UNIVERSITY OF TWENTE.

Faculty of Behavioural Management and Social Sciences

Clustering of aircraft maintenance jobs at AIS airlines

Sander Kroep

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Supervisor:

dr. M.C. van der Heijden

Faculty of Behavioural Management and Social Sciences

Dep. Industrial Engineering and Business Information Systems

University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Colophon

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Postbus 217
7500 AE Enschede
www.utwente.nl

Author: dhr. S. Kroep
s1558609
s.kroep@student.utwente.nl

Institution supervisor: Dr. M.C. van der Heijden (1st supervisor)
Dr. H. Heerkens (2nd supervisor)

External supervisor: Dhr. M. van der Meer

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Preface

Hereby I would like to present my report that I have written in the context of my bachelor assignment. By conducting the research at AIS aviation group in Lelystad, I complete my bachelor degree in Industrial Engineering and Management. I have worked on my bachelor thesis from April 2017 until July 2017 with great pleasure at AIS in Lelystad. Before moving to the content related parts of my thesis, I would like to take some time for expressing my gratitude to everyone who was involved in my bachelor thesis.

An already existing interest in the aviation industry was fuelled even more during the minor of Aeronautical Engineering and Management. For this I would like to thank Dr. H. Heerkens who also contributed to my bachelor thesis as a second supervisor. When I was offered the opportunity to conduct my bachelor thesis at AIS aviation group it was a *'dream come true'*. I have learned what a great organization AIS is and how versatile it is to work in the aviation industry. Being able to support AIS in its' goal of 'perfection in aviation' and research potential improvements has motivated me a lot to work on the project over the past three months.

To start I would therefore like to thank Martin and Arend van der Meer for opening up the opportunities within AIS and shaping the assignment. Secondly, a moment of gratitude will go to my 'colleagues' of the CAMO department and AIS Technics, who have given me an amazing time working at the company and provided me with the required information.

Moreover, I would like to thank Dr. M.C. van der Heijden for his support from the University. He helped me by pointing me in the right direction during the research and, with his feedback, I have managed to deliver the report as it now is in front of you.

I could not have done all of this it without the continuous support of my family and friends. Throughout the past three years they have helped me during the completion of my bachelor's degree, allowing me to now complete the first phase of my time at the university.

Sander Kroep

Enschede, July 2017

Management summary

Explosive growth from the past years has caused AIS airlines to face optimization problems regarding their maintenance planning and scheduling. Set-up activities are redundantly executed due to the lack of a clustering method. As a result of this, not only the maintenance costs are higher, but the inefficiency also leads to a situation where not all desired maintenance is executed.

While all base-maintenance of AIS is executed at the maintenance location in Lelystad, the aircraft are utilized in Croatia, Sweden and Germany. As a result, large set-up costs are incurred when maintenance is executed.

This challenge is however not the only one that we identified during our research at AIS. After mapping the current situation concerning the maintenance planning, we discovered multiple challenges. We discovered that no spare-part management model was currently used. As a result of this, the management of spare parts formed a challenge for AIS.

Another challenge was found in the personnel planning. AIS struggled with finding enough aircraft ground engineers who are willing to work over the weekends on the aircraft maintenance. These two challenges are respectively related to the materials and personnel planning. The materials and personnel planning can be deducted from the activity schedule.

As a result of this we have been asked by our clients to investigate the opportunity of optimizing the activity scheduling. More specifically, to look at implementing a clustering method at AIS aviation. The research question that we will answer with this study is therefore: *How can the maintenance activities of AIS be clustered so that redundancy in set-up activities is reduced?*

To answer the research question, we described the problem definition and problem solving approach in chapter 1 of this report. We proceeded with a literature study from which we selected the use of the common set-up clustering method by van Dijkhuizen et al. (1997). We test this model in two different scenarios, each of which includes different maintenance activities. The first scenario includes maintenance jobs from the front section of the aircraft and the second scenario includes replacement activities from the whole aircraft.

In the current situation we noticed that no clustering method for maintenance jobs is applied in the creation of the maintenance schedule. This was identified as a cause for the redundant execution of the set-up activities. It leads to a current situation where 23 hours of set-up activities was saved while executing maintenance jobs on average 7.43 days too soon.

The main emphasis of applying the clustering method on the two mentioned scenarios was on potential cost reductions that can be achieved. We found a larger cost-reduction when applying the clustering method in the second scenario. We relate this to the different number of maintenance jobs that were included in both situations. We also looked at other side-effects such as savings in set-up time and waste of useful life-time. Table 1 presents an overview of the results from both scenarios. Chapter 4 describes how these results are substantiated.

	Cost reduction	**Life-time wasted per component**	**Set-up time saved per aircraft**
Nose Bay scenario	€215,21/month	23 months	45 hours
Replacement scenario	€2859,05/month	4,8 months	99 hours

Table 1 Summary outcomes

The model we used only includes common set-ups. The clustering method based on common set-ups is not advanced enough to directly be implemented. We strongly recommend AIS to include shared set-ups in their clustering method. For this we developed a stepwise plan which allows for the full implementation of clustering in the scheduling activities at AIS. By including shared-set ups, the

complete maintenance tree is constructed. Solving this with the help of an adjusted dynamic programming algorithm, leads, in our believes, to a more cost efficient situation. For this, data should be gathered from the maintenance manual and presented in a maintenance tree that captures the maintenance tasks to the complete aircraft.

Stemming from our research have recommended topics for further research. We believe that there is for instance a potential for AIS when relocating the maintenance activities. A second recommendation is to analyse if adjustments in the prescribed maintenance intervals can potentially reduce the number of corrective maintenance jobs to be executed. Furthermore, we recommend AIS to look into the distribution of the aircraft over the weekends. This way, the workload for the maintenance department can be balanced. Lastly we noticed that the development of a spare part strategy for critical parts of the aircraft can yield cost reductions for AIS.

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Definitions and list of abbreviations

CAMO	Continuing Airworthiness Management Organization
KPI	Key Performance Indicator
AMP	Aircraft Maintenance Program
AMM	Aircraft Maintenance Manual
AIS	AIS Aviation Group
PH-DCI	Three letter code Aircraft
Technics	Executing maintenance department
VBA	Visual Basics of Applications
Cluster	Grouping of one or multiple maintenance jobs
Clustering	Grouping of one or multiple clusters
Job Order	Overview of maintenance related tasks
Due-date	Latest date in time at which a maintenance activity needs executing
NLG	Nose Landing Gear
MLG	Main Landing Gear
DVI	Detailed Visual Inspection

1. Introduction

The first Chapter describes the background for the research to the maintenance planning of AIS aviation group. Section 1.1 introduces the maintenance planning and its relation to the rest of the company. Section 1.2 to 1.6 give an overview of the origin of the problem and the approach to solve it. We conclude this Chapter by describing the final scope and the structure of the remainder of our report.

1.1 Introduction maintenance planning

AIS airlines(AIS) is a Dutch airline that is situated at Lelystad Airport. The company was started in 2009 by the brothers Arend and Martin van der Meer. The company is unique because of its integrated maintenance department, development centre and flight academy which are, together with the airline, all part of the AIS aviation group. The research as it is described in this report, was conducted in the maintenance department of AIS. The maintenance department is subdivided in two other sub-departments. We present the organizational structure of the maintenance department and the planning activities in Figure 1**.**

- Activity planning. The activity planning is done by the Continuing Airworthiness Management Organisation (CAMO). CAMO is a department that is responsible for tracking the technical state of the aircraft in the fleet of AIS. For the activity planning, the CAMO department identifies what items of an aircraft need maintenance and when the parts of the aircraft are due.
- Activity scheduling. The activity scheduling is done by the CAMO manager based on the output from the activity planning. The activity schedule includes when and in what order the activities will be executed and determining the resources that are needed.
- Materials planning. The materials planning is done by the Technics manager and provides an overview of all the parts that are needed for the execution of the maintenance activities.
- Personnel planning. The personnel planning is a part of the activity scheduling. It determines the workforce that is needed in order to complete the maintenance to the fleet of AIS.

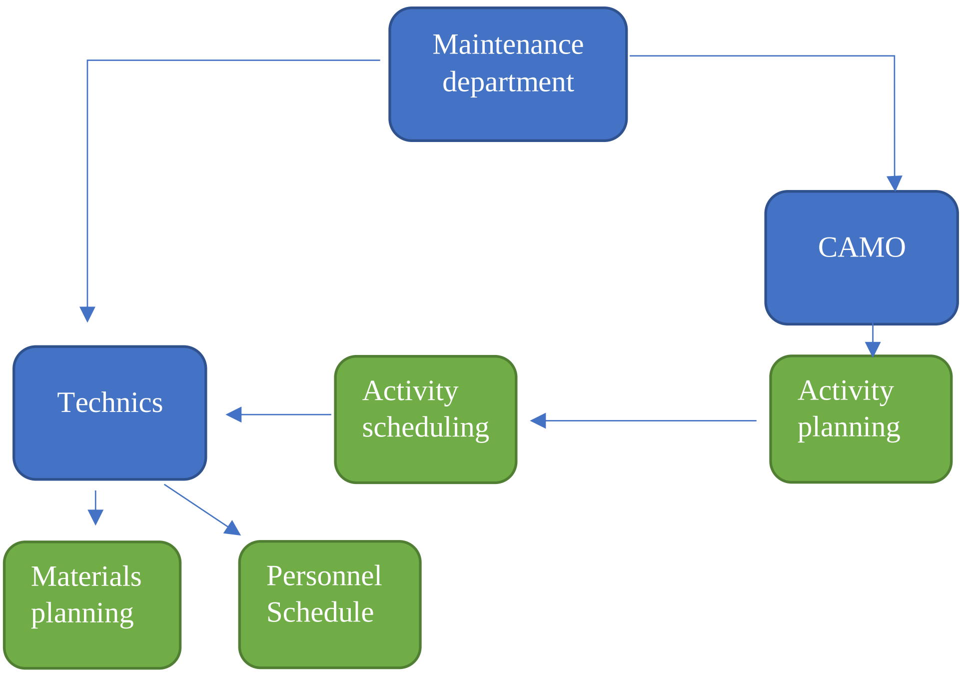

Figure 1 Organizational Structure Maintenance AIS

In the current situation the activity planning has a horizon of three months ahead in which the items of an aircraft that reach their due-date are identified. The challenge here lays in the translation from the activity planning to the activity scheduling. The CAMO department, schedules the activities solely based on their due date, and clusters them based on common sense without using optimization methods.

The research will be done in order to investigate methods that allow for the optimization of this activity scheduling. These methods are meant to decrease the redundancy in the execution of the maintenance activities.

The activity planning and scheduling is done for the 24 aircraft that are included in the fleet of AIS. These aircraft have varying maintenance prescriptions and usage, leading to a number of implications for the activity planning and scheduling. Most of the maintenance to these aircraft is done in-house at the maintenance facility at Lelystad Airport. For this, AIS currently employs 8 workers that are skilled and allowed to perform maintenance to these aircraft. To narrow the scope of this research, let's look more into detail in the composition of the beforementioned 24 aircraft. Of these aircraft there are 7 BAE Jetstream 32's that fly daily routes from Monday until Friday. The maintenance activities to these aircraft are therefore executed over the weekends. The scope of this research is to investigate how the clustering of maintenance activities should look like for these particular aircraft. The choice for this is due to the limited time available in the weekend, and by making more efficient use of this time, the potential for improvements within the activity scheduling is larger.

1.2 Problem cluster and core problem

1.2.1 Problem Cluster

To conduct the research as it was briefly introduced so far, a problem cluster is constructed. This cluster shows the relationship between the various problems that were identified during interviews with employees of the company. Figure 2 shows the problem cluster preparatory to the explanation to these problems.

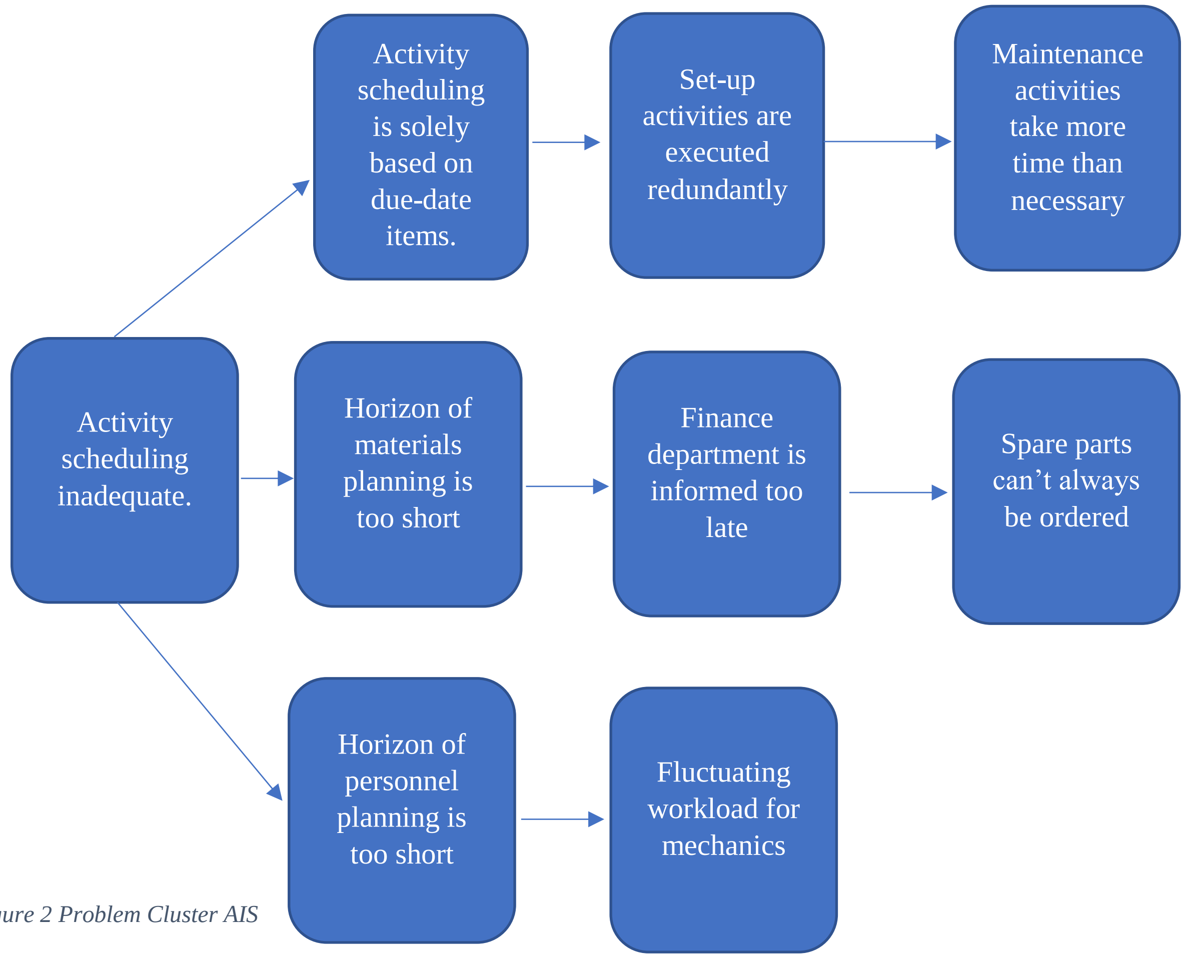

Figure 2 Problem Cluster AIS

Activity schedule inadequate.
From interviews within the company, a number of problems become apparent. These problems are:

1. Maintenance activities take more time than necessary
2. Horizon of materials planning is too short
3. Horizon of personnel planning is too short.

