# Work Task Order Optimization in Aircraft Hangar Maintenance: A Constraint-Based Heuristic Programming Approach

MSc. Thesis

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# Work Task Order Optimization in Aircraft Hangar Maintenance: A Constraint-Based Heuristic Programming Approach

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by

J. Hampsink

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Friday October 25, 2019 at 10:00 AM.



| | | |
|---|---|---|
| Student number: | 4269500 | |
| Project duration: | March 8, 2019 – October 25, 2019 | |
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# Preface

The past months have literally flown by. Months in which I have worked with pleasure on my thesis. With my passion for aircraft, the airline industry, and the maintenance behind the former and latter, I therefore proudly present my MSc thesis. A thesis which, some might say, portrays myself: a little stubborn, likely to get off the beaten path, and a no-nonsense mentality.

The pleasure I have had working on my MSc thesis could not have been possible without the great amount of support and guidance, for which I would like to show my gratitude. First of all I would like to thank Wim Verhagen, my thesis supervisor at *Delft University of Technology*. With our bi-weekly meetings, Wim has continuously shared his knowledge on aircraft maintenance. With his critical view I am of the opinion to have been able to augment the quality of my work. Through this way I would also like to wish you all the best in your further career in Melbourne, Australia. I have no doubt this life-changing event will be a tremendous success for you and your family.

From an academic perspective I would also like to express my gratitude towards Bruno Santos. Even though our meetings have not been numerous, his knowledge on optimization techniques has helped me choosing a direction at the start of this work.

Furthermore, I am thankful for the support of my supervisor at *KLM Engineering & Maintenance*, Elgar van Veggel. With his background at *Delft University of Technology* and his experience at *KLM Engineering & Maintenance*, Elgar has always been able to help me in finding the right balance between academia and industry. Also at our bi-weekly meetings I look back as having been enormously fruitful. Furthermore, I would like to thank Anouk Akkermans at *KLM Engineering & Maintenance*. With her position within the Digitizing department, Anouk helped me envisioning the implementation possibilities of this thesis work.

However, I would also like to say a special thanks to two of my direct colleagues at *KLM Engineering & Maintenance*. Shariff Jacob and Jeroen Pool have challenged and guided me throughout my thesis work with their aircraft maintenance knowledge. The pleasure you both bring to work has continuously inspired me. Also to all other colleagues at *KLM Engineering & Maintenance* who have made these past months unforgettable, thank you!

Finally, I would like to give my warmest thanks to my family and friends. Not only have they supported me the past months during this thesis, they have also stood by my side during my studies in Delft. Jasmijn, thank you for being part of my life. Your love and support makes me feel complete. It is fantastic to sometimes hear you say: *"Look there in the sky, an aircraft with 4 engines! What do you think, is that a B747 or A380?"*

*J. Hampsink*
*Delft, October 2019*

# Summary


For an aircraft operator to continue the airworthiness of its fleet, both scheduled and unscheduled maintenance has to be performed. Because the airline is not able to generate any revenue with an aircraft undergoing maintenance, it is of utmost importance for the airline that maintenance is executed efficiently and the aircraft returned to service on-time, whilst reliability is not sacrificed. For most airlines the maintenance is performed by a Maintenance, Repair, and Overhaul (MRO) organization. In the case of KLM Royal Dutch Airlines, the maintenance is executed by its Engineering & Maintenance (E&M) department. Because the current on-time completion performance for some of the scheduled maintenance at KLM E&M has been below par, for example only 33% for the A-check on the Boeing 787, KLM Royal Dutch Airlines demanded improvements. To execute maintenance more efficiently, a possible improvement was seen to lie in revising the order in which maintenance tasks are executed during scheduled aircraft hangar maintenance. Currently, the order is solely based on experience and can therefore not guarantee an optimum. Moreover, insight in the estimated turnaround time or the progress of the maintenance check is limited. This thesis focused on researching whether a model can be produced which improves the order of maintenance tasks both proactively as well as reactively.

Most models which optimize the order of tasks, focus on minimizing the total length of the schedule. Moreover, with an increasing amount of tasks, the amount of possible outcomes becomes infinitely large and the outcome can vary between different runs. The computational performance for these kind of models is often insufficient for practical use. Additionally, the decisions made by such model are difficult to understand. To solve these problems, the taken approach focused not only on minimizing the total length of the schedule, but also on employing a robust, easy-to-understand approach. For minimizing the total length of the schedule, also the possibility for extra work from non-routine maintenance tasks, which can originate from inspection work performed on the aircraft, is taken into account. A robust, easy-to-understand approach, on the other hand, assures that the work task order does not alter significantly when one or more tasks are removed from or added to the set of tasks, by always basing its decisions on the same rules. This resulted in a model produced on the basis of a constraint-based heuristic programming approach.

The main idea of the model is to schedule the maintenance tasks with the highest priority, which is the heuristic in this approach, as early as possible in the maintenance check whilst adhering to a set of constraints. The priority factor is based on elements which try to minimize the overall length of the schedule. For example, maintenance tasks with the highest chance on non-routine work should be performed as early as possible during the scheduled maintenance to assure the total length of the schedule is not elongated during execution. When these kind of elements are not taken into account, a shorter initial schedule could lead to a longer final schedule. The set of constraints assures that there are not more tasks planned in parallel than physically possible. Additionally, a semi-automatized process assures that the model can be run both proactively as well as reactively.

For a case study at KLM E&M on the Boeing 787 A-check, the results of the model show that within 3 minutes a correct work task order can be produced, as was confirmed by experts in the field. Some of the maintenance tasks, however, are differently planned than originally done for the Boeing 787 A-check, which was mostly seen to be due to the fact that humans tend to remember bad memories better. This resulted in maintenance tasks which only few times have caused issues, having been planned at the start of the check. This work task order model is solely data-driven and not based on experience. Moreover, it was proven that the order does not alter significantly when tasks are taken out or added. Furthermore, the model is able to closely predict the actual length of the schedule. In other cases, the actual length of the maintenance check was longer than initially predicted. This validates the reason for the model to not just minimize the initial length of the schedule, as the actual length cannot always be predicted due to unscheduled circumstances such as the aforementioned extra non-routine work.

For KLM E&M the work task order model and its results mean that scheduled hangar maintenance checks can be planned and executed more efficiently and with augmented insight. Before the start of the maintenance check, an initial estimation on the turnaround time indicates whether the tasks can be executed in the allocated time. During the maintenance check, the model provides extra insight in the progress of the check. When unforeseen circumstances occur, such as a change in available manpower or extra unscheduled work, the model provides a new work task order and indicates a newly estimated turnaround time. Additionally, the robust approach of the model allows for a standardization of the maintenance and subsequently an improvement in the turnaround time. Academically, the constraint-based heuristic approach to modelling this problem shows an alternative to the common Mixed Integer Linear Programming (MILP) approaches for the Resource-Constrained Project Scheduling Problem (RCPSP). Moreover, the combination of minimizing the total length of the schedule and using a robust, easy-to-understand approach, by simultaneously taking into account the available resources, provides an original solution to the execution order of maintenance tasks in aircraft hangar maintenance.

Lastly, many recommendation for future work are proposed and largely focus on the improvements before application at KLM E&M. The two most important recommendations for an improvement in the model are seen to be the investigation on the estimated task duration when multiple mechanics work concurrently on the same maintenance tasks and the implementation of an intelligent way of assuring that tasks which are to be executed together for efficiency purposes, are also planned together by the work task order model.

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# Nomenclature

**Abbreviations**

| | |
|---|---|
| AD | Airworthiness Directive |
| AFI | Air France Industries |
| AML | Aircraft Maintenance Licence |
| AOG | Aicraft On Ground |
| ATA | Air Transport Association of America |
| BDP | Bedrijfsdrukte Profiel |
| CAA-NL | Civil Aviation Authorities of the Netherlands |
| CMM | Cabin Maintenance Mechanic |
| CP | Constraint Programming |
| CRS | Certificates of Release to Service |
| E&M | Engineering & Maintenance |
| EASA | European Aviation Safety Agency |
| EO | Engineering Order |
| FAA | Federal Aviation Administration |
| GVI | General Visual Inspection |
| GWK | Grondwerktuigkundige |
| IATA | International Air Transport Association |
| IQR | Interquartile Range |
| JIC | Job Instruction Card |
| JSSP | Job Shop Scheduling Problem |
| KPI | Key Performance Indicator |
| MAM | Maintenance Authorisation Manual |
| MILP | Mixed-Integer Linear Programming |
| MOLP | Multi-Objective Linear Programming |
| MPD | Maintenance Planning Document |
| MRO | Maintenance, Repair, and Overhaul |
| MSG | Maintenance Steering Group |
| MSPSP | Multi-Skill Project Scheduling Problem |
| NP | Nondeterministic Polynomial |
| NR | Non-Routine |
| NRP | Non-Routine Predictor |
| OEM | Original Equipment Manufacturer |
| OMP | Operator's Maintenance Program |
| OOP | Out-Of-Phase Task |
| PSFC | Planning, Scheduling & Fleet Control |
| RCPSP | Recourse-Constrained Project Scheduling Problem |
| SB | Service Bulletin |
| SMW | Sheet Metal Work |
| TAT | Turnaround Time |
| TPSO | Technical Plant Support Officer |

**Symbols**

| | |
|---|---|
| $A_i$ | Job $i$ |
| $b_{ik}$ | Demand of job $i$ of resource $k$ |
| $B_k$ | Availability of resource $k$ |
| $d_i$ | Duration of job $i$ |
| $FF_{ij}$ | Finish-Finish of job $i$ and $j$ |
| $FS_{ij}$ | Finish-Start of job $i$ and $j$ |
| $R_q$ | Set of $q$ renewable resources |
| $S_i$ | Start time of job $i$ |
| $SF_{ij}$ | Start-Finish of job $i$ and $j$ |
| $SS_{ij}$ | Start-Start of job $i$ and $j$ |

# 1 Introduction

With the global aircraft fleet projected to grow from approximately 24,400 in 2017 to almost 38,000 by 2028 [1], it is fair to say the airline industry is rapidly growing. The growth of over 50% in total aircraft also demands the Maintenance, Repair, and Overhaul (MRO) market to follow accordingly. Moreover, according to IATA, 9.5% of the airline's total operating costs can be related to maintenance [2]. MRO service providers therefore need to keep innovating and place a high value on efficiency to be able to keep up with the augmenting demands. IATA [2] describes the trends in aircraft maintenance by, amongst others, focusing on efficiency resulting in optimized on-time performance, digitization of aircraft operations, and common use of big data analytics to support maintenance programs and planning.

One of the largest MRO service providers in the market is the Engineering & Maintenance division of KLM Royal Dutch Airlines. KLM E&M provides the scheduled and unscheduled maintenance for its operator, KLM Royal Dutch Airlines. Together with Air France Industries (AFI), AFI KLM E&M accounted for over 4 billion euros in revenues in 2017 [3]. KLM Royal Dutch Airlines too is expanding its fleet with currently 17 aircraft on order. The lion's share of these orders is on Boeing's showpiece, the 787 Dreamliner [4]. With a fleet reaching 122 aircraft [5] in November 2019, it is of utmost importance for the airline to utilize that fleet effectively and maximize the operating hours. One of the focus points in that is to assure maintenance on the fleet is executed with a high on-time completion performance, while not sacrificing reliability. One of the maintenance checks carried out by KLM E&M is the A-check, which, for the Boeing 787, is carried out every 3 months. The airline has agreed with the MRO to allocate 17.5 hours for the A-check on the Boeing 787. For this specific case, KLM E&M has an on-time completion performance of only 33%, measured from the introduction of the Boeing 787 at KLM Royal Dutch Airlines. This leads to delays in the operator's network.

While previous research has focused on optimizing the match between maintenance task allocation and the available resource capacity, further progress in the on-time completion performance can be sought in the work task order, trying to improve the order in which the maintenance tasks are executed. Currently, the order in which maintenance tasks are executed at KLM E&M in based solely on experience. Moreover, insight in the estimated turnaround time or the progress of the maintenance check is limited. This hinders the possibility to assure the maintenance can be completed on-time while planning the content of the maintenance check, as well as to reactively produce a work task order based on the situation during the maintenance check. This thesis therefore describes a model which improves the work task order by focusing on minimizing the overall length of the schedule, both proactively as well as reactively.

To formally denote the aforementioned description of the model, a research objective is set up. The research objective is formulated as:

*"To improve the work task order for Boeing 787 A-checks, by providing a robust technique that is able to both proactively and reactively support decision-making"*

To aid in achieving the research objective, research questions are formulated. One main research question is provided, followed by several sub-questions, helping in answering the main question:

- How can on-time aircraft hangar maintenance performance be achieved through incorporating work task order improvement?
  - What is the state-of-the-art in work task orders of maintenance tasks?
  - What is the current performance of the A-check on the Boeing 787 at KLM E&M?
  - What is a robust approach for the work task order model?
  - What kind of model can be used to improve the work task order?
  - What kind of constraints have to be incorporated in a work task order model?
  - What is needed to reactively schedule the maintenance tasks during maintenance execution?
  - What is needed to implement the model at KLM E&M?

Lastly, the structure of the report is laid out. The report starts with a review of the literature in Chapter 2. It provides a background on all necessary knowledge and the state-of-the-art of scheduling models. Secondly, Chapter 3 continues on the literature review, yet with an emphasis on KLM E&M. Thereafter, the work task order model is formulated in Chapter 4. In this chapter the model is explained in a global manner, without specifying on the model's possible use during a specific maintenance check. Only in Chapter 5 the model is used on real data from a Boeing 787 A-check. Furthermore, Chapter 6 and 7 provide the verification and validation of the model, respectively. Subsequently, a brief sensitivity analysis is performed in Chapter 8. The conclusions on the research and the answers on the research questions are stated Chapter 9. Finally, Chapter 10 presents several recommendations for further work.

# 2

# Literature Review

A literature review was conducted to get an overview on the state-of-the-art in both aircraft maintenance in general as the sequencing of maintenance work tasks. Section 2.1 introduces aircraft base maintenance and its planning. Hereafter, Section 2.2 examines aircraft zones and systems. Furthermore, several scheduling models are discussed in Section 2.3. Lastly, Section 2.4 provides a discussion on this chapter and shows the literature gap examined.

## 2.1. Aircraft Maintenance & Planning

To better understand the reason behind improving the order in which maintenance tasks are performed, it is important to understand why and by whom aircraft base maintenance is performed, what kind of aircraft maintenance exists, and what kind of tasks specifically maintenance checks consist of.

Firstly, the reason for carrying out aircraft maintenance is discussed by Kinnison and Siddiqui [6] as "the assurance of flight safety, reliability, and airworthiness". The operator of the aircraft has the responsibility of continuing the airworthiness of its fleet by performing maintenance; nonetheless, the operator often delegates the necessary work to a so-called Maintenance, Repair, and Overhaul (MRO) organization. Examples of such MRO organizations are Lufthansa Technik, Delta TechOps, and Air France Industries KLM Engineering & Maintenance.

The maintenance tasks which have to be performed can essentially be divided into scheduled and unscheduled maintenance tasks. The unscheduled tasks, or non-routine tasks, are maintenance tasks which "may result from scheduled maintenance tasks, pilot reports, or unforeseen events such as hard or overweight landings, tail strikes, lightning strikes, or engine overtemperature" [7]. Scheduled maintenance tasks, on the other hand, are nearly all stated in the Maintenance Planning Document (MPD), which is provided by the Original Equipment Manufacturer (OEM). Originally, the OEM would prescribe the maintenance checks for the operator. This resulted in groups of bundled maintenance tasks such as letter checks (A, B, C, and D) [6]. All of these check were listed with an interval of either flying hours, cycles, or calendar days before which the maintenance had to be performed. However, the limited flexibility to the operators invoked a lot of criticism. Thus, since the Maintenance Steering Group-3 (MSG-3) revision 2 the MPD only states the maintenance intervals for the specific maintenance tasks (instead of the grouped maintenance tasks) [8]. Figure 2.1 shows part of the MPD for the Boeing 787 Dreamliner, in which the example maintenance task has a maintenance interval of 6000 flight hours or 18 months, whichever comes first.

Part of the scheduled maintenance which is not stated in the MPD is a result of modification tasks, which can be in the form of airworthiness directives (ADs) or service bulletins (SBs). Airworthiness directives are issued by regulatory authorities (often the FAA) and are mandatory in order to continue the airworthiness of the aircraft. Service bulletins are issued by the OEM and can be(come) mandatory, yet are often advantageous for the operator to carry out. Engineering orders (EOs) are created by the airline/MRO to execute the ADs or SBs. All these scheduled maintenance tasks, including the MPD and non-MPD tasks, are contained in a so-called Operator's Maintenance Program (OMP). With the OMP the operator is responsible for planning the

787 Maintenance Planning Document
*SYSTEMS AND POWERPLANT MAINTENANCE PROGRAM*

| MPD ITEM NUMBER | CAT | TASK | INTERVAL | | ZONE | ACCESS | APPLICABILITY | | MAN-HOURS | TASK DESCRIPTION |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | THRES. | REPEAT | | | APL | ENG | | |
| | | | | | | | | | | ***ATA 12: SERVICING*** |
| 12-010-00 | 8 | LUB | 6000 FH<br>18 MO<br>NOTE | 6000 FH<br>18 MO<br>NOTE | 335<br>336<br>345<br>346 | 335CB<br>335FBX<br>345CB<br>345FBX | ALL | ALL | 1.00 | Lubricate the ELEVATOR HINGE BEARINGS, POWER CONTROL UNIT ROD ENDS, REACTION LINK ROD ENDS<br><br>SPECIAL NOTE: CMR Item 27-CMR-03 interval is 6000 FH.<br>See CMR Document D011Z009-03-03.<br>INTERVAL NOTE: MSG-3 Interval for this item is 6000 FH / 18 MO whichever comes first.<br>See CMR Document D011Z009-03-03 for additional information. |

Figure 2.1: Part of the Maintenance Planning Document of the Boeing 787 [9]

maintenance tasks according to their interval. A popular approach is known as blocking [10], which means that the majority of maintenance tasks are grouped based on a common interval. This approach results in the aforementioned letter checks. However, other approaches have tried to cut the grouped checks into smaller work packages [11], known as equalized maintenance. These smaller work packages are executed during the aircraft's ground time or its overnight stops. The former approach is often preferred by long haul carriers, while the latter is preferred by short-haul carriers [10].

Furthermore, during base maintenance, mechanics with specific licences are needed to assure the airworthiness of the aircraft. These licences are defined by the European Aviation Safety Agency (EASA) in Part 66 [12]. In the Netherlands an Aircraft Maintenance Licence (AML) is issued by the Civil Aviation Authorities of the Netherlands (CAA-NL) [13]. The different licence categories applicable to base maintenance are:

- Category B1
- Category B2
- Category C

A holder of a Category B1 licence is allowed to perform maintenance on "aircraft structure, powerplant, mechanical, and electrical systems and avionic systems requiring simple tests to prove their serviceability and no troubleshooting" [12]. Further, a Category B2 licence is able to perform maintenance on "avionic and electrical systems and electric and avionics tasks within powerplant and mechanical systems requiring only simple test" [12]. Lastly, a mechanic with a Category C licence is allowed "to issue certificates of release to service following base maintenance on aircraft. The privileges apply to the aircraft in its entirety" [12]. A certificate of release (CRS) assures that the aircraft is airworthy. During base maintenance Category B1 and B2 can serve as support staff for mechanical and avionic maintenance tasks. Support staff is defined in [12] as those who "shall ensure that all relevant tasks or inspections have been carried out to the required standard before the Category C certifying staff issues the certificate of release to service".

## 2.2. Aircraft Zones & Systems

In the previous section aircraft maintenance in general has been discussed, providing answers on why and by whom aircraft maintenance is carried out, what kind of maintenance exists, and what kind of maintenance tasks the maintenance checks consist of. However, to dive deeper into the specific maintenance tasks and the scheduling of these during a check, aircraft zones and systems are analyzed. This is important because maintenance task have to be executed on specific locations and systems of the aircraft. Moreover, the execution of some maintenance tasks leads to certain zones not being accessible during execution. The aircraft zones are discussed first, after which the systems are considered.

Aircraft zones were introduced by the Air Transport Association of America (ATA) in 1956 to standardize the division of the aircraft. The zoning of aircraft was specified by the ATA in the ATA-100 specifications. After the year 2000, the ATA-100 was not actively maintained anymore and followed up by the iSpec 2200 specifications [14]. A zone number consist of three numbers: X00 indicates a major zone, XX0 indicates a major sub-zone, while XXX simply indicates a zone. An overview of the 8 major zones is shown below. For example, major zone

300 is the empennage, major sub-zone 320 is the vertical stabilizer and rudder, and zone 321 is the vertical stabilizer leading edge [14]. Furthermore, the zones are represented visually in Figure 2.2. Even though this figure depicts the Boeing 777, the ATA zones are the same for all aircraft.

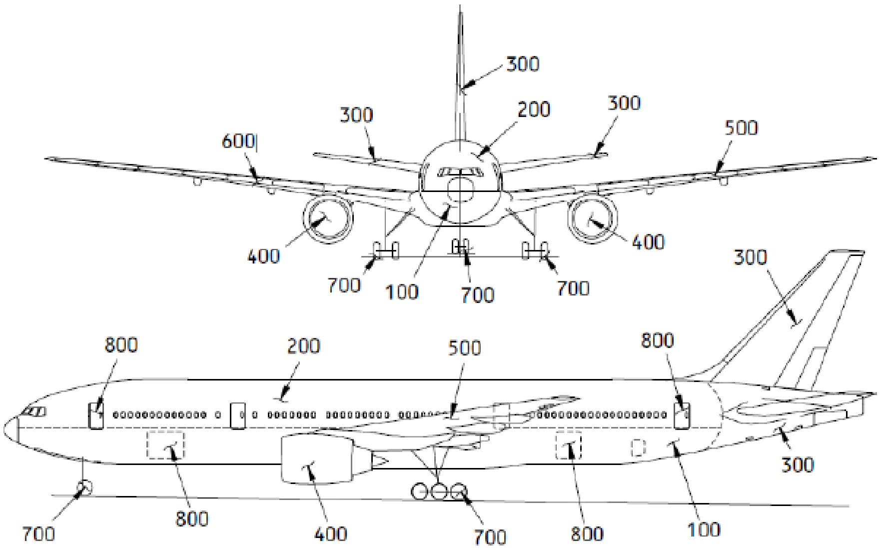


Figure 2.2: Major ATA zones depicted on the Boeing 777 according to the MPD [15]

- Zone 100: Lower Fuselage
- Zone 200: Upper Fuselage
- Zone 300: Empennage
- Zone 400: Power Plants and Pylons
- Zone 500: Left Wing
- Zone 600: Right Wing
- Zone 700: Landing Gear Compartment
- Zone 800: Doors

Further, the aircraft consist of thousands of systems. To easily distinguish which system, subsystem, or unit the maintenance should be performed on, ATA numbering is employed. This ATA numbering system consists of 6 digits (XX-XX-XX). The first two digits indicate the aircraft on system level (chapter), the next two indicate the subsystem (section), and the last two mark the unit (subject). Table 2.1 shows the ATA chapters which are independent of the aircraft type or manufacturer. However, some are seen to not be applicable to the considered aircraft in this thesis. The aircraft zoning together with the ATA numbering clearly pinpoints the locations and the (sub)system the maintenance is to be carried out on.

