Aligning logistics with MRO to improve spare parts availability

A case study at KLM Engineering & Maintenance

by

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TIL5060 Graduation project

Aligning logistics with MRO to improve spare parts availability

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Summary

Most MRO systems deploy through a closed-loop supply chain. A central depot functions as the main stocking facility of spare parts. Once these parts, or components, are used up, they are restored and re-stocked in that same warehouse. Larger MRO systems, which have excess capacity, not only provide the service of restoring to their own parts, but also commercialise their capacity through providing the service to third parties or customers. However, when the capacity fails to achieve the desired output, services are often outsourced. Besides capacity, required skill set, available secondary resources, and labour intensity are often factors that weigh in the decision to outsource specific services. Especially the aircraft component MRO supply chains are facing specific challenges, of which the majority is caused by deviating demand characteristics. Previous research has aimed to minimise these challenges primarily from an inventory allocation perspective or through business process design.

The research is conducted at one of the world its largest aircraft (component) MRO companies: KLM Engineering & Maintenance. The company deploys through a similar supply chain as described above. Time is predominantly used as performance measure. The time to restore a component from the moment it is removed from an aircraft until re-stocked is the time to restore. This aggregated time configuration is divided on two separate delays: administrative and logistics delay and repair lead time. The latter depends on the required work scope and the facility in which the MRO services are provided. This also determines the cost. Currently, cost are not considered in the decision to outsource or not, but is largely affected by this decision. Concluded from the data of the case study outsourcing takes longer on average. Outliers of in-house repair lead time may result in the conclusion that for these cases, outsourcing may be a viable option. The repair vendors are often large organisation with a significant higher capacity than the in-house workshops. The vendors that operate the fastest provide these services at a relatively high price, which portrays the trade-off between time and cost.

Currently, large shares of jobs are pushed to repair shops and vendors which have either proven to deliver relatively late or at high cost, whereas the shops that provide a smaller share of services have the potential of performing well. The topic of this study is therefore a task allocation problem to distribute the different parties in the closed-loop supply chain. Fourteen assignment policies are developed and evaluated using discrete event simulation. The system is scoped to one central depot, six repair vendors, and five repair shops. The choice for these repair facilities is substantiated by their amount of services and available skill set. In other words, a certain commodity type can be repaired by multiple shops or vendors. The developed assignment policies which represent shop selection expression can be divided in four categories: random, time bases, cost-based, and mixed. All the policies in these categories are elaborated with the addition of priority to larger tasks to restrict the probability of excessive delays. The random assignments only considers the commodity types, which limits the list

of candidate shops. The time based assignment policies include a naive policy where only the active repair time is considered and two policies that also incorporate the load at each candidate shop. The addition of load results in a limited amount of inflow in the shops that, initially, reveal the lowest repair lead time. Hence, buffer accumulation is avoided. The second category of policies is cost based. Two policies are developed that aim to minimise cost of MRO whilst also considering the shop load. Additionally, priority assignment at the central depot is tested. Finally, a mixed policy is evaluated which includes a weighted multi-criteria selection expression. Both cost of MRO and active repair time respective to the shop load is included using different weights for both cost and time.

The results of this study consists of three parts: the current state, the assignment policies, and robustness of these policies. The current current state results are used for both validation as well as quantifying newly set performance metrics, such as resource utilisation. This is used to measure the balance of repair jobs as a result of the assignment policies. When looking at the results at shop-level, the same results are found as analysed in the internal data. Hence, these results function primarily as a reference for the assignment policy results.

The result of the assignment policies in terms of the KPIs is a non-dominating set of solutions. The naive, random, and mixed policy with emphasis on the cost are not part of this set, for they do not compete with the remaining policies. The time based assignment policies are able to reduce to time to restore as a result of a lower repair lead time and administrative and logistics delay. Hence, the policy is able to allocate the tasks to the shops in a way the returning rate is more balanced over time. This improvement comes at a cost, for the cost of MRO is increased by nearly 10% over the run time of the model (104 weeks). The cost based assignment reveals a slightly increased time to restore as a result of a longer repair lead time (+14%), but also a reduction in cost (-27%). The mixed policies result in fall between the time and cost based policies. Based on the set system characteristics the mixed policy with emphasis on time presents an improvement in both cost as well as time.