These three problems are all in a way affected by the activity scheduling since it provides the basis to the materials and personnel planning. Next to that, the way the current activity schedule is constructed leaves room for optimization when it comes to clustering of maintenance activities.

Maintenance activities take more time than necessary.
The maintenance department often struggles to execute all required/desired items within the 60 hours that the weekend offers. This is caused by an inefficient activity schedule that results in redundancy within the set-up proceedings of the maintenance activities. Chapter 2 describes how big this problem is.

Horizon of materials planning is too short.
When the activity schedule is insufficient, making a materials planning becomes even harder. AIS identified that they were struggling with making a materials planning since they are facing problems in constructing the activity schedule. This leads to postponing of maintenance activities and down-time of aircraft. In the scope of this research we explain that we do not look into this problem.

Horizon of personnel planning is too short.
Just like the materials planning, AIS identified problems regarding the construction of a long-term personnel plan. This can also be traced back to the insufficient activity schedule, which leads eventually to a highly fluctuating workload among the workers of the maintenance department. This problem will be outside the scope of the current research.

1.2.2 Core problem

The problem cluster in Figure 2 displays three "branches" of possible problems: the optimization of the activity schedule, the improvement of the materials planning and the personnel planning. In the description of Section 1.2.1, the most severe problem was identified by AIS as the activity scheduling being inadequate and leaving room for optimization. In this research, the materials planning and personnel planning will not be included, since they are later easily deducted from the activity schedule by workers from the company.

1.3 Research aim and research questions

The aim of the research is to develop an activity schedule for the maintenance department of AIS which reduces the redundancy in set-up activities of various maintenance jobs. For this, the constraints to clustering of maintenance jobs needs to be investigated, a suitable method for clustering of maintenance jobs needs to be identified and, at last, this method needs to be applied or adjusted to fit the situation at AIS. Section 1.2.1 already identified the core problem, but to solve the core problem we must answer the following main question: *How can the maintenance activities of AIS be clustered so that redundancy in set-up activities is reduced?*
In order to answer the main question, we answer the following research questions in this report:

1. How does the current process for activity scheduling of maintenance jobs with common set-ups look like, what are its constraints and what is its performance?
2. Which models for clustering maintenance jobs with common set-ups exist in literature?
3. How can the model from literature be adjusted to fit at AIS?
4. What is the performance of the newly designed model?
5. How can the model be implemented at AIS?

The above 5 research questions are treated in the remaining chapters of this report. The answers allow us to present recommendations to AIS regarding the clustering of maintenance jobs.

1.4 Stakeholders

The stakeholders that are related to the project are all parties that make use of the activity schedule or encounter any other form of involvement. This means that the CAMO department, Technics department and financial department will be directly involved in the research.

The CAMO department wants to have a clustering method that ensures that all the legal deadlines are met and that the aircraft do not have to be grounded as a result of missing due-dates. The financial department has similar interests, but that is mainly due to the costs that are associated with grounding an aircraft.

The technics department, is looking for a clustering method that is easy to use and allows them to deduct the personnel planning as well as the resources/materials planning later. They are also the stakeholder that has most technical information available about the maintenance activities. This information is needed to develop a clustering model.

1.5 Scope of the research

For a small part, we already mentioned the scope of the research multiple times during this report. A first note that was made is that the research does not include the maintenance activities to all the aircraft of AIS. Only 7 aircraft from which the maintenance is done during the weekends in Lelystad are subject to the research. Next to that, the research is only concerned with the activity scheduling and how maintenance jobs with similar set-ups can be clustered. There is also the possibility to look at materials or personnel planning, but after conversations with the CEO of AIS, the final scope does not include these challenges.

The model that we recommend for use during the bachelor assignment is assessed for usefulness in AIS and the performance is measured with the help of Key performance indicators. Afterwards a proposal for the implementation of this model in the activity schedule for AIS is constructed.

1.6 Problem solving approach

In order to answer the main question of this research, we conduct a literature study and research within the company. Based on this, we select the clustering model.

In the literature study, we look for models and techniques for clustering maintenance jobs with similar set-up activities. Following, we look at different clustering methods that may be suitable for the situation at AIS. We work out the most suitable technique/model in detail to fit the situation at AIS.

Based on this literature research, the models that we find, and from close cooperation with the technics manager, we select a clustering model that is suitable for AIS. We test this model and with the outcomes, provide AIS with a decision making tool for further clustering of maintenance jobs.

After the selection of the model and testing, we measure the new performance based on a set of key performance indicators that we develop to describe the current situation. If the situation is indeed an improvement and meets all requirements and demands from the company, we write a proposal for implementation.

1.7 Conclusion problem identification

In this first Chapter, a stepwise approach is presented towards solving the core-problem. The structure of the remainder of this report is therefore as follows:

Chapter 2. Describing the current situation by answering research question 1.

Chapter 3. Conducting the literature study and in that way answering research question 2.

Chapter 4. Adjusting the findings of Chapter 3 to suit for the situation at AIS, measure the performance of the newly designed clustering method and present an implementation plan for the new clustering method.

Chapter 5. Recommendations and conclusion

2. Analysis of current situation

Chapter 2 answers the first research question: How does the current process for activity scheduling look like, what are its constraints and what is its performance. We hereby specifically look at how clustering of maintenance jobs is done. By getting insight in the current situation, developing a new clustering method for the activity schedule will be easier afterwards.

2.1 System structure tree

Before analysing the different types of maintenance activities, we first start with the development of the (partial) system-structure tree. This structure tree gives us an overview of the structure of the aircraft, which helps us to identify maintenance jobs. Based on this structure tree, we also later determine what information we include in the clustering problem. The aircraft to which we restrict ourselves during this research is the PH-DCI, but the development of structure trees of other aircraft follows similar procedures. The construction of the system structure tree starts with identifying the highest level of sub-systems. The highest level of sub-systems is identified in the maintenance manual as so-called sections. We present a complete overview of these sections in Table 2.

Aircraft	Radome
	Nose Bay
	Flight compartment
	Main Cabin Area
	Rear Cabin Area and Entrance door
	Rear equipment bay
	Tailcone
	Tailplane
	Left side Mainplane
	Left side leading edge
	Left side trailing edge
	Right side leading edge
	Right side trailing edge
	Rigth rear fillet
	Left rear fillet
	Rigth forward fillet
	Left forward fillet
	Nose landing gear bay
	Left main landing gear bay
	Right main landing gear bay

Table 2 Aircraft Structure Tree

2.2 Maintenance activities

In the previous section, we developed an overview of the sections of the aircraft. The parts that belong to these zones all require maintenance in order to keep the aircraft flying. This second section will therefore provide more insight in the maintenance activities that take place.

2.2.1 Types of maintenance activities

In aviation there are mainly two types of maintenance activities that can be distinguished: first of all the preventive maintenance activities that are prescribed in the handbooks of the aircraft, and secondly corrective maintenance that is done after inspections on the aircraft. The preventive maintenance activities for the Jetstream 32 are prescribed in the Aircraft Maintenance Program (AMP). This AMP describes which individual actions need to be executed per maintenance task. The AMP also prescribes the required intervals at which the maintenance jobs need to be fulfilled. The types of inspections or maintenance actions can be classified into two maintenance types.

First of all there is the line-maintenance. As the name already implies, these activities are executed while an aircraft is at the ground in between flights. These activities usually take only a small amount of time and effort and can therefore be performed while the aircraft is at the gate.
The largest part of the maintenance activities however takes more time than is available during two successive flights. Within these previously mentioned two maintenance types, there are multiple categories which we present in Table 3**.**

Action	Explanation
Adm	Administrative maintenance task. Usually related to the aircraft maintenance program.
ARC	Inspection of the airworthiness review certificates
CHK	Check of mentioned parts
CPCP	Corrosion Prevention and Control Program. Aims at the identification and prevention of Corrosion
DVI	Detailed visual inspection
FC	Functional Check
Hydro	Check on the hydraulic system of the Aircraft
INSP	Inspection of the mentioned parts in the maintenance task
Life Limit	Parts need to be overhauled or approach a maximum life limit
NDI	Non-destructive inspection (eg. X-ray)
OH	Overhaul
PROG	Software updates
REPL	Replacement of the parts that are mentioned in the maintenance task
Replace	Replacement of the parts that are mentioned in the maintenance task
SER	Service check
W&B	Weight and Balance

Table 3 Maintenance categories explanation

The abovementioned maintenance activities are all preventive or planned maintenance activities. The corrective maintenance activities are mostly done after inspections on the aircraft or due to failures during flight. Since the goal of the research is to develop a model that clusters preventive maintenance activities with common set-ups, corrective maintenance activities are not important to further specify here.

The classification of maintenance jobs is not the only way to distinguish between different maintenance activities. The interval in which the maintenance activities are executed also differs. On one hand, the interval of an inspection is expressed in terms of flight hours. A replaceable item, on the other hand, uses flight cycles to express its lifetime. The limits are already set in the AMP and will therefore be assumed as fixed and know in the remainder of this research.

2.2.2 Set up activities

Before the maintenance activities that were mentioned in Section 2.1.1 can be executed, a lot of preparation to the aircraft has to take place. These preparation activities can vary from towing the aircraft in the hangar to demounting parts of the aircraft. The aim of this section is to identify the list of set-up activities that are currently used in the clustering method and explain what exactly they are. This list will later in Chapter 4 be extended with costs that are involved with the maintenance activities.

No.	Set-up activity	Average time
1	Fly aircraft to maintenance base	3 hours

Table 4 Overview of set-up activities

In Table 4 we have identified that currently there is only one set-up activity that is taken into account. Since the aircraft of AIS are utilized at different locations in Europe, they have to be flown back to the maintenance base in Lelystad and there are no passengers using the aircraft it means that the flight can be seen as a set-up cost. On average it takes 3 hours to fly the aircraft back to the base in Lelystad.

2.3 Scheduling and planning activities

After discussing the maintenance jobs that take place at an aircraft, we now provide an overview of all the planning and scheduling activities that take place as part of the maintenance process. Here we can take a closer look at the clustering method that is applied at AIS. The research aim to develop an improved model for clustering within the activity scheduling, but in order to do this, an understanding to the activity planning is needed.

2.3.1 Activity planning

The planning of the activities lays at the basis of all the maintenance activities. In the activity planning, a list of items with due dates is created by the CAMO department of AIS. The list with items and its due dates are presented in Figure 3**.** The due dates are based upon legal requirements that are set by the aviation authorities and the manufacturer of the aircraft and they depend on the usage of the aircraft. The activity planning solely provides an overview of the activities that need to be executed and the date at which this can latest be done. Based on this list the activity schedule, in which the exact dates, maintenance jobs and location at which the maintenance will take place are identified, can be constructed.

Task No.	Description	Due
08-20-001	Weight and balance	23-12-2019
100/110/IN/02 C1	Inspection of aft wing root fairing internal area for corrosion	23-12-2023
110/IN/01 C1	Inspection of NLG bay for corrosion, SB 53-JA860921	
120/IN/03 C1	Inspection of front pressure bulkhead fwd face for corrosion	23-12-2017
130/EX/01 C1	Inspection of external skin including horizontal lap joints and vertical butt joints at Stn 57-130	09-01-2018
130/EX/01 C2	Inspection of windshield frames external surface for corrosion	15-12-2018
130/EX/01 C3	Inspection of skin under antenna external area for corrosion	15-12-2018
130/IN/02 C1	Inspection of below floor area Stn 57 to 130 for corrosion , SB 53JM5284	15-12-2018
130/IN/03 C1	Inspection of above floor area Stn 57 to 130 for corrosion	05-05-2019
130/IN/03 C2	Inspection of internal area of windshield frames for corrosion, SB 53-JM7331	15-12-2018

Figure 3 Activity planning

Figure 3 shows part of the due-list of the PH-DCI [1]aircraft of AIS. The activity planning provides an overview of all the maintenance tasks that are due and need to be executed. The first column assigns a task number to each task so that it can be found in the aircraft maintenance program. Next to that, a description of the task is given, together with a classification for the action that is needed. The planning distinguishes between 16 number of classifications which were presented above in Table 3.

[1] Registration number from one of the 8 Jetstream 32's of AIS

2.3.2 Activity scheduling

Activity scheduling is the basis for the materials and personnel schedule and it is deducted from the activity planning. The list of due items as presented in Figure 3 predicts the due dates for years ahead. However the planning is uncertain because of the flight scheduling and utilization of the aircraft. In order to create an activity schedule, the activity planning is reduced to only include items that have a due date in the upcoming three months. Based on this, the activity schedule as presented in Figure 4 is created. This planning schedules aircraft for maintenance for the upcoming three months. This work is done manually by the CAMO manager and is usually created one or two months in advance of the first maintenance activity. The overview includes the maintenance activities of the 7 Jetstream 32's but the fleet of smaller training aircraft are not taken into account here. In the first column, a date is assigned at which the maintenance will take place. The second column of figure 4 describes first of all the registration code of the aircraft that needs maintenance. Underneath that, the headline of the maintenance task is written down. A more detailed description of the maintenance jobs is presented in the job orders and the AMP. In the third column the maintenance location where the aircraft has to be located is recorded. Columns 4-7 are duplicates of the previous ones and are available in case multiple maintenance activities to different aircraft have to be executed at the same time.

Upcoming Maintenance			**4-5-2017**			
Date	**A/C**	**Maintenance Location**	**A/C**	**Maintenance Location**	**A/C**	**Maintenance Location**
6-mei-2017	BCI: **NDI**+200+400 +CPCP	Lelystad				
10-mei-2017	DCI: 200 hrs+ Hyd valve	Kroatie				
12-mei-2017	HCI:**(Incl. Extension)** 200+400+800+1200	Lelystad				
20-mei-2017	DCI: RH Nozzles	Kroatie	CCI: LH&RH Nozzles	BLE	OCI: LH Nozzles	Lelystad
27-mei-2017	NCI: 200+400 hrs+**NDI**	Lelystad	CCI: 4x Fire bottles repl.	BLE		
10-jun-2017	RCI: 200+**NDI plus**	Lelystad	HCI: RH Radius rod	BLE		
17-jun-2017	DCI: NLG change	Lelystad	CCI: NLG fluid change	BLE		
24-jun-2017	CCI: 200+2000+4000+NTS+Ali	Lelystad	OCI: 200 hrs	BLE		
1-jul-2017	NCI: 2000+4000 hrs	Lelystad				
8-jul-2017			RCI: LH Engine	BLE		
14-jul-2017			RCI: LH Radius rod	BLE		
22-jul-2017	DCI: Nose uplock OH+ **NDI**	Lelystad				
12-aug-2017	RCI: LH Propeller OH	Lelystad	OCI: CPCP's plus	BLE		

Figure 4 Activity schedule

2.3.3 Clustering

We discovered that most of these dates are planned in weekends. This is done on purpose to ensure that the maintenance activities do not disturb the normal operations of the aircraft. It can be seen that in the current situation, activities are already clustered. This is done to reduce the 'travel costs' of the aircraft to the maintenance bases. The travelling of the aircraft to the maintenance base can be seen as a set-up activity for the maintenance jobs (see table 4). However, this is the only common set-up that is taken into account on purpose at the moment of determining clusters. Clustering is for the rest only based on the remaining time until an item is due. This is currently done based on the expertise and insights of the CAMO manager and aims to optimise the use of the parts on the aircraft.