## 2.3. Scheduling Models

After having discussed aircraft base maintenance in general and more specifically the different zones and systems within an aircraft, this section focuses on the actual scheduling of tasks. To do so, the scheduling models in literature are discussed such that an overview of all methods is presented. Although the discussed models do not necessarily relate to aircraft maintenance, the focus lies on the models which do have a close resemblance with the scheduling of tasks during aircraft maintenance. The first type of scheduling model is the Resource-Constrained Project Scheduling Problem (RCPSP), discussed in section 2.3.1, after which the closely related Job Shop Scheduling Problem (JSSP) is discussed in section 2.3.2. Lastly, the scheduling models in earlier theses are described in section 2.3.3.

### 2.3.1. Resource-Constrained Project Scheduling

The first scheduling model being discussed is the Resource-Constrained Project Scheduling Problem (RCPSP). In the RCPSP a set $A$ of $n$ jobs (A = $\{A_0,\ldots,A_{n+1}\}$) has to be scheduled. Here, $A_0$ is the dummy start job and $A_{n+1}$ the dummy end job. A set $E$ denotes the precedence relations between the set of jobs. That is, $(A_i, A_j) \in$ E means that job $A_i$ has to precede job $A_j$. Moreover, all jobs have a certain starting time, which is denoted by a point in time $S$. $S_i$ is thus the starting time of job $A_i$. These jobs should run until completion once they

Table 2.1: ATA chapters applicable to all aircraft types [14]

| JASC/ATA 100 Code Listing | | | | | |
|---|---|---|---|---|---|
| 11 | Placards and Markings | 34 | Navigation | 64 | Tail Rotor |
| 12 | Servicing | 35 | Oxygen | 65 | Tail Rotor Drive |
| 14 | Hardware | 36 | Pneumatic | 67 | Rotor Flight Control |
| 18 | Helicopter Vibration | 37 | Vacuum | 71 | Powerplant |
| 21 | Air Conditioning | 38 | Water/Waste | 72 | Turbine/Turboprop Engine |
| 22 | Auto Flight | 45 | Central Maintenance System | 73 | Engine Fuel and Control |
| 23 | Communications | 49 | Airborne Auxiliary Power | 74 | Ignition |
| 24 | Electrical Power | 51 | Standard Practices/Structures | 75 | Air |
| 25 | Equipment/Furnishing | 52 | Doors | 76 | Engine Controls |
| 26 | Fire Protection | 53 | Fuselage | 77 | Engine Indicating |
| 27 | Flight Controls | 54 | Nacelles/Pylons | 78 | Engine Exhaust |
| 28 | Fuel | 55 | Stabilizers | 79 | Engine Oil |
| 29 | Hydraulic Power | 56 | Windows | 80 | Starting |
| 30 | Ice and Rain Protection | 57 | Wings | 81 | Turbocharging |
| 31 | Instruments | 61 | Propellers/Propulsors | 82 | Water Injection |
| 32 | Landing Gear | 62 | Main Rotor | 83 | Accessory Gearboxes |
| 33 | Lights | 63 | Main Rotor Drive | 85 | Reciprocating Engine |

are started. More formally: preemption is not allowed. To carry out these jobs, resources are needed. Generally, a set $R$ of $q$ renewable resources (R = $\{R_1,\ldots,R_q\}$) exists, which have a limited availability. $B_k$ denotes the availability of resource $R_k$. The demand of a job is denoted as $b_{ik}$, which indicates the amount of resource job $A_i$ needs from resource $R_k$. The objective of the RCPSP is to schedule the jobs in such a sequence which minimizes or maximizes a certain performance metric, such as the makespan, which is the length of the total schedule [16]. The RCPSP can be mathematically described with the following objective function and constraints:

Objective function:

$$Minimize: S_{n+1} \tag{2.1}$$

Subject to:

$$S_i + d_i \leq S_j \qquad \forall i, j \in E \tag{2.2}$$

$$\sum_{A_i \in A_t} b_{ik} \leq B_k \qquad \forall k \in R \tag{2.3}$$

$$S_0 = 0 \tag{2.4}$$

The objective function in (2.1) minimizes the starting time of the dummy end job $A_{n+1}$. Equation (2.2) denotes that the starting time of job $S_j$ cannot be before the end time of job $S_i$. Here, $d_i$ describes the duration (or processing time) of job $A_i$. Equation (2.3) assures that only the available amount of resource $B_k$ of resource $R_k$ is used at time $t$. The set $A_t$ denotes all jobs that are in process at time t. Lastly, Equation (2.4) constrains the starting time of the dummy start job $A_0$ to be zero (beginning point of the schedule).

For many applications, however, the basic model of the RCPSP is too restrictive. Consequently, many variations on the basic model have been proposed in literature. These variations can be classified into the following categories:

- Constraint and objective variations
- Resource variations
- Processing time variations

Bianco et al. [17] discuss the ability to lift the preemption constraint. They assume that jobs can be interrupted at discrete points in time. The model is then solved with a branch and bound algorithm by adapting a weighted coloring technique. Hartmann [18] describes both a model in which jobs require a varying amount of resources in time and a model in which resource capacities are varying in time. Some test instances were solved with the use of so-called tournament heuristics; however, Hartmann acknowledges that further research seems to be promising with more advanced heuristics. Nonetheless, Hartmann demonstrates the relevance of such a model by a real-world medical research project.

An extension to the model with solely renewable resources is proposed by Słowinski [19]. Here, nonrenewable resources (such as money, fuel, energy, or raw materials) are added to the existing model. The author argues that in reality projects often require both renewable and nonrenewable resources. Moreover, the model also allows for jobs to be paused at certain moments in time (preemption is allowed). The author applies different Multi-Objective Linear Programming (MOLP) methods for solving the model. These multi-objective methods are employed because of the combination of resource types. That is, when the nonrenewable resource concerns a project budget, the objective could be to minimize the use of the budget together with minimizing the makespan of the schedule.

Regarding the duration (or processing times) of jobs, which are known and set in the basic RCPSP, uncertainties can be included in the form of stochastic job times, job success/failure, and dependency on the amount of allocated resources. Choi et al. [20] outline the uncertainties in job processing time, as well as the uncertainties in job success or failure by using a discrete time Markov chain. This is done to capture the correlation among the uncertainties. The problem is then solved with dynamic programming in a heuristically confined state space.

Li and Womer [21] and Stork [22] both model the RCPSP with stochastic job processing times. Li and Womer base their model on large-scale projects which can last for months or even years. In these kind of projects, schedules are often dynamic and of adaptive nature. During a training phase, the stochastic job durations are evaluated with Monte Carlo simulations and a lookup table is constructed. Li and Wormer assume that large computational times during the training phase are acceptable due to the long-term nature of the project. The lookup table, which decides which job to start next, is used during the project every time a job is finished (this is a decision moment). A limitation of this model is that it is not built for projects with a short makespan, where computational time is more important. Stork's work assumes that the duration of a job follows a given probability distribution, which can be constructed on the basis of historical data. Stork combines the stochastic job durations with AND/OR precedence constraints. This means that from a set $X$ of jobs at least one has to be finished before the next job (not from $X$) can be started.

Daniels et al. [23] discuss the possibility to make the processing time of jobs dependent on the amount of resource allocated to the job. For example, when more manpower is allocated to a job, the job can be processed faster. Daniels et al. employ skill matrices which indicate which worker can be assigned to which job. The limitation of this work lies in the fact that this model is focused on flow shops (which will be further explained in Subsection 2.3.2). This means that there is already a particular order in which the jobs have to be executed. Moreover, the processing time of a job can also be dependent on the *mode* in which the job is processed. Hartmann [24] created a genetic algorithm to solve its multi-mode RCPSP. However, the main aim of the work was to improve the average deviation from the optimal makespan with respect to earlier work.

Additionally, it might be the case that a certain resource needs time to be set up between the execution of different jobs. Mika et al. [25] therefore included setup times in their model. In other models, possible setup times have been either neglected or included in the actual processing times. The model of Mika et al. distinguishes setup times to be either dependent or independent of the sequence of jobs. Again, the limitation of this work is that setup times are mostly useful for large-scale project, in which setup times take a considerable amount of time. An easy alternative would be to model the setup times for these kind of projects as a precedence constrained job. In literature the setup times are often referred to as minimal time lags. For example, Demeulemeester and Herroelen [26] integrated time lags between two jobs. However, where the setup time is the time between the end of job $A_i$ and the beginning of job $A_j$, the minimal time lag is extended to be the time between the start-start ($SS_{ij}$), finish-finish ($FF_{ij}$), finish-start ($FS_{ij}$), and start-finish ($SF_{ij}$) relation of job $A_i$ and $A_j$.

Closely related is the idea of release dates and deadlines. Drezet and Billaut [27] describe this extension with a model where every job has such a release date and deadline (or due date). In fact, the jobs have a specific time window in which they have to be executed. Their model also includes the varying amount of resources needed per time unit, as described by Hartmann [18]. Specifically, the jobs need a varying amount of skilled workforce per period of time. The latter touches upon a variation of the classical RCPSP: the Multi-Skill Project Scheduling Problem (MSPSP). Here, an available workforce is assigned to jobs. Each job can require multiple skills simultaneously. A single employee can possess multiple skills, yet can only use one at a time. Li and Womer [28] describe the MSPSP and solve their model by using a hybrid Mixed-Integer Linear Programming (MILP) and Constraint Programming (CP) algorithm. Moreover, they make use of the constraint that the workload of an employee cannot exceed the maximum allowed during the entire makespan. Furthermore, the objective of the model is not to minimize the makespan of the project, but the minimize the total staffing costs. A limitation of the model is the fact that the proficiency of an employee in a certain skill is not taken into account. A certain job might be able to be performed faster by an employee with more proficiency in the needed skill.

A last variation on the general RCPSP is not to generate a predictive baseline schedule, but to make a reactive schedule on the basis of disruptions that occur during the project. Many types of disruptions have been identified in literature: "jobs take longer than primarily expected, resource requirements or availabilities may vary, ready times and due dates may change, new jobs might have to be inserted" [29]. A different option is to schedule proactively, taking into account uncertainties *a priori*. This option has been discussed with the stochastic job processing times. Van de Vonder et al. [29] describe a model where the objective is to reschedule all jobs (including the extra unexpected events) such that the sum of the new finishing times (compared to the old finishing times) is minimized.

It has therefore been shown that a wide variety exists for the RCPSP. A tabular overview is given in Table 2.2. This makes the RCPSP a widely applicable method. However, the RCPSP suffers from the fact that it is NP-hard. This means that the problem cannot be solved deterministically in polynomial time. This is the reason why many papers have discussed different solution techniques, as to optimize the computational time to find a (near) optimal solution.

Table 2.2: Variation categories of the Resource-Constrained Project Scheduling

| Category | Authors |
|---|---|
| **Constraint & objective variations** | |
| Preemptive scheduling | Bianco et al. [17] |
| Rescheduling objective | Van de Vonder et al. [29] |
| **Resource variation** | |
| Varying resource demand | Hartmann [18] |
| Varying resource availability | Hartmann [18] |
| Nonrenewable resources | Słowinski [19] |
| Multi-skill project scheduling | Li and Womer [28] |
| **Processing time variation** | |
| Uncertain processing time | Choi et al. [20] |
| Stochastic processing time | Li and Womer [21], Stork [22] |
| Recourse dependence | Daniels et al. [23] |
| Multiple modes | Hartmann [24] |
| Setup times | Mika et al. [25] |
| Time lag | Demeulemeester and Herroelen [26] |
| Release dates and deadlines | Drezet and Billaut [27] |

### 2.3.2. Job Shop Scheduling Problem

The second scheduling model is the so-called Job Shop Scheduling Problem (JSSP). In fact, the JSSP is a special case of the RCPSP, previously discussed. Correspondingly, the JSSP consists of a set $A$ of $n$ jobs ($A = \{A_0, \ldots, A_{n+1}\}$). However, now the resources are specified to be a set of $m$ different machines. In other words, the JSSP is exactly the RCPSP, yet with all resources capacities $B_k$ being equal to one. As with the RCPSP, the JSSP allows each machine to only process one job at a time. Moreover, some jobs have to be processed before another operation can start. The latter is similarly called a *precedence constraint*. Moreover, once a job is started, it must run until completion (*preemption* not allowed). Again, the objective of the JSSP is to schedule the jobs in such a sequence which minimizes or maximizes a certain performance metric, such as the makespan [30]. Figure 2.3 provides a visual example of a JSSP in which 3 jobs need to be scheduled on 3 different machines. Each job consists of different operations which need to be executed on different machines. These operations cannot be executed during the execution of an operation of the same job. The optimal makespan of the schedule is 11 time units.

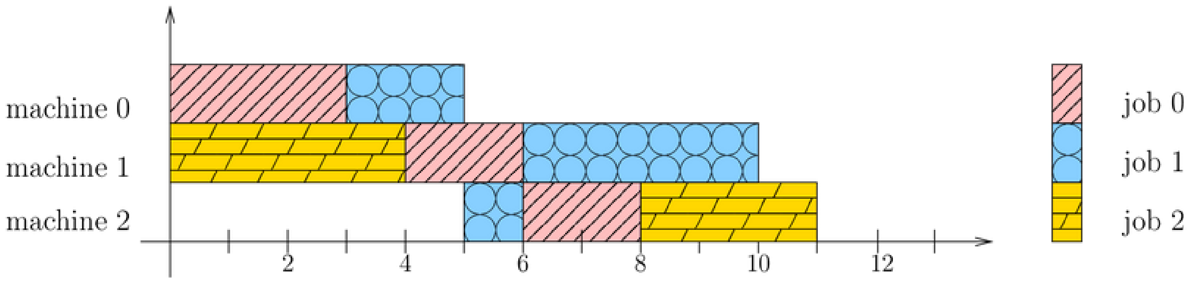


Figure 2.3: Example schedule of the Job Shop Scheduling Problem [31]

Multiple variations of the JSSP exist. In the flow shop problem the amount of jobs is equal to the amount of machines, $m$. Here, the $i$-th job must be processed on the $i$-th machine. The open shop problem is similar to the flow shop problem, yet with the difference that the jobs do not have to be executed in a particular order. Lastly, the multi-processor task scheduling problem addresses the situation where one single job occupies multiple machines at once.

The Job Shop Scheduling Problem was first introduced in literature by Muth and Thompson [32] in 1963. Here, the problem consisted of 10 jobs and 10 machines. It was not until 25 years later that this problem could actually be solved. This is due to the fact that the JSSP too is NP-hard. Most papers in literature therefore discuss different techniques to solving the JSSP. These techniques fall either into the category of *exact methods* or *approximation methods*. Jain and Meeran [33] give a good overview of the techniques used and the researchers involved. Comparing the *exact methods* and the *approximation methods*, the most important limitation to *exact methods* remains the large computation time, whereas the *approximation methods* are limited as they attempt to find a near optimal solution; hence approximating the exact solution. Figure 2.4 provides a detailed overview of the solution techniques of the JSSP [33].

### 2.3.3. Thesis work

With regard to specifically scheduling aircraft maintenance tasks, four previous theses are of interest. All of these have been written at KLM E&M. From a higher level perspective, planning the maintenance tasks before the actual start of a check has been discussed by Coolen [34] and Peschier [35]. The work of Peschier [35] tries to better match the base maintenance tasks (including non-routine tasks and modifications) with the available resource capacity during the maintenance check. Peschier's model takes into account the available maintenance capacity together with the interval of the maintenance tasks. Even though the model is focused on scheduling modification tasks, the author argues that it is also beneficial for out-of-phase (OOP) tasks, which are maintenance tasks that do not fall in any of the standard maintenance blocks. The non-routines are 'planned' with the use of the Non-Routine Predictor (NRP), which is an algorithm developed by KLM E&M. The NRP tries to predict the amount of non-routine work resulting from the routine work planned. The model of Peschier is, however, limited to the Boeing 787 aircraft. Coolen [34], on the other hand, has investigated the option for KLM E&M to minimize base maintenance downtime by modelling a tool which tries to maximize the amount of maintenance tasks planned during in-service ground time (scheduled turnarounds). In

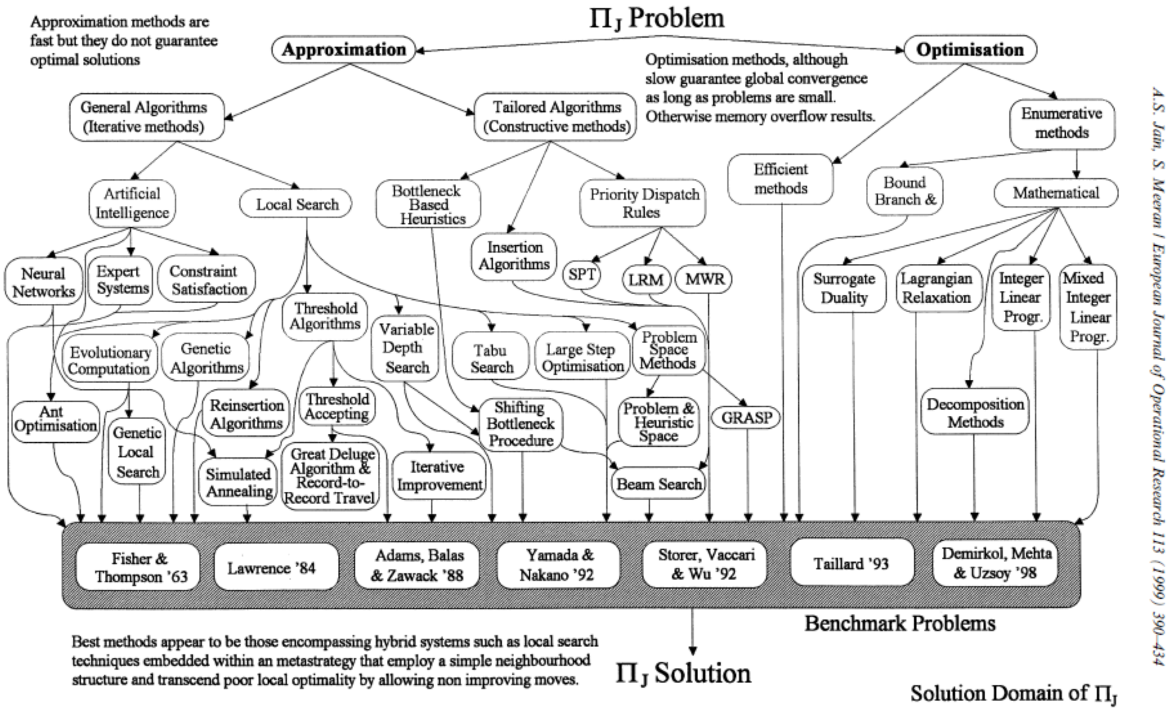


Figure 2.4: Overview of the solution techniques for the JSSP [33]

his model the only considered resource is a skilled workforce. Materials, tool, and equipment were not taken into account. Coolen's solution consists of two different models: the first tries to maximize the amount of work shifted from hangar maintenance to line maintenance, whereas the second tries to schedule this work as close to the due date as possible, taking into account available capacity and the fleet of aircraft. However, the entire tool is limited to the use with the A-checks of the Boeing 777.

The theses by Van den Hoed [15] and Winters [36] are more focused on the sequencing of the maintenance tasks during the actual check. The thesis of Van den Hoed focuses on a task planning model for the C-check of the Boeing 777 aircraft. However, because the amount of maintenance tasks within a C-check is large, Van den Hoed only modeled a work order for the inspection tasks. The author argues that this is the most important phase to stabilize a check, as non-routine tasks mostly follow from the inspection phase. According to Van den Hoed, a C-check could thus be stabilized when the inspection phase is finished in 20% of the total turnaround time (TAT). Furthermore, to find a feasible schedule, a heuristic procedure is employed. The heuristic procedure is based on task complexity, which is defined by six factors: task duration, amount of mechanics needed, task successors, chain length, zone occupancy, and zone blocks. Even though the model is based on the JSSP, it is not programmed as such. This is due to the fact that in the JSSP the machines are not coupled, whilst Van den Hoed implemented aircraft zone dependencies and aircraft zone blocks, thus having coupled 'machines'. Moreover, the model does not include any constraint on the manpower capacity per shift. That is, the model assumes that the manpower needed according to aircraft zone maximums and task specifications is present. This could result in delays when the needed manpower capacity is not present.

The thesis by Winters [36] performed initial research on the work task order during the A-check of the Boeing 787. Winters created a model which groups the individual maintenance tasks by aircraft zone and task type. The used zones are the work areas together with a task type such as 'inspection'. Each of these grouped maintenance tasks is then assigned a TAT and together with precedence constraints a critical path is formed. Through the use of a Gantt chart a visual representation is given of the work task order. With the TAT per zone and the visual representation, the model could be used during operations. Any delay in a specific maintenance zone would then automatically show a possible new critical path. A major limitation of this model is that it is not data-driven and can therefore solely be used for one particular A-check. All input, such as the TAT per aircraft zone, is based on the experience of planners. Moreover, since the maintenance tasks are grouped, it is still up to the mechanics to decide upon the order of specific tasks. Furthermore, the model by Winters does not include any manpower constraints or zone blocks. All grouped maintenance tasks without any precedence constraint would therefore be able to be performed simultaneously. Lastly, any non-routine tasks occurring during the check are not taken into account and also will not be planned during the check.

## 2.4. Discussion & Literature Gap

The scheduling model with the closest resemblance to scheduling maintenance tasks is the RCPSP. That is, the jobs in the RCPSP can be seen as the maintenance tasks and the resources to be aircraft zones and/or mechanics. Minimizing the makespan of the RCPSP can be compared to minimizing the total turnaround time. Many variations on the basic RCPSP are proposed in literature, which have been categorized in either constraint and objective variations, resource variations, or processing time variations. However, the RCPSP suffers from the fact that it is NP-hard. This means that the problem cannot be solved deterministically in polynomial time. For this reason many papers have used different solving techniques to approximate the optimal solution. However, literature lacks when the objective is not to only minimize the overall makespan, rather to also employ a robust approach for proactive and reactive scheduling. Robust in that sense means the work task order should not alter much when one or more tasks are added or removed. Moreover, much of the literature, except for the thesis works, is not focused on application of theory, rather on methodology development. Thus, the RCPSP is seen to be the basis of inspiration for the model to be discussed in this thesis. The main sources of inspiration are the work of Van de Vonder et al. [29], in which rescheduling was discussed, and the work of Li and Womer [28], where the idea of Multi-Skill Project Scheduling Problem was examined.

Summarizing, with the literature discussed and analyzed, the principal contributions of this thesis are noted. These are seen to be the following items:

- Providing a work task order which tries to minimize the overall length of the schedule, whilst taking into account extra unscheduled work;
- Providing a robust work task order technique, meaning that the sequence will not alter significantly when one or more tasks are added or removed;
- Providing a work task order model which is able to both proactively as well as reactively schedule maintenance tasks;
- Providing a work task order model which takes into account available resources in the shape of manpower;
- Providing a work task order model which is applicable in industry, meaning that the computational time is within acceptable limits;

# 3

# Background on KLM E&M

As a major share of this thesis concerns the application of the work in a case study at KLM Engineering & Maintenance, more in-depth information is provided with regard to KLM E&M. As mentioned in Section 2.1, KLM Engineering & Maintenance is a Maintenance, Repair, and Overhaul (MRO) organization where the maintenance of, among others, KLM Royal Dutch Airlines is executed. The organizational structure is shortly explained in Section 3.1, while more specific information on aircraft maintenance and its planning is provided in Section 3.2. Section 3.3 describes the current situation concerning the work task order. Lastly, Section 3.4 provides an overview of the data analysis performed on the Boeing 787 A-check.

