	937.50	1			
40	160/IN/01 C1	Inspection of internal area Stn 421 to 463 for corro	208.00	17.33		2.00	0.00	25.00	1			
41	170/IN/01 C1	Inspection of internal area Stn 463 to 511 for corro	208.00	17.33		2.00	0.00	25.00	1			
42	150/EX/01 C1	Inspection of external skin including horizontal la	208.00	17.33		1.00	0.00	12.50	1			
43	160/EX/01 C1	Inspection of external skin including lap joints Stn	208.00	17.33		1.00	0.00	12.50	1			
44	150/EX/01 C2	Inspection of external skin under antennas for cor	208.00	17.33		2.00	0.00	25.00	1			
45	130/EX/01 C1	Inspection of external skin including horizontal la	208.00	17.33		1.00	0.00	12.50	1			
46	140/EX/01 C1	Inspection of external skin includig horizontal lap	208.00	17.33		1.00	0.00	12.50	1			
47	130/EX/01 C3	Inspection of skin under antenna external area fo	208.00	17.33		2.00	0.00	25.00	1			
48	140/EX/01 C2	Inspection of external area of skin under antenna	208.00	17.33		2.00	0.00	25.00	1			
49	3/420/EX/01 C1	Inspection of external area of the wing trailing ed	208.00	17.33		0.50	0.00	6.25	1			
50	26-20-000	Fire extinguisher system F/C Firing circuits with bo	208.00	17.33		2.00	0.00	25.00	1			
51	55-10-012 C1	Perform int. Corr. Inspection of internal area of ho	208.00	21.67		2.00	0.00	25.00	1			
52	130/EX/01 C2	Inspection of windshield frames external surface	208.00	39.00		2.00	0.00	25.00	1			
53	55-40-006 C1	Inspect the rudder internal area for corrosion - bo	208.00	39.00		1.00	0.00	12.50	1			
54	53-11-014-ALI	Perform NDI of RPB boundary angle using X-ray te	222.22	2.08		1.00	1000.00	1012.50	1	1		
55	26-20-001B (2)	Hydrostatic test of the fire extinguisher bottle LH	260.00	4.33		1.00	300.00	312.50	1			
56	26-20-001B	Hydrostatic test of the fire extinguisher bottle RH	260.00	47.67		1.00	300.00	312.50	1			
57	57-30-221-ALI	Detailed visual inspection of lower wing skin acce	300.00	20.17		1.00	0.00	12.50	1			
58	32-10-001E	Overhaul RH MLG assy (including yoke bearings) R	312.00	26.00		8.00	0.00	100.00	1			
59	32-10-001E (1)	Overhaul LH MLG assy (including yoke bearings) R	312.00	39.00		8.00	0.00	100.00	1			
60	61-00-001A (1)	McCauley Propeller LH OH	312.00	41.16		4.00	0.00	50.00	1			
61	32-20-001E	NLG overhaul Ref MM 32-20-11	312.00	43.33		12.00	0.00	150.00	1			
62	32-10-005 (1)	Overhaul LH up-lock actuator Ref MM 32-10-51	312.00	47.67		2.00	0.00	25.00	1			
63	61-00-001A	McCauley Propeller RH OH	312.00	51.34		4.00	0.00	50.00	1			
64	32-00C (1)	NDI Radius rod cylinder LH, AD 2012-0212	333.33	8.96		1.00	0.00	12.50	1	1		
65	32-00C	NDI Radius rod cylinder RH, AD 2012-0212	333.33	42.96		1.00	0.00	12.50	1	1		
66	73-20-001 (1)	LH Fuel control unit OH	338.10	20.50		4.00	0.00	50.00	1			
67	73-20-001	RH Fuel control unit OH	338.10	23.02		4.00	0.00	50.00	1			
68	73-10 (1)	LH Fuel Pump	338.10	47.97		4.00	0.00	50.00	1			
69	57-30-210	Perform NDI inspection of the RH MLG cut-out low	411.11	2.13		1.00	0.00	12.50	1	1		
70	57-30-210 (1)	Perform NDI inspection of the LH MLG cut-out low	411.11	2.13		1.00	0.00	12.50	1	1		
71	55-10-010-ALI	Detailed visual inspection of attachments and fitti	416.00	45.27		1.00	0.00	12.50	1			
72	55-30-001-ALI	Detailed visual inspection of attachment fittings v	416.00	45.27		1.00	0.00	12.50	1			
73	57-50-021-ALI.	Detailed visual inspection of the aileron upper an	416.67	28.08		1.00	0.00	12.50	1			
74	53-10-079-ALI	DVI of escape hatch surround structure including p	483.33	17.92		2.00	0.00	25.00	1			
75	57-40-005-ALI	Detailed visual inspection of RH engine mount att	516.67	42.92		0.50	0.00	6.25	1			
76	57-40-005-ALI (1)	Detailed visual inspection of LH engine mount att	516.67	42.92		0.50	0.00	6.25	1			
77	25-60-030C (1)	Overhaul of the portable cabin fire extinguisher R	520.00	52.00		0.50	0.00	6.25	1			