2.3.4 Materials and personnel scheduling

Materials and personnel scheduling is done based on the previously presented activity planning. Based on the workload for the maintenance tasks, personnel is scheduled to work during the weekend by the Technics Manager. This maintenance schedule also provides the input for the parts needed list. The parts needed list can be extracted from the job-orders that the Technics Manager receives from the CAMO-manager. The job order describes all actions such as replacements or inspections that need to be undertaken. I already described before that the materials and personnel schedule won't be treated extensively in this report. It solely aims to provide a complete overview of the planning and scheduling activities.

2.3.5 Maintenance process

The aim of this section is to give a schematic overview of the current maintenance process with a special focus on the planning and scheduling activities. The aim of this scheme is to identify possible bottlenecks in the process with relation to the scope of this research.

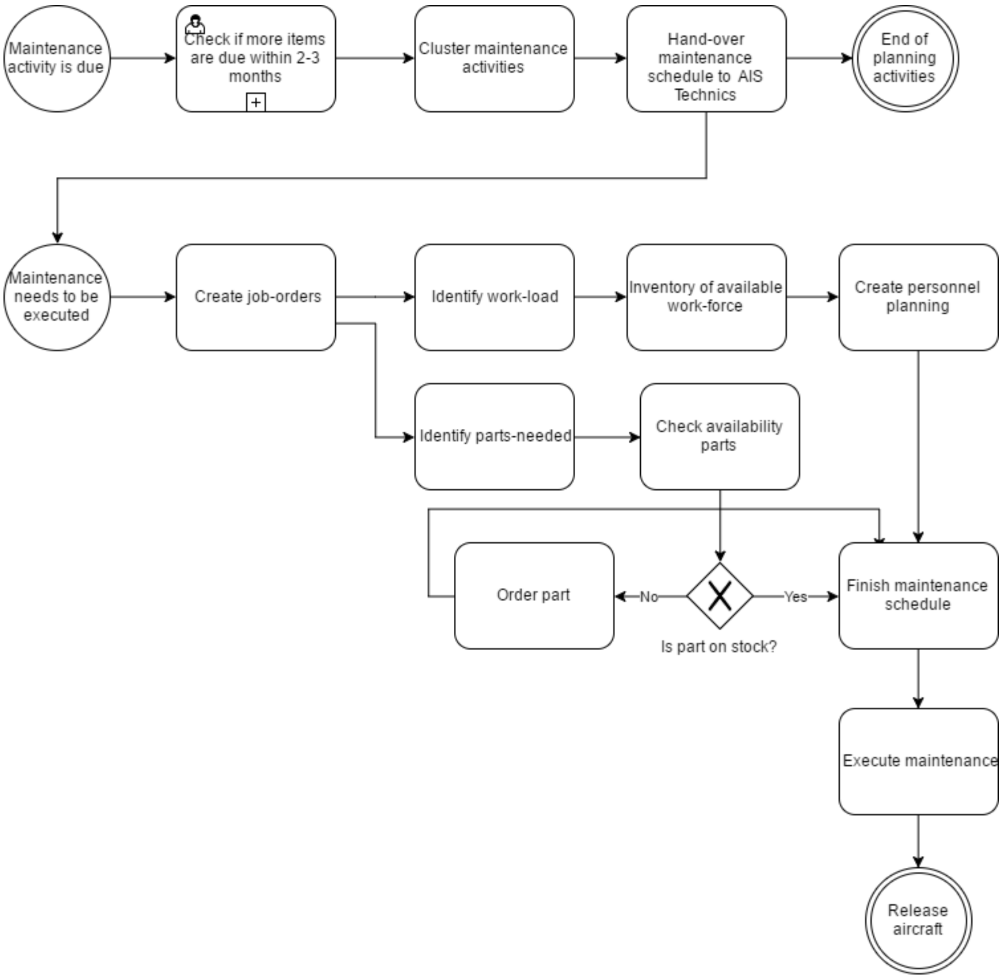

Figure 5 Maintenance Process Scheme

The scheme in Figure 5 shows how the maintenance schedule is constructed and where the information comes from. Looking at the clustering of maintenance jobs, it can be seen that the process is triggered as soon as an item is due for maintenance. The item is then clustered with other items that are due in the upcoming 2 to 3 months. This means that there is not a specific long-term clustering method applied at this moment. Since there is no specific clustering method applied, redundancy in the execution of maintenance jobs is likely to occur.
A second thing that can be seen is that the detailed maintenance schedule is created based on the job-orders. Job orders provide an overview of all the actions that a maintenance worker has to execute in

order to complete the maintenance task. Since these job-orders are only received two weeks in advance of the date at which the maintenance activity is scheduled, this can be a potential cause for one of the issues discussed in the problem cluster of Section 1.2.1. We pointed out there that the financial department was notified too late about the ordering of the spare parts. This can potentially be caused by the fact that the parts-needed list is created based on the job-orders. Since this is outside the scope of this research, I will not treat this further.

2.4 Constraints

In the previous Section, we already identified some constraints to the planning. We pointed out there that the aim of the maintenance schedule is to optimize the use of the individual parts. This means that parts may not be replaced too soon and therefore count as a restriction to the creation of the maintenance schedule. There are however two more constraints that have to be taken into account. First of all, there is a capacity constraint in terms of the space and personnel that is available for the maintenance. Secondly, the time that is available to take the aircraft out of service puts also a restriction on the scheduling activities.

- **Capacity restriction**
  The location at which the 'large' maintenance activities take place is currently restricted to the maintenance base in Lelystad. Maintenance activities are identified to be large if they cannot be executed between flights. The maintenance location in Lelystad however has the restriction that only one aircraft at a time can be handled. This is due to the limited space and resources that are available in the maintenance hangar. Next to that, the maintenance crew forms a restriction. It is namely not possible to work with a large group of workers on maintaining an aircraft due to the restricted space available in or on the aircraft. When determining the maintenance schedule, these constraints have to be taken into account and not too many tasks can be assigned to an aircraft at the same time.

- **Time/personnel constraints**
  The second restriction that needs to be taken into account when constructing the maintenance schedule is the time constrained. I already wrote before that the maintenance activities are mostly executed in the weekend. That means that roughly 60 hours are available to execute all the required maintenance jobs. This is a decision made by AIS since they believe that cancelling a scheduled flight is too pricy in terms of direct costs and loss of goodwill from their customers. When creating the maintenance schedule, it is important to ensure that the total time of all maintenance jobs can be executed in the weekend.

2.5 Performance

In order to assess possibilities for improvement, it is important that performance of the current situation is measured. To achieve this, we will make use of three Key Performance Indicators(KPI's). These KPI's will be specified for the performance of the activity scheduling that we are assessing. We describe the KPI's in section 2.5.1 and how they will be calculated, while section 2.5.2 provides an overview of the scores of the current clustering method on these KPI's.

2.5.1 KPI definition

It can be seen in Section 1.3 that the goal of this research is to develop a clustering model that reduces redundancy of set-up activities of various maintenance jobs while not wasting an unnecessary amount of remaining hours for the maintenance activities/parts.
To measure if the new situation outperforms the current one, we will identify three Key Performance Indicators(KPI's). These KPI's are the savings in set-up time, the maintenance costs and the amount of remaining lifetime that is wasted.

Amount of remaining lifetime wasted.
As could be seen in Section 1.3, clustering of maintenance activities cannot be done at all costs. A constraint is the frequency at which the maintenance activities have to take place. By executing maintenance sooner than the frequency described, remaining hours are wasted leading to financial consequences. The number of remaining hours/cycles wasted therefore cannot increase too much in the new to be designed clustering method compared to the current one. To calculate this, the due dates of the maintenance activities and the date at which it is actually scheduled will be taken into account. By taking the difference between these dates and taking the average score of this, the performance of the current situation on this KPI can be determined. The performance is not expressed in number of hours, but in number of days. This is because the calculation becomes easier, and a detailed calculation in terms of hours is not necessarily required.

Hours of set-up time saved
This KPI measures how much time is saved by jointly executing set-up time. We calculate this by looking at the maintenance activities and then applying the method of clustering as we described it in Section 2.3.4. For this, we take into account set-up activity 1 from table 4. Including this KPI in the research, we can later measure if the proposed clustering method will save set-up time.

Maintenance costs
The most important KPI that we identify is the maintenance costs. The main purpose of clustering maintenance jobs is that costs are saved by jointly executing set-up activities. Resulting we calculate the maintenance costs by multiplying the frequency of each individual job by the direct price of the task and the costs of the related set-up activity. It follows from the conclusion of section 2.3.4 that maintenance jobs are not specifically clustered and therefore are mostly executed individually.

2.5.2 KPI performance
Now that it is clear what the KPI's mean, the actual scores will be presented in this Section. Only parts of the calculation are explained since the main focus is on the actual outcomes.

Hours of set-up time saved
To calculate this KPI, we apply the current clustering method of jointly executing maintenance jobs that have a due date falling within the planning horizon of 3 months. Resulting, we find that on average 7,8 hours of set-up time is saved monthly by jointly execution of the maintenance jobs. This is based on an average set-up time of ±3 hours. We base this calculation on a selection of maintenance jobs going back 1 year.

Amount of remaining life-time wasted
From the current data, a selection of activities with their due dates going back 1 year until 3 months from now are included in the calculation of this KPI. Figure 6 shows part of the overview of all the activities with their due-dates and the date at which it was actually executed.

Task No.	Description	Due	Planned	Difference
29-20-003C	Hydraulic power emergency selector valve Seal change Ref MM29-10-32	29-7-2017	10-5-2017	80
32-20-001E	NLG overhaul Ref MM 32-20-11	28-6-2017	17-6-2017	11
32-20-008	Nose uplock actuator overhaul Ref MM 32-20-61	2-8-2017	22-7-2017	11
53-10-080-ALI	Eddy Current Inspection NDI of fuselage skin at passenger window cut-outs LH/RH Ref NDI manual 53-10-15	29-7-2017	22-7-2017	7
53-10-081-ALI	NDI of all window pans LH and RH side Ref SB 51-JA020940 App1 Part 14	28-7-2017	22-7-2017	6

Figure 6 Remaining days wasted

In column "Due", "Planned" and "Difference", the due-dates of the items, the date at which the maintenance is planned and the difference between these two dates can be respectively found. By taking the average value over the differences, the score of the KPI becomes momentarily 7,43 days. Meaning, on average a maintenance job is executed 7,43 days earlier than its prescribed due-date.

Maintenance costs

For the measurement of this KPI, we distinguish between two different scenarios. These scenarios are explained in detail later in this report. Since both scenarios include a different number of maintenance jobs, the costs of these scenarios also differs.

- *Nose-bay activities*
  When applying the current method of clustering to the maintenance activities of the nose-bay, each activity is executed separately. Resulting the costs can be calculated by multiplying each frequency against the respective costs, added with the set-up costs. This however is not completely fair, since some of the inspections are part of a larger cluster of inspections. (eg. 800hrs. inspection consist of multiple maintenance inspections) To overcome this, we will distribute the set-up costs for such an inspection proportional over all the inspections that are included in the task-list. Resulting, when applying the current method of clustering to the maintenance tasks in the nose-bay, the total monthly costs are €1808,53

- *Replacement activities*
  If we apply the current method of clustering to the replacement activities of the complete aircraft, we find a total monthly costs of €8279,-. Here we have assumed that each maintenance activity is separately executed and hence the set-up costs have to be completely paid each time. We have calculated again the total costs by multiplying the frequency with the sum of the set-up costs and the direct maintenance costs.

2.6 Conclusion current situation

Chapter 2 gave an insight in the current situation concerning the maintenance activities and the planning and scheduling jobs. We started with providing an overview of the maintenance activities that serve as a background for the planning activity. An overview of the types of maintenance activities that are included in the maintenance planning and maintenance schedule was given.

In the scheme of the maintenance process it could be seen that no clustering method for maintenance jobs is applied in the creation of the maintenance schedule. This was identified as a cause for the redundant execution of the set-up activities. A method for clustering will therefore be developed in the remainder of this report.

The chapter concluded with the performance of the current situation. We discovered that on average 7,43 days of remaining life time at this moment is wasted by the current planning. Although the goal of this research is not to change this situation, the newly developed clustering model needs to be compared also on this indicator.

In order to develop the clustering model, in Chapter 3 a review of the existing literature on clustering of maintenance jobs is given. Based on this literature review the clustering model can then be designed for AIS.

3. Literature review

In Chapter 2 we described the current scheduling activities and maintenance process. We identified that currently no method for clustering maintenance activities is used at AIS. This chapter discusses different methods for clustering of maintenance jobs that are restricted in their frequency by legislation. At the end of the analysis, a method for clustering the maintenance activities is chosen from the literature study. To make that possible, an outline of the clustering methods that exist in literature are discussed. Besides that, multiple ways in which the clustering models can be solved are analysed. This all falls within the boundaries of a theoretical framework that is discussed at the start of this review.

3.1 Theoretical framework

Since aircraft are becoming more and more complicated and the costs for maintenance are rising, there is a growing importance to design the maintenance activities in an efficient manner. The execution of many of these maintenance jobs results in a situation where the aircraft has to be grounded. As a result, a large potential for improvement here lays in the design of the planning of the maintenance activities. A study by (Gits, 1984) constructed a framework for the design of a maintenance concept. This framework applies to all so called technical systems and in the end provides the company with a maintenance concept. *"A maintenance concept is the set of ordered maintenance rules prescribing what maintenance should be carried out when."* Gits, (1984). The framework is shown in Figure 7.

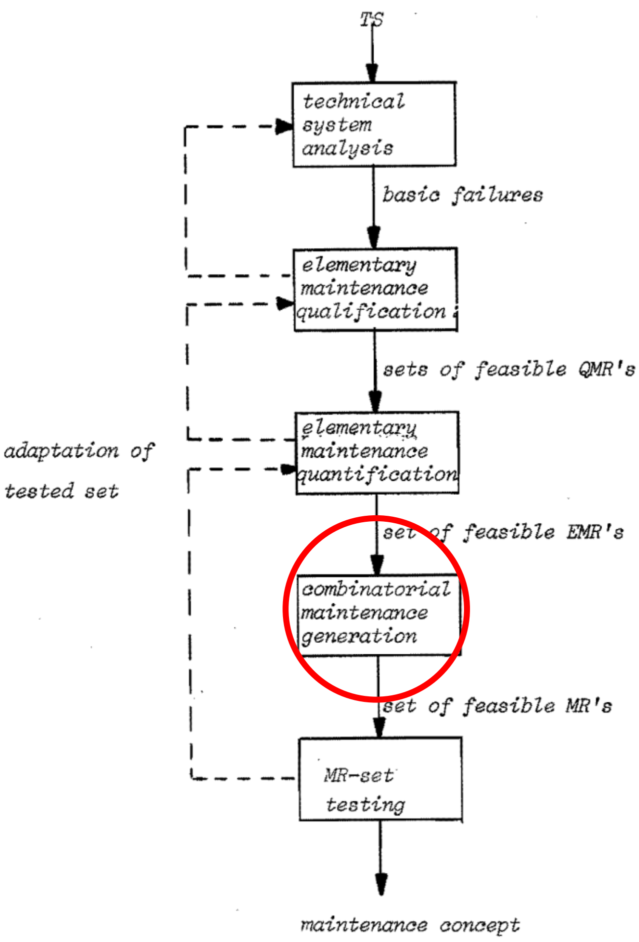

Figure 7 A framework for maintenance concept

3.1.1 Technical system analysis

It can be seen that the framework starts with the input from the technical system, or in the case of this paper, the aircraft. The technical system analysis consists of two steps: basic failure determination and hardware structure analysis. The basic failure determination step includes that the system is decomposed into multiple components where the system is described on a part-level.
Next to that, parts are classified into critical and non-critical parts. To finalise the failure determination, failures are analysed. Meaning, an analysis of failure mechanisms, consequences of failures and failure behaviour is made.
The second step in the technical system analysis is the analysis of the hardware structure. With this, we identify the dependency between multiple parts that should be included in the decision making about the design of the maintenance activities.