## 3.1. Organizational Structure

KLM Engineering & Maintenance is divided into three major units: Airframe, Engine Services, and Component Services. Airframe is the unit providing MRO services to the aircraft in its entirety. A further division within Airframe is made between base maintenance and line maintenance. Base maintenance refers to the maintenance executed in the hangar. Generally base maintenance concerns 'heavy' maintenance and the aircraft is therefore brought into the hangar at predefined intervals for routine maintenance tasks which are bundled into letter checks, such as the A- and C-checks. Within KLM E&M, the A-checks are performed in both Hangar 11 and Hangar 12, while the C-check is executed in Hangar 14. More information on letter checks and their planning is provided in Section 3.2. Line maintenance is generally referred to as minor (scheduled and unscheduled) maintenance and is carried out at the gate or apron. The main purpose of line maintenance is to keep the aircraft serviceable such that it can perform its scheduled flights. Unscheduled maintenance which cannot be executed during line maintenance will be executed during base maintenance.


Figure 3.1: The three different maintenance units within KLM E&M: Airframe, Engine Services, and Component Services

Furthermore, within the unit of Engine Services the engines of both KLM and third parties are maintained. It concerns large gas turbine engines from General Electric: the GEnx, the CF6-80C2, the CF6-80E1, as well as the LEAP-1B and the smaller CFM56-7b from CFM International [37]. Lastly, Component Services assures the availability of serviceable component for KLM and third parties.

The Airframe unit is the core of this thesis work. More specifically, the A-checks executed in Hangar 12 on the Boeing 787 will be used as a case study for the work task order model.

## 3.2. Aircraft Maintenance & Planning

As mentioned in previous section, KLM E&M has been using letter checks to maintain the fleet of its operator KLM Royal Dutch Airlines. This method is known as blocking, which was discussed in Section 2.1. The most common letter checks are the A- and C-check. An A-check consists of maintenance tasks with relatively low intervals (high scheduling frequency), while a C-check consists of tasks with a higher interval (low scheduling frequency). Inasmuch as not all maintenance tasks have the same interval, KLM E&M has defined 24 unique A-blocks and 15 unique C-blocks (e.g. defined as an A06-block or C01-block). This means that a 1A task occurs every A-block, while a 3A task only occurs in the blocks A03, A06, etc. Generally, tasks with an interval smaller than 1A are executed during line maintenance. Furthermore, certain maintenance tasks do not fall in any of the blocks and are therefore referred to as out-of-phase (OOP) tasks. Moreover, the SBs and ADs are also not clustered in the blocks because these are often non-recurrent (or only recurrent for a limited time only). In addition, KLM E&M also carries out B-checks under the name of cabin checks. These originated from the desire to fill the gap between the A- and C-checks with extra cabin work, which is not mandatory to keep the aircraft airworthy, but is performed per request of the operator. That having said, the B-check is not completely optional in terms of airworthiness, because it often contains other tasks to fill up the maintenance check.

In terms of carrying out the maintenance, at KLM E&M the same set of licence categories as defined by the EASA and discussed in Section 2.1 are used. KLM E&M has also defined these licence categories in their Maintenance Authorization Manual (MAM) [13]. Next to the Category B1, B2, and C mechanics, KLM E&M also employs a level system. A level 0 mechanic is not allowed to perform any work, can only assist, and should always be accompanied by a mechanic of at least level 1. A level 1 mechanic is allowed to work independently (except for functional tests), while a level 2 mechanic can perform functional tests and sign-off maintenance tasks. Within Hangar 12 the philosophy is not to train people either as future Category B1 or B2 mechanic, but to have multi-skilled mechanics called M&A. A level 3 mechanic is a licensed Category B1 or B2 mechanic and are called 'grondwerktuigkundige' (GWK). The latter can also have both Category B1 and B2 licenses (called B1B2). A GWK can act as support staff and therefore sign-off tasks performed by others (such as level 1 and level 2 mechanics). The lead-GWK is a Category C mechanic and is responsible for the CRS of the aircraft [13]. Note, however, that signing off a task is not the same as issuing a CRS. The last available skill is the Cabin Maintenance Mechanic (CMM). The mechanic with this skill is specialized in the maintenance within the cabin of the aircraft. A CMM can either be a level 1 or level 2 mechanic. Figure 3.2 shows graphically how the level system works at KLM E&M.

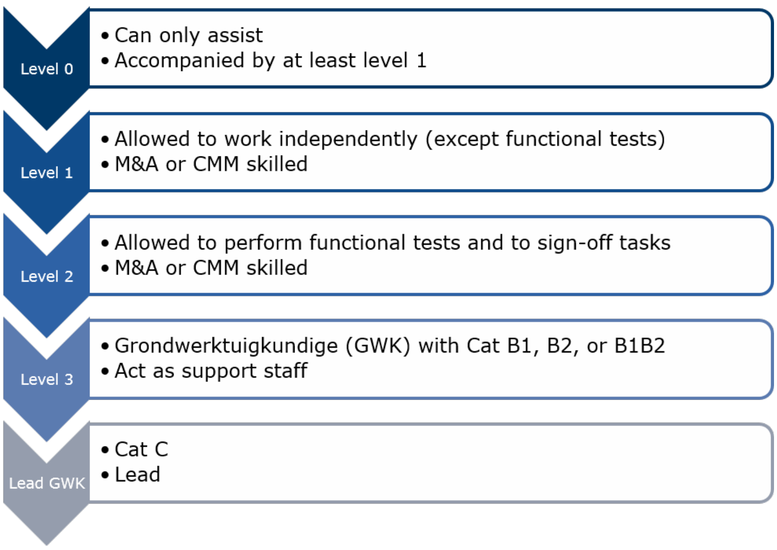


Figure 3.2: Graphical explanation of the level system used at KLM E&M

Lastly, at KLM E&M both the ATA zoning as well as the ATA chapters, as introduced in Section 2.2, are actively used. In Figure 3.3 a Job Instruction Card (JIC) of a Boeing 787 A-check (A04) is shown. From this a lot of information is retrieved, such as the zone and the ATA chapter. The ATA zone is seen to be 411, which denotes the task should be carried out on the left hand engine. Furthermore, the ATA number is 24-21-00, which stands for the electrical power generation and start system. It should be noted, however, that KLM E&M also uses what is called a 'work area'. The major work areas are defined as: langs (longitudinal direction), dwars (cross direction), cabine (cabin). In case of this specific task, the work area is seen to be 'Dwars/LH engine'.

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| KLM<br>Royal Dutch Airlines | TASK DESCRIPTION<br>Inspect (Detailed) the ENG 1 L1 Outboard VFSG Magnetic Chip Collector magnetic probe for metallic deposits. | | | | | | |
| | TRFX9009ZYUN | | | | | | TASK TYPE<br>Detailed Inspection |
| SEQUENCE NO<br>100 | A/C TYPE<br>787 | LINE #<br>657 | EFF #<br>KL011 | TECH (HRS*MEN)<br>00:21 * 1 | CERT<br>00:00 | INSP<br>00:00 | SKILL<br>G_M&A |
| Registration<br>PH-BHN | CHECK NAME<br>A04 | | STATION<br>AMS | WORK AREA<br>Dwars/LH engine | | | CONDITIONS |
| VISIT NUMBER<br>WO - 23573043 | REQUIREMENT / Mxi TASK CARD #<br>2421-0010-01<br>MPDDI-411-4001 | | | PLAN PHASE<br>P04 (Inspection) | | | START SHIFT MILESTONE<br>Fase 2 |
| ETOPS | | | | ETOPS | | | |
| ACCESS PANELS<br>413AL-GE; 414AR-GE; 415AL-GE; 415DB; 416AR-GE | | | | ZONES<br>411 | | | |

Figure 3.3: Example of a maintenance JIC during a Boeing 787 A-check at KLM E&M

An overview of all other work areas is provided below. However, these work areas are hangar specific. The listed work areas are those used in Hangar 12. Differences might apply to other hangars. It should be noted, however, that some of these work areas are in fact no real work areas. Some of these *areas* are more related to the type of work that is involved (such as Langs/Avionics and Langs/Software) or the preferred execution time (Langs/Final).

- Cabin/Section A
- Cabin/Section B/C
- Cabin/Section D
- Cabin/Emergency Equipment
- Cabin/Galleys
- Cabin/General
- Cabin/Lavatories
- Cabin/Seats C-Class
- Cabin/Seats M-Class
- Cabin/Water Disinfect
- Dwars/LH Engine
- Dwars/LH Main Gear
- Dwars/LH Wing
- Dwars/LH & RH Wings
- Dwars/Nose Landing Gear
- Dwars/RH Engine
- Dwars/RH Main Gear
- Dwars/RH Wing
- Langs/Admin
- Langs/AFT Cargo
- Langs/APU
- Langs/Avionics
- Langs/Cargo Doors
- Langs/Cockpit
- Langs/Final
- Langs/FWD & AFT Cargo
- Langs/FWD Cargo
- Langs/Lower Fuselage
- Langs/Pax Entry Doors
- Langs/Preliminary
- Langs/SMW
- Langs/Software
- Langs/Tail
- Langs/Tests

## 3.3. Current Work Task Order

To stress the necessity of improving the work task order, the current situation is clarified. Considering that the thesis work concerns a case study on the Boeing 787 A-check, which is performed in Chapter 5, the emphasis is put on the current way of working during this particular maintenance check.

The current work task order used during the Boeing 787 A-check is made by the Technical Plant Support Officer (TPSO) before the start of every check. This is done manually. The work task order of the A-check is divided into 3 shifts. This is because KLM has agreed with its Engineering & Maintenance division that the A-check should be executed within 17.5 hours. All shifts are then further divided into 3 phases to roughly indicate where in the shift the specific maintenance is to be carried out. Every maintenance task (or group of maintenance tasks) is assigned a phase, together with a work area and the needed skills. The complete workflow is printed such that the mechanics can refer to the work task order at any moment during the A-check. Figure 3.4 shows part of the current work task order planning in use in Hangar 12.

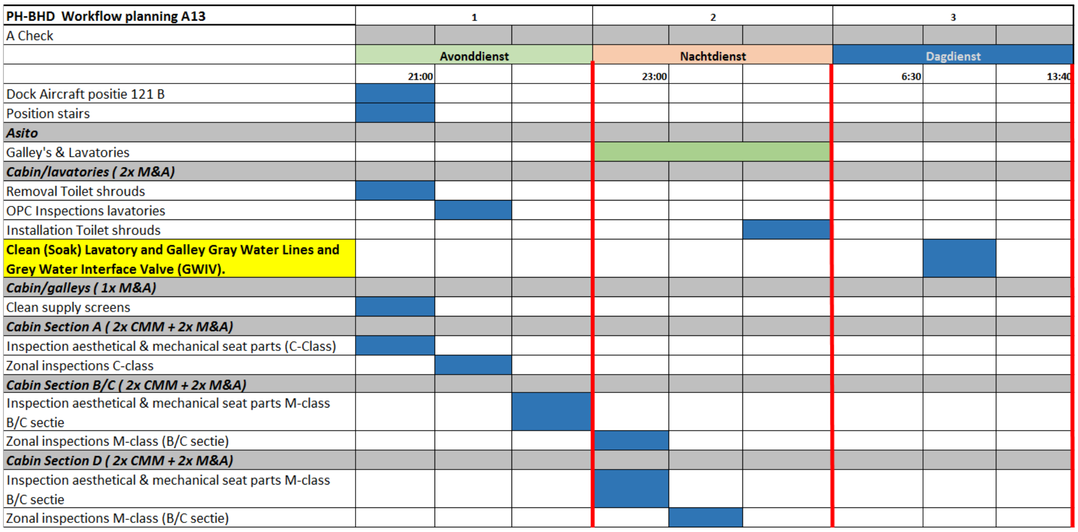


Figure 3.4: Example work task order used during the Boeing 787 A-check

However, the current way of working presents several drawbacks, which are acted upon in this thesis work. Firstly, the current work task order can only be made by one person, the TPSO. It is therefore dependent on the presence and experience of this one person. If the TPSO is not present, no work task order will be available to the mechanics during the Boeing 787 A-check. In addition, the sequence in which the maintenance tasks are placed within the work task order is based on experience and is thus subjective. The latter indicates that an optimal work task order cannot be guaranteed. The work task order model discussed in this thesis should thus be automatized enough such that it can be used by a larger group of people. Furthermore, the work task order model should not base its decision on experience, rather on (historic) data.

Secondly, the fact that this work task order is made manually, suggests that this is a laborious task. According to the TPSO it currently takes between 20 to 30 minutes to make a new workflow planning, depending on the amount of extra maintenance work on top of the standard A-blocks. An improved work task order should therefore be able to be computed quicker. In Section 4.1 a specific norm on this computational performance is set.

Another drawback of the current situation is the fact that the work task order is only available as a static, printed version. Firstly, no estimation on the turnaround time can be provided. Additionally, the work task order will not change during the execution of the A-check. Moreover, when a certain maintenance task is not carried out during the phase it should have, no change in the order will be visible. This can lead to maintenance tasks being forgotten when another shift assumes the task had already been executed. Luckily, a lead mechanic can only issue a CRS when all tasks have been executed, yet this means that a forgotten tasks might have to be executed all the way at the end of the maintenance check, potentially leading to even more work. The work task order model discussed in further chapters can therefore improve the current situation by assuring the model can both proactively schedule the maintenance tasks (before the start of the maintenance), as well as reactively (during the execution of the maintenance). In this way the level of insight is augmented at all stages of the maintenance check.

Lastly, the work task order does not take into account the actual amount of available manpower during each shift. Some maintenance could thus potentially not be executed simultaneously due to fewer mechanics than expected, or more maintenance could potentially be executed simultaneously when more manpower than expected is available. It is readily clear that the available manpower should be taken into account in an improved work task order model.

## 3.4. Data Analysis Boeing 787 A-check

Next to the clarification in previous section concerning the current work task order situation, this section analyzes the performance of the Boeing 787 A-check to better understand some of the decisions made while constructing the work task order model.

The data considered for this analysis ranges from the introduction of the Boeing 787 at KLM (November 2015) up to and including April 2019. Several A-checks were left out of the analysis, which was due to the fact that these were not *clean*. An A-check not being clean could e.g. be due to a cabin check (B-check) having been executed at the same time.

Firstly, the on-time completion performance of the A-check is discussed. As previously discussed in Section 3.3, the norm to perform a Boeing 787 A-check in is 17.5 hours. Figure 3.5 shows that only 33% of the A-checks were performed within the aforementioned norm. Next to the norm on the length of the maintenance check, KLM E&M also makes use of a norm on the amount of scheduled manhours in a maintenance check. These manhours indicate the total amount of hours to be worked by the available workforce and should not be exceeded during the planning stage. KLM E&M has set this norm on xxx manhours for the Boeing 787 A-check. However, when Figure 3.6 is inspected, it can be observed that the amount of manhours within a Boeing 787 A-check is scattered (and often exceeded) and that there is no clear relation between the manhours and the length of the maintenance check (turnaround time), while a linear trend was expected. Because of this high variance in both scheduled manhours and turnaround time, one could wonder whether a norm on the amount of scheduled manhours should be the only planning variable to assure an on-time performance of a maintenance check.

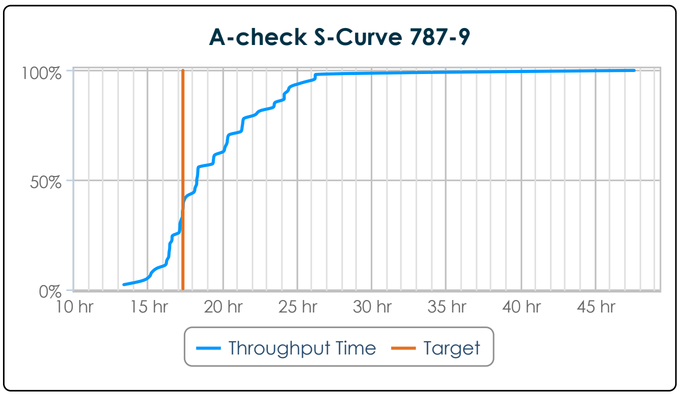


Figure 3.5: Current performance of the Boeing 787 A-check, adapted from KLM

Furthermore, next to the scheduled manhours also a calculated amount of unscheduled work is taken into account. When planning a Boeing 787 A-check, 30% of non-routine (unscheduled) work is taken into account on top of the scheduled work. That is, if 100 routine hours are scheduled, 30 non-routine hours will be added in the planning. By means of Figure 3.7, the actual percentage of non-routine work is depicted per Boeing 787 A-check to check whether the 30% factor is realistic. Overall, the average non-routine factor is seen to be 26%. However, when only the later checks are taken into consideration, the average non-routine factor is exactly

30%. This increasing trend is the reason why KLM E&M started the development of a so-called Non-Routine Predictor (NRP). This tool is supposed to be able to predict the amount of non-routine work based on the specific scheduled work. Anyhow, it is shown that the unscheduled work represents a considerable share of the total work and should therefore definitely be taken into account by the work task order model.

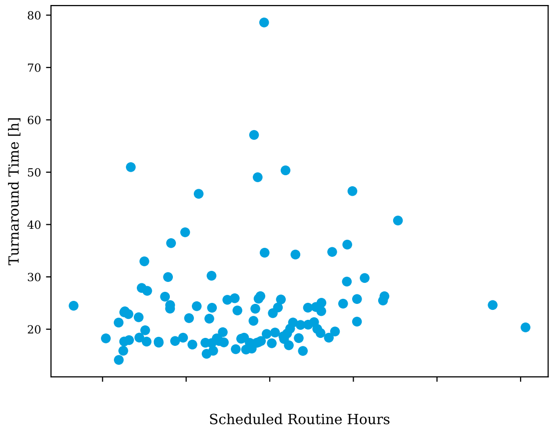


Figure 3.6: Relation of the turnaround time with the scheduled routine hours

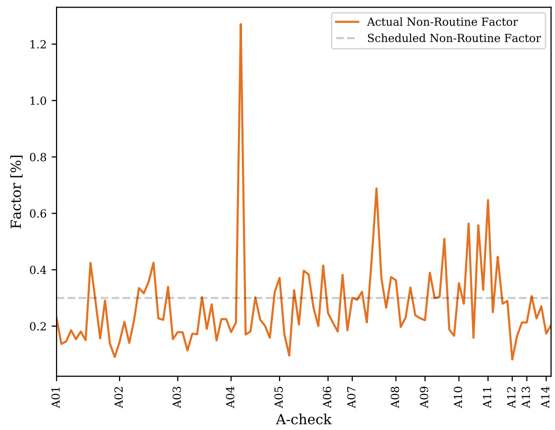


Figure 3.7: Amount of non-routine [%] per check with respect to the routine work

However, it is also of interest to dive deeper into the unscheduled work and analyze whether certain tasks generally generate more unscheduled work than others. For this analysis, tasks are bundled by their respective ATA chapter. From Figure 3.8 is is readily clear that ATA chapter 25, which is the equipment and furnishing chapter, resulted by far in the most non-routine tasks. Within ATA chapter 25, Figure 3.9 discloses that ATA subchapter 25 resulted in the most non-routine tasks. The ATA 25-25-xx is the 'passenger compartment seats' subchapter. This analysis indeed stresses the necessity to not only take non-routine work into account, but to also put more emphasis on those tasks actually generating the most non-routine tasks.

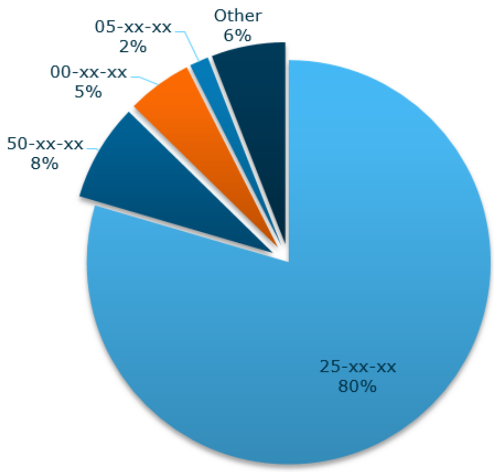


Figure 3.8: Percentage of non-routine findings per ATA chapter

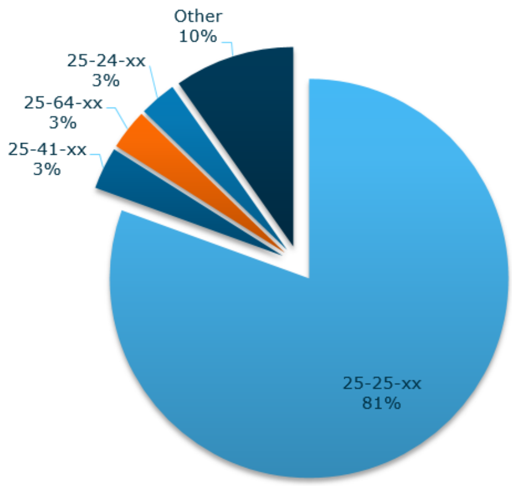


Figure 3.9: Percentage of non-routine findings in ATA 25-xx-xx per subchapter

Lastly, the severity or weight of the non-routine tasks are investigated. That is, the latter analysis only focused on the *amount* of non-routine tasks generated by specific routine tasks. It may, however, be the case that certain scheduled tasks do not often result in unscheduled work, but when it does, many manhours are taken up. Therefore, the ATA chapters are also ranked by their relative non-routine hours. Equation 3.1 explains how these relative hours are computed.

$$\text{Relative Non-Routine Hours} = \frac{\text{Total Non-Routine Hours}}{\text{\# of Occurrences}} \tag{3.1}$$

Figure 3.10 indicates that actually ATA chapter 73, which is the ’engine fuel and control’ chapter, has the highest amount of relative non-routine hours. This means that if a non-routine is found in chapter 73, this will generally result in a high amount of manhours. Furthermore, ATA chapter 25 is seen to be ranked much lower now, indicating that even though there is a high amount of non-routine tasks, these do generally not result in many non-routine manhours. Concluding, the work task order model should not only take into account the chance of a non-routine task occurring, but also the severity of this possible occurrence.

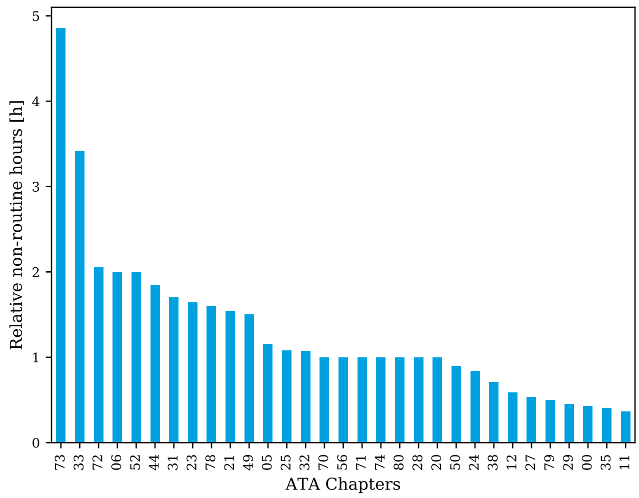


Figure 3.10: Relative non-routine hours computed according to Equation 3.1

With a background on the current situation concerning the work task order at KLM E&M, more specifically at Hangar 12, and an increased insight in the current performance of the Boeing 787 A-check through a data analysis, the next step is to formulate a model which is able meet the current needs at KLM E&M.