Appendix 4 – VBA code Single component heuristic

```
Sub StartLatestPlanning()'Dim Numweeks, Interval, Ext, Due, Counter, hoffset,
voffset, j, i, k As Integer
Dim counter, Interval, ext, due As Integer


For j = 0 To k - 1 'for all jobs
'obtain interval of job j
    Interval = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(4
+ j, 4), 0)
'obtain initial due date of job j
    due = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(4 + j,
5), 0)
'unneccecary: obtain max extension of job j
    ext = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(4 + j,
6), 0)
'counter counts how far in planning we are


    counter = due                                  'set counter on initial due
date
    Cells(voffset + 1 + j, hoffset + counter) = 1   'plan first execution on
initial due date

    'for i is 1 to minimal number of executions in planning horizon for job j
    For i = 1 To (Numweeks / Interval)
     counter = counter + Interval                  'add interval to counter
        If counter <= Numweeks Then                'only when counter does not
surpass planning horizon
            Cells(voffset + 1 + j, hoffset + counter) = 1 'plan next execution of
job j
        End If
    Next i
Next j




End Sub
```

Appendix 5 – VBA code Opportunity-list heuristic

```
Sub HeuristNiek() 'Opportunity listOpportunityList ("HeuristNiek") 'Initiate
graphical format of sheet


'Dim Numweeks, Interval, Ext, Due, Counter, hoffset, voffset, j, i, k As Integer
Dim counter, Interval, ext, due, opp, n, m, shift As Integer
'clear schedule
Range(Cells(1 + voffset, 1 + hoffset), Cells(k + voffset, Numweeks +
hoffset)).ClearContents


'plan first job
j = 1
    Interval = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3
+ j, 4), 0)
    due = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3 + j,
5), 0)
    ext = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3 + j,
6), 0)


With Application.WorksheetFunction
    'set the shifting parameter to the earliest due time, the first executions will
be done in this period
    shift = .RoundDown(.Min(Range(Cells(voffset + 1, hoffset + Numweeks + 3),
Cells(voffset + k, hoffset + Numweeks + 3))), 0) - 1
End With

'set the counter at the first period
counter = shift + 1
'plan first execution of job 1 on period 1
Cells(voffset + j, hoffset + counter) = 1
    For i = 1 To (Numweeks / Interval)
        counter = counter + Interval 'add interval to counter
        If counter <= Numweeks Then 'only when counter does not surpass planning
horizon
            Cells(voffset + j, hoffset + counter) = 1
        End If
    Next i

'plan other jobs


For j = 2 To k
    Interval = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3
+ j, 4), 0)
    due = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3 + j,
5), 0)
    ext = Application.WorksheetFunction.RoundDown(Worksheets("Input").Cells(3 + j,
6), 0)

    counter = due
    For m = 1 To 100 ' while in PlanningHorizon
        If counter <= Numweeks Then 'if still in planning horizon

            For n = 1 To 100 ' for all possible executions
            ' select first opportunity before current execution
            ' the -shift is important as otherwise, due dates might
                If Cells(voffset + k + 2 + 1, hoffset + Numweeks + 5 + n).Value <=
counter Then
                    opp = Cells(voffset + k + 2 + 1, hoffset + Numweeks + 5 +
n).Value
                Else: Exit For
                End If
```

```
            Next n

            'set counter to selected opportunity
            counter = opp
            'plan maintenance execution on this opportunity
            Cells(voffset + j, hoffset + counter).Value = 1
            counter = counter + Interval
        Else: Exit For
        End If
    Next m
Next j

'VISUAL
Range(Cells(voffset + 1, hoffset + 1), Cells(voffset + k, hoffset +
Numweeks)).Borders.LineStyle = xlContinuous


End Sub
```