The tests for robustness of the policies is performed by altering both the demand as well as the ratio of work scopes. The major repairs are increased, which affects the active repair time and the cost of MRO. The policies in which a priority is given to this work scope shows the lowest sensitivity. In some cases, the performance metrics are even improved compared to the base input. Generally, a slight reduction in demand does not result in any notable results, rather than for some shops the minimum time is reached in the steady state of the model (min-average). This also applies to the administrative and logistics delay. Cost of MRO remain equal, due to the fact that the work scopes are not altered. By increasing the demand, the time to restore rises considerably. The majority of this increase is a result of fully utilised resources at the central depot, causing large buffers at the central depot. The actual repair lead times are not influenced majorly with regard to most assignment policies. The prioritised assignments show no change or even a decrease in time and cost of MRO. The second scenario tested is the increase of major repairs. Again, the prioritised assignment policies perform best overall in terms of robustness.

The most effective policy depends on the importance that is given to either cost or time. In only few scenarios a Pareto optimum is achieved, where at least one policy dominates over the other. This is a managerial implication for KLM E&M, as to decide what performance metric is considered most imperative. A more practical implication from this study is to re-evaluate the available flexibility KLM E&M has with regard to the contractual agreements with the repair vendors and shops. Furthermore, sharing of information in terms of load and available capacity of all vendors and shops results in a more balanced allocation of jobs and therefore reduces any buffer holding times and thus the overall time to restore a component. Additionally, it is recommended to adopt the classification of priority to the unserviceable components. By providing priority to larger tasks, the probability of large delays is limited. Especially in the context of aircraft component MRO where demand rate is stochastic, priority assignment provides robust results in terms of performance.

This research does cope with several limitations. The first one is the lack of data and the reliability of the available data. Different data sources are used as input in the simulation, which facilitates the connection of the data. Furthermore, opportunities for future research lie within the inclusion of transportation schedules, for this is hypothesised to be of large influence on the total repair lead time of a component. The model considers a continuous flow. Hence, components are directly pushed to a repair shop or vendor once it is finished with administrative and logistics handling. In the actual system these are batched onto an aircraft of truck, depending on the assigned repair facility. This research project made a selection of repair shops for the analysis of the problem and evaluation of the assignment policies. However, by considering additional commodity types, such as wheels and engines, many other shops are involved. For these commodity types other shop selection expressions may be in place.

Preface

The thesis that lies before you is written to complete the masters program of Transport, Infrastructure and Logistics at the Delft University of Technology. The topic of this study was the allocation of aircraft component maintenance, repair and overhaul services to multiple repair shops and vendors, carried out in collaboration with KLM Engineering & Maintenance.

First and foremost, I would like to express my gratitude to my thesis committee. I want to thank Mark Duinkerken, who always had eye for detail and therefore provided much, but very much justified, feedback. This does not only apply to the content of this study, but also regarding more practical things such as writing the report. Secondly, I would like to thank Yousef Maknoon, who I have met with less frequently at the end of my thesis but regardless of that still saw right through any insecurities I had on my work and therefore actually played a considerable role in the supervision. Finally, I also want to thank the chairman of my committee, Lóri Tavasszy, who facilitated mental support during the meetings and gave very helpful feedback from a more aggregated perspective.

Finding my way in a big organisation and getting in touch with the right people has been difficult in the beginning. Therefore, I want to thank all the people at KLM E&M that made my internship possible, easier, and enjoyable. Everybody was extremely helpful and were always available for questions. This includes my supervisor and all the other employees with many different functions I have spoken to. Furthermore, I want to thank the fellow interns for the coffee breaks and interesting and fun walks through the hangars.

Many thanks to my family and friends who have stood by me throughout the entire graduation process. Special thanks to my parents who supported me unconditionally. My mom, who always provided a listening ear when I needed and did everything in her power to make the whole process easier for me. My dad, who contributed with his advice on how to deal with the challenges in big organisations such as KLM E&M. My sisters, who helped by distracting me from the work occasionally. To my boyfriend, thank you for all the support, laughter, and carefree moments. Not to mention my friends from home, who always either shown interest and motivated me or simply allowed me to take my mind elsewhere. Finally, special thanks to some of my fellow TIL students, who have become real good friends. I could not have done this without our lunch and coffee breaks, moments of complaining, working on our theses, walks over campus, and of course the laughter.