3.1.2 Elementary maintenance qualification

The elementary maintenance qualification is the first step in generating a set of maintenance rules. In this phase, the information from the technical system analysis sets the basis for a maintenance activation. The maintenance activation describes in which state the system requires maintenance. (E.g. age-based, time based) The second set of rules that is developed in this phase is the maintenance operation qualification. Gits (1984) describes two types of maintenance operations: Verification, also known as inspection and reconditioning, which is in its turn subdivided in repairing and replacement.
To complete this phase of the maintenance concept design, each maintenance activation is assigned one or multiple maintenance operations.

3.1.3 Elementary maintenance quantification

In the previous phase of the maintenance concept design, the maintenance activation and the connected actions were identified. The next step of the development of the maintenance concept is to determine the intervals between two consecutive maintenance jobs. Based on the behaviour of the failure related to the usage of the system, a "fatal norm" is determined. This fatal norm makes the trade-of between safety on one hand and economical or financial factors on the other hand. Before this norm has been reached, the respective maintenance operation has to be executed. Intervals between two consecutive maintenance jobs in aviation are determined in terms of flying hours or flight cycles.

3.1.4 Combinatorial maintenance generation

The steps so far have been executed for each maintenance item individually, but in modern day systems, interdependency no longer exists. In this last phase, which also embraces the scope of this research, the possibility for aggregation of maintenance jobs is investigated. This process of clustering maintenance jobs contains four steps in total.

First of all, individual maintenance rules that have been developed so far are aggregated into nominal sets of maintenance rules. The resulting aggregations of maintenance rules are then qualified in which the individual rules are classified and redundant rules are eliminated. These above two steps are also referred to as combinatorial maintenance qualification.

A third part of this phase is the maintenance interval clustering. Here, the intervals from the individual maintenance rules are transformed into common maintenance intervals of the so-called clusters. Once the intervals of the clusters are determined, Gits (1984) describes the last part of this phase as the structuring of maintenance demand. Here, the intervals of the clusters are normalised and turned into a demand planning for future maintenance activities. The workload is identified and cyclic demand patterns are described.

3.2 Concept matrix

Section 3.1 described the framework which embraces this literature study. In the remainder of this study, we investigate a number of concepts that contribute to executing the Bachelor assignment. Section 3.2 therefore describes an overview of the concepts that are included in the literature study. The scope of this research was already described in Section 1.5 and aims at finding models that allow for clustering of frequency constrained maintenance jobs with common set-ups or the so called combinatorial maintenance generation step.

Maintenance scheduling in the aviation industry includes a wide variety of aspects, such as safety, financial, operational, organizational and legislation. Since legislation aspects are usually fixed, they form the most significant constraint to take into account when scheduling maintenance activities. This, however, often results in situations in which a schedule is created where maintenance costs are not optimized. A method in order to overcome this issue is the clustering of maintenance activities. Once maintenance activities are clustered, cost benefits can be achieved. These so called clusters can be constructed based upon common or shared set-ups, but also among activities that fall in the same time span of the schedule.

The success of the literature study depends on the search strings and criteria that are used. In order to search in the right direction in the large databases that are available nowadays, specific search strings have been used. The most relevant articles that remained are presented in the concept matrix that is shown in Table 5. Afterwards the main findings of the literature review are presented.

Article No.	Concept						Evaluation
	Joint replacement	Common/shared set-ups	Planning-horizon	Linear programming	Dynamic programming	Heuristic	
1	x	x	X		x	x	Models with common set-ups are easier to solve, but models with shared set-ups have better results.
2	x	x	X		x	x	Model with finite horizon is easier to solve, but for more cost efficient solution, infinite horizon has to be assumed.
3	x	x	X		x	x	Rolling horizon is decomposed in 5 phases.
4	x		X		x		For condition based maintenance, the trade-off between corrective and preventive maintenance has to be taken.
5	x	x	X				Makes use of independent maintenance activities and thus does not cluster on set-up activities.
6	x		X			x	Grouping is not done based upon set-ups and is applied in railway setting. Legislation is strongly included though.
7				x			No application in joint replacement theories

Table 5 Concept Matrix

3.2.1 Joint replacement

In this research, we investigate the joint execution of maintenance activities for aircraft. After conducting a literature study we identify multiple approaches for joint replacement methods.

All articles that are included in this literature review follow a somehow similar structure towards solving the problem. First of all, a mathematical formulation to the problem is developed. In order to solve this mathematical problem, constraints to the solution are identified and a planning-horizon is determined. As a next step, possible clusters of maintenance activities are identified. The problem is often solved in a mathematical manner or with help of a heuristic approach.

For the formulation of the problem, articles make a decision to either include or not include the opportunity for corrective maintenance. Next to that, we have found different constraints or penalty functions that are used. Furthermore, different planning-horizons are possible with regard to the problem. More specifically, this can mean a finite-time horizon, an infinite-time horizon or a rolling time-horizon. For the construction of clusters of maintenance activities, a selection based on common or shared-set ups can be used or a set partitioning algorithm is applied. To solve the problem, a linear programming model, a dynamic programming algorithm or a heuristic approach is usable.

All these different approaches to how the joint replacement can be designed will have various advantages and disadvantages that will have to be considered. The remainder of this literature review discusses these topics into more detail, to substantiate our decision for the to-be-used model within AIS.

3.2.2 Problem formulation

The textual formulation of the clustering problem is presented in a study by Dekker, et al. (1992). For the clustering problem, one has to consider a number of independent maintenance activities that all have a due date at which the activity has to be executed. These due dates all fall in a planning horizon that was determined beforehand. The execution date of each activity within this planning horizon can be altered by the maintenance planner. With this textual formulation, the problem cannot be solved yet, but it can serve as the input for the mathematical formulation.

A study by van Dijkhuizen, et al. (1997) describes this mathematical formulation of the clustering problem. The authors here describe a set of m set-up activities $I = \{1, \dots.. m\}$ and a set of n maintenance jobs $J = \{1 \dots n\}$ that are constrained by the frequency at which they have to be executed. Additional variables that belong to this mathematical formulation are:

$f_j = Maintenance\ frequency$

$t_j = Costs\ of\ maintenance\ jobs$

$U \subseteq J\ cluster\ of\ maintenance\ jobs$

$S(U) = Set - up\ costs\ of\ cluster\ U$

$\lambda(U) = f(U) * \big(s(U) + t(U)\big); Cost\ function\ per\ cluster$

The goal function is minimizing the sum of the costs over all the clusters. The disadvantage of this model is that not all information may be available. It is, for instance, difficult to determine exact costs for a set-up activity or maintenance activity. Next to that, the search space of the model increases drastically with an increasing number of maintenance jobs. At last, the model does not allow for inclusion of corrective maintenance activities unlike the model developed by Dekker et al. (1996). Here, at each decision point both preventive and corrective maintenance can be executed. It is assumed here that the failure distribution of each part is known, which not always is the truth in reality. Next to that, replacement time is neglected which may not be applicable in each situation.

The above two models are applicable to maintenance jobs that have a predetermined frequency at which they have to be executed. According to the framework presented by Gits (1984), the clustering of maintenance jobs depends on the elementary maintenance rules.

Besides frequency constraints, there is also the possibility of clustering within condition based maintenance policies. An advantage of using condition based intervals is that it is possible to make more efficient use of the parts of a system. It is for this research not so relevant to look at the condition based interval but the way clustering methods are applied here are more interesting to investigate. Keizer et al. (2016) describe a model that allows for clustering of maintenance activities within a condition based maintenance policy. Here they assume a K out of N-system from which the technical condition of the components is known at the beginning of a time period. Although in reality the condition of a part is often not known the model presented in the paper is proven to result in an improvement in performance compared to different maintenance policies.

In general, these mathematical models cope with high complexity if the number of variables increase. The more variables have to be taken into account, the higher will the number of possible 'optimal solutions' be. In order to overcome this complexity, a number of solutions are described in the articles of this literature study. One way of reducing the number of possible outcomes is to reduce the planning horizon in which the possible clusters are selected. These possible time horizons are discussed in the next Section 3.2.3.

3.2.3 Planning horizon

In total, we identify three types of planning horizons in literature: a finite planning horizon, an infinite planning horizon and a rolling planning horizon. These time horizons are the basic rule for determining the potential clusters that can be constructed.

A finite planning horizon is described in a study of Dekker et al. (1992). Making use of a finite planning horizon means that only maintenance activities that are planned to take place within this planning horizon will be considered in the model. The date at which the maintenance job will be executed can be altered as long as it remains within the planning horizon. A disadvantage of this model is that a cluster from activities of different planning horizons is not taken into account while this may be advantageous. An important benefit from this approach is that the number of possible clusters is reduced and as a result of this, the model will be easier and faster to solve while delivering relatively good solutions. The goodness of this solution depends strongly on the planning horizon that is selected.

The infinite planning horizon is used in the mathematical model developed by van Dijkhuizen et al. (1997). The mathematical model is based on an infinite planning horizon which means that a larger amount of clusters can be later allowed. Unlike in the finite planning horizon, the goodness of the solution does not depend on the planning horizon that is selected. It is usually assumed to deliver a better solution than clustering within a finite planning horizon. The downside of this is that more possible clusters are available and, therefore, solving the model will be more time-consuming.
For an infinite planning horizon, clusters are determined only once and therefore new information is hard to add to the model. As a result, potential improvements are missed over time.

To overcome the disadvantages of the previously two mentioned planning horizons, Wildeman et al. (1997) constructed a model with a rolling planning horizon. The model as it is described has a great advantage in the number of items that can be included compared to the previous two methods. To solve the model, a five steps approach is used starting with the development of an individual frequency for each component. After this, penalty functions for deviating from these frequencies are composed. Based on a fixed time-horizon, a grouping of maintenance activities is then made. As a last step, the rolling horizon is applied which means that the planning is changed if the maintenance manager is not satisfied with the result. An advantage of this approach is that it can be applied to each underlying maintenance policy and as a result of this, each item can have its own optimal maintenance policy. On the other hand, a large implication to this model is the composition of the penalty functions. In reality it may be difficult to determine the cost function or an estimation of the cost function for deviating from the optimal maintenance interval.

3.2.4 Clustering

By setting the planning horizon from an infinite to a finite time-span, the number of potential clusters can be reduced drastically. The next step in the clustering process would be to identify different clustering methods. In the literature review we have identified three different ways for clustering the maintenance activities. These methods include clustering based on common set-ups, shared set-ups and time interval based clustering.

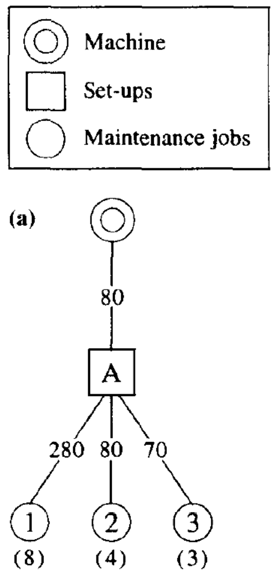

Figure 8 Maintenance tree for common set-ups

Figure 8 shows a tree-like structure in which the set-up activities and the maintenance activities are connected to each other. Here it can be seen that all the maintenance jobs (1,2,3) have one common set-up activity “A”. A possible cluster in this case would be to execute jobs 1,2 and 3 all at the same time such that set-up activity A only has to be executed once. Besides the general advantages of clustering maintenance activities, this clustering method results in a restricted number of clusters and hence the model can be solved numerical in an acceptable time period. When restricting the number of clusters, the optimal solution may not be found. Following, if a more cost-efficient situation is required, a clustering based on shared-set ups can be used. We present the tree-like structure of shared-set ups from maintenance jobs in **Figure 9.**

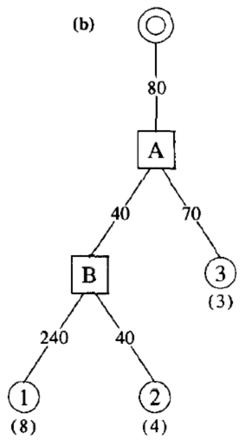

Figure 9 Maintenance tree with shared set-ups

With the shared-set up clustering, activities that do not have all set-up activities in common can be included in the same cluster. Resulting, the number of possible clusters is much larger than in the previous situation. This means that the time required to solve the problem exactly will also be larger. Van Dijkhuizen et al. (1997) have developed a heuristic in order to overcome this problem and allow the model to be solved within a reasonable time. The shared-set up clustering method results however in better outcomes due to the larger number of possible options.

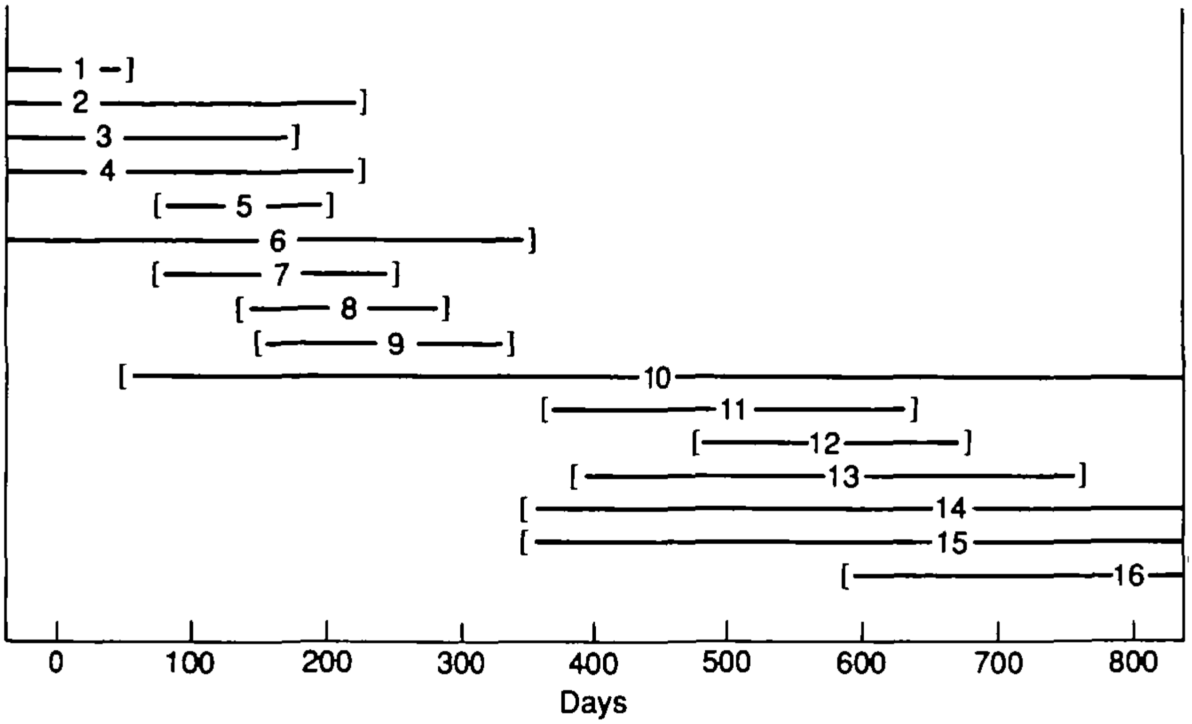

Figure 10 Maintenance activities timeline

Figure 10 provides a timeline for the execution of the maintenance activities. This timeline is the basis for the clustering method described by Dekker et al. (1992). Each maintenance activity has an initial due-date and an interval from which the execution of the job may deviate. A disadvantage of this model is that the complexity increases when the number of activities increases. Next to that, the solution is strongly dependent on the penalty functions that determine the ultimate deviation from the due-date. The composition of these penalty functions also faces complications. It is in reality often difficult to determine the costs that are associated with the early or late execution of a maintenance job. The final clusters are in the end determined by applying a set-partitioning algorithm. This algorithm makes use of an initial list of combinations from which an optimal solution is derived. The model is easily extended with further constraints to possible combinations or due-dates of maintenance jobs. A note has to be made here that the clustering is not done based on set-up activities as the description of this research requests.