# 4 Model Formulation

After having reviewed both the theoretical and industry context, in Chapter 2 and 3 respectively, the actual work task order model is laid out here. The model is presented in such a way that it is applicable to all hangar maintenance checks within KLM E&M. Only in subsequent chapters will the A-check be used as a case study for the work task order model. Firstly, Section 4.1 discusses the objectives of the model. Then, in Sections 4.2 and 4.3 the principles of heuristics and constraints are explained, respectively. Finally, the model is further specified by graphical examples in Section 4.4. The chapter is shortly concluded in Section 4.5 by stating the hardware and software environment, which can be further connected to the computational time in Section 5.3.

## 4.1. Model Objective

With regard to aircraft hangar maintenance, an often heard objective is to minimize the turnaround time of the maintenance check. While this is indeed important to assure the operator can utilize its fleet most effectively, other objectives and considerations are often left out.

When the objective is solely to minimize the turnaround time of the maintenance check, a Mixed-Integer Linear Programming (MILP) model could be one way to tackle the problem. However, as noticed in Section 2.3, many of these problems, such as the RCPSP, are NP-hard. NP-hard stands for non-deterministic polynomial hard, which means the problem cannot be solved deterministically in polynomial time. Koné et al. [38] compared different MILP techniques for the RCPSP. For a data set with only 30 tasks, the computational time ranged from just under 1 minute, to nearly 7 minutes, depending on the used model. Even then, not in all cases an optimum was found. Considering most of the maintenance checks contain much more tasks than the aforementioned example, the reason for opting out of the MILP is hereby validated.

Furthermore, a work task order which is solely based on minimizing the turnaround time of routine maintenance tasks does not take into account the possible extra work due to the non-routine maintenance tasks. Non-routine maintenance tasks thus have to be taken into account in some way when modelling the work task order to assure non-routine maintenance tasks disturb the total turnaround time as little as possible.

Another important objective next to the minimization of the turnaround time is to employ a robust technique. A robust model sequences the maintenance tasks such that the order does not alter significantly when one or more task are added or removed. The first reason for this being of importance is the fact that completely altered sequences of nearly similar maintenance checks could confuse the mechanics. Moreover, MĺIkva et al. [39] notice that the baseline for continuous improvement is standardized work. Secondly, when the model is used during the maintenance check to reactively sequence the maintenance tasks, the order should also not alter drastically. Again, a MILP approach was opted out for because this could lead to solutions which contain similar expected turnaround times, but completely different orders of the maintenance tasks. Additionally, a robust approach always bases its decision on the same set of rules, which makes the result of the model easier to understand and more accessible.

As shortly mentioned before, the model should also be able to schedule the maintenance tasks both proactively as well as reactively, meaning that a work task order should be available at the start of the maintenance check, but should also be capable of altering the work task order while the maintenance is executed and changes occur. The latter ranges from replanning unfinished tasks to replanning when the available manpower alters.

The last objective is to produce a model which is applicable in industry. That is, for a relatively short maintenance check the computational time should be low in order for it to be practically used. It was decided that the computational time should be 0.5% or less of the agreed turnaround time. For this reason the model was opted to be deterministic and not stochastic. No exact numbers can be provided; however, it is readily clear that the computational time of a stochastic model is higher than that of a deterministic model.

Providing all of the above, a model was created with a constraint-based heuristic programming approach, which is able to sequence the maintenance tasks such that the tasks with the highest *priority* are scheduled prior to those with a lower *priority*. Furthermore, a set of constraints is applicable to all concurrent tasks. The priority factors, which is the heuristic in the model, are further explained in Section 4.2. The set of constraints is clarified in Section 4.3.

## 4.2. Heuristics

The work task order model makes use of heuristics. This approach was chosen because finding an optimal solution is nearly impossible with these kind of problems. Therefore, heuristics can speed up the process by finding a solution which is close to the optimum. In this work task order model the heuristics are called *priority factors*. All maintenance tasks receive a priority factor such that the model can opt which task to sequence earlier than the other. The final priority factor is computed based on the addition of four different elements:

1. Duration of the maintenance task [hours]
2. Total duration of all successive tasks in chain [hours]
3. Chance of non-routine task resulting from routine task [%]
4. Manhours of possible non-routine task [hours]

The reason for specifically choosing these four elements is based on the fact that these are all related to the turnaround time (TAT) of the maintenance check. During the process of modelling, also other elements such as: the amount of mechanics needed for a maintenance task, number of tasks in a chain, etc were considered. However, it was deemed that these did not have a direct relation to minimizing the overall turnaround time of the maintenance check and were therefore not used.

The first element is simply the amount of time it takes for the maintenance task to be finished. This duration is provided by the Engineering department of KLM E&M. The longer the duration, the earlier a task should be executed in the maintenance check. Element (2) is the addition of the duration of all successive tasks of maintenance task *i*. That is, some tasks can only be executed after the completion of another task. This forms a chain. The longer the chain, the earlier the tasks in this chain should be executed during the maintenance check. Element (3) is the chance a non-routine task results from a routine task. These routine tasks are generally inspections and the chance is computed based on historical data. A routine task can only have a valid chance on a non-routine task when the routine task has been executed at least ten times before. A routine task with a high chance on a non-routine task should be executed as early as possible in the maintenance check to assure all the *unknown* work is *known* rather sooner than later. The last element denotes the severity or weight of the possible non-routine task, expressed in the amount of manhours. Specifically, a routine task can have a high chance on a non-routine task, yet when this non-routine task only takes 1 mechanic 5 minutes (i.e. $5/60 = 0.083$ manhours), it might be deemed less important than a non-routine task with a lower chance of occurring, but with a higher amount of manhours. Element (3) and (4) together can be seen as the *risk* of a non-routine tasks. The reason for not combining both into one *risk* element is the fact that such a *risk* element would be low for a routine maintenance task with for example a high chance on generating a non-routine task, but a low *weight* in terms of non-routine manhours, thus cancelling each other out. To capture the importance of both, elements (3) and (4) are taken into account separately.

These four elements were all chosen with the aforementioned objective, to minimize the turnaround time, in mind. Elements (1), (2), and (4) were first normalized (also called unity-based normalization) with the use of Equation 4.1. Here, $X_{min}$ is the minimum in the list of to-be normalized numbers (per element), while $X_{max}$ is the maximum. $X$ is the non-normalized number. With all elements having a *score* between 0 and 1, the scores could be added to give the maintenance task its final priority factor. With an equal weighting adding up to 1 (i.e. 0.25 per element), the maximum score could thus be 1.

$$X' = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{4.1}$$

## 4.3. Constraints

Ideally, all maintenance tasks are executed right at the start of the maintenance check. However, due to several reasons this is not possible. For this, a set of constraints is set up. These constraints apply to all concurrent tasks, i.e. all maintenance tasks being executed at the same time step *t*. The following constraints apply to the work task order model:

1. Dependent maintenance tasks cannot be executed simultaneously
2. Maintenance tasks with conflicting aircraft zones cannot be executed simultaneously
3. Per aircraft zone a maximum amount of mechanics can work simultaneously
4. Power-off tasks can only be executed during breaks of at least 30 minutes, power-on tasks can never be executed during breaks
5. The amount of simultaneous tasks is dependent on the amount of available mechanics with a specific skill

### Constraint (1)

Constraint (1) is closely related to heuristic (2). That is, certain tasks can only be executed when all of the preceding tasks have been finished. A simple example is that certain tasks on the engine can only be executed when the fan cowling has been opened. Thus, opening the fan cowling and executing the engine task simultaneously is not possible. Another seemingly logical example is that removing the beverage makers from the galleys should be performed before the beverage makers are reinstalled in the galleys.

### Constraint (2)

Constraint (2) prevents maintenance tasks with conflicting aircraft zones to be executed simultaneously. For example, the slats on the wing cannot be extended while the fan cowling is opened (this is physically not possible). Considering that the flaps cannot be extended without the extension of the slats, it is assumed that tasks on the wing cannot be executed when tasks on the engine are executed (and vice versa).

### Constraint (3)

Constraint (3) denotes the maximum amount of mechanics that can physically work simultaneously in a certain work area. For this, the work areas as explained in Section 3.2 are employed. As mentioned in Section 3.2, some work areas do not denote an actual area. The non-physical work areas, such as *Langs/Tests*, do not denote the maximum amount of mechanics that can physically work simultaneously; rather, it denotes the amount of mechanics performing similar work simultaneously. For this research, however, the work areas are used as is and are not altered. The maxima are set up in consultation with mechanics within KLM E&M and are visible in Table 4.1. The administrative tasks and sheet metal work (SMW) zones are left out, as it was later assumed that these are either not executed at a set moment in time or not executed by the available workforce (but by a specialist team). Moreover, even though these values are set up in consultation with mechanics, these are still subjective, yet for this model assumed to be correct.

Table 4.1: Maximum amount of mechanics allowed per work area

| Work Area | Max | Work Area | Max | Mechanics | Max |
|---|---|---|---|---|---|
| Cabin/Section A | 2 | Dwars/LH Wing | 4 | Langs/FWD & AFT Cargo | 2 |
| Cabin/Section B/C | 6 | Dwars/LH& RH Wings | 6 | Langs/FWD Cargo | 2 |
| Cabin/Section D | 6 | Dwars/Nose Landing Gear | 2 | Langs/Lower Fuselage | 8 |
| Cabin/Emergency Equipment | 4 | Dwars/RH Engine | 2 | Langs/Pax Entry Doors | 4 |
| Cabin/Galleys | 6 | Dwars/RH Main Gear | 2 | Langs/Preliminary | 15 |
| Cabin/General | 4 | Dwars/RH Wing | 4 | Langs/Software | 1 |
| Cabin/Lavatories | 6 | Langs/AFT Cargo | 2 | Langs/Tail | 2 |
| Cabin/Seats C-Class | 2 | Langs/APU | 2 | Langs/Test | 5 |
| Cabin/Seats M-Class | 6 | Langs/Avionics | 5 | | |
| Cabin/Water Disinfect | 6 | Langs/Cargo Doors | 2 | | |
| Dwars/LH Engine | 2 | Langs/Cockpit | 2 | | |
| Dwars/LH Main Gear | 2 | Langs/Final | 15 | | |

## Constraint (4)

Next, constraint (4) explains that generally no maintenance tasks can be executed during the breaks. There are two kinds of breaks, 15- and 30-minute breaks. During 15-minute breaks, no maintenance tasks can be executed. During the longer 30-minute break, only maintenance tasks which require the power on the aircraft to be turned off can be executed. This is due to the fact that when the power on the aircraft is off, other maintenance tasks requiring power cannot be executed. For this reason, the moment during which these power-off tasks disrupt the maintenance flow least, is during breaks. Moreover, the mechanics working on the power-off tasks during the break, will be given a break once the power-off task(s) is/are finished. The latter is related to constraint (5).

## Constraint (5)

Lastly, constraint (5) assures that the amount of simultaneously planned tasks is not more than the amount of mechanics with a specific skill available. That is, every single maintenance task can only be executed by a minimum required skill. The skills are according to what has been discussed in Section 3.2. Table 4.2 shows which required skills the maintenance tasks can contain and which maintenance mechanics can execute these tasks. From Table 4.2 it is visible that a mechanic having both Category B1 and B2 licenses (B1B2) can execute all maintenance tasks and are thus very beneficial to have. With regard to M&A and CMM tasks, a B2 mechanic can execute these tasks too, albeit only electrical and avionics related.

Table 4.2: Required skills with their respective allowed skills

| Required Skill | Allowed Skill |
|---|---|
| M&A | M&A<br>B1<br>B2<br>B1B2 |
| CMM | CMM<br>M&A<br>B1<br>B2<br>B1B2 |
| B1 | B1<br>B1B2 |
| B2 | B2<br>B1B2 |
| B1B2 | B1<br>B2<br>B1B2 |

## 4.4. Model Specification

With the heuristics and constraints explained, the way the model sequences the tasks is now further clarified. In short, the model builds the schedule in a sequential order by planning as many tasks concurrently as possible. At all moments in time, the concurrent tasks should adhere to all constraints. When one of the constraints is not adhered to, the maintenance task with the lowest priority factor is delayed. This process, essentially following a set of rules, is explained upon in more detail below.

However, before the maintenance tasks can be sequenced, an adjacency or precedence matrix is set up first. This is a matrix indicating whether certain tasks needs to take place before other tasks can be executed. The matrix is simply filled in a binary manner, with zeros indicating no relation between the two tasks and ones indicating the opposite. In the example in Table 4.3 a precedence matrix is set up. Here, task 3 can only be executed when task 1 has been finished. No other relations exist.

Table 4.3: Example precedence matrix

| | | After | | | |
|---|---|---|---|---|---|
| | **Task Number** | 1 | 2 | 3 | 4 |
| **Before** | 1 | 0 | 0 | 1 | 0 |
| | 2 | 0 | 0 | 0 | 0 |
| | 3 | 0 | 0 | 0 | 0 |
| | 4 | 0 | 0 | 0 | 0 |

When the precedence matrix has been set up, the priority factors of all tasks are computed. The final factor is the addition of the four normalized elements as discussed in Section 4.2. It was assumed that the four different elements have equal weighting in the final priority factor. In Chapter 8 a sensitivity analysis will be performed to compare the outcome when different weighting is used.

Next, all steps taken by the model are clarified below. Table 4.4 shows the used (fictitious) data to exemplify the model's steps. The example is based on the proactive schedule before the start of the maintenance check. The reactive schedule during the maintenance check is shortly explained afterwards.

Table 4.4: Used data of the example tasks for the model explanation

| Task | Work Area | Skill | Priority | Duration | Predecessor(s) | Power |
|---|---|---|---|---|---|---|
| 1 | Engine | M&A | 3.1 | 1.3 | - | On |
| 2 | Wing | B1 | 2.9 | 2.3 | - | On |
| 3 | Engine | M&A | 2.7 | 2 | Task 1 | On |
| 4 | Cabin | CMM | 0.6 | 0.5 | - | On |

**Step 1.** In the first step the model lets all tasks start at the beginning of the maintenance check, being t=0. This is visually clarified in Figure 4.1. The model builds the schedule sequentially from start to end. Therefore, the first step in building the schedule starts at t=0.

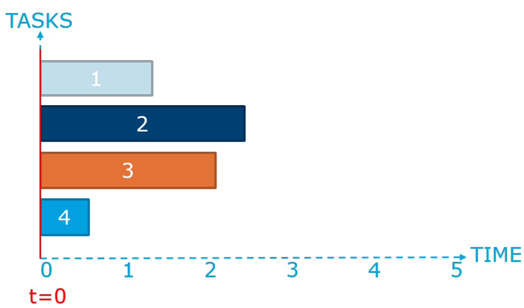


Figure 4.1: The model places all maintenance tasks are the start of the check, t=0

**Step 2.** After that, all constraints are to be checked in a specific order. This order is chosen specifically such that the constraints do not interfere. The constraints apply to all maintenance tasks taking place at that current time step. Firstly, all dependent tasks (with a precedence relation) are moved. As shown in Table 4.4 task 3 can only be executed when task 1 has been finished. This means that task 3 is delayed until the end of task 1, being t=1.3. No other precedence relations exist. Figure 4.2 shows indeed that task 3 is delayed until t=1.3. In Appendix A, Figure A.2 explains in more depth the process of moving tasks with predecessors.

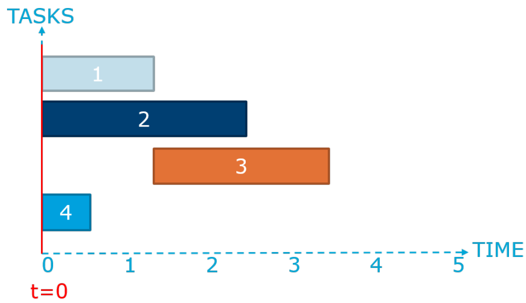


Figure 4.2: All tasks with a precedence relation are delayed until the end of its (latest) predecessor

**Step 3.** Then it is checked whether the current time step is a break. When there is no break, possible power-off tasks are delayed until the start of the next 30-minute break. When there is a break, power-on tasks which start at the current time step are moved towards the end of the break and power-off tasks are untouched. However, power-off tasks can only start at the beginning of a 30-minute break, not once the break has started. Power-on tasks which have been started before the break are paused. The model, however, does not literally pause these tasks, yet provides these tasks extra duration in the shape of the length of the break. In this example there is no break at time step t=0; moreover, no power-off tasks are present. No steps are taken by the model here. In Appendix A, Figure A.3 explains how this process works with a detailed flowchart.

**Step 4.** The next step is to check whether the current time step (t=0) contains any conflicting aircraft zones. As explained in Section 4.3, maintenance tasks on the wing cannot be executed simultaneously with maintenance tasks on the engines. In the example, task 1 and 2 both take place at the same moment (t=0). The aircraft zone with the lowest priority is delayed. In this case, as can be seen in Table 4.4 and Figure 4.3, task 2 taking place on the wing has the lowest priority and is therefore moved until the end of the engine zone, being t=3.3. In Appendix A, Figure A.4 clarifies how the above constraint works in terms of a flowchart.

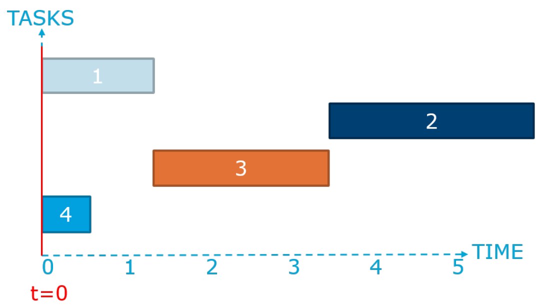


Figure 4.3: Tasks from a conflicting work area are delayed until the end of the other aircraft zone

**Step 5.** The penultimate constraint to check is the maximum amount of mechanics per zone. With tasks 2 and 3 delayed, only tasks 1 and 4 are currently under consideration. As these take place in two different zones, no maintenance tasks have to be delayed in this step. However, if there were multiple tasks of the same aircraft zone taking place simultaneously and the maximum allowed in that zone was exceeded, the conflicting tasks with the lowest priorities are delayed to the earliest end time (of the aircraft zone) until the constraint is adhered to. In Appendix A, Figure A.5 shows in more depth how this constraint works in terms of a flowchart.

**Step 6.** The last and foremost constraint is to check whether the amount of present mechanics (and their respective skill) is able to execute the maintenance tasks under consideration. This is checked with the *waterfall method.* In essence, the maintenance tasks under consideration (in this case task 1 and 4) are ranked by their priority (highest first). The maintenance tasks are then filled by a mechanic with preferably the needed skill or otherwise a higher skill. In Appendix A, Figure A.6 explains in more detail how this *waterfall* concept works. In the specific case of this example, in which we assume to have one M&A mechanic, one B1 mechanic, and one CMM mechanic available, no problems arise here.

**Step 7.** All constraints have now been checked and all are adhered to. The final step is to move to the next time step. The next time step is always the next moment a constraint can be broken again. The only moment this can happen is at the start of new tasks. In the case of this specific example this means that the next time step is the start of task 3, or t=1.3, as can be seen in Figure 4.4. When the model has chosen a new time step, all steps from 2 to 6 are repeated before again going to the next time step (as shown in Figure 4.5). The model is finished computing the work task order when no new task is to be planned and thus no further time step needs to be taken. In Appendix A, Figure A.7 shows how the next time step is chosen in terms of a flowchart.

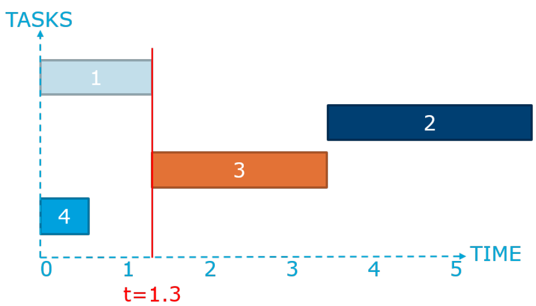


Figure 4.4: Model moves the time step to the earliest next start time, t=1.3

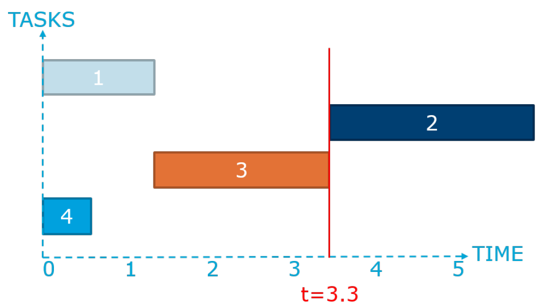


Figure 4.5: Model moves the time step to the earliest next start time, t=3.3

In Appendix A, Figure A.1 shows a detailed flowchart of all steps explained above. Only missing in the explanation is the reactive part of the model, used whilst the maintenance check takes place. Therefore, when the model is run during the check, the status of all maintenance tasks is checked. That is, tasks can either be completed and will not be taken into account anymore, or can be currently in work and will also not be taken into account, or can be uncompleted and will still need to be planned (again). Moreover, non-routine tasks are loaded into the current set of maintenance tasks. Also these can be completed, in work, or uncompleted. For non-routine tasks, the priority factor is solely based on the task duration as the other elements cannot be computed. This means that routine tasks will nearly always have a higher priority than non-routine maintenance tasks. It was assumed that this would not result in any problems, as routine maintenance tasks are preferably executed either before or in parallel with non-routine tasks.

Anyhow, all yet to be executed tasks are given a new start time equal to the current time step. The current time step is computed based on the computer time and the actual start time of the maintenance check. In this example the time step is t=3.0. From there on the same steps are gone through (step 2 up and including step 7) such that a new work task order is provided. The discussed steps are also visually provided in a flowchart in Figure A.8. Moreover, Figure 4.6 shows within the provided example that when task 4 has not been executed at the designated time, it will be planned again when the model is run during the check. In this case, task 4 will be planned at t=3.0. Lastly, Figure 4.7 explains that when all the steps are gone through with the tasks under consideration (task 2, 3, and 4) that task 2 will move due to the zone block constraint (wing and engine tasks cannot be executed simultaneously). To simplify the visualization, no non-routine tasks were added in the latter part of the example.

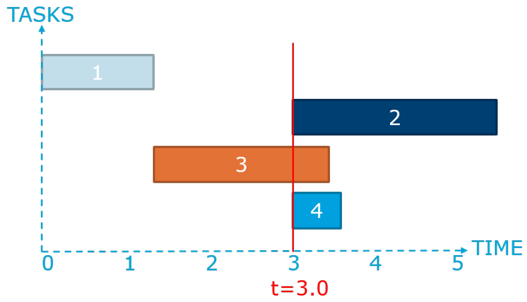


Figure 4.6: During the maintenance check all uncompleted tasks get a new start time equal to the current time

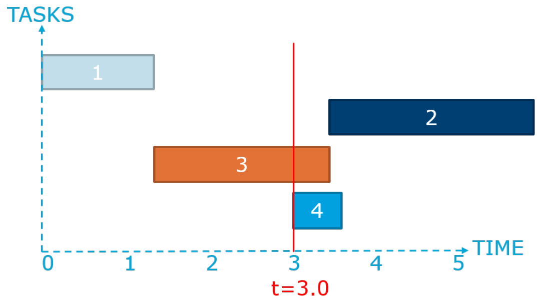


Figure 4.7: Updated work order with the applied aircraft zone block constraint applied

To conclude this chapter, pseudo code has been written to indicate the steps the work task order takes. Together with the sets, indices, and variables, the pseudo code can be found in Figure 4.8.