Nicole Bosdijk
Delft, July 2019

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Introduction

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1.1 Background

The focus on maintenance, repair and overhaul (MRO) as a separate profit centre has evolved in recent history. Especially in the aviation industry. Before airlines were deregulated, the majority of the carriers and airlines conducted their maintenance in-house. To this day, industries are depending largely on their maintained capital equipment, putting pressure on the efficiency of MRO activities. After fuel, maintenance is the largest operational cost component for aircraft carriers and airlines. Therefore, the downtime of an aircraft, when due for maintenance or component exchange, is aimed to be minimised. Quick dispatch of an aircraft requires availability of spare parts (Kashyap 2012). Larger maintenance, repair and overhaul (MRO) organisations have commercialised this demand and have created a pool of these parts or components. The airline can then request a component from this pool. The requested 'serviceable' component is then exchanged for their 'unserviceable' component. The unserviceable component is shipped back to the MRO provider, repaired, and finally re-stocked to be further exchanged in the future (Kilpi et al. 2009).

Established airlines used to have their own shops for component repair and replacement. Nowadays, some of these repair activities are still performed in-house, but many services are outsourced. Airlines, and even MRO providers, look for component support solutions that are flexible, with predictable costs (McFadden and Worrells 2012). As a result of lacking capital to start up own maintenance programs or due to carrier's cost cutting efforts, the phenomenon of outsourcing MRO services previously in-house efforts has risen (McFadden and Worrells 2012). Since this is rather new, real benchmarks on outsourcing decisions, as well as the fitness of vendors being considered, are lacking (Wezter et al. 2012). Generally, outsourcing does not reduce MRO cost but it is likely to increase the technical punctuality (Al-Kaabi et al. 2007).

The context of aircraft MRO and spare parts management consists of multiple challenges that heavily impact the availability of spare parts. Firstly, the spare parts are rather heterogeneous in terms of specificity, criticality, and physical characteristics. In addition, The amount of spare parts for aircraft MRO is enormous. These different parts result in varying life-cycles, which facilitates to a fluctuating demand pattern (Ghobbar and Friend 2003). Aircraft spare parts demand rates for 'operational type' items, such as brakes and tires, can be forecast with few challenges. However, the demand for other parts, such as wing tips and stabilisers, which do not have a discernible rate wear can be rather erratic and unpredictable (Brown 1956).

Case study: KLM Engineering & Maintenance

This research project is collaboration with one of the worlds leaders in aircraft MRO: KLM Engineering & Maintenance. KLM Engineering & Maintenance (KLM E&M) is part of the Air France-KLM Group, specialised in aircraft MRO services. It maintains three large pools of spare parts located in Amsterdam, Kuala Lumpur and Miami (Spaan 2018). With approximately 5,000 employees, KLM E&M is the third business of KLM Royal Dutch Airlines, next to Passenger Aviation and Cargo. Stationed at Amsterdam Schipol Airport, KLM E&M is able to facilitate 10 wide body and 11 narrow body positions and deploys various storage, repair, and test facilities. Its core business is to guarantee flight safety, manage aircraft operation management, whilst minimising operational cost. The division Component Services is responsible for the availability of serviceable parts to both KLM as well as other customer airlines. The logistical chain of activities to restore a component, as deployed by the company, is visualised in Figure 1.1. For this research project data and process logic by KLM E&M is used.