3.2.5 Solving the problem

To solve the problems defined in Section 3.2.1, multiple techniques exist. These techniques are:

- Dynamic programming
- Branch and bound algorithm
- Set partitioning algorithm
- Linear programming

In this Section, we will explain the most important aspects of these techniques including the benefits and drawbacks as well as the model it can be applied to.

- **Dynamic programming**

  The first technique for solving the cluster model that we found is the dynamic programming technique. A general approach for the dynamic programming theory in replacement models is described by Winston & Goldberg (2004) as the equipment-replacement model. In general dynamic programming is a technique that is used to solve optimization models by working backwards and assessing the outcomes of multiple decisions. This model does not include the joint replacement of parts, but this extension to the theory is done in research papers by van Dijkhuizen et al. (1997), Dekker et al. (1996), Wildeman et al. (1997) and Keizer et al. (2016). Van Dijkhuizen et al.(1997) apply the dynamic programming theory in the case of clustering based on common set-ups which results in a relatively good solution. We found several ways in which dynamic programming can be used. This includes calculating the total savings or minimizing the total costs. However, as the number of maintenance activities increases, the computational time for the dynamic programming technique also increases. Dynamic programming is by all papers that are found identified as less suitable for large problems with many set-up activities and maintenance jobs that are included.

- **Branch and bound algorithm**

  A branch and bound algorithm is a tool that is used to solve combinatorial optimization problems from which the state space is too large to be completely searched. Applied to the clustering problem, the branch and bound algorithm makes use of a number of steps to find the optimal solution. First an initial solution is found with the use of a heuristic approach. The nodes that aren't included in a clustering yet, are assigned to a new cluster only if this yields a better solution. If no better solution can be found, the node will be assigned to a new clustering. By using this algorithm, a solution is found that deviates from the optimal solution within a relatively small computation time. The algorithm deviates more from the optimal solution as soon as the problem becomes larger. Resulting, a trade-off between accuracy and solving-time must be made.

- **Set partitioning algorithm**

  The goal in joint optimization is to find the optimal combination at which maintenance jobs are executed. This means that maintenance jobs are to be clustered into one or multiple 'sets'. A method to determine these sets, is with the set-partitioning algorithm. The principle behind this idea is finding the cluster with the lowest costs among all possible solutions. It was already identified before that the number of possible sets becomes really large with the number of maintenance jobs. To reduce this number of possible sets, Dekker et al. (1992) makes use of penalty functions that determine how much a maintenance activity may deviate from its optimal frequency and in this way reducing the number of possible clusters. If the problem is reduced in this way, it will be possible to analyse all potential clusters and identify the one that results in the lowest costs, or largest savings.

- **Linear programming**

  In the literature that we studied, no linear programming model was applied to the combinatorial maintenance problem. According to Winston et al. (2004), linear programming is a tool that is often used in order to solve optimization problems. Linear programming makes use of an objective function that describes the relationship between the various decision variables. The values of these decision variables are all subject to a series of constraints to which the solution has to obey. The technique has a number of drawbacks that may cause some complications when applying it to the combinatorial maintenance problem. First of all, are all relationships between variables linear and non- exponential. Although this makes solving the problem easier, this may not always be an valid representation of the reality. Linear programming also has the similar problem as dynamic programming when it comes to the computational time of the model. If the number of possible solutions increases, the time needed to solve the model will also increase. Since no existing literature about the application of linear programming in the combinatorial maintenance problem is found, it is important to be extra cautious when applying this technique.

3.3 Conclusion literature study

The findings from the literature study in this Chapter provide an in-depth look into the joint execution of (aircraft) maintenance jobs. The Chapter describes various views on the problem definition, clustering methods and problem solving approaches that are all applicable to the situation of AIS. The theories are not designed specifically for the situation of maintenance to an aircraft, but we believe that these theories are generally applicable.

According to the literature study, we can formulate the problem in several ways. We also found that the joint replacement can be applied to different types of elementary maintenance strategies, from age-based replacement to condition based replacement. It is also possible to include the corrective maintenance activities into the models if the situation at hand asks for this. A common problem with the mathematical formulation was that the time needed to solve the problem can grow very large. A way to overcome this last issue was to set a restriction to the planning-horizon at which the joint replacement would take place. A finite planning-horizon only looks at the clustering of maintenance activities that fall within the planning-horizon and results in a reduction of the number of potential clusters. However, this leads to a model that will not provide the optimal solution since no clusters from activities of different horizons are allowed. This is allowed in the infinite planning-horizon approach, but this results in a model that needs a large time to be solved. To overcome these issues, a rolling horizon approach was developed that allows the maintenance manager to adjust the planning with multiple iterations whenever needed.

Within the clustering set that remains, there are a number of techniques for selecting the final sets. The literature describes models for clustering of activities with common set-ups, shared set-ups or common time-intervals. Here the model based on shared set-ups provides the best solutions but this comes at the cost of a large time for solving. In the literature study, multiple ways of solving the joint replacement problem are available. The exact models such as dynamic programming and linear programming often result in the best solution but the time to solve the problem exact, may become large. The heuristic approaches provides a good solution that is solved much faster.

In chapter 2 we identified that currently no clustering methods are used at AIS. To investigate if clustering of maintenance jobs can yield a better performance for AIS, we will make use of the common-set up approach. According to the literature study, this approach is compared to different approaches, easy to solve with the help of a dynamic programming algorithm. We believe that due to this, the clustering method is most suitable for the initial research at AIS. We believe that this will allow us to solve the problem within the available time of the Bachelor assignment while providing AIS with enough insights into clustering of maintenance jobs. The different approaches that we identified in the literature study, can be investigated as a follow up to this report by other researchers.

4. Clustering of maintenance jobs with common set-ups

We discussed in the conclusion of Chapter 3 that we test the clustering model that allows for clustering of maintenance jobs with common set-ups. This model is relatively easy to solve, and can provide us with an indication of the benefits of clustering of maintenance jobs at AIS. We make use of the clustering method as it is described by van Dijkhuizen et al. (1997). We start this chapter by describing this clustering method, its assumptions and problem definition. Following, we test the method in two different scenarios that we elaborate in section 4.2. By assessing the outcomes of the two scenarios we make recommendations to AIS regarding the combinatorial maintenance generation.

4.1 Model assumptions and simplifications

The clustering technique we chose to apply to the problems of AIS is the technique based on common set-ups. This technique utilizes a number of assumptions about reality in order for it to be applicable. In this section we discuss these assumptions and see if until what extend we can justify the use of clustering of common set-ups at AIS.

4.1.1 Assumptions

The first assumption that the clustering model uses is the assumption of common set-ups which means that the maintenance tree of the aircraft looks like the tree of Figure 8. Here there is only one set-up that is executed preparatory to the completion of all the maintenance jobs. We identified before that one of the set-up activities at AIS is to fly the aircraft back to the maintenance base. Since the aircraft is flown back to the base for each maintenance task, some jobs are executed at the line station, the assumption of common set-ups is in that case not completely correct. As a result, not each maintenance job can be included in the same clustering model and the problem has to be subdivided into multiple smaller problems.

A second assumption that is done by van Dijkhuizen et al. (1997) is that fixed costs are made for each set-up activity and maintenance task. Combining this with the previous assumption, we question if the costs for a maintenance task are in reality always fixed. When changing a part of the aircraft, very often other parts have to be also removed in order to gain access. In this case a large part of the costs of the replacement of an item are made by the removal of other parts. When the items are clustered, the costs of removal of items are also shared. The clustering model does not take this into account, unlike the shared set-up model.

A third assumption of this model is the infinite horizon assumption. Resulting, the clustering method by van Dijkhuizen et al. (1997), creates static clusters. Meaning, maintenance jobs that fall within multiple planning horizons can be included in the same cluster. We believe that this doesn't put a restriction to the model for implementation at AIS.

Lastly it is assumed that a maintenance job is always executed at a certain interval. In this assumption, corrective maintenance is not allowed to the model. Corrective maintenance furthermore causes that the due-dates of maintenance items are growing apart. Meaning, executing a certain maintenance job within a cluster, results in a larger amount of remaining hours being thrown away. The model does not account for the extra costs of this.

4.1.2 Simplifications

A simplification made by the clustering model is that shared set-ups are not permitted. It means that the set-up activities included in the model have to be connected to all of the included maintenance jobs. While doing research to the structure of the aircraft and the maintenance manual, we noticed that there are a large number of shared set-ups. Hence, the resulting maintenance tree from the common set-up model does not reflect reality as it really is. The model therefore does not take into account all of the improvements that can be achieved. Jointly execution of shared set-ups results namely also in cost reductions.

We have explicitly chosen for this due to the format in which the current information is presented. All the set-up activities and maintenance jobs have to be gathered from the Maintenance Manual by hand. We therefore have to simplify the problem in order to solve it within the available time.

4.1.3 Goodness of Fit

We believe that the model can be applied to the situation of AIS, despite the assumptions and simplifications that have to be made. It is true that by representing the maintenance tree of the aircraft of AIS with solely common set-ups simplifies the reality, it does not make the model unusable. We believe that the problem will be easier to solve, but does not result in the most cost-efficient solution. To reach this cost efficient situation, shared set-ups have to be included.
Furthermore, we have seen that it does not occur very often that maintenance jobs with similar intervals possess different due-dates. This due to the fact that failures to critical parts are largely prevented by the determination of the individual maintenance intervals.

4.1.4 Model description

After describing all the assumptions of the clustering model and the input data that we use, we now proceed with the general mathematical description of the clustering model.
For the mathematical formulation, we use the same variables as van Dijkhuizen et al. (1997).

$$I = \{1 \ldots . m\}\ set\ of\ preparatory\ set - up\ activities$$
$$J = \{1 \ldots . n\}\ Set\ of\ frequency\ constrained\ maintenance\ activities$$
$$s_i: Costs\ for\ the\ preparatory\ set - up\ activity$$
$$f_j: Frequency\ of\ maintenance\ job$$
$$t_j: Cost\ of\ maintenance\ job$$
$$U: Cluster\ of\ maintenance\ activities$$
$$\lambda(U) = f(U) * (S(U) + t(U)) \qquad (1)$$

Equation (1) describes the cost function for each cluster. It consists of a multiplication of the frequency of the cluster with the costs for executing the cluster. The frequency is determined by the maintenance activity that has the highest prescribed frequency. The costs depend on the costs for the set-up activity and the costs for each maintenance job individually.

The aim would be to find the combination of clusters that results in the lowest possible total costs. To do so, we will use the dynamic programming algorithm as it was described by van Dijkhuizen et al. (1997). The dynamic programming algorithm breaks the problem up into multiple smaller problems which should lead to the most cost-efficient composition of the clusters of maintenance jobs. The dynamic programming equation we use is: $F(k) = \min_{1 \leq i \leq k: f_i \leq f_{max}^k} \{F(i-1) + f_i * (S + \sum_{j=1}^{k} tj)\}$ (2)
Equation (2) follows directly from van Dijkhuizen et al. (1997) and describes the minimal costs for the clustering of the respective maintenance jobs. With this formula, the trade-off to perform the maintenance job against a higher frequency or the extra execution of the set-up activity is evaluated. For each activity, the function determines whether it is cheaper to combine the maintenance job with an activity that has a larger prescribed frequency so that set-up costs are saved, but remaining life time is thrown away.

4.2 Scenario description

Since constructing the clustering model for the complete aircraft won’t be completable within the time of our thesis, we test the clustering method to two different scenarios. We describe these two scenarios underneath:

Scenario 1: Nose Bay Zone

In the first scenario we focus ourselves on only one zone of the aircraft. We refer to figure Table 2 for a complete overview of all the zones of the aircraft. The structure tree in table 1 only provides an overview on the highest level of detail. Because of the limited time during the bachelor assignment, we only work out the nose bay zone.

<table>
<tr><td rowspan="15">Nose Bay</td><td rowspan="4" colspan="2">Structure</td><td>Skin</td></tr>
<tr><td>Panels</td></tr>
<tr><td>Stringers</td></tr>
<tr><td>Bulkhead</td></tr>
<tr><td rowspan="11">Equipment</td><td rowspan="3">NLG-bay</td><td>Landing gear</td></tr>
<tr><td>Hydraulics</td></tr>
<tr><td>Lights</td></tr>
<tr><td rowspan="8">Equipment bay</td><td>Communication</td></tr>
<tr><td>Electrical power</td></tr>
<tr><td>Flight controls</td></tr>
<tr><td>Ice & Rain</td></tr>
<tr><td>Recording</td></tr>
<tr><td>Navigation</td></tr>
<tr><td>Electrical</td></tr>
</table>

Table 6 Nose Bay Structure

Within the nose-bay we identify two categories for assemblies, the structural part of the aircraft and the equipment that is installed. The most important parts of the structure of the nose bay are the bulkheads, the stringers, access panels and the skin. The hydraulics, electrical equipment, flight controls and navigation parts can be found in the equipment bay, while the landing gear is placed in the Nose Landing Gear Bay. The Nose Landing Gear Bay and the Equipment Bay are two compartments within the nose bay. In these two compartments, a large list of parts are located which we present in **Appendix I.** The maintenance tasks and its set-up activities that belong to these parts are presented in **Appendix II.**

The list of maintenance jobs that are included in this first scenario can be found in **Appendix III.** Due to copyright issues, we have not published the official names of the maintenance jobs, but replaced them with a number. An exact overview of the input data is given in the next section of the report.

Scenario 2: Replacement activities

Unlike Scenario 1, we will look at the whole aircraft in this second scenario. We have chosen however not to include all types of maintenance activities to keep the problem controllable. Therefore, we only include replacement and overhaul activities in this scenario. We have explained the different types of maintenance activities earlier in **Chapter 2**. More information on the activities we include in this scenario is presented in **Section 4.3.3.**

4.3 Input data

Since we have identified two problems earlier in our report, we will also make use of two different sets of input data. We first identify the input data for the activities in the Nose bay, before presenting the input data of the second problem statement.

4.3.1 Parameter estimation

In order to solve the clustering model as we previously described, we are in need of certain information, the so called parameters. These parameters serve as the input of the clustering model and provide us with the required data to solve the clustering problem.

The first parameter we use is the frequency of the maintenance jobs. Since the life-time of a part is presented in terms of a certain interval, we calculate the frequency as following:

$$Frequency = \frac{1}{interval\ in\ months}$$

Resulting from the previous equation, we find the monthly frequency at which the maintenance jobs is executed. Some parts have a life-time that is prescribed in terms of flight hours instead of a fixed interval. To calculate the monthly interval of these parts, we have assumed an average amount of flight hours the aircraft makes each year.