**Sets and Indices**

| | |
|---|---|
| M | Set of maintenance tasks |
| Break | Set of breaks |
| Zone | Set of aircraft zones |
| Skill | Set of labor skills |
| i | Maintenance task |
| t | Current model time step |

**Variables**

| | |
|---|---|
| $\text{JIC}_i$ | JIC of maintenance task i |
| $\text{JIC\_Type}_i$ | Type of JIC of maintenance task i |
| $\text{Duration}_i$ | Estimated duration of maintenance task i |
| $\text{LaborSkill}_i$ | Labor skill of maintenance task i |
| $\text{Mech}_i$ | Number of mechanics needed during maintenance task i |
| $\text{PowerState}_i$ | Required power state of maintenance task i |
| $\text{WorkArea}_i$ | Work area of maintenance task i |
| $\text{Pred}_i$ | Predecessor tasks of maintenance task i |
| $\text{Succ}_i$ | Successor tasks of maintenance task i |
| $\text{SuccDuration}_i$ | Total duration of successor task of maintenance task i |
| $\text{Priority}_i$ | Priority of maintenance task i |
| $\text{StartTime}_i$ | Start time of maintenance task i |
| $\text{Status}_i$ | Status of maintenance task i |
| $\text{NonRoutine}_i$ | Non-routine chance of maintenance task i |
| $\text{NonRoutineDuration}_i$ | Non-routine manhours of maintenance task i |
| current_time | Current real time |
| next_time | Boolean variable |
| last_power_off | Time step of end last power-off moment |
| start_check | Start time of maintenance check |

```
Load data set M with Jic[i], Jic_Type[i], Duration[i], LaborSkill[i], Mech[i], PowerState[i], WorkArea[i], Pred[i], Succ[i], Status[i]

Make precedence matrix based on Pred[i]

for all i:
    SuccDuration[i] <- sum of durations of Succ[i]
    Priority[i] <- normalized Duration[i] + normalized SuccDuration[i] + NonRoutine[i] + normalized NonRoutineDuration[i]
    StartTime[i] <- 0
    Move all Succ[i] to start after (StartTime[i] + Duration[i])
end for

if current_time <= start_check:
    t <- 0
else:
    t <- current_time
    add all task i with Jic_Type is CORR to precedence matrix
    for all i:
        Check Status[i]
        if Status[i] is ACTV:
            StartTime[i] <- t
        end if
    end for
end if

t <- 0
last_power_off <- -0,5
next_time <- True
skills_break <- empty list

while next_time:
    current_tasks <- all Jic[i] occurring at time t
    future_tasks <- all Jic[i] occurring after time t

    if current time t is a break:
        if duration of break is 0.25:
            for all i:
                Move tasks starting during break to end of break
                Add 0.25 to duration of tasks in current_tasks which started before the break
            end for

        else duration of break is 0.5:
            for all i:
                Move tasks starting during break with (PowerState[i] == 1 or 2) to end of break
                Add 0.5 to duration of tasks in current_tasks which started before break and with (PowerState[i] == 1 or 2)
                Remove shifted tasks from current_tasks
            end for
        end if

        while constraints are broken:
            shift task i with lowest Priority[i]
        end while

        skills_break <- all skills during break
        last_power_off <- max(StartTime[i] + Duration[i]) of current task with PowerState[i] == 0

    else:
        if t < (last_power_off + 0.5) and t >= last_power_off:
            available skills <- available skills - skills_break
        else:
            skills_break <- empty list
        end if

        while constraints are broken:
            shift task i with lowest Priority[i]
        end while
    end if

    if future_tasks is empty:
        next_time = False
    else:
        t = min(StartTime[i]) in future_tasks
    end if
end while

TAT <- max(StartTime[i] + Duration[i])
```

Figure 4.8: Pseudo code of the work task order model

## 4.5. Software & Hardware

The entire model has been coded in Python 3.7, which was driven by the fact that this is the language taught at the Aerospace Faculty within the Delft University of Technology and by the fact that it is primarily used at KLM E&M. The model and its runs were executed on a laptop with an Intel Core i5 2.4GHz processor and 8GB of RAM.

# 5

# Case Study Boeing 787 A-check

To assure the contributions discussed in Section 2.4 are met, a theoretical model has been set up in Chapter 4. In this chapter the theoretical model and its results are presented by means of a case study. The case study is conducted on the Boeing 787 A-check, which is executed in Hangar 12 at KLM E&M. Firstly, the necessary data for the work task order model and the manipulations of the data are discussed in Section 5.1. Thereafter, the assumptions which were made are stated in Section 5.2. The results of the case study are shown and discussed in Section 5.3. Finally, Section 5.4 examines the business value of the work task order model for KLM E&M.

## 5.1. Used Data

For this specific case study the A06-check on the Boeing 787 with registration PH-BHO is used. For the work task order model to be able to sequence the maintenance tasks, the data should first be retrieved and manipulated, and new variables added.

To retrieve the data, all maintenance tasks within the A06 work package are downloaded from Maintenix. Maintenix is the MRO software KLM E&M uses for its maintenance support. In Chapter 4 it was already shown that certain information on each specific task is necessary to be able to either compute the priority factors or handle the constraints. The following variables are directly retrieved from Maintenix for each specific maintenance task:

- JIC Code
- Aircraft Registration
- Task Definition
- Estimated Duration
- Labor Skill
- Nr. of Mechanics
- Work Area

The data itself is not disclosed, but is of the same format as was shown in Table 4.4, with the difference being the fact that the tasks are not specified by numbers, but codes (JIC Code). Moreover, the 'Task Definition' variable provides a short explanation of the content of the maintenance task.

Even though all maintenance tasks within the A06 work package are retrieved from Maintenix, not all are taken into account by the model. Firstly, administrative tasks are not performed at a set moment in time and therefore not planned accordingly. Secondly, tasks from the *Langs/SMW* zone are executed by specialist mechanics which are not part of the A-check team and therefore also not taken into account in the available workforce. Lastly, tasks which miss certain vital information, such as the estimated duration, labor skill, or work area are also not used by the model. Assuming a certain value for these missing entries is an option, but it was chosen not to do so because the result could potentially be more disturbed than simply not planning these tasks, assuming the number of unplanned tasks is lower than 2% of the entire data set. The model will, however, list these latter tasks as 'unplanned' to inform the user. For this specific case study 183 maintenance tasks need to be sequenced by the work task order model. None are listed as being 'unplanned'.

In addition to the existing data set, one specific task is always added to every Boeing 787 A-check. This is the cleaning of the galleys and the lavatories. Even though this is not a task being executed by the mechanics, it is of influence on the work task order of the A-check as the duration of this cleaning is on average 8 hours. It should be investigated further whether similar tasks exist for different maintenance checks on different aircraft types.

Furthermore, tasks related to the testing of the emergency transmitter on-board the aircraft can only be started on the hour or five minutes after due to agreements with the regulatory authorities. Therefore, these tasks are removed from the initial set of 183 maintenance tasks and are only planned by the model after all other maintenance tasks are sequenced. This is done in a manner in which the model checks at which moment during the check the necessary mechanic(s) are available. The first moment on the hour when the required skill is available (often B2), the specific emergency transmitter task is planned. The only times the model is not able to plan these emergency transmitter tasks is when no B2 mechanic is present or when all B2 mechanics are occupied with other avionics tasks. However, this situation did never occur during testing. When it would occur, the model currently is not able to delay other B2-skilled tasks to make room for the emergency transmitter testing.

Next to the aforementioned variables directly available through the data in Maintenix, some variables need to be added in order for the model to work. These newly added variables are:

- Power Condition
- Predecessors
- Priority

Firstly, every maintenance task requires information about its power condition: power required, no power required, no power requirements. Only with this information the power-off constraint can be adhered to. Furthermore, all tasks require information on potential predecessors, which are tasks which need to be finished before the task under consideration. This information can then be used to set up the precedence matrix as discussed in Section 4.4. These two variables are saved in a database from which the data can be easily loaded for other A-checks. A disadvantage from this method is that new maintenance tasks will not have this information available. All new maintenance tasks will therefore need to be added manually with respect to the latter two variables.

Lastly, for all maintenance tasks the priority factor is computed. As explained in Section 4.2, the final priority factor is computed based on four different elements. With the duration of the maintenance tasks known and the precedence matrix set up, only the non-routine part of the priority factor is left to be computed. For the Boeing 787 A-checks, the used non-routine information dates from the introduction of the aircraft at KLM until June 2019. This leads again to the fact that new maintenance tasks which have not been executed before, do not have any non-routine information and will therefore not score on this part of the priority factor. Ideally, this non-routine information is updated after every A-check such that the non-routine part of the priority factor is always up-to-date.

Other essential information lies within the breaks. Section 4.3 discussed the break and power-off constraint. Breaks are moments in which the mechanics generally do not work and thus no maintenance tasks are planned. Only tasks with a power-off requirement can be planned during the longer 30-minute breaks. Within Hangar 12 the breaks are planned at the moments shown in Table 5.1. An important reason for taking breaks into account is that the total time of all breaks is a large portion of the turnaround time. For the A-check the breaks account for around 15% of the total turnaround time. Not taking into account breaks would result in a distorted work task order with an unrealistic turnaround time.

Table 5.1: Planned breaks within Hangar 12

| Time | Duration | Remark |
|---|---|---|
| 1:30 | 30 min | |
| 4:30 | 30 min | |
| 6:30 | 15 min | Shift handover |
| 8:30 | 15 min | |
| 11:30 | 30 min | |
| 13:30 | 15 min | |
| 15:00 | 15 min | Shift handover |
| 17:30 | 30 min | |
| 20:30 | 30 min | |
| 22:45 | 15 min | Shift handover |

Table 5.2: Indication on the amount of available mechanics per skill

| Skill | Number |
|---|---|
| B1 | 5 |
| B2 | 2 |
| CMM | 1 |
| M&A | 7 |

Furthermore, for the model to make a work task order, an indication on the amount of mechanics per skill needs to be available. Before the start of the maintenance check the amount indicated in the *bedrijfsdrukte profiel* (BDP) is used. These numbers are shown in Table 5.2. This is the minimum needed to execute the A-check and applies to one entire shift. Closer to the start of the maintenance check or during the execution of the maintenance check, the amount of available mechanics per skill can be altered to match the current situation. This is due to the fact that the amount of available mechanics alters every shift, or even throughout a shift (e.g. when an unexpected aircraft on ground situation occurs). The model will then be run again and the new work task order will match the newly inputted available manpower. For the case study in this chapter, the amount of available mechanics per skill is assumed to be constant during all three shifts (nominal duration for 17.5 hours of work) and equal to the numbers described in Table 5.2.

## 5.2. Assumptions

Before the results of the work task order model on the PH-BHO A06-check can be shown, all assumptions are summarized below. These assumptions are specific for the Boeing 787 A-checks performed in Hangar 12 at KLM E&M and might differ for different maintenance checks on different aircraft types.

- Administrative tasks and tasks from the *Langs/SMW* zone are not taken into account by the model.
- Maintenance tasks in which multiple mechanics are needed are assumed to be all from the same (single) skill.
- The work areas as stated in Table 4.1 are used, even though these are not all real areas.
- The estimated duration denoted on the maintenance task cards are assumed to be correct and assumed to be revised regularly.
- Power-off tasks are only started during a break.
- If a mechanic needs to work on a power-off task during the break, the mechanic will be given a break after the power-off task. This mechanic is therefore not taken into account in the available manpower 30 minutes after the end of the power-off maintenance task.
- The mechanics take breaks exactly at the designated moments discussed in Table 5.1.
- The hydraulic state of certain tasks is not taken into account.
- Maintenance tasks are not being split up at the start of a break, instead these tasks are given an extra duration in the shape of the length of the break.
- The amount of available mechanics per skill is constant throughout all shifts and equal to the amount indicated in the BDP.
- Only mechanics which are 100% available are taken into account in the available manpower. The lead mechanic and support staff are therefore not taken into account.
- A shift handover is seen as a break in the model, even though this is not a real break.
- The A-check is assumed to start at 21:00.

- The model assumes a mechanic to constantly work on a maintenance task (except for breaks) even when the maintenance task does not require a mechanic to be constantly present (e.g. disinfecting the potable water system).
- A non-routine maintenance task can be planned and executed at any moment. Any ordered parts and their respective lead time are not taken into account.
- Once a maintenance task has started, it cannot be paused or stopped. Preemption is not allowed.

## 5.3. Results

Finally, the data discussed in Section 5.1 is processed by the work task order model. The results are shown and analyzed on four different areas, as were mentioned as being the model objectives in Section 4.1:

- Model computational time performance
- Turnaround time
- Robustness
- Proactive & reactive scheduling

The first objective of the model is to produce a work task order within reasonable time such that it is potentially usable at KLM E&M. Reasonable is here defined as being 0.5% or less of the total (desired) turnaround time. For the Boeing 787 A-check in Hangar 12 this means that the computational time of the work task order model should be 5 minutes or less, keeping in mind that the desired turnaround time is 17.5 hours, as discussed in Section 3.3. To get a rough indication on the computational performance of the model, five runs are performed for the same A06-check. In Table 5.3 the five runs and their computational times are shown. From this it is clear that the average computational time of the model is 2 minutes and 44 seconds. Ideally, more runs are performed on different hardware to analyze the influence hereof, yet this does not lie in the scope of this thesis.

Table 5.3: Performance of the model in terms of computational time

| Run | Time [min:sec] |
|---|---|
| 1 | 3:15 |
| 2 | 3:13 |
| 3 | 2:18 |
| 4 | 2:27 |
| 5 | 2:29 |
| Avg | 2:44 |

Secondly, the estimated turnaround time of the work task order model is discussed. However, it is important to keep in mind that the estimated turnaround time before the start of the maintenance check is only an indication. The model can never completely indicate the turnaround time due to the unscheduled work resulting from non-routine maintenance tasks. For the A06-check under consideration the model estimated a turnaround time of 16.4 hours. It could be very well possible that a shorter initial turnaround time can be found by scheduling the maintenance tasks differently; however, as indicated in Section 4.1, it is not the model's purpose to minimize the initial schedule, but to minimize the overall schedule including possible extra unscheduled work from non-routine work.

A little indication in the amount of extra work (non-routine maintenance tasks) that can be planned throughout the A-check, is the amount of mechanics working simultaneously throughout the check. Figure 5.1 depicts this latter description. From this figure it is clear that after 11 hours the number of mechanics working concurrently drops significantly. In the current work task order there thus is enough manpower available between hour 11 and 16.4 to accommodate extra non-routine maintenance tasks. The explanation on the question why there is this drop in concurrently working mechanics anyhow, lies in the zone block constraint discussed in Section 4.3. In this A06-check the engine zone had a higher priority than the wing zone and the latter was therefore planned after the former. Moreover, after the end of the engine zone most work in other zones is finished and therefore the wing zone is nearly the only work performed nearing the end of the check.

Furthermore, from Figure 5.1 it is also clear that not every single moment in the beginning of the A06-check is occupied by the full 15 mechanics available. This effect is due to the B2-skilled mechanics generally having less available tasks than other mechanics. Additionally, owing to the fact that the model does not literally pause maintenance tasks during breaks, rather provides extra duration in the shape of the length of the break, Figure 5.1 does not depict these breaks.

Nonetheless, Figure B.1 shows a Gantt chart of the work task order of the A06-check on the PH-BHO. The tasks in the Gantt chart are grouped by work area. However, for clarity purposes the JIC codes of the 183 maintenance tasks are not shown on the Gantt chart. The digital/online version of the Gantt chart does show the JIC code by means of hover text.

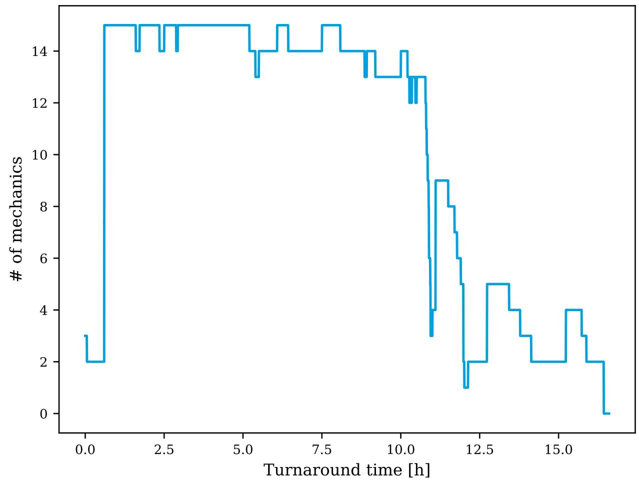


Figure 5.1: Number of mechanics working concurrently throughout the A06-check on the PH-BHO

The third result to be shown is the robustness of the work task order model. This was described as the work task order not changing significantly when one or more tasks are removed. To test this, a random task (in this case the "Visual check of SOB cards for presence after replacement by third party") was deleted from the original data set. The model was run again and the turnaround time was seen to remain unchanged: 16.4 hours. Visually, the work task order can be compared on the Gantt chart in Figure B.2 with the Gantt chart shown in Figure B.1, both available in Appendix B. It can be observed that the order hardly changes. The reason for the turnaround time not changing is because the longest chain of tasks (critical path) in the original work task order is untouched with the removal of this selected task. The critical path in this work task order is the aforementioned chain of engine and wing tasks. When removing a task which is part of this critical path, except for a vital maintenance task such as opening the engine cowls, the total turnaround time was seen to change to 15.9 hours. For this test the "Inspect the C sump tube bracket, booster acoustic panel bolts and P-clamps on the right engine" task was randomly removed from the data set. The Gantt chart and its differences with the original can be compared in Figure B.3, which again shows little difference. All three different work task orders have shown the model to be robust for changes in the data set. The same experiment can be repeated by deleting more than just one single task. Up until a certain amount of tasks the order will still not alter significantly; however, when the amount of tasks taken out of the data set becomes too large, the entire experiment would defeat its purpose: comparing work task orders of nearly identical data sets.

Lastly, the reactive scheduling capabilities of the work task order model are shown. This is done by having run the model again during the actual execution of the maintenance check. The idea behind the reactive scheduling is to create more insight in the situation during the maintenance check: showing which maintenance tasks have been finished, showing a new work task order for the unfinished maintenance tasks, and providing a new estimate on the turnaround time. Figure B.4 shows a newly created Gantt chart for the A06-check of the PH-BHO, after around 13.7 hours into the maintenance check. Moreover, the new turnaround was estimated to be 17.6 hours, just 1.2 hours more than initially predicted and only 6 minutes later than the A-check norm of 17.5 hours. The lead mechanic is now able to act upon the newly acquired insight.

## 5.4. Business Value

With the results of this case study shown in the previous chapter, the potential value of this work task order model for KLM E&M is discussed in this section.

Firstly, with regard to the computational time of the model, the discussed model is able to produce a work task order 10x to 15x faster compared to the time the TPSO needs, of which the latter was shown in Section 3.3. Not only does this give the TPSO extra time for other work, this model can also be run by other people, which assures that not just one person is responsible for producing a work task order.

Furthermore, the TPSO makes the work task order based on experience and the sequence is therefore subjective. An optimal order of the maintenance task can thus not be guaranteed. The model discussed in this thesis solely relies on data and is hence objective. Moreover, this work task order model is able to react to the situation occurring during the maintenance check, called 'reactively scheduling' previously. Whether non-routine maintenance task occur, or whether the amount of available manpower changes, the model is able to adapt by providing a new work task order. The reactive scheduling provides the lead mechanic with more insight concerning the current status of the maintenance check. The lead mechanic is able to better validate which maintenance tasks are finished and which are still to be executed, and of these unfinished tasks which have the highest priority. Besides, with a continuously updating work task order, the turnaround time becomes more and more accurate nearing the end of the check. This allows the lead mechanic to better communicate the end-time to the fleet planners at KLM Royal Dutch Airlines. Again, when the maintenance check is delayed a new end-time can be communicated based on data instead of experience.

Additionally, because the model's approach follows a robust set of rules, the results (and the decision behind the results) are easy to understand and allow for standardization of the maintenance checks. As such the model is more likely to get accepted by the maintenance mechanics. Moreover, standardization of the process can subsequently lead to improvements in the turnaround time.

Lastly, the work task order model can also be used within KLM E&M by the Planning, Scheduling & Fleet Control (PSFC) department. This department builds the work packages for the maintenance checks. That is, the content of the maintenance check on a task level is controlled in this unit. The model can therefore be used well before the start of the maintenance check, once the content of the work package is known, to get a first indication on the turnaround time. When the model illustrates that the maintenance check is not able to be executed within 17.5 hours, the department can rebuild their work package well ahead or indicate that more manpower is needed. This could finally result in the turnaround time of all maintenance checks having less variation.

Notwithstanding, many of these benefits can only be used to full potential when the mechanics executing the maintenance check do actually work according to the new work task order. When the decision is made to deviate from this work task order, not all benefits stated above can be guaranteed.

Moreover, the current work task order model is solely focused on the Boeing 787 A-check. Even though the model has been built such that it can be extended to different maintenance checks on different aircraft types, certain drawbacks have to be overcome first. For example, the used database, as discussed in Section 5.1, should then be extended manually.

# 6 Model Verification

The verification of the model is intended to show the model performs as was designed for. The verification process was mostly executed throughout the programming of the model itself. That is, every time a new constraint was programmed, it was tested with a set of dummy data tasks. A small dummy data set is therefore ideal since the outcome can be computed by hand and compared to the outcome of the programmed model. In Table 6.1 the used dummy data is shown. It can be seen that the data is of the same format as in Table 4.4 in Section 4.4, with the difference being the fact that the power variable consists of the options 0, 1, and 2. A 0 means that the task requires the power to be shut down. A 1 means that the maintenance task does require power for it to be executed. Lastly, a 2 means that the task does not have any power requirement: the power can either be on or off.

The priority factor shown in the dummy data is the priority computed only based on the duration of the task itself and the total duration of the tasks in the successor chain. Thus, for this verification it has been assumed that the priority factor does not consist of any non-routine information. However, for the verification of the model the numerical value of the priority factor is less important than the use of the factor.

Table 6.1: Dummy data set used for verification purposes

| **Task** | **Work Area** | **Skill** | **Priority** | **Duration** | **Pred.** | **# of Mech** | **Power** |
|---|---|---|---|---|---|---|---|
| 1 | Cabin/Section A | CMM | 0.13 | 1 | - | 2 | 1 |
| 2 | Cabin/Section B/C | CMM | 0.86 | 2 | 7 | 2 | 1 |
| 3 | Cabin/Section D | CMM | 0.13 | 1 | - | 2 | 1 |
| 4 | Cabin/Emergency Equipment | B2 | 0.009 | 0.3 | 5 & 13 | 1 | 1 |
| 5 | Dwars/LH Wing | B1 | 0.16 | 0.5 | - | 1 | 2 |
| 6 | Cabin/Water Disinfect | M&A | 1.0 | 6 | - | 1 | 2 |
| 7 | Langs/Lower Fuselage | M&A | 1.1 | 0.65 | - | 1 | 0 |
| 8 | Langs/Lower Fuselage | M&A | 0.13 | 1 | - | 1 | 0 |
| 9 | Cabin/General | M&A | 0 | 0.25 | 5 | 1 | 2 |
| 10 | Langs/FWD & AFT Cargo | B1 | 0.10 | 0.85 | - | 1 | 2 |
| 11 | Langs/Tests | B1 | 0.04 | 0.5 | - | 1 | 1 |
| 12 | Dwars/RH Main Gear | B1B2 | 0.009 | 0.3 | - | 1 | 2 |
| 13 | Dwars/LH Engine | B1B2 | 0.28 | 1.5 | 2 | 1 | 2 |
| 14 | Cabin/Emergency Equipment | B2 | 0.09 | 0.75 | 2 | 1 | 1 |

Moreover, because the amount of maintenance tasks is much lower than in the case study in Section 5.1, the amount of available manpower is also altered in the verification process. Table 6.2 presents the available skills. In the verification of the model, no different shifts are used. Therefore, the aforementioned available manpower does not alter throughout the verification (apart from the possible time after a power-off task). Furthermore, the maximum amount of mechanics per work area is lowered too. This latter change is visible in Table 6.3. These numbers are chosen arbitrarily and do not reflect the real aircraft maintenance situation.