Appendix 6 – VBA code Improvement heuristic

```
Sub Improvement(Shee As String)Dim MSetups(), MSetupsPeriod(), NumTasksPerSetup,
NumSetupsPerPeriod, c, s, q, qsave, n As Integer
Dim cost1, cost2 As Long


Worksheets(Shee).Activate


Setups = WorksheetFunction.Count(Worksheets("Input").Range("J2:U2")) 'number of
setups
k = Worksheets("Input").Cells.Find(What:="*", SearchOrder:=xlRows,
SearchDirection:=xlPrevious, LookIn:=xlValues).Row - 3 'number of maintnenance jobs
hoffset = Worksheets("Dashboard").Cells(4, 3)
voffset = Worksheets("Dashboard").Cells(5, 3)
Numweeks = Worksheets("Dashboard").Cells(3, 3) 'number of weeks in planning horizon


For i = 2 To Setups 'for each secondary setup

    NumTasksPerSetup =
Worksheets("Input").Application.WorksheetFunction.Count(Worksheets("Input").Range(W
orksheets("Input").Cells(3 + 1, 9 + i), Worksheets("Input").Cells(3 + k, 9 + i))) -
1 'number of tasks per setup

    'MSetups is the array of maintenance job that require setup i
    ReDim MSetups(NumTasksPerSetup) 'redimension for every setup i from 0 to
NumTasksPerSetup

    c = 0 'counter = 0
    For j = 1 To k 'Fill the array with the maintenance jobs that require setup i
        If Worksheets("Input").Cells(3 + j, 9 + i) = 1 Then 'if setup i is
neccesary
            MSetups(c) = Worksheets("Input").Cells(3 + j, 1) 'the cth input is
maintenance job j
            c = c + 1 'next c
        End If
    Next j 'go through all maintenance jobs

    ' for every executtion of setup (opportunitylist)from last to first, for all
secondary setups
    For q = Application.WorksheetFunction.Count(Range(Cells(voffset + k + 2 + i,
hoffset + Numweeks + 5 + 1), Cells(voffset + k + 2 + i, hoffset + Numweeks + 50)))
To 2 Step -1

        cost1 = Cells(voffset, Numweeks + hoffset + 6).Value 'costs to compare with
after shifting jobs
        NumSetupsPerPeriod = 0

        For n = 1 To (UBound(MSetups) - LBound(MSetups) + 1) ' for every task that
needs secondary setup i
            'the number of maintenance jobs that require setups i for opportunity q
(starting from the last opportunity)
            NumSetupsPerPeriod = NumSetupsPerPeriod + Cells(voffset + MSetups(n -
1), hoffset + Cells(voffset + k + 2 + i, hoffset + Numweeks + 5 + q))
        Next n
        'redimension array
        ReDim MSetupsPeriod(NumSetupsPerPeriod - 1)

        c = 0
        'Fill Array MSetupsPeriod with the maintenance jobs that require setup i on
opportunity q
        For n = 1 To (UBound(MSetups) - LBound(MSetups) + 1) 'for all jobs that
require setup 1
        s = Cells(voffset + k + 2 + i, hoffset + Numweeks + 5 + q).Value
```

```
            If Cells(voffset + MSetups(n - 1), hoffset + s) = 1 Then 'if job is
executed on opportunity q
            MSetupsPeriod(0) = MSetups(n - 1) 'put in array
            c = c + 1 'check next maintenance job
            End If
        Next n

        For n = 1 To (UBound(MSetupsPeriod) - LBound(MSetupsPeriod) + 1) 'shift all
maintenance jobs back if possible (no job of the same type already planned)
            If Cells(voffset + MSetupsPeriod(n - 1), hoffset + Cells(voffset + k +
2 + i, hoffset + Numweeks + 5 + q)) = 1 And Cells(voffset + MSetupsPeriod(n - 1),
hoffset + Cells(voffset + k + 2 + i, hoffset + Numweeks + 5 + q - 1)) = "" Then
                qsave = Cells(voffset + k + 2 + i, hoffset + Numweeks + 5 + q)
                Cells(voffset + MSetupsPeriod(n - 1), hoffset + Cells(voffset + k +
2 + i, hoffset + Numweeks + 5 + q)) = ""
                Cells(voffset + MSetupsPeriod(n - 1), hoffset + Cells(voffset + k +
2 + i, hoffset + Numweeks + 5 + q - 1)) = 1

            End If
        Next n
        cost2 = Cells(voffset, Numweeks + hoffset + 6).Value 'new total costs

        If cost1 <= cost2 Then ' compare the two costs, if costs are higher, switch
back
            For n = 1 To (UBound(MSetupsPeriod) - LBound(MSetupsPeriod) + 1)
            'If UBound(MSetupsPeriod) >= 0 (more than one setup execution) Then
                If Cells(voffset + MSetupsPeriod(n - 1), hoffset + qsave) = "" And
Cells(voffset + MSetupsPeriod(n - 1), hoffset + Cells(voffset + k + 2 + i, hoffset
+ Numweeks + 5 + q - 1)) = 1 Then
                    Cells(voffset + MSetupsPeriod(n - 1), hoffset + qsave) = 1
                    Cells(voffset + MSetupsPeriod(n - 1), hoffset + Cells(voffset +
k + 2 + i, hoffset + Numweeks + 5 + q - 1)) = ""
                End If
            'End If
        Next n
        End If
    Next q
Next i
End Sub
```