The second parameter we use is the costs of a maintenance job. We have used different methods to determine the costs of different types of maintenance jobs. For the replaceable items, we have used the price of an item as the value for the parameter. We based the costs for inspections and checks only on the costs of manpower that is required for executing the job. For that we use an average hourly salary of €50,- per ground engineer.

4.3.2 Input data Nose Bay problem

Based on the parts-list, and the requirements of the AMP, we have developed a list of maintenance activities with its frequencies. This list consists only of maintenance activities that have a life-time of at least 800 hours. Maintenance activities with a smaller interval are not worth including since these jobs have a small time required for executing the task and therefore are executed in the line-station. The list with 17 maintenance activities that we have identified is presented in **Appendix III.** We have included overhauls, replacements and inspections into this list and resulting, these different types of maintenance activities can be included in the same cluster. We have however used a different method for the determination of the costs for these respective maintenance tasks. Where the costs for an overhaul or replacement follow from the price of a spare part, inspections don't make use of spare parts. In order to determine these costs, based on an experts' opinion, the time for each inspection is decided. Multiplying this with the hourly salary of a maintenance engineer, gives in our opinion a good approximation of the costs of a maintenance inspection. An overview of the maintenance activities that we include is presented in **Appendix III**. Here you can also find the costs and the frequencies that belong to each of the maintenance jobs.

We have indicated before that the frequency of a maintenance job is determined by either a fixed date, a number of flight hours or a number of flight cycles. This however makes it difficult to compare the individual frequencies. We overcome this by expressing the frequency in terms of a monthly frequency. Based on an average number of flight hours or flight cycles the PH-DCI makes yearly. We remain then with a number that indicates how often each maintenance activity is executed per month.

From the above mentioned list, we derive the set-up activities that are required in order to start the maintenance tasks. The complete list of set-up activities related to each maintenance task is given in **Appendix II.** Since this is a rather extensive list of set-up activities, we will focus on the largest four common set-ups according to the ground engineers.

(1) **Fly aircraft to base**
This set-up was already taken into account in the current clustering of maintenance activities and will, for this reason, be also taken into account in our model. It is assumed to take on average 3 hours to fly the aircraft back to base. Estimated costs for the aircraft per flying-hour are found in **appendix III**. Since the aircraft also has to be flown back after executing the maintenance, the total ferry flight takes 6 hours.

(2) **De-energize aircraft DC-bus-bars**
In order to start the maintenance activities to the electrical equipment that is placed in the equipment bay, the DC-system of the aircraft needs to be de-energized. Executing this this task is estimated to take 10 minutes.

(3) **Open access panels to the nose bay**
Removing these panels is essential in order to gain access to the previously mentioned equipment bay. Having this panel removed by the aircraft ground engineer is expected to take 20 minutes.

(4) **Raise aircraft on jack**
Prior to any work being done on the landing gear, or in the landing gear bay, the aircraft needs to be placed on jacks. Placing the aircraft there requires approximately 30 minutes of work.

Combining the abovementioned 4 set-up activities with the earlier identified maintenance tasks of **Appendix III**, we present the maintenance tree in **Figure 11.** The above four mentioned set-up activities are executed consecutive for each maintenance jobs. Resulting we refer hereafter to them as one set-up activity: 'S_1".

Aircraft													
S_1													
M2	M3	M5	M6	M7	M14	M15	M16	M8	M9	M 10	M11	M12	M13

Figure 11 Maintenance Tree

4.3.3 Input replacement scenario

The second scenario that we test upon request from AIS is one that only includes the overhauls and replacements that are scheduled for the complete aircraft. In this scenario we only include the one set-up activity which concerns the flying of the aircraft to the maintenance base. In order to solve the clustering model, we first construct a list of overhauls and replacements that take place on the aircraft with the respective costs and frequencies at which the maintenance takes place.

In **Appendix IV** the list of overhauls and replacements is presented. We include all these maintenance jobs in our second scenario. We have chosen not to include all replaceable items in our model, but only the ones that are not executable at the line-station and therefore require the aircraft to fly back to the maintenance base. For each of these items, a price is determined. This price is based on the overhaul costs, or the costs of buying a new part and follow directly from the AIS-database. This means we assume the costs for the ground engineers and tools used to be neglectable. As we said before, the list only contains maintenance jobs that are to be executed at the maintenance base in Lelystad. Resulting, all jobs are related to the one single set-up activity of flying the aircraft back to the base with a set-up cost that can be found in **Appendix IV.**

4.4 Problem resolving

4.4.1 Nose Bay Zone scenario solved

In the clustering of maintenance jobs within the nose-bay, we have included a total of 17 maintenance jobs and 1 set-up activity, so $j = \{1 \dots 17\}$ and $i = \{1\}$. The complete overview of these maintenance tasks and set-up activity is found in **Appendix III**. We solve the dynamic programming for the first two maintenance jobs and present its respective results in **Appendix V**.
Since there are in total 17 maintenance jobs for which we need to solve this, the reaming iterations are done with the support of VBA-coding in excel. The results for this are also presented in **Appendix V** and the VBA code is found in **Appendix VII.**

We are however not only interested in the costs that follow from the model, but also in the composition of the optimal clustering. Analysing the results, leads to a clustering composition as we present in **Table 7.**

Cluster	1	2
Jobs	{M9,M10,M12,M13,M16,M11,M14,M17}	{M1,M2,M3,M4,M5,M6,M7,M8,M15}
Frequency	0,01388 times/ month	0.1667 times/month

Table 7 Cluster results Scenario 1

More concretely, this means that NLG overhaul, Nose Uplock actuator overhaul, Steering Jack overhaul, Steering selector valve overhaul, Detail visual inspection LH and RH vertical channels on front face of front pressure bulkhead, NLG down-lock overhaul, DVI NLG trunnion fitting and DVI NLG retraction jack upper attach bracket bolts are included in the first cluster. Meaning, the second cluster consists of LH/RH Main battery check , Replace NLG hydraulic fluid, Emergency V.H.F F/C, Compass swing, Inspection of NLG bay for corrosion, Inspection of front pressure bulkhead fwd face for corrosion, Avionic Bay DVI Internal, Inspection of Stns 36, 51, 83 including surrounding skins for corrosion and DVI front pressure bulkhead FWD face intercostals.

4.4.2 Replacement scenario solved

We described before that the second clustering model would include parts and assemblies from the complete aircraft. Resulting we include 41 maintenance jobs and 1 common set-up activity so that that $j = \{1 \dots 41\}$ and $i = \{1\}$. The dynamic programming algorithm is solved in a similar way as the clustering model of Section 4.4.1. For the first two items, we present the calculations and outcomes in **Appendix V.** Here we also present the outcomes of the remaining 39 maintenance jobs that are included in this scenario.

Analysing the results, based on the maintenance jobs in **Appendix IV.** we find that the most cost-efficient solution is given by the following clusters:

Cluster	1	2	3	4	5	6	7	8
Jobs	{M85,M86}	{M69,M75,M76,M77,M78,M79,M80,M81,M82}	{M105,M106,M109,M110,M111,M112,M53,M54,M55,M56,M64,M33}	{M83,M84,M101}	{M63,M65,M67,M68}	{M107,M1,M50,M59}	{M34}	{M113,M4,M61,M62,M2,M57}
Frequency	0,00078	0,004875	0,010985915	0,013888889	0,013888889	0,015294118	0,016666667	0,173333333

Table 8 Clusters Replacement scenario

4.5 Outcomes

In Chapter 4, we have applied the clustering model to two different scenarios in which we derived a cost-efficient composition of clustered maintenance jobs. Before rushing to implement these models, it is important to know, what the performance of each of these models is, and how it relates to the performance of the current situation. We base our comparison of performance on a cost indicator for each of the three scenarios. Additionally we also make a comparison based on the KPI's that we defined in Section 2.5. Based on the results of both scenarios, we make a recommendation for implementation of clustering in the scheduling activities at AIS.

4.5.1 Outcomes Nose Bay scenario

Following from the dynamic programming technique of section 4.4.1, we have already determined that the monthly costs associated with this model are €1593,32. Comparing this with the current clustering method, we see that a small reduction in costs of €215,21 can be achieved by clustering maintenance jobs in the nose-bay each month. This seems as a small amount, but if the clustering method is applied in the long-term, this can yield up to significant numbers. To further compare the two clustering methods, we also asses the performance of this clustering method based on the earlier defined KPI's.

By applying clustering to the Nose Bay Zone scenario it is possible to save 45 hours of set-up time. Instead of 17 individual maintenance tasks, there are only 2 moments at which the jobs are executed. This is more than the 23,4 hours saved in the current situation. On the contrary, the zone-clustering wastes about 28 months of remaining life-time to reach this saving. Since the average life-time of a component in the nose-bay is about 63 months, this is a large number according to the CEO of AIS. Before drawing arbitrary conclusions, we will first assess the performance of our second scenario.

4.5.2 Outcomes replacement scenario

Clustering the replacement activities over the complete aircraft results in a total costs of €5420,- per month. Including these maintenance jobs in the current clustering method, a total of €8279,05 is incurred. Meaning, a reduction of €2859,05 can be achieved each month. This is not only a significant reduction in cost compared to the current situation, but also a larger reduction compared to the zone-clustering scenario that we tested. Our last conclusion is not completely justifiable, since the Nose Bay zone scenario embraces a smaller number of maintenance jobs and hence the two scenarios cannot directly be compared. It can namely be that the total savings over all zones of the aircraft together are larger than the savings in the replacement scenario. The replacement scenario results in a total saving of 99 hours in set-up activities, and an average of 4,8 months of remaining life-time wasted. The average wasted remaining life-time is significantly lower than the Nose Bay scenario together with a larger saving in set-up activities. A comparison of all the performance indicators is given below in **Figure 12 to 14.**