Table 6.2: Available manpower for the verification of the work task order model

| Skill | Number |
|---|---|
| B1 | 3 |
| B2 | 1 |
| CMM | 1 |
| M&A | 3 |
| B1/B2 | 1 |

Even though unit testing, in the sense of verifying the constraints separately, has been performed, only the working of the complete model with all separate units together is shown in this document. For this, the dummy data as shown above is run by both the model and by hand. The steps taken by hand are completely similar to those discussed in Section 4.4 and the flowcharts in Appendix A. Finally, the outcome of both methods is compared. When the dummy tasks are all planned at exactly the same moment, the model is seen to be verified. In Figure 6.1 the Gantt chart made by hand is shown. When comparing this to Figure 6.2, in which the Gantt chart of the work task order model is shown, it is observed that there are no differences in terms of the order of the dummy maintenance tasks. Besides, when checking the constraints, it can be seen that all are adhered to in both outcomes. To aid the Gantt charts, the start and end times of the dummy maintenance tasks can be found in Table 6.4, assuming this 'verification' maintenance check started at 20:00.

Table 6.3: Maximum amount of mechanics per work area for the verification of the work task order model

| Work Area | Max | Work Area | Max | Work Area | Max |
|---|---|---|---|---|---|
| Cabin/Section A | 4 | Dwars/LH Wing | 2 | Langs/Cockpit | 2 |
| Cabin/Section B/C | 4 | Dwars/LH & RH Wings | 2 | Langs/Final | 1 |
| Cabin/Section D | 4 | Dwars/Nose Landing Gear | 2 | Langs/FWD & AFT Cargo | 2 |
| Cabin/Emergency Equipment | 1 | Dwars/RH Engine | 2 | Langs/FWD Cargo | 2 |
| Cabin/Galleys | 4 | Dwars/RH Main Gear | 2 | Langs/Lower Fuselage | 1 |
| Cabin/General | 4 | Dwars/RH Wing | 2 | Langs/Pax Entry Doors | 1 |
| Cabin/Lavatories | 1 | Langs/Admin | 1 | Langs/Preliminary | 1 |
| Cabin/Seats C-Class | 4 | Langs/AFT Cargo | 2 | Langs/SMW | 1 |
| Cabin/Seats M-Class | 4 | Langs/APU | 2 | Langs/Software | 1 |
| Cabin/Water Disinfect | 1 | Langs/Avionics | 1 | Langs/Tail | 2 |
| Dwars/LH Engine | 2 | Langs/Cargo Doors | 1 | Langs/Tests | 1 |
| Dwars/LH Main Gear | 2 | | | | |

Table 6.4: Start and end times of the dummy maintenance tasks

| Task Number | Start Time | End Time |
|---|---|---|
| 1 | 20:00:00 | 21:39:00 |
| 2 | 21:09:00 | 23:24:00 |
| 3 | 20:00:00 | 21:39:00 |
| 4 | 00:54:00 | 01:12:00 |
| 5 | 20:00:00 | 20:30:00 |
| 6 | 20:00:00 | 03:15:00 |
| 7 | 20:30:00 | 21:09:00 |
| 8 | 01:30:00 | 02:30:00 |
| 9 | 21:39:00 | 21:54:00 |
| 10 | 21:39:00 | 22:30:00 |
| 11 | 20:00:00 | 20:30:00 |
| 12 | 20:00:00 | 20:18:00 |
| 13 | 23:24:00 | 00:54:00 |
| 14 | 23:24:00 | 00:09:00 |

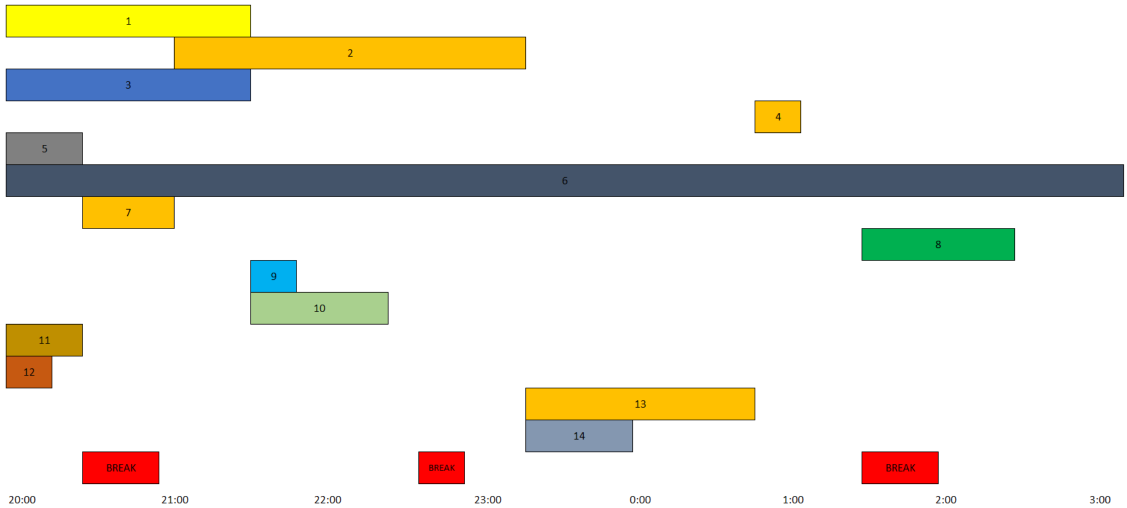


Figure 6.1: Gantt chart for the dummy data, computed by hand

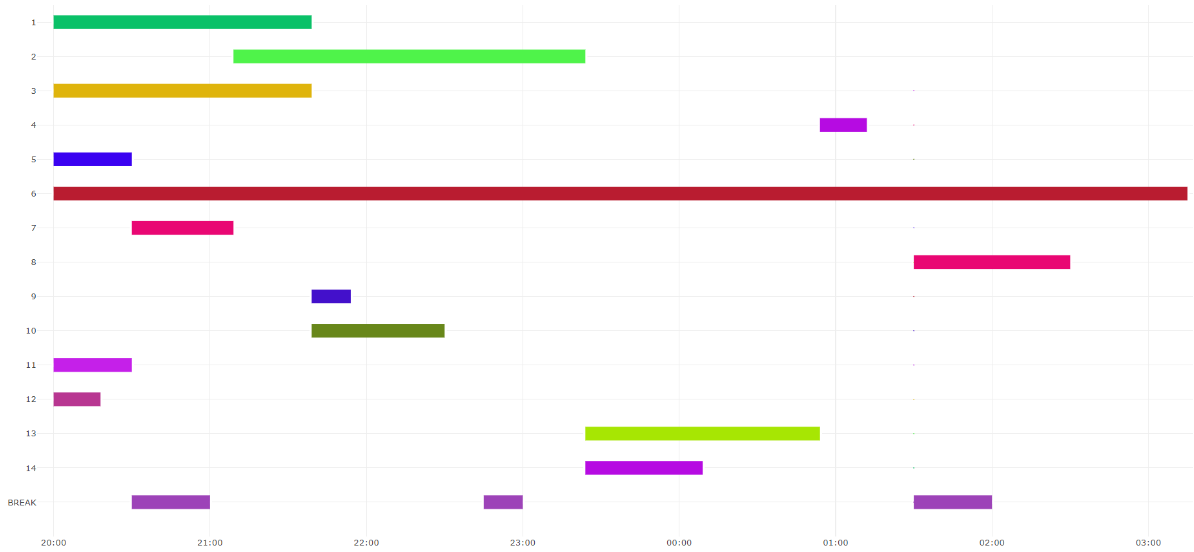


Figure 6.2: Gantt chart of the work order for the dummy data, run by the model

# 7 Model Validation

The validation of the work task order model is executed to check whether the outcome of the model is in line with the expectations of the possible end-users. For the validation it was assumed that the end-users are those working in Hangar 12 at KLM E&M, which is the same location as for the case study performed in Chapter 5. In this chapter the results from the conducted interviews with experts in the field are presented first in Section 7.1. Secondly, in Section 7.2 the work task order of the discussed model is compared with the current situation by means of the same A-check as used in the case study in Chapter 5. Lastly, the turnaround time forecasts by the model are compared to the actual turnaround times of previous A-checks in Hangar 12 at KLM E&M. The latter is discussed in Section 7.3.

## 7.1. Expert Interviews

In this section the results from the interviews conducted with experts in the field are presented. The experts in the field are those possibly using the model in the future, or in case of the Technical Plant Support Officer using the current work task order method. Considering that the model could potentially be used by three different divisions at KLM E&M, one person from each of these divisions is interviewed:

1. Technical Plant Support Officer in Hangar 12 at KLM E&M
2. Lead Work Preparation of Planning Scheduling & Fleet Control at KLM E&M
3. Lead Mechanic in Hangar 12 at KLM E&M

The interviews were conducted in a structured manner with predefined questions. The questions concern the work task order of the A06-check on the PH-BHO, which is the same maintenance check as discussed in the case study in Chapter 5. The questions and their answers are stated below.

### Are there any tasks which are planned incorrectly?

According to both the Technical Plant Support Officer as the Lead Mechanic, no tasks are planned incorrectly. Certain tasks are, however, planned at different moments than accustomed to. Moreover, certain tasks belonging together are now planned separately. As an example the General Visual Inspection (GVI) of the curtains are taken. Ideally these are planned and executed in parallel (or at least closely together), but the model plans these separately since it does not take into account the efficiency of certain tasks being executed in parallel. Another Lead Mechanic in Hangar 12, who is B2-skilled, did mention that in the work task order two tasks are planned incorrectly. Specifically, two avionics tasks needed to be swapped: the operational check of the cabin service system is to be executed before the ceiling panels in the cabin are opened. This information has later been added to the maintenance task database.

The Lead Work Preparation is mostly concerned with the content and planning of the work package on a long-term basis. Hence, this person indicates to have insufficient knowledge on the specific order of maintenance tasks during the A-check. The Lead Work Preparation not indicated whether the work task order of the model is correct or not.

### Are there any tasks missing in the work task order? Would that be unacceptable?

On first sight neither the Technical Plant Support Officer, nor the Lead Mechanic recognize any missing maintenance tasks in the work task order. This is indeed correct as the model did not have any unplanned tasks for the A06-check on the PH-BHO. Should there have been unplanned (and thus missing) tasks, the model would have indicated these JIC codes as being unplanned. The Lead Mechanic indicates the importance of all maintenance tasks being planned (and thus none missed). To overlook a task during the execution of the check, or performing rework, will therefore be nearly impossible. Having tasks with missing data, which the model does not plan, is hence highly unfavourable. The Technical Plant Support Officer, on the other hand, argues that there needs to be a focus on the standard A-block and OOP tasks in the A-check. This person is of the opinion that when the standard work cannot even be executed in an efficient and standardized manner, infrequently occurring tasks should not be taken into account yet.

The Lead Work Preparation cannot tell whether any tasks are missing or not. However, this person indicates that the benefit of the model for PSFC lies in the forecast of the turnaround time of the A-check. The Lead Work Preparation would therefore prefer no tasks to be missing from the work task order such that the forecast is as reliable as possible.

The model discussed in this thesis finds the middle ground in all opinions. First of all, the model *tries* to plan all maintenance tasks such that no tasks can be missed during execution and the turnaround time estimate is as accurate as possible. However, when a maintenance task is missing data, the model will not plan this task and refer to it as being *unplanned*. The goal is hence to have reliable and complete data for all maintenance tasks.

### What features of the model are missing?

For both the Technical Plant Support Officer and the Lead Work Preparation, the model is already very complete from the perspective of using the model before the start of the check (proactive schedule). However, both do indicate that an extra feature or improvement lies in how the model receives the knowledge on the amount of available manpower. Now, the end-user has to fill in the amount of available mechanics per skill and per shift manually. Ideally, this information is received automatically from an external source such that these variables are always up-to-date. Moreover, the Technical Plant Support Officer suggests the idea of adding extra Key Performance Indicators (KPIs) to the output, such as the amount of still to be executed inspection tasks. In that way, the user can more easily see the status of the maintenance check.

The Lead Mechanic agrees with the former improvement from both a proactive and reactive schedule point of view. Furthermore, this person wonders whether the lead time of ordered materials for non-routine maintenance tasks is taken into account in the model. Because this is not the case, the Lead Mechanic expresses that this would also be a good improvement such that non-routine maintenance tasks can only be planned when the ordered material is available.

### What is the maximum allowable computational time for a work task order?

The Lead Mechanic's answer on this question is very clear: when a button is pushed, the work task order should appear as quickly as possible without any waiting times. A computational time of one minute would still be acceptable, but not any more. The Technical Plant Support Officer's opinion is different. This person answers that it is understandable that the model needs time to compute and that it cannot be expected to deliver an output immediately. For the Boeing 787 A-check, the Technical Plant Support Officer indicates that a computational time of three minutes is still very acceptable. The longer the check, the longer the computational time is allowed to be. The Lead Work Preparation shares the same opinion as the Technical Plant Support Officer in that waiting a few minutes (e.g. 3 minutes) should not be an issue because planned hangar maintenance is something which is known well-ahead in time.

Altogether, the computational time as discussed in Section 5.3, which was around 2 minutes and 44 seconds, is still acceptable for most of the interviewees. An improvement in hardware and a more efficient coding of the model will undoubtedly improve the computational time of the model.

### Is the current visualisation (Gantt chart) of the work task order clear?

For all three, the opinions are nearly identical. The current visualization as shown in Figure B.1 provides a first indication on how all maintenance tasks are sequenced within the check, yet needs improvement. The printed/pdf version does not show which JIC belongs to which bar, which makes matters unclear. Nonetheless, the digital version, for which the model was designed for, uses hover text to indicate the JIC belonging to the specific bar. Inasmuch as the amount of maintenance tasks is large, even the digital version becomes unclear. The three persons agree that the visualization needs an improvement in terms of both user interface and user experience before the model could be used in operation.

### Would you use the model in the future?

Even though the intended use of the three interviewees is different, all are enthusiastic about a future use of the model. The benefits indicated by the interviewees are bipartite. Firstly, the benefit lies in the extra insight on the status of all tasks in the maintenance check and the turnaround time indication both before as well as during the check. Secondly, the discussed model works towards standardization, which is the first step towards improvement. The latter was also explained upon in Section 4.1.

Summarizing, the three interviewees are positive about the work task order model. All indicate that they would use the model in the future. The benefits the model brings (or might bring) about outweigh the currently missing features or the slightly unclear representation of the results. The setup of and the general idea behind the model are good and the current results are correct and promising. The interviewees hence agree that the development of the model should be continued.

## 7.2. Current Situation Comparison

A second step in the validation process is to check the output of the work task order model with a work order from a past Boeing 787 A-check. For this, the A06-check on the PH-BHO was used again. The work order of the actual executed check is made by plotting the actual start and end times of all maintenance tasks (including the non-routine tasks). Because mechanics often (administratively) start and end tasks after they have actually performed the work, the start time of all maintenance tasks is taken as being the end time minus the estimated duration. However, even the actual end times are not completely reliable as mechanics tend to sign-off tasks close to the start of a break or at the end of a shift. These aforementioned phenomena are visible in Figure B.5, where especially in the first shift *blocks* of tasks are seen. This is one of the main differences with the output of the model, as the model assumes a task to be (administratively) started and ended at the exact true moments corresponding to the work.

Furthermore, these blocks do also show one of the earlier mentioned recommendations: combining tasks belonging together. When comparing the actual order with the output of the model, maintenance tasks such as the *removal and installation of the left and right ozone converter* are seen to be performed together in the actual order and seen to be planned separately in the output of the model. Moreover, the major share of all maintenance tasks are seen to have been executed in the first shift, while the output of the model in Figure B.1 shows the maintenance tasks to be more spread out. The latter is logical, because the model assumed the amount of manpower to be constant throughout the check. Looking back at the actual manpower available that shift, the amount was higher than the input in the model, proving why much more work was performed in that shift than planned by the work task order model. On the other hand, the actual order also shows that nearly no work was performed between 7:00 and 11:00, which makes up for the earlier amount of work at the start of the maintenance check.

Another vital difference in the order of the actual A-check and the output of the model is due to the way of working of the mechanics. The order is often based on the either the work task order made by the TPSO or the experience of the lead mechanic/support staff. Both the former and the latter base their order mostly on experience. A specific maintenance task which has once caused major problems in the past, does not necessarily cause problems every time again. This is because of the fact that humans tend to remember negative memories more easily, as was discovered by Kensinger [40]. The work task order model solely bases its order on data and will thus not plan a task earlier every time when it has only caused problems once before, due to the priority factor.

In summary, it is hard to validate the output of the work task order model with an actual order of a maintenance check. It is not completely remarkable that the order of both is quite different. The amount of manpower changes throughout the check and the understanding of which tasks have a higher priority is vitally different from people deciding upon experience and a model deciding upon data. Thus, the current way of working logically differs from the work task order model. Ideally, the work task order model was validated during an actual Boeing 787 A-check, or even better an A/B test; however, the current operation at KLM E&M did not allow for this kind of testing.

## 7.3. Turnaround Time Forecast

As was read in the interview with the Lead Work Preparation, one of the benefits of the model is the indication on the turnaround time of the check. However, Section 2.4 also states that the model does not solely optimize for the turnaround time because the turnaround time is difficult to predict correctly due to unforeseen circumstances, such as non-routine maintenance tasks and an altered availability in manpower. Even though the above seems contradictory, both are true. Not always will the maintenance check be disturbed due to unforeseen circumstances: the maintenance check then elapses normally and more according to what was predicted.

To check whether the aforementioned is true, twenty different Boeing 787 A-checks in 2019 have been run through the model and its forecast turnaround time is compared with the actual turnaround time. Figure 7.1 shows a boxplot in which the difference in predicted and actual turnaround time is shown. From this figure it is clear that the median lies close to 1 hour difference. That is, the model is likely to forecast the turnaround time correctly. However, from the boxplot it is also clear that the largest part of the interquartile range (IQR) and the maximum indicate a positive difference. The latter proves that the actual turnaround time of the Boeing 787 A-check is often higher than initially modelled. Thus, the reason for the model to not only optimize for minimum turnaround time is hereby validated. Moreover, from a planning perspective at PSFC, the model is seen to nearly always indicate the *minimum* turnaround time. When the estimated turnaround time already exceeds the norm, the actual turnaround time is likely to be exceeded too.

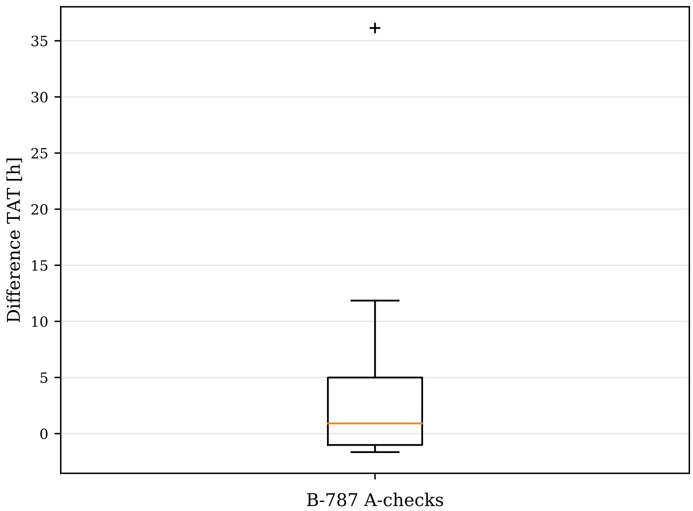


Figure 7.1: Boxplot of the predicted and actual turnaround time of twenty Boeing 787 A-checks

Summarizing, the two most important additions to the validation of the work task order model are the interviews discussed in Section 7.1 and the turnaround time analysis in Section 7.3. The interviews with three different possible end-users of the model indicate that the work task order model complies with the desires of the interviewees. Next to some potential improvements in the future, the benefits the model might bring about are seen to be most valuable. The analysis on the turnaround time, on the other hand, shows that the work task order model is performing well in forecasting the turnaround time of the Boeing 787 A-check. However, it also shows that the model is right in not solely optimizing for turnaround time, as unscheduled circumstances can elongate the total duration of the maintenance check.

# 8 Sensitivity Analysis

In this chapter a short sensitivity analysis is performed. The emphasis lies on the weights of the different elements in the priority factor. For the current work task order model, the weight has been assumed to be equally distributed between all elements, meaning that all are equally important. The latter was discussed in Section 4.4. Since varying the weights of the priority factor can be done for an infinite amount of options, just a concise selection was made. The selection with the different weights and the corresponding results on the turnaround time can be seen in Table 8.1. As in previous chapters, the A06-check on the PH-BHO was used to perform the sensitivity analysis on.

Table 8.1: Different weighting of the priority factor and the resulting turnaround times

| Estimated Duration | Chain Duration | NR Chance | NR Manhours | TAT |
|---|---|---|---|---|
| 0.25 | 0.25 | 0.25 | 0.25 | 16.43 |
| 0 | 0.33 | 0.33 | 0.33 | 16.43 |
| 0.33 | 0 | 0.33 | 0.33 | 19.59 |
| 0.33 | 0.33 | 0 | 0.33 | 16.43 |
| 0.33 | 0.33 | 0.33 | 0 | 16.43 |
| 0.5 | 0.5 | 0 | 0 | 16.43 |
| 0.5 | 0 | 0.5 | 0 | 19.8 |
| 0.5 | 0 | 0 | 0.5 | 20.3 |
| 0 | 0.5 | 0.5 | 0 | 16.43 |
| 0 | 0.5 | 0 | 0.5 | 16.63 |
| 0 | 0 | 0.5 | 0.5 | 16.43 |
| 1 | 0 | 0 | 0 | 23.14 |
| 0 | 1 | 0 | 0 | 22.75 |
| 0 | 0 | 1 | 0 | 17.08 |
| 0 | 0 | 0 | 1 | 17.87 |

As is visible in Table 8.1, the focus lies on leaving out one or more of the elements of the priority factor and augmenting the others such that the total still equals one. With the different weighting, a new work task order for the A06-check on the PH-BHO was made and the turnaround time was noted. A clear observation is that with the different weighting, the turnaround time often remained unchanged.

The reason for the turnaround time not changing is seen to lie in the critical path. Section 5.3 already discussed that when the critical path is untouched, the turnaround time is not altered. The same occurs when changing the weights in the priority factor. Only for some of the combinations leaving out the *Chain Duration* element, the turnaround time was seen to increase significantly. Not illogically this element assures that tasks in a long chain receive a higher priority. One might argue, however, that when the change in weight does not alter the turnaround time significantly, the idea of the heuristics is superfluous. Nonetheless, it was noticed that the entire work task order did change, even though the critical path and thus the turnaround time remained unchanged. Once again this proves that solely optimizing for the turnaround time is not ideal, inasmuch as infinitely many orders exist in which the turnaround time does not alter. Thus, the order does matter when taking into account the possible non-routine maintenance tasks. This unknown part of the maintenance check is desired to be known as soon as possible. Summarizing, having all elements of the priority factor present not only minimizes the turnaround time, it also assures that routine tasks with possible non-routine work are executed earlier. Additionally, the priority factor aids in the robustness of the work task order model, as the set of rules assure the same decisions are made every time again. The latter had already been proved in Section 5.3.