Appendix 7 – Comparison between scheduling methods

BCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 111,950.30	€ 76,394.56	€ 77,412.52	€ 77,609.80	€ 77,957.31
	100.0%	214.9%	224.1%	226.0%	229.3%
Opportunity List	€ -76,394.56	€ 35,555.74	€ 1,017.97	€ 1,215.24	€ 1,562.75
	-68.2%	100.0%	2.9%	3.5%	4.6%
Opportunity List with improvement Heuristic	€ -77,412.52	€ -1,017.97	€ 34,537.77	€ 197.27	€ 544.78
	-69.1%	-2.9%	100.0%	0.6%	1.6%
MIP (no extension)	€ -77,609.80	€ -1,215.24	€ -197.27	€ 34,340.50	€ 347.51
	-69.3%	-3.4%	-0.6%	100.0%	1.0%
MIP (with extension)	€ -77,957.31	€ -1,562.75	€ -544.78	€ -347.51	€ 33,992.99
	-69.6%	-4.4%	-1.6%	-1.0%	100.0%

DCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 140,541.02	€ 96,484.59	€ 96,484.59	€ 97,868.00	€ 98,078.47
	100.0%	219.0%	219.0%	229.3%	231.0%
Opportunity List	€ -96,484.59	€ 44,056.43	€ -	€ 1,383.41	€ 1,593.88
	-68.7%	100.0%	0.0%	3.2%	3.8%
Opportunity List with improvement Heuristic	€ -96,484.59	€ -	€ 44,056.43	€ 1,383.41	€ 1,593.88
	-68.7%	0.0%	100.0%	3.2%	3.8%
MIP (no extension)	€ -97,868.00	€ -1,383.41	€ -1,383.41	€ 42,673.02	€ 210.47
	-69.6%	-3.1%	-3.1%	100.0%	0.5%
MIP (with extension)	€ -98,078.47	€ -1,593.88	€ -1,593.88	€ -210.47	€ 42,462.55
	-69.8%	-3.6%	-3.6%	-0.5%	100.0%

FCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 75,576.03	€ 44,391.11	€ 44,391.11	€ 44,699.05	€ 45,077.90
	100.0%	142.3%	142.3%	144.8%	147.8%
Opportunity List	€ -44,391.11	€ 31,184.92	€ -	€ 307.94	€ 686.79
	-58.7%	100.0%	0.0%	1.0%	2.3%
Opportunity List with improvement Heuristic	€ -44,391.11	€ -	€ 31,184.92	€ 307.94	€ 686.79
	-58.7%	0.0%	100.0%	1.0%	2.3%
MIP (no extension)	€ -44,699.05	€ -307.94	€ -307.94	€ 30,876.98	€ 378.85
	-59.1%	-1.0%	-1.0%	100.0%	1.2%
MIP (with extension)	€ -45,077.90	€ -686.79	€ -686.79	€ -378.85	€ 30,498.13
	-59.6%	-2.2%	-2.2%	-1.2%	100.0%

HCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 92,061.75	€ 71,504.14	€ 71,504.14	€ 71,504.14	€ 72,133.50
	100.0%	347.8%	347.8%	347.8%	362.0%
Opportunity List	€ -71,504.14	€ 20,557.61	€ -	€ -	€ 629.36
	-77.7%	100.0%	0.0%	0.0%	3.2%
Opportunity List with improvement Heuristic	€ -71,504.14	€ -	€ 20,557.61	€ -	€ 629.36
	-77.7%	0.0%	100.0%	0.0%	3.2%
MIP (no extension)	€ -71,504.14	€ -	€ -	€ 20,557.61	€ 629.36
	-77.7%	0.0%	0.0%	100.0%	3.2%
MIP (with extension)	€ -72,133.50	€ -629.36	€ -629.36	€ -629.36	€ 19,928.26
	-78.4%	-3.1%	-3.1%	-3.1%	100.0%

NCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 102,886.94	€ 71,588.44	€ 72,598.33	€ 74,416.23	€ 74,640.41
	100.0%	228.7%	239.7%	261.4%	264.2%
Opportunity List	€ -71,588.44	€ 31,298.50	€ 1,009.89	€ 2,827.79	€ 3,051.97
	-69.6%	100.0%	3.3%	9.9%	10.8%
Opportunity List with improvement Heuristic	€ -72,598.33	€ -1,009.89	€ 30,288.61	€ 1,817.90	€ 2,042.08
	-70.6%	-3.2%	100.0%	6.4%	7.2%
MIP (no extension)	€ -74,416.23	€ -2,827.79	€ -1,817.90	€ 28,470.71	€ 224.18
	-72.3%	-9.0%	-6.0%	100.0%	0.8%
MIP (with extension)	€ -74,640.41	€ -3,051.97	€ -2,042.08	€ -224.18	€ 28,246.53
	-72.5%	-9.8%	-6.7%	-0.8%	100.0%

OCI	Single Component	Opportunity List	Opportunity List with improvement Heuristic	MIP (no extension)	MIP (with extension)
Single Component	€ 102,833.24	€ 70,578.90	€ 70,578.90	€ 71,544.15	€ 71,849.94
	100.0%	218.8%	218.8%	228.7%	231.9%
Opportunity List	€ -70,578.90	€ 32,254.34	€ -	€ 965.25	€ 1,271.04
	-68.6%	100.0%	0.0%	3.1%	4.1%
Opportunity List with improvement Heuristic	€ -70,578.90	€ -	€ 32,254.34	€ 965.25	€ 1,271.04
	-68.6%	0.0%	100.0%	3.1%	4.1%
MIP (no extension)	€ -71,544.15	€ -965.25	€ -965.25	€ 31,289.09	€ 305.79
	-69.6%	-3.0%	-3.0%	100.0%	1.0%
MIP (with extension)	€ -71,849.94	€ -1,271.04	€ -1,271.04	€ -305.79	€ 30,983.30
	-69.9%	-3.9%	-3.9%	-1.0%	100.0%

In this overview, we compare the outcomes of the several heuristics and the MIP models. We compare the methods to the left to the methods on the top. The orange cells are the actual values (100%) of the methods on the aircraft on the top left of each table. Then, for every combination, you can see the absolute difference between the methods and the difference in percentage.