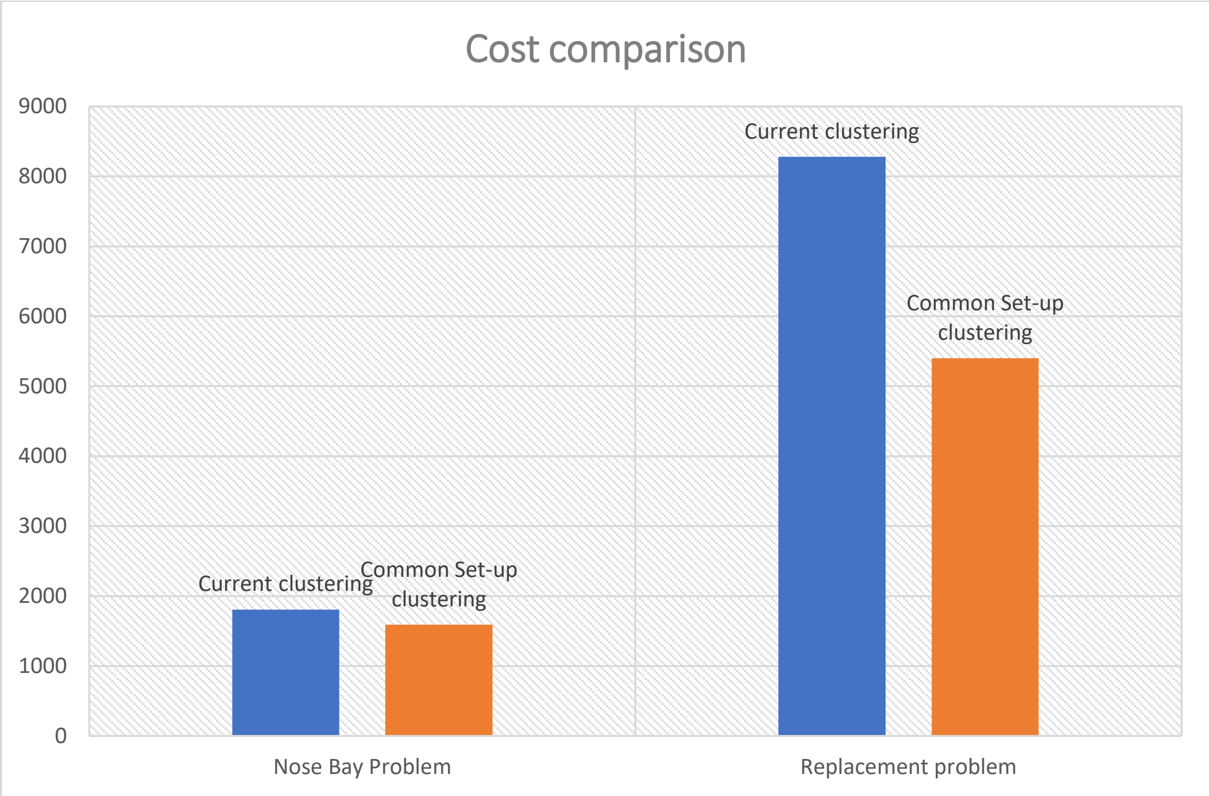

Figure 12 Cost Comparison

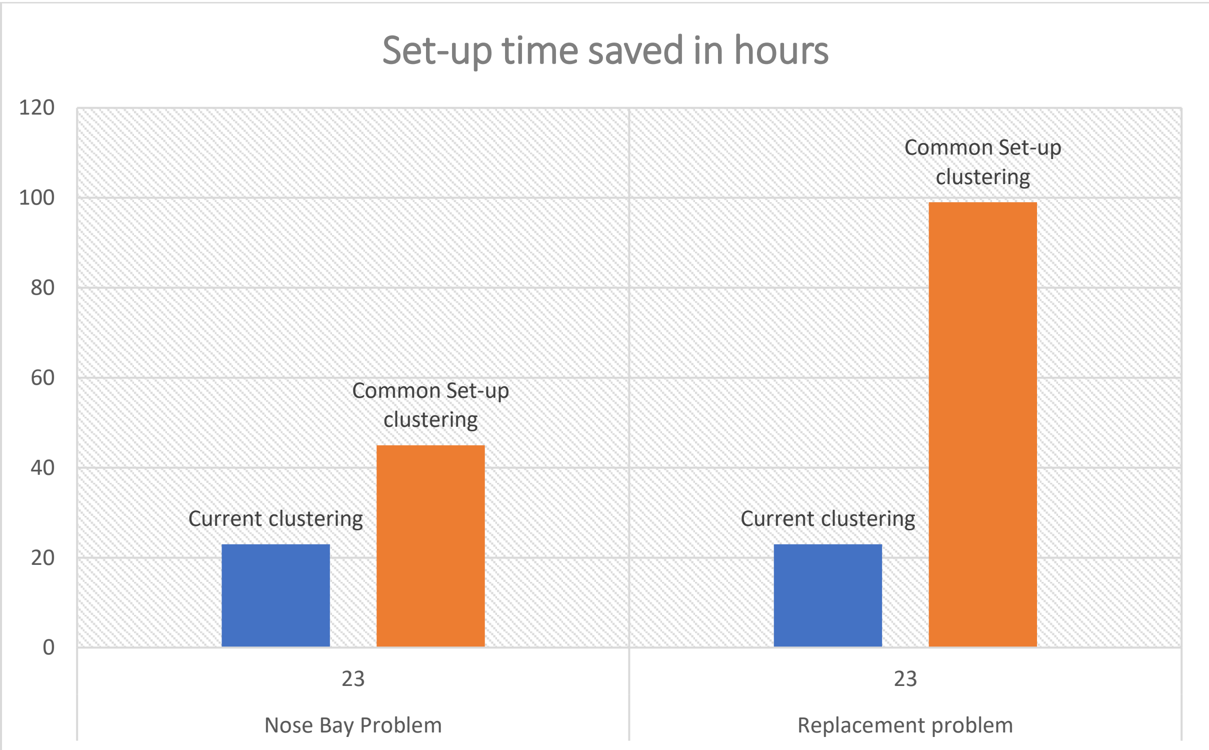

Figure 13 Set-Up time saved

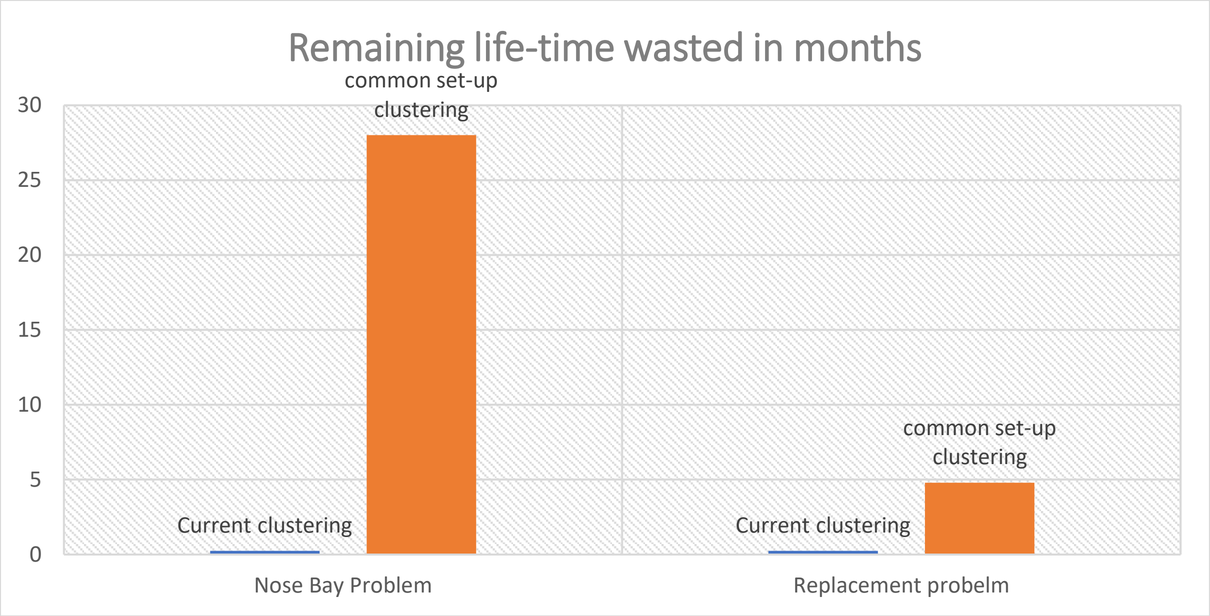

Figure 14 Remaining life-time wasted

Figure 12-14 show us that there is a large difference between the two scenarios. In each performance indicator, the outcomes of the replacement scenario are better. The remaining life-time wasted is a lot lower in the replacement problem than in the nose bay problem. We assume this is caused by the fact that there are less maintenance jobs included in the nose bay problem. As a result of this, the difference in interval between items in a clustering is a lot larger than for the replacement problem. Since more life-time is wasted, and the set-up costs are less often shared it directly implies that the cost savings in that scenario are also lower.

4.6 Implementation plan

In the previous section, we tested the clustering model of van Dijkhuizen et al. (1997) on two different scenarios. We found that the model provides a more cost-efficient situation in both scenarios for AIS. We believe however that there are a number of steps that have to be undertaken before a clustering method can be implemented in the planning process of AIS. Following these steps ensures that the maintenance tasks and set-up activities of the complete aircraft are taken into account.

Step 1: Data collection

As a first step in the implementation plan we recommend to collect the data from the maintenance manual. We discovered that the information is published in a way it is hard to process in a clustering problem. For that, the maintenance jobs and set-up activities for the whole aircraft need to be collected from the maintenance manual and presented in a spreadsheet or similar database. This ensures that the during the development of the clustering model, all required information is easily accessible.

Step 2: Identify shared set-ups

The maintenance manual describes detailed steps that an engineer undertakes when executing the maintenance. The maintenance manual however does not yet distinguish between a set-up activity and a maintenance task. In this first step, we would recommend to create a list of set-up activities that belong to each maintenance task that is prescribed. During the testing of the two scenarios, we already came across a large amount of shared set-ups. We therefore recommend to allow for shared set-ups in the to be developed clustering method.

Step 3: Construct maintenance tree

After all set-up activities have been listed and shared set-ups are identified, the relationship between the maintenance jobs is presented in a maintenance tree. This tree furthermore contains the information with regard to the frequency and costs belonging to each maintenance job.

Step 4: Adjust dynamic programming algorithm
The dynamic programming algorithm that we used previously, does not allow for inclusion of shared set-ups. We believe that with the computers of these days it should be possible to find an exact solution to the clustering problem with shared set-ups by solving the dynamic programming algorithm. In the current algorithm a maintenance job is either individually executed, or jointly within a cluster. It is however not possible to include a maintenance job in a cluster if it does not have all set-up activities in common. In this step another technique can also be used for solving the clustering problem. A Mixed Integer Linear Programming technique was notified to be useful as well. Moreover, Van Dijkhuizen et al. (1997) also describe a heuristic that can be used to solve the clustering model.

Step 5: Solve dynamic programming algorithm
Once all the information is gathered in a maintenance tree and the dynamic programming algorithm is adjusted, it is possible to solve the problem for the complete aircraft. By choosing the most cost-efficient solution from the dynamic programming algorithm, the desired clusters for AIS can be found.

Step 6: Asses performance clustering
Before finalising the implementation step, the performance of the newly designed clustering method should be assessed. It is possible to use the KPI’s that we identified in Chapter 2 for that. We believe that those KPI’s provide the decision maker with enough information to see if the newly developed model is desirable for implementation.

4.7 Conclusion

In Chapter 4, we have tested the clustering model with common set-ups by van Dijkhuizen et al. (1997) in two different scenarios for AIS. We first gave an overview of the different zones of the aircraft. We chose to further investigate the nose-bay and identify the set-up activities of this zone. We formulated the clustering problem of common set-ups and solved this with a dynamic programming technique. We then ended up with a cost-efficient solution for the nose-bay clustering from which we derived the construction of the clusters.

Besides that, we solved the same model for the clustering problem of the whole aircraft, but this time we only included overhauls and replacements. To solve this problem, we used the same dynamic programming technique from the first scenario. The composition of these clusters was different from the clusters of the first scenario. The first scenario placed the NLG down-lock overhaul in the same cluster as the NLG overhaul, Nose Uplock actuator, Steering Jack overhaul and the Steering selector valve overhaul. In the second scenario on the other hand, the NLG down-lock overhaul was included in a cluster with different maintenance jobs.

Concluding, we believe cost-reductions are achieved by the implementation of a clustering model. Applying the method of clustering with commons set-ups yielded improvements for both of our scenarios. Clustering activities from the nose-bay resulted in this case in a cost reduction of little over €213,-. The cluster construction of replacement items yields a large cost-reduction of €2859,05 each month while wasting 4,8 months of remaining life-time. The clustering based on common set-ups results in both scenarios in an increase in wasted remaining life-time. According to the costs KPI, this is however preferable due to the costs-savings incurred. The clustering model based on common set-ups is the best performing model we can deliver during this bachelor assignment to AIS. In addition, we presented how shared set-ups can also be included in the model and how to implement this. We believe that it is essential to include shared set-ups in the model as well since it will lead to even better results for AIS.

5. Conclusion and recommendations

In this chapter, we will present our conclusions and recommendations following from the clustering method we have tested for AIS. By critically analysing our results, we will also present the limitations of our thesis and potential topics for further research.

5.1 Conclusions

The main research question that we aimed at answering with this report is: *How can the maintenance activities of AIS be clustered so that redundancy in set-up activities is reduced?* After our research, we can report the following points:

- By analysing the current situation regarding the scheduling of maintenance jobs, we noticed that there was no adequate clustering model applied. Resulting from this, there was a large redundancy in the execution of the set-up activities. We found that in the current situation, approximately 23 hours of set-up activities was saved.

- By conducting a literature study, we determined the suitability of the various available clustering models. We found that because of its simplicity and accuracy the clustering based on common-set ups had the opportunity of providing AIS with a model that proves cost reductions.

- We worked out the clustering model for two different problems with the support of a dynamic programming algorithm. The first scenario resulted in a monthly cost reduction of approximately 11%. The second scenario included all the overhaul and replacement activities of AIS. Applying the clustering model to this scenario resulted in a monthly cost reduction of approximately 33% compared to the current clustering method. It was found that several maintenance jobs were executed sooner than their prescribed frequency in order to reduce redundancy in set-up activities. This resulted on one hand in the above-mentioned cost-reductions, but also resulted that respectively 28 and 4,8 months of remaining life-time was wasted in both scenarios.

- The clustering method based on common set-ups is not advanced enough to directly be implemented. Therefore, we developed a stepwise plan which allows for the full implementation of clustering in the scheduling activities at AIS. By including shared-set ups the complete maintenance tree is constructed. Solving this with the help of an adjusted dynamic programming algorithm, leads, in our believes, to a more cost efficient situation.

5.2 Recommendations

In this research we have shown that a restricted clustering method can result into cost savings for AIS. We however recommend AIS to improve the clustering method by allowing shared-set ups. For this AIS needs to gather all required information from its maintenance manuals and present it in a tree-format. This way, relationships between maintenance tasks and set-up activities becomes clear. Gathering this information from the maintenance manual turned out to be a large and relatively complicated tasks. Because of this reason we recommend AIS to hire external workforce who will research the maintenance manuals and create the previously mentioned overview.

Another recommendation we would like to make to AIS is related to the execution time of maintenance jobs. While solving the two scenarios we based the estimation of the times for the set-up activities and maintenance inspections on the experience of the ground engineers. More reliable information can be acquired if during the maintenance, the proceedings are accurately measured by an external party.

5.3 Limitations

The first limitation to our clustering model results from the fact that the model we presented works under the assumption of frequency constrained maintenance jobs. Resulting, we assumed that maintenance jobs that have a similar frequency also have common due-dates. Research about this teaches us that in practice this not always is true. Meaning, corrective maintenance executed to parts or assemblies of the aircraft have interrupted synchronized execution of maintenance jobs. Next to that, because of different norms that are used for the life-time (age-replacement vs. usage based replacement) due-dates for maintenance activities have drifted apart. For AIS to make the step towards joint execution of maintenance jobs with common frequencies, we recommend to force the prescribed clusters the moment the individual due-dates are least apart. Meaning, the maintenance job with the latest due-date is executed simultaneously with the prescribed cluster the moment the difference in due-dates with the other jobs is the smallest.

A second restriction from this research comes from the current AIS-Database. Since the list of maintenance jobs is rather long, it is undesirable to keep an eye on the clusters all by hand. To ease the process, the clusters can be included in the current AIS-database. There is however the problem with the current AIS-database that there is no planning module existing. Resulting the planning is made by hand and the clusters have to be included in this planning also by hand. In order to implement the newly designed planning method, the process as described in Appendix VI: Adjustment AIS Database has to be followed.

A last restriction to the clustering method as we have presented it here, relates to the tool that we have used to determine the optimal clusters. It is relatively easy to implement changes in frequencies to the maintenance jobs, but to derive the cluster structure is relatively hard. Determining the optimal construction of the clusters needs to be done manually and changes in frequencies are therefore not automatically taken into account in the composition of the clusters.

5.4 Further research

The research showed that maintenance jobs with similar intervals not always had a similar due-date. We assumed that this happened in most cases because of the execution of corrective maintenance. In next research, we advise to take a closer look at these cases. If there are parts that are repeatedly executed too soon, the intervals of the maintenance part can be adjusted. In other projects, researchers can seek for the patterns in failure data and propose solutions to this.

Where this report describes a static way of clustering the maintenance activity, the literature study showed that potential improvements can also be realized when clustering is done dynamically. This requires a different approach, different data and other scenarios to investigate. The dynamic clustering can be executed in addition to the static method this research presented.

In the problem identification phase, we identified two more problems. We identified that the part management was sub-optimal. In additional research, a spare-part policy can be designed in which the stock levels of critical parts are assessed.

A fourth recommendation for further research would be the inclusion of corrective maintenance in the clustering model. When an aircraft is down for corrective maintenance activities, it can be possible as well to execute preventive maintenance at the same time. This requires the research to different types of models by other researchers.

A last potential for further research is related to the complete structure of the maintenance process. In the current situation almost all maintenance is executed at the maintenance base in Lelystad. This not only incurs high set-up costs of ferry flights back to the base, but also puts a restriction on the amount of aircraft that can be treated simultaneously. In further research the opportunity of (partly) outsourcing of the base maintenance activities to local maintenance providers.

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Appendix I: Parts overview nose bay

Nr	Assembly	Categorie
1	Transceiver-VHF COMM	Communication
2	KIT-ADAPTER	Communication
3	TRAY-MOUNTING	Communication
4	Relay Instal-cockpit voice recorder	Communication
5	Inverters instal AC power	Electrical Power
6	Battery Assy	Electrical Power
7	Battery Temperature Monitor	Electrical Power
8	Battery Instal Nickle Cadmium LH/RH	Electrical Power
9	Battery Instal-NoseBay, LH/RH	Electrical Power
10	Socket External Power	Electrical Power
11	Cable clipping Nose Bay	Electrical Power
12	Earth Terminal	Electrical Power
13	Cables Power distribution	Electrical Power
14	Insulation Nose-Bay RH/LH	Equipment
15	Aileron Drive and Cable LH/RH	Flight controls
16	Switch	Flight controls
17	Fairleads	Hyrdaulics
18	Brake Pipes	Hyrdaulics
19	Hydraulic Pressure indication	Hyrdaulics
20	Windscrean heating	Ice and Rain protection
21	Indication Outside Air temperature	Indicating/Recording systems
22	Switch Flight data recorder	Indicating/Recording systems
23	NLG Door Central	Landing gears
24	NLG Door Side	Landing gears
25	NLG Leg	Landing gears
26	Rod Nosewheel door	Landing gears
27	Lever Door mechanism	Landing gears
28	Mechanism Centre Door	Landing gears
29	Hydraulic NLG	Landing gears
30	Actuating NLG	Landing gears
31	Wheel	Landing gears
32	Tyres	Landing gears
33	Pipe pressure relief valce	Landing gears
34	Hydraulic break equipment	Landing gears
35	Nosewheel Steering	Landing gears
36	Hydraulic noswheel steering	Landing gears
37	Microswitch Landing-Gear position	Landing gears
38	Taxi light	Lights
39	Radio Altimeter Transceiver	Navigation
40	Directional Gyro System	Navigation
41	Vertical Gyro Sperry	Navigation
42	Computer Fligth director	Navigation