When one would like to further minimize the turnaround time, only one option is possibly available. That is, available manpower is to be increased. More manpower means that more tasks can be performed simultaneously. However, this also reaches a maximum due to the constraint maximizing the amount of mechanics per work area. To test what the ultimate minimum turnaround could be, the amount of available mechanics per skill and per shift was increased to 20. Surprisingly, the turnaround time was again 16.4 hours and thus unchanged. Once again the reason is the critical path, on which the maximum amount of mechanics per work area was already reached before the increase in available manpower. Only when the critical path changes, for example during the maintenance check when non-routine tasks are generated, an augmentation in the amount of available manpower could be beneficial. The Gantt chart in Figure B.6 displays the work task order for the case in which the amount of available manpower is increased. It is readily visible that most of the maintenance tasks are now performed at the start of the check, yet that the tasks in the critical path cannot be performed any faster with more manpower. Alternatively, the way in which the mechanics work on the engines and the wings is to be changed such that this work can be performed more efficiently; however, these kind of improvements are out of scope for this thesis.

# 9 Conclusion

In this chapter the conclusions of this research are laid out. By answering the seven research sub-questions stated in the Introduction with the discussed material in this report, the main research question will be answered subsequently. The main research question has been defined as: *How can on-time aircraft hangar maintenance performance be achieved through incorporating work task order improvement?* This chapter will end by providing an overview of the principle contributions of this thesis.

### What is the state-of-the-art in work task orders of maintenance tasks?

Within KLM E&M the order in which maintenance tasks are executed is solely based on experience. An optimal order cannot be guaranteed and the order can alter significantly between other similar maintenance checks. Furthermore, since the work task order is purely static, the work task order cannot react to the situation during a maintenance check, nor does it provide insight in the status of the maintenance check. Additionally, the current work task order does not provide insight in an estimated turnaround time. Hence, maintenance work packages are only planned based on a manhour limit which does not provide any information on the interdependence of maintenance tasks. To tackle these issues, the research has focused on producing a model which is data-driven and can schedule maintenance tasks both proactively and reactively.

### What is the current performance of the A-check on the Boeing 787 at KLM E&M?

In the data analysis performed on the Boeing 787 A-check at KLM E&M in Section 3.4, the current performance was seen to be below par. The agreed turnaround time of 17.5 hours was only attained in 33% of the A-checks since the introduction of the Boeing 787 at KLM Royal Dutch Airlines. Furthermore, this section stressed the importance of non-routine work. Even though non-routine tasks do not always lead to an augmentation of the turnaround time, it is an important part (30%) of the entire work package. It is therefore important to perform the inspection tasks with a high chance of leading to extra non-routine work as early as possible in the maintenance check. Moreover, it was seen that the scheduled manhours do not have a clear relation with the turnaround time. Hence, the work package planners at KLM E&M would benefit from additional information on whether the content of the maintenance check allows for an on-time performance.

### What is a robust approach for the work task order model?

A robust work task order model is described as being a model which assures that the order does not alter significantly when one or more tasks are added or removed. This should be the case both during the maintenance check, as well as between similar maintenance checks. Namely, two maintenance checks consisting of nearly the same tasks, should not differ greatly in their work task order. A robust approach was attained by the model building the schedule sequentially and basing its decisions on the combination of the priority factor and the set of constraints. The model was proven to follow a robust approach when random tasks were taken out and the schedule was seen to hardly alter. Undoubtedly, certain vital tasks, such as the opening and closing of panels, can never be removed without disturbing the schedule. Additionally, up until a certain amount of removed or added tasks the order will not alter significantly; however, when the amount of tasks taken out of or added to the data set becomes too large, the entire experiment would defeat its purpose: comparing work task orders of nearly identical data sets.

### What kind of model can be used to improve the work task order?

Models to improve the order of tasks or jobs have frequently solely been focused on minimizing the length of the schedule. These kind of problems are often modeled with the use of Mixed Integer Linear Programming (MILP) techniques. However, the problem as discussed in this report cannot only be solved by optimizing for the length of the schedule. This was seen to be due to the possible extra work in the form of non-routine maintenance tasks. When these kind of elements are not taken into account, a shorter initial schedule could lead to a longer final schedule. The problem in this report is therefore solved by using a constraint-based heuristic model.

The heuristic, which is based on minimizing the turnaround time, also assures the robustness of the work task order. It was discussed that improvements in work can only be attained when the work is standardized (and in this case robust to changes). Within the model, the heuristic is used in the form of a *priority factor*. That is, every maintenance task is assigned a priority factor. Based on the individual priority the maintenance task is planned within the maintenance check. Additionally, with the use of a constraint-based heuristic approach, the decisions made by the model are easy-to-understand and could potentially be reproduced by hand, albeit computationally intensive. This kind of model and its results lead to standardization of the maintenance check, which is the first step towards further improvements.

### What kind of constraints have to be incorporated in a work task order model?

During the research it was found that a set of constraints is necessary simply because not all tasks can be performed in parallel. The constraints were set up by keeping the physical impossibilities in mind. The result was a set of five constraints used within the model. Firstly, tasks with a set of predecessors can only be executed when all of its predecessors have been completed. Secondly, tasks taking place in conflicting work areas, such as the engine and the wing, cannot be executed simultaneously. The zone with the highest priority is executed first. Thirdly, all work areas have a certain maximum amount of mechanics that can work concurrently. Based on this maximum, the amount of parallel tasks is defined by the model. Furthermore, since tasks which require the aircraft power to be turned off disturb the process of the maintenance check, it was chosen for the model to only schedule these tasks during breaks. Lastly, maintenance tasks can only be executed simultaneously when the required manpower is available. The available manpower changes per shift and can also be altered during the check when the live situation changes.

### What is needed to reactively schedule the maintenance tasks during maintenance execution?

For the model to be able to reactively plan both the routine and the possible non-routine tasks during the execution of the check, it was noticed that information on the current status of the task is vital. With that information the model can decide whether the task has been completed already, is currently in work, or is to be executed yet. For non-routine maintenance tasks the priority factor was only computed based on its own estimated duration. Non-routine tasks which were not given an estimated duration, could not be planned by the model. With the set of non-completed tasks, the report then described in Section 4.4 that the steps taken by the model are similar to those taken for the proactive planning of the work task order.

### What is needed to implement the model at KLM E&M?

To be able to implement the described model in an organization such as KLM E&M, a certain amount of vital steps need to be taken. For the code to be stable and backed by an IT department, the model needs to be rewritten. Furthermore, it was indicated by some experts in the field that the computational performance of the model can still be improved upon. Additionally, to be able to use the model for different maintenance checks on different aircraft types, the used database should either be extended or the variable availability increased. Lastly, a user interface should be made to assist the user in running the model and visualizing the results, which the experts in Chapter 7 indicated to be insufficient at this moment. Next to these necessary steps, also a set of recommendations is provided in Chapter 10. These recommendations are not necessary, but can improve the model and ease the implementation at KLM E&M.

With the research sub-questions answered, the main research question remains to be tackled.

### How can on-time aircraft hangar maintenance performance be achieved through incorporating work task order improvement?

The research in this report focused on a constraint-based heuristic programming model to improve the work task order in aircraft hangar maintenance. By not only focusing on minimizing the turnaround time, but also on employing a robust approach which can both proactively and reactively plan the maintenance tasks, maintenance checks can be executed in a more standardized manner. The heuristic, based on minimizing the turnaround time, assures the tasks are planned in a robust manner both during the maintenance check as well as between similar maintenance checks. On top of that, an improved and semi-automatized work task order can provide insight in the estimated turnaround time and the status of the maintenance check. Maintenance checks can thus be planned more accurately with the use of the estimated turnaround time, instead of solely planning based on a manhour norm. Work packages will therefore become more stable. Moreover, a continuously updating work task order during the maintenance check provides information on the status of the check. When the maintenance check is bound to be completed late, the lead mechanic can decide upon the possibilities to assure an on-time completion. However, when on-time completion is deemed impossible, the lead mechanic is able to better communicate the end-time to the fleet planners at KLM Royal Dutch Airlines.

In summary, the work task order model can never *guarantee* an on-time completion of the maintenance check. On-time completion of the maintenance check is based on several other factors next to the order in which maintenance tasks are executed. However, this model aids in the process of augmenting the on-time completion performance and provides more information concerning the estimated turnaround time and the status of the maintenance check.

Lastly, the principle contributions of this research are stated. Whilst the individual contributions by itself are not filling an existing gap in both literature and industry, the combination of all is novel and has not been encountered before:

- Providing a work task order which tries to minimize the overall length of the schedule, whilst taking into account extra unscheduled work;
- Providing a robust work task order technique, meaning that the sequence will not alter significantly when one or more tasks are added or removed;
- Providing a work task order model which is able to both proactively as well as reactively schedule maintenance tasks;
- Providing a work task order model which takes into account available resources in the shape of manpower;
- Providing a work task order model which is applicable in industry, meaning that the computational time is within acceptable limits;

# 10

# Recommendations

Previous chapter discussed the conclusions on the performed research and the results from the case study. This chapter uses these conclusion to focus on the recommendations for future work, which, when implemented, could further ameliorate the work task order model.

- It is recommended that the work areas are revised. Currently, the work areas do not solely denote areas, yet also specifications to clarify either the sort of work, the necessary skill, or the moment in time the task should be executed. Clear work areas could also be narrowed down to allow for a better implementation of the constraint concerning the maximum amount of mechanics working in a work area. A more specific work area supports more mechanics working simultaneously.
- It is recommended that the zone block constraint is replaced by a *state constraint.* All maintenance tasks should in that case be assigned a state, e.g. engine open, flaps out, power off, etc. Conflicting states are also more extensive than the original conflicting zones.
- It is recommended to investigate the resulting work task order when the task duration and chain duration elements of the priority factor are combined into one *duration* element.
- It is recommended to investigate how the emergency transmitter tasks can be scheduled when the current method is not sufficient, e.g. by delaying B2-skilled tasks to make room for the emergency transmitter tasks.
- It is recommended to investigate the concept of rolling breaks. From a turnaround time perspective, it could be more efficient to have breaks at dynamic moments in time. Closely related to this concept are the power-off moments, which are now planned during the breaks. Breaks could, for example, follow from the best time to plan a power-off moment, instead of vice versa.
- It is recommended that the maintenance task database with the predecessor variable is replaced with an alternative. The database is set up manually and therefore not ideal with regard to new maintenance tasks or tasks on different aircraft types. One of the options is to write a program which can automatically detect the predecessors per task, potentially based on the ATA chapters. Another options is to add all predecessors as standard information on all maintenance tasks.
- It is recommended that the non-routine information of all routine maintenance tasks is updated automatically after a maintenance check. With the updated information, new maintenance tasks can be assigned a non-routine factor quicker and existing maintenance tasks have more reliable non-routine information (e.g. after a modification of a certain component).
- It is recommended that the estimated duration of all maintenance tasks is updated more regularly for the model to produce a better estimate on the turnaround time. Ideally, the duration of a maintenance task is intelligently tracked such that no human input concerning the estimated duration is needed. The current human input is often biased: either the *suggested* duration is filled in or the *suggested* duration is augmented.

- It is recommended that the current results are compared to the results of an optimization model, in which the robustness of the approach is less important and more emphasis is put on the minimization of the overall length of the schedule, including the extra unscheduled work. For example by exploring stochastic models.
- It is recommended that all hangars within KLM E&M use so-called open/close maintenance tasks. These are tasks which denote a specific panel or door to be opened or closed for maintenance. With these kind of tasks, predecessors can be defined more easily. Moreover, task durations will be more accurate because the same duration is currently used throughout all hangars, even though it does or does not include the actual opening or close of the panels, depending on the specific hangar.
- It is recommended to investigate the task duration when multiple mechanics work concurrently on the same maintenance task. Currently, the task duration is based on the duration of work for the stated amount of mechanics, even though the task could potentially be executed faster with more mechanics assigned to the task. This is for example the case for the seat inspection in the cabin.
- It is recommended to implement an intelligent way of assuring tasks belonging together are also planned together. It is often quicker to execute similar tasks in series than to wait and return to the same work area at another time to perform nearly the same maintenance. A suggestion would be to smartly combine tasks with the same ATA (sub)chapters.
- It is recommended to investigate a *bucket-type* approach, in which tasks are either bundled together based on aircraft work area or bundled together for each mechanic. This might aid the efficiency of the work and the insight in the overall progress.
- It is recommended that lead times for ordered materials are taken into account. To be able to do so, the current system at KLM E&M has to be replaced such that the materials can be tracked and an estimated delivery time can be provided. With the lead times available, non-routine maintenance tasks for which materials are ordered, can only be planned by the work task order model on or after the estimated delivery time.
- It is recommended that the available manpower per shift is updated automatically instead of the current manual fashion. For this, the software at KLM E&M behind the manpower needs to be improved or replaced. The change minimizes the labor to be able to use the model and also allows for a future implementation of *automatic appointing*. This enables the model to appoint an available mechanic by itself, such that the lead mechanic does not have to appoint all maintenance tasks manually.
- It is recommended to rewrite the model more efficiently. A rewritten code aids in the computational performance of the model, which was seen to be an important factor for the model to be implemented within KLM E&M. Moreover, an implemented model within an organization as KLM E&M needs to be stable. In case of any problems, an IT team needs to be able to help and solve these issues.
- It is recommended that the visualization of the model's results is improved upon. A user interface designed with user experience in mind will not only declutter the current way in which the Gantt chart of maintenance tasks is represented, it will also enable the user to run the entire model, which is currently only possible by physically running the Python code. Furthermore, also other visualizations which clarify the status of the maintenance check could be added. For example, a view on the aircraft could denote the status of all different work areas. Additionally, a combination with the aforementioned *bucket-type* approach could be investigated.

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# A

# Detailed Flowcharts

This Appendix depicts the flowcharts of the work task order model. A global overview is presented first, after which the detailed graphical explanations are provided.

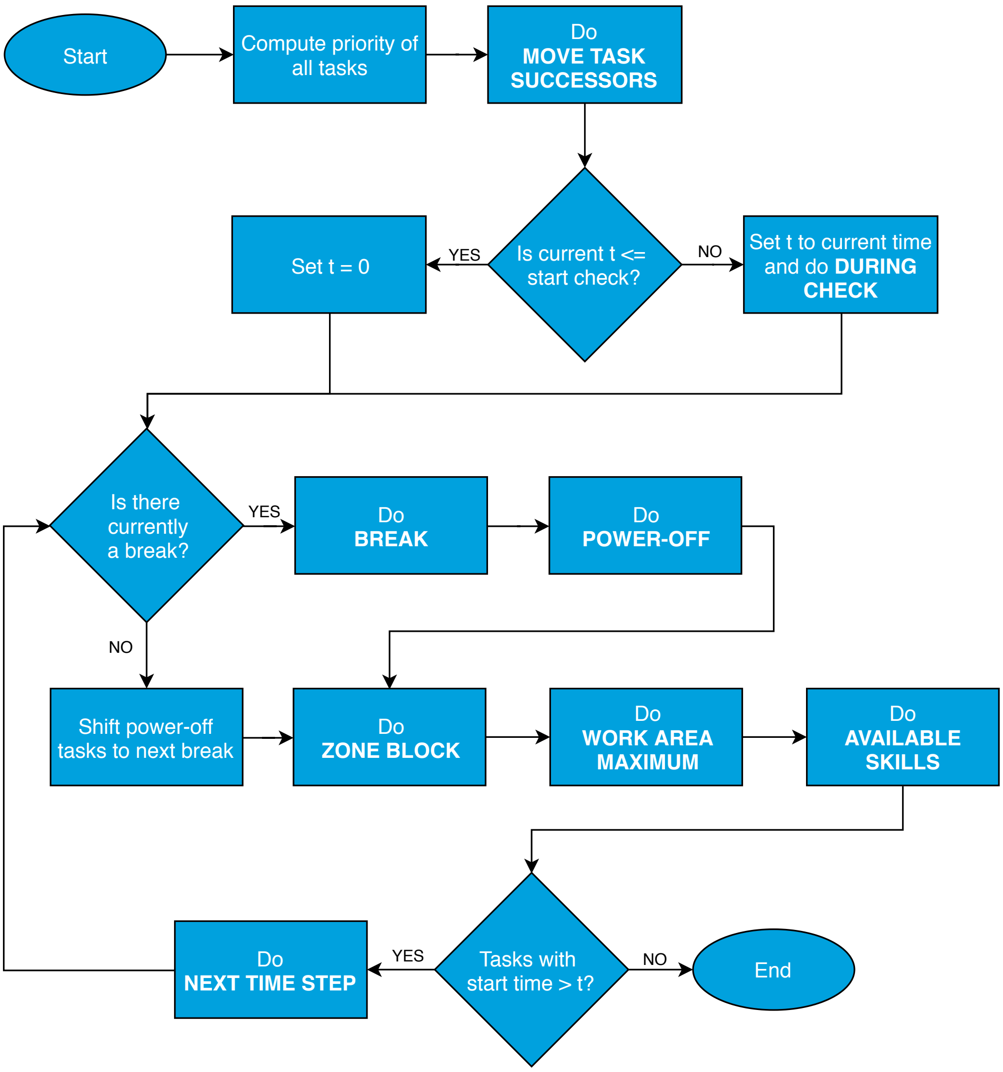


Figure A.1: Detailed flowchart of all steps taken by the work task order model

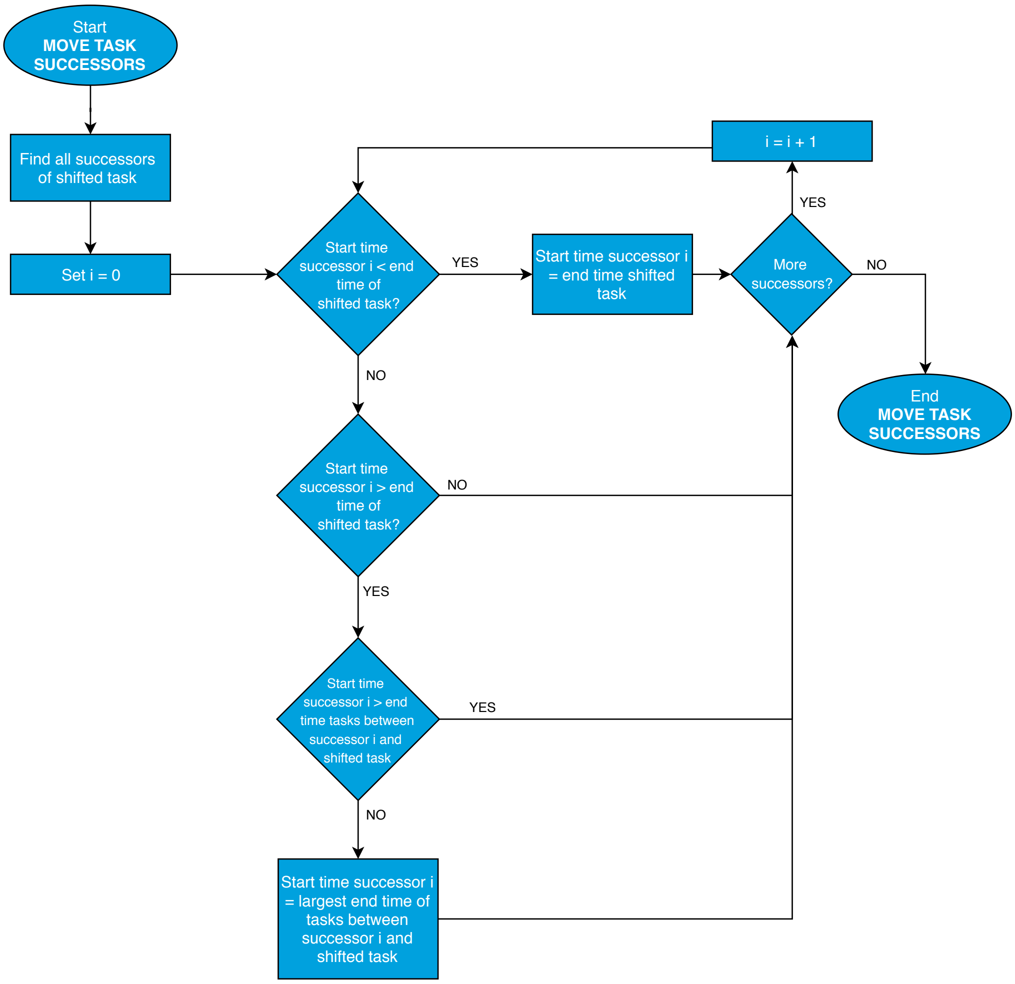


Figure A.2: Detailed flowchart on how task successors are moved within the work task order model

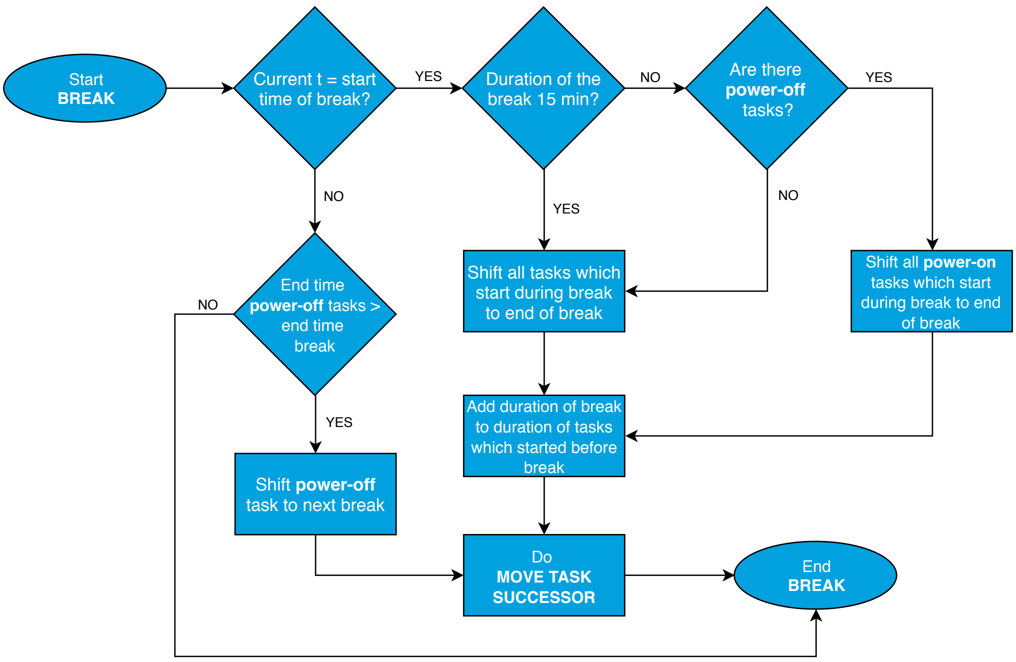


Figure A.3: Detailed flowchart on the models checks the breaks and power-off constraint

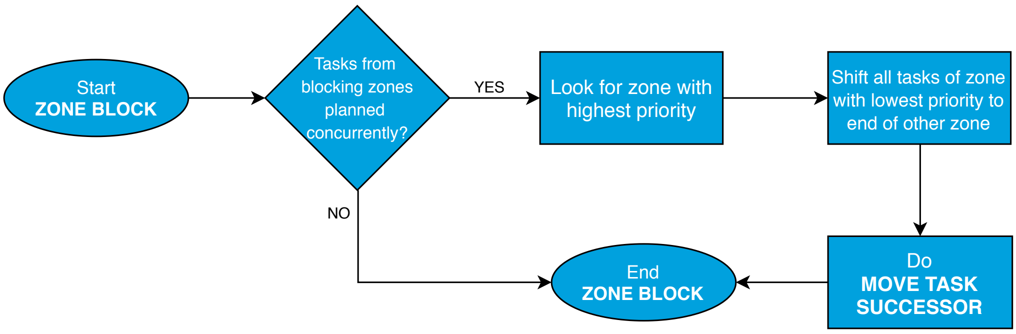


Figure A.4: Detailed flowchart on how the conflicting zone constraint works within the work task order model

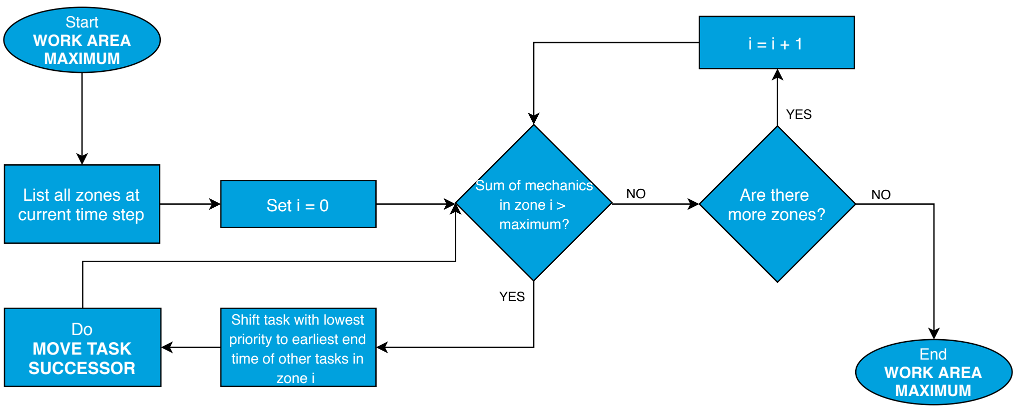


Figure A.5: Detailed flowchart on how the constraint on the maximum amount of mechanics per work area is used

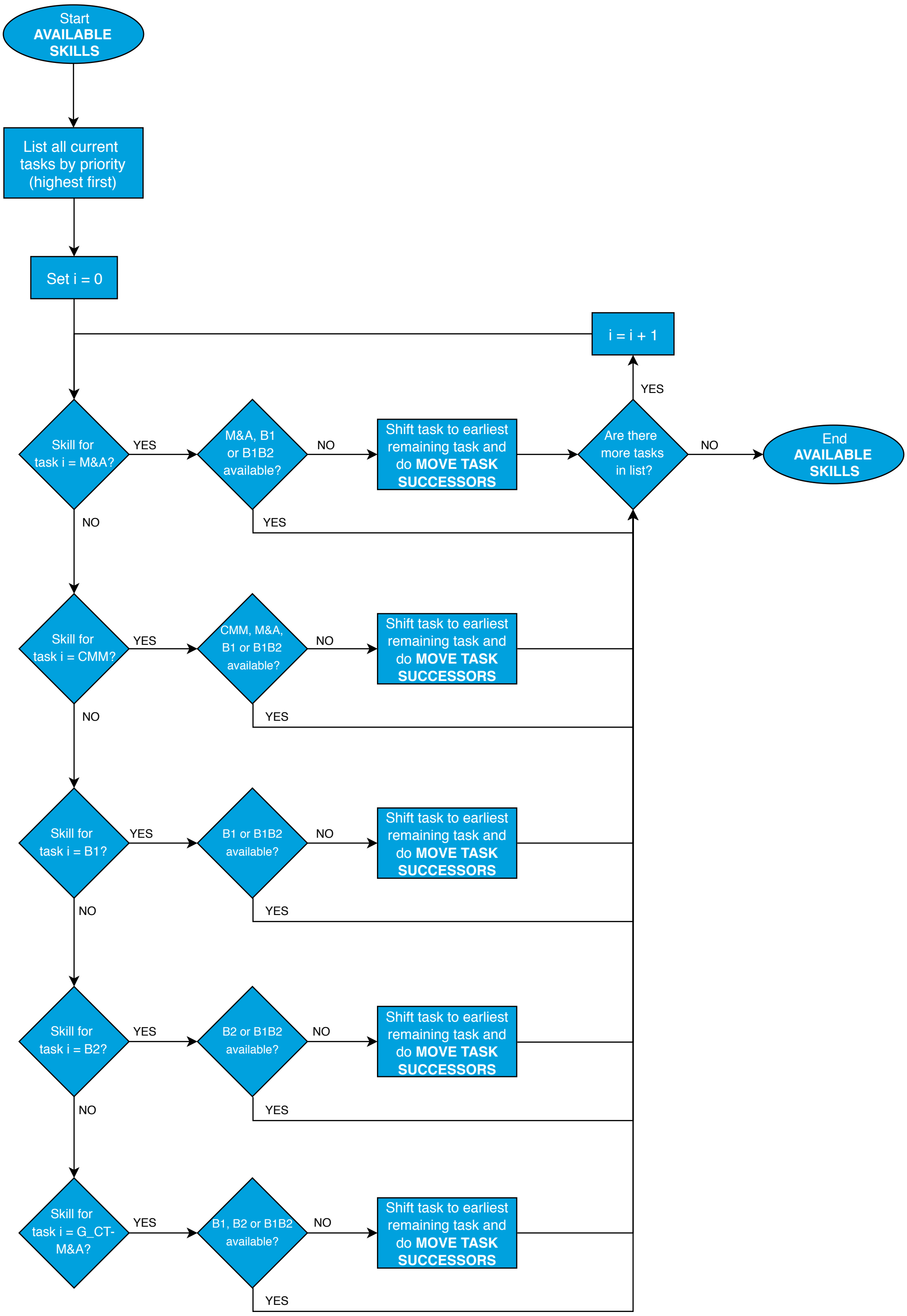


Figure A.6: Detailed flowchart on how the *waterfall method* works within the work task order model

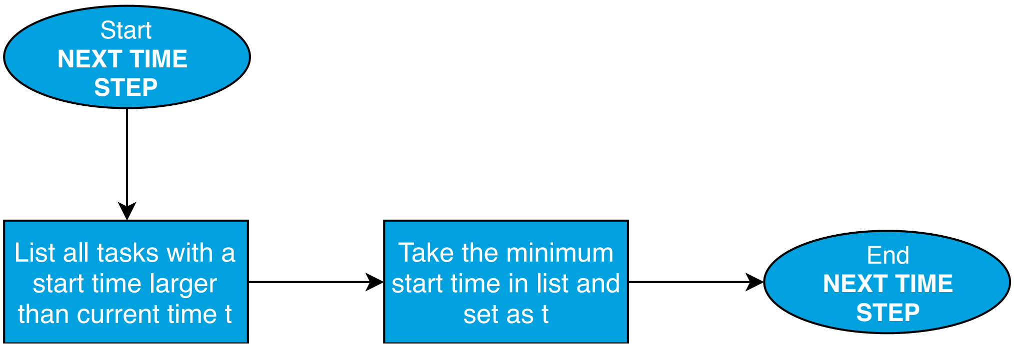


Figure A.7: Detailed flowchart on how the work task order model chooses the next time step

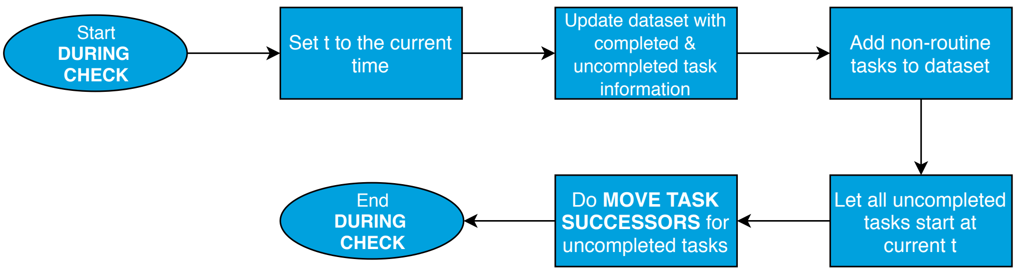


Figure A.8: Detailed flowchart on the reactive scheduling of the work task order model

# B
# Gantt Charts

This Appendix shows the Gantt charts of the A06 check on the PH-BHO. The first Gantt chart in Figure B.1 presents the normal work task order as produced by the current model. The other Gantt charts show an alternative work task order when either the reactive scheduling is show, tasks are removed or manpower is increased. Also, Figure B.5 shows the actual order after the execution of the A06 check on the PH-BHO.


Figure B.1: Gantt chart of the A06-check on the PH-BHO

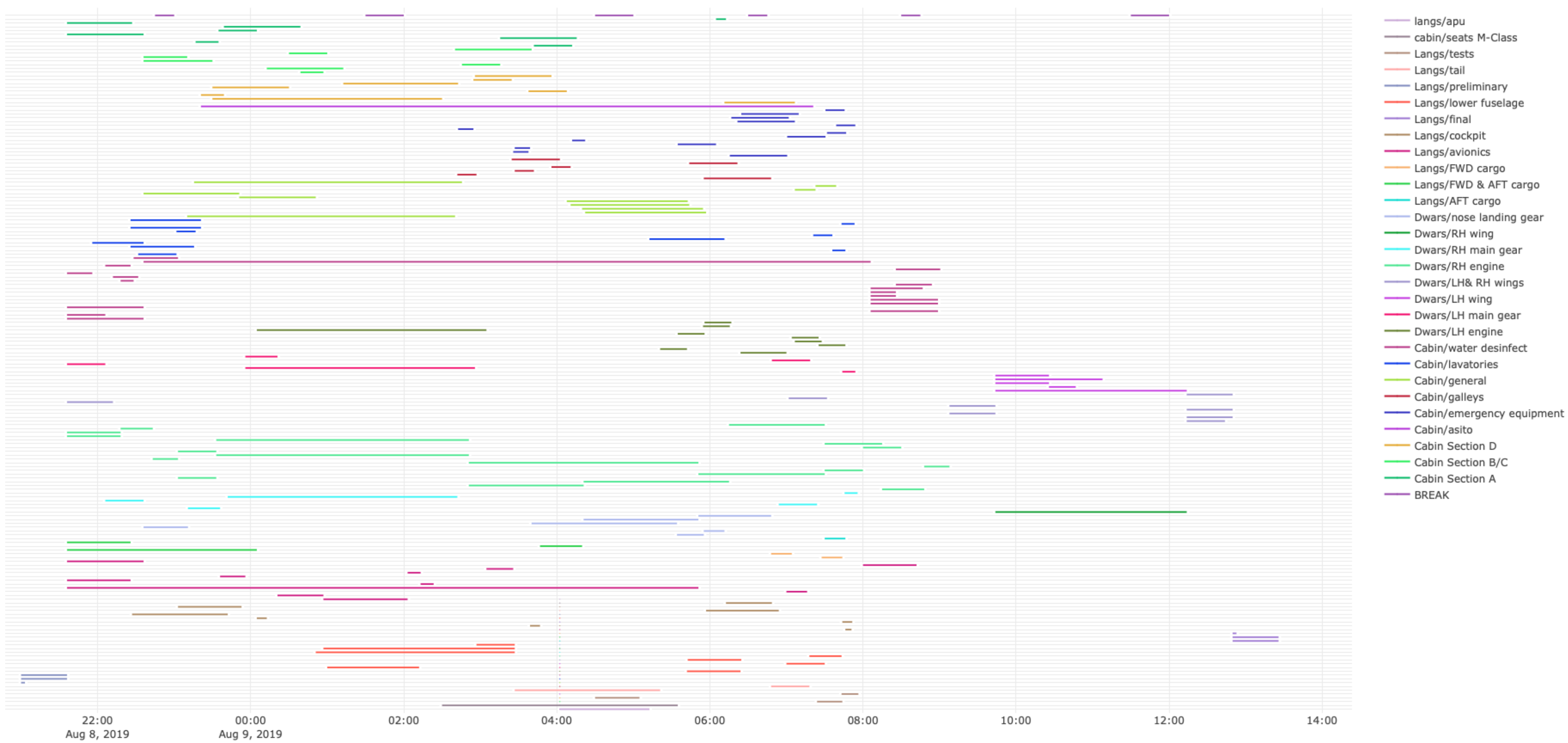


Figure B.2: Gantt chart of the A06-check on the PH-BHO with one task removed

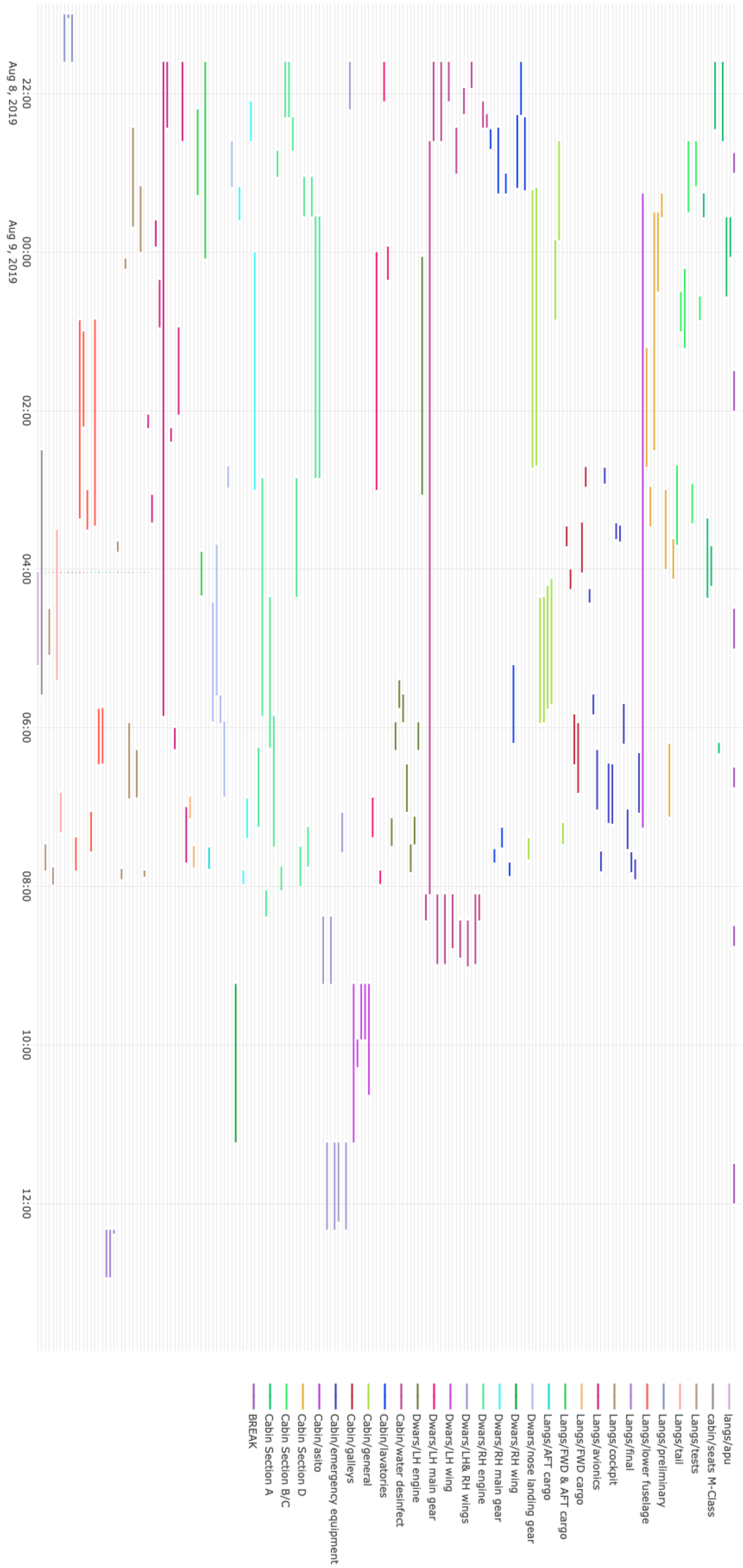


Figure B.3: Gantt chart of the A06-check on the PH-BHO with one task removed from the critical path


Figure B.4: Gantt chart of the A06-check on the PH-BHO during execution, showing reactive scheduling

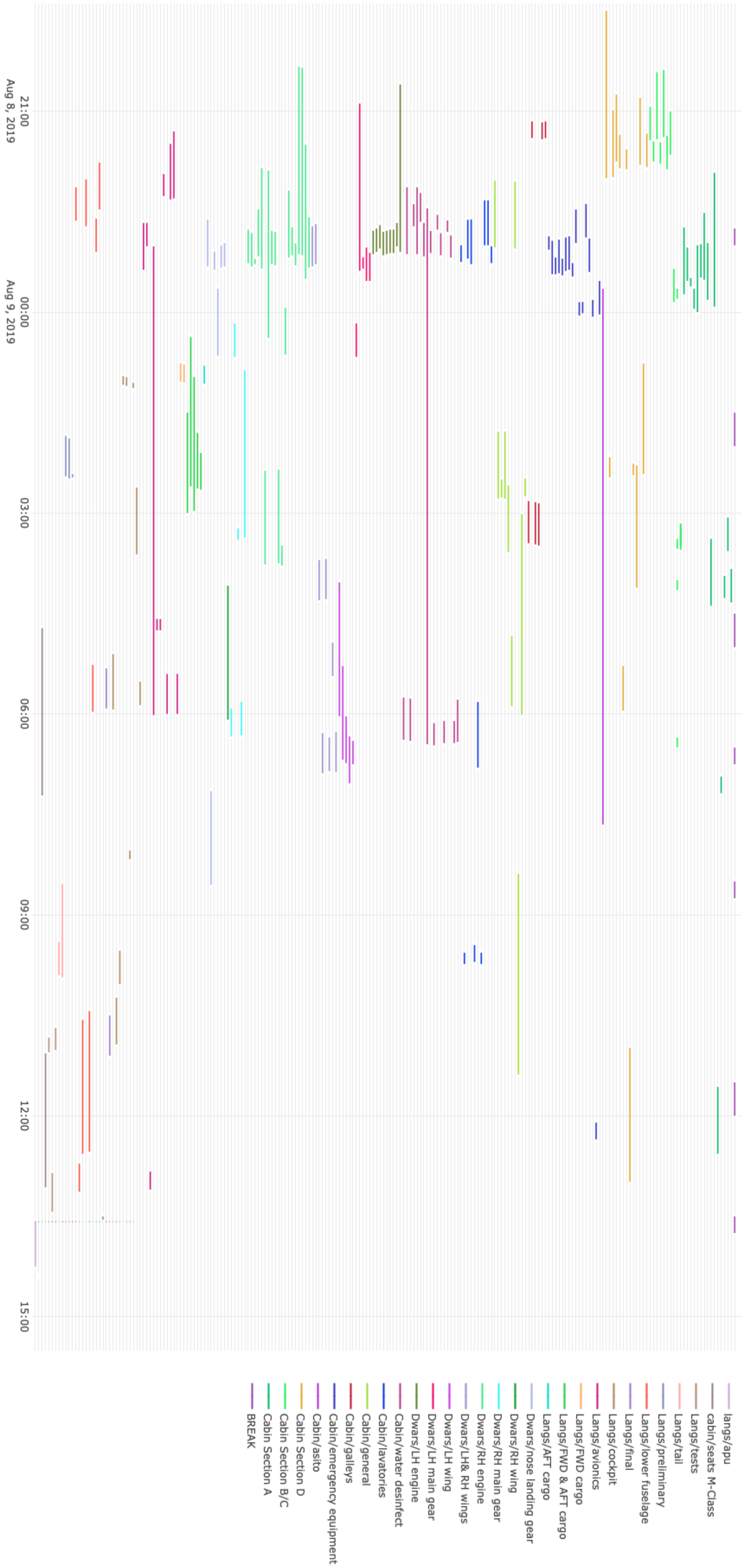


Figure B.5: Gantt chart of the A06-check on the PH-BHO, after execution of the check

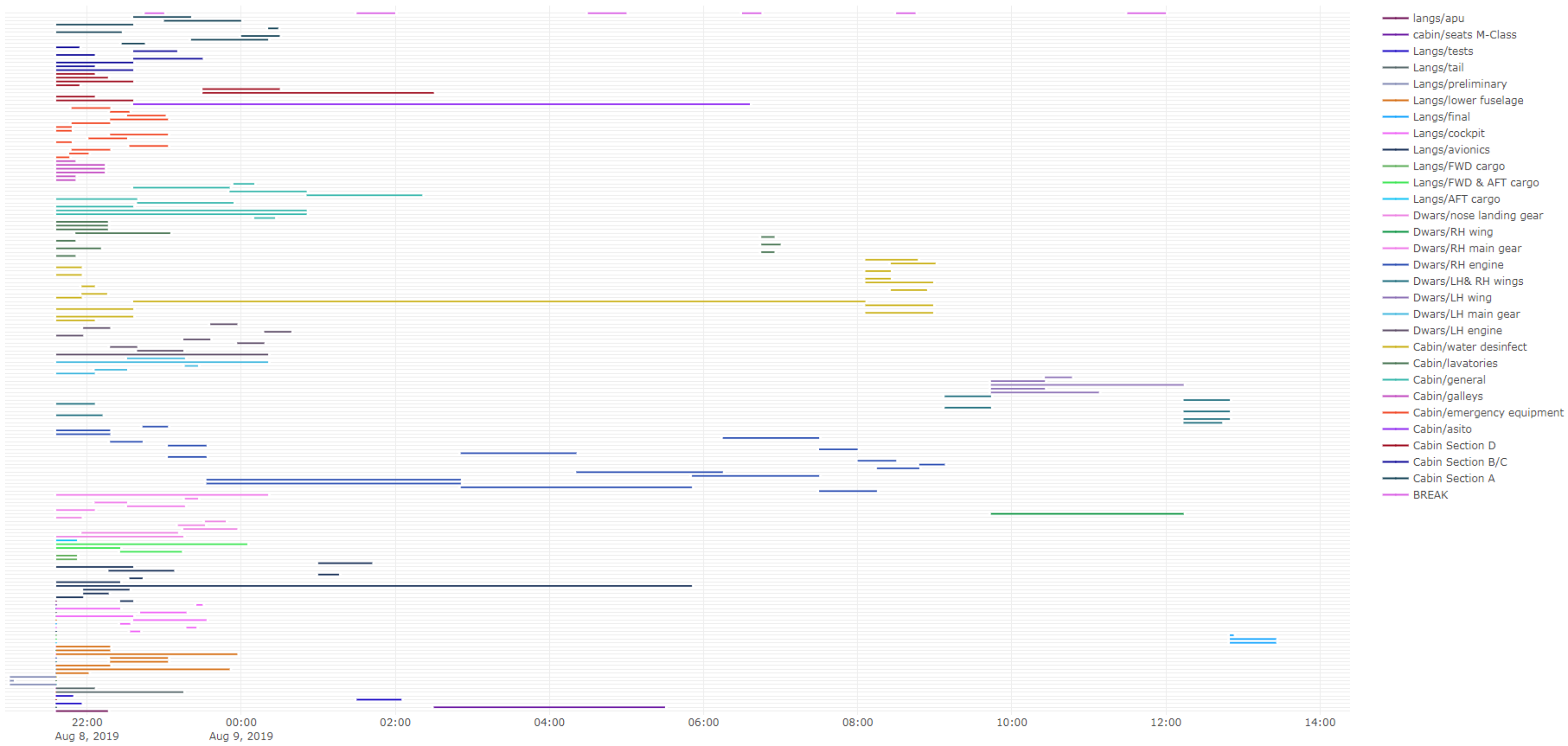


Figure B.6: Gantt chart of the A06-check on the PH-BHO, with increased available manpower