43	Aerial Glideslope	Navigation
44	Aerial Marker Beacon	Navigation
45	Diplexer marker	Navigation
46	Aerial DME	Navigation
47	Aerial ILS	Navigation
48	Dual ATC System	Navigation
49	Dual ATC System	Navigation
50	ADF Receiver	Navigation
51	ADF Adapter-Controller	Navigation
52	Transceiver DME	Navigation
53	Receiver Nav	Navigation
54	Equipment tray control unit	Electrical/Electronic panels and multi purpose parts
55	DC Control Box	Electrical/Electronic panels and multi purpose parts
56	Relay box	Electrical/Electronic panels and multi purpose parts
57	Radio Rack	Electrical/Electronic panels and multi purpose parts
58	Radio Junction Box	Electrical/Electronic panels and multi purpose parts
59	Avionics junction panel	Electrical/Electronic panels and multi purpose parts
60	Door Nose Access	Doors
61	Door NLG Bay access	Doors

Appendix II: Maintenance jobs and Set-up activities Nose Bay

M	Set-Up Activity
1	Fly aircraft to Base
2	Lower access panels, F12 and F18 , either side of rear nose landing gear door.
3	Make sure aircraft dc bus-bars are de-energized.
	Display warning notice.
4	De-energize aircraft dc bus-bars
	On avionics circuit breaker roof panel, open and tag 28V dc essential unswitched
	Place a warning notice on avionics circuit breaker roof
	Open access panel F3 and locate VHF 1 (VHF 2 transceiver
	Remove and discard lockwire from two knurled nuts which secure transceiver in mounting tray.
	Loosen two knurled nuts and lower two hinged clamp bolts.
	Using hinged handle provided, carefully pull transceiver to disconnect rear-mounted connector and to disengage guide pins.
	Install blanking caps on electrical connectors on mounting tray and transceiver.
5	Make sure aircraft bus-bars are de-energized.
	Remove access panels F7 and F8 .
	Open access panels F2 and F3 .
6	Open access panels F2 and F3 to gain access to No.1 and No.2 batteries.
7	Remove access panels F7 and F8 .
	Open access panels F2 and F3 .
8	Raise aircraft on jacks
	Open nose landing gear bay forward doors (Ref. Chapter
	Remove blanking cap from gas charging valve, attach inflation adapter , then release gas pressure.
	Using 4 ton (4 tonne) jack , compress sliding tube into upper chamber until gas pressure is released and leg is fully compressed.
	Remove filler plug in nose left top plate and connect hydraulic fluid replenishment rig to fluid charging point.
9	Raise aircraft on jacks (Ref. Chapter 07-10-00, page
	Release hydraulic pressure (Ref. Chapter 29-10-00, page
	Lower access panels, F12 and F18 , either side of rear nose landing gear door.
	Disconnect, open and restrain forward nose landing gear doors (Ref. Chapter 32-30-00, page block 201
	Disconnect rear door operating rod from nose landing gear leg. Restrain door in open position and remove nose landing gear leg ground lock.
	De-energize aircraft dc bus-bars (Ref. Chapter
	Open and tag essential bus-bar circuit breakers GEAR CONT and GEAR POSN IND.
	Place a warning notice on circuit breaker panel stating that circuit breakers must not be closed.
	Make sure taxi lamp switch on roof panel is set to OFF. Disconnect and remove lamp (Ref. Chapter 33-40-10, page
	Disconnect oleo switch from mounting bracket, leaving upper nut undisturbed. Release switch loom conduit from leg and secure conduit clear of leg with no strain on switch cables.
	Remove nose wheels (Ref. Chapter 32-40-11, page block
	Disconnect retraction jack from leg.

	Remove free bearing and split bearing from leg and half bearing from aircraft. Clean in solvent (white spirit) and examine for condition and wear.
	Disconnect door break rod connection.
	Disconnect and remove steering hoses. Cap open ends.
	Disconnect and remove bulkhead unions from right yoke web.
	Disconnect and remove unions from steering jack. Discard O-ring seals.
	Remove follow-up mechanism upper link from aircraft. Note direction of travel and assembly from removed leg.
10	Raise aircraft on jacks (Ref. Chapter 07-10-00
	Open nose landinggear bay doors and secure (Ref.
	Operate release valve to reduce system pressure to zero.
	De-energize aircraft dc bus-bars (Ref. Chapter
	Open and tag28V dc essential bus-bar circuit breaker GEAR POSN IND.
	Remove the microswitch (Ref. Chapter 32-60-05, Page
	Remove nuts, washers and bolts securingmicroswitch and guard to hook. If necessary, disconnect electrical cables and remove microswitch. Identify cables for subsequent connection.
	Disconnect hydraulic pipes from uplock jack. Install blankingcaps to pipe ends.
	Remove universal unions from left side of jack. Discard O-ringseals.
	Remove split pins, nuts, distance tubes and bolts securinguplock unit. Make sure distance tubes between structure sidewalls and uplock side plates do not drop out when bolts are removed. Retain securingitems.
11	Raise aircraft onjacks (Ref. Chapter 07-10-00, page
	Open nose landing gear bay doors and restrain (Ref.
	Disconnect nose landing gear bay rear door operating rod from nose leg.
	Energize aircraft dc bus-bars (Ref. Chapter 24-00-00,
	Set emergency hydraulic selector to NORMAL, select LANDING GEAR selector to UP, operate emergency hydraulic hand pump and raise leg sufficiently to disengage downlock and give access to downlock unit. Restrainleg inthis position
	De-energize aircraft dc bus-bars (Ref. Chapter
	Open and tag 28V dc essential bus-bar circuit breaker GEAR POSN IND.
	Disconnect electrical connectors from microswitch unit. Identify leads for subsequent installation.
	Operate release valve to reduce hydraulic pressure to zero (Ref. Chapter 32-30-00, page block 201
12	Raise aircraft on jacks (Ref. Chapter 07-10-00, page
	Open the two forward Nose LandingGear (NLG doors
	Remove NLG ground lock.
	Make sure the followingessential bus-bar circuit breakers are closed:
	Energize aircraft dc bus-bars (Ref. Chapter 24-00-00,
	Set emergency hydraulic selector to NORMAL.
	Set LANDING GEAR selector to UP and operate emergency hydraulic hand pump to release NLG down lock.
	Release hydraulic system pressure (Ref. Chapter
	De-energize aircraft dc bus-bars (Ref. Chapter
	Open and tagthe followingessential bus-bar circuit forbiddinguse of electrical power.
	Remove and discard lockwire securingbleed screws on steeringjack.
	Position drain container under steeringjack.
	Open bleed screws to release pressure and drain residual hydraulic fluid.

	Identify two flexible hoses connected to S1 and S2 adapters on connection block on steeringjack.
	Disconnect two flexible hoses from S1 and S2 adapters on connection block.
	Install blankingcaps
	Remove split pin, nut, washer, and bolt securing attachment link of follow-up mechanism to pillar of top cap. Discard split pin.
13	Open nose landing gear bay doors (Ref. Chapter
	Raise aircraft on jacks (Ref. Chapter 07-10-00, page
	Open nose bay doors F2 and F3 .
	Disconnect and remove equipment as required to give access to differential mechanism cover. Remove cover.
	Remove nose landing gear ground lock.
	Energize aircraft dc bus-bars (Ref. Chapter 24-00-00,
	Make sure emergency hydraulic selector is set to NORMAL, select LANDING GEAR selector to UP and operate emergency hydraulic hand pump sufficiently to release nose leg down lock and retract leg approximately 10° from vertical. Secure leg in this position.
	Disconnect follow-up mechanism at centre joint.
	Release hydraulic pressure (Ref. Chapter 29-10-00, page
	Disconnect hydraulic pipes from selector.
	Remove half clamp from selector body.
	Remove selector attachment bolts and manoeuvre selector sufficiently to disconnect input drive endless chain.
	Remove selector retaining bolts, washers and slotted nuts for installation of replacement selector.
	If removed selector is not to be installed, remove split pin and disconnect and remove block, complete with upper follow-up toggle link, by extracting pin and barrel.
14	Open nose landing gear bay doors and restrain (Ref.
	Open nose bay doors F2 and F3 .
15	Make sure aircraft dc bus-bars are de-energized.
	Display warning notice.
	Gain access to forward pressure bulkhead through nose landing gear bay doors.
	Inspect intercostals (Ref. Chapter 51-11-00
	Remove warning notice.
16	Make sure aircraft dc bus-bars are de-energized.
	Display warning notice.
	Gain access to forward pressure bulkhead through nose landing gear bay doors.
	Remove warning notice.
17	Make sure aircraft dc bus-bars are de-energized.
	Display warning notice.
	Inspect retraction jack brackets (Ref. Chapter
	Inspect NLG retraction jack upper attachment
	Check torque loading of attachment bolts (Ref. Chapter
	Remove warning notice.

Appendix III: Nose Bay Data

Confidential information

Appendix IV: Replacement Data

Confidential information

Appendix V: Cost functions Dynamic Programming

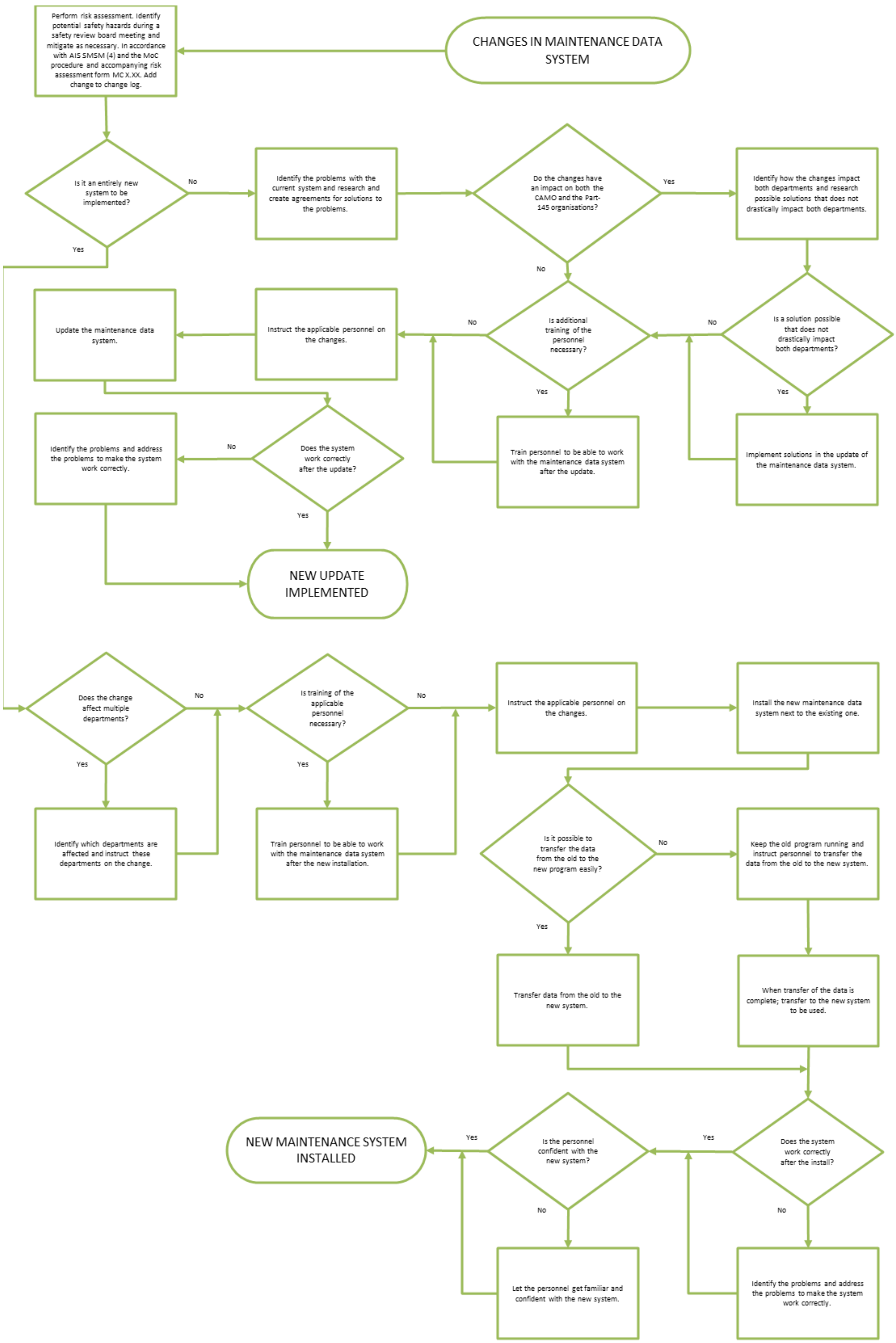
k	F(k)
0	**0**
1	1026
2	1031
3	1036
4	1051
5	1053,5
6	1056
7	1061
8	1066
9	1068,5
10	1369,194
11	1395,931
12	1513,986
13	1572,319
14	1572,528
15	1592,903
16	1593,111
17	1593,319

Figure 15 Outcomes Nose-Bay Clustering

k	F(K)
0	**0**
1	1248
2	1521,867
3	1532,267
4	1537,467
5	1828,667
6	1841,719
7	1886,645
8	2088,385
9	2154,219
10	2252,007
11	2264,507
12	2505,556
13	2534,997
14	2664,997
15	2729,232
16	3223
17	3709,111
18	3765,778
19	4204,356
20	4588,863
21	4613,032
22	4637,201
23	4647,748
24	4658,294
25	4658,458
26	4658,622
27	4667,006
28	4675,39
29	4691,506
30	4705,458
31	4780,046
32	4825,383
33	4870,721
34	4916,058
35	4961,396
36	5006,733
37	5052,071
38	5097,408
39	5103,936
40	5264,616
41	5420,616

Figure 16 Outcomes Aircraft clustering

Appendix VI: Adjustment AIS Database



Appendix VII: VBA-Code dynamic programming

```
Option Explicit

Dim Kosten

Dim k As Integer

Dim i As Integer

Dim j As Integer

Dim clustercost



'sub to solve the dynamic programming problem for the complete aircraft

Sub dynamicprogrammingPartClustering()

Application.ScreenUpdating = False

ThisWorkbook.Sheets("PartClustering").Activate

For k = 1 To 41

    For i = 1 To k

        ThisWorkbook.Sheets("PartClustering").Range(Cells(i + 4, 6), Cells(k + 4, 6)).Select

        clustercost = WorksheetFunction.Sum(Selection) 'Costs for the indicidual maintenance activities
that are included in the cluster

        Kosten = ThisWorkbook.Sheets("PartClustering").Cells(i + 3, 8) +
(ThisWorkbook.Sheets("PartClustering").Cells(i + 4, 5) *
(ThisWorkbook.Sheets("PartClustering").Cells(2, 6) + clustercost))

        ThisWorkbook.Sheets("PartClustering").Cells(k + 4, i + 9) = Kosten

    Next i

Next k

Application.ScreenUpdating = True

End Sub


'sub to solve the dynamic programming problem for the nose-bay

Sub dynamicprogrammingZoneClustering()

Application.ScreenUpdating = False

ThisWorkbook.Sheets("ZoneClustering").Activate

For k = 1 To 17

    For i = 1 To k

        ThisWorkbook.Sheets("ZoneClustering").Range(Cells(i + 4, 7), Cells(k + 4, 7)).Select
```

```
        clustercost = WorksheetFunction.Sum(Selection) 'Costs for the indicidual maintenance activities that are included in the cluster

        Kosten = ThisWorkbook.Sheets("ZoneClustering").Cells(i + 3, 9) + ((ThisWorkbook.Sheets("ZoneClustering").Cells(i + 4, 5) * (ThisWorkbook.Sheets("ZoneClustering").Cells(2, 6) + clustercost)))

        ThisWorkbook.Sheets("ZoneClustering").Cells(k + 4, i + 11) = Kosten

    Next i

Next k

Application.ScreenUpdating = True

End Sub
```