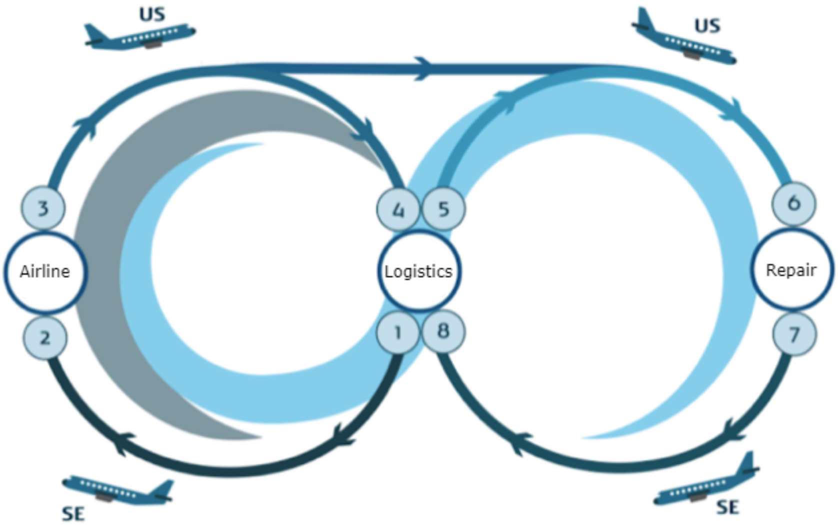

Fig. 1.1.: Closed-loop supply chain (KLM E&M 2018)

1.2 Problem statement

The MRO supply chain creates demand globally. Therefore, it is most efficient for large maintenance facilities to hold components at central warehouses closeby (Axsäter 1993). The management of inventory is rather complex as they suffer from low consumption probabilities on component level, large varieties in demand size over time, many different components and high inventory holding costs (Cohen and Wille 2006). Many research is performed regarding inventory management and demand forecasting in similar fields as aircraft MRO (Axsäter 1993; Ghobbar and Friend 2003; Regattieri et al. 2005). This research project focuses on the reduction of the time to restore a component from the time of entering the MRO provider's network until the moment of re-stocking whilst coping with the challenges of the industry rather then trying to eliminate them.

Generally, an aircraft component MRO system consists of a central depot, internal repair workshops, and repair vendors for outsourced repair (Rezaei Somarin et al. 2018). The deployment of storage, service (MRO), and distribution takes place within the system. Customer airlines send in a request for a serviceable part from the central depot, which is thereafter exchanged for the unserviceable in need of MRO part[1]. The unserviceable part is shipped to the MRO operator, where it is initially determined which repair facility takes on the repair for that specific part. The part is sent to repair, which can either be internal or external (outsourced).

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[1] Serviceable parts are airworthy, whereas unserviceable parts are in need of MRO

The part is thereafter sent back to the MRO operator where it is re-stocked in the central depot (Tracht et al. 2013). The situation in form of a system diagram is presented in Figure 1.2

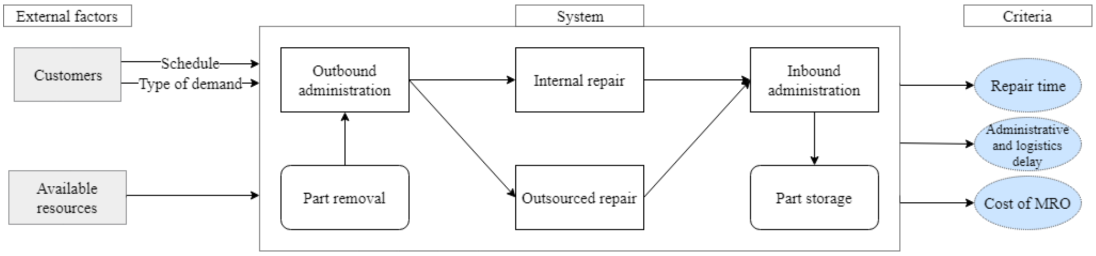


Fig. 1.2.: System diagram

External factors, which are the factors that are not assumed in defining decision variables, but are considered to be given parameters, are the available resources (man, material, and machines) and customers. The configurations variables are (repair) lead times, administrative and logistics delay, and repair cost. Based on these variables, the system its performance can be measured. Outsourced repair is part of this research' system, but from the perspective of the MRO operator used in the case study, no direct influence can be provided in terms of repair lead time and cost. Repair lead times are therefore also considered a given parameter. Additional explanation on how the outsourced repair is considered in this research is provided in Chapter 3.

The objective of MRO providers in general is to assure safety and punctuality of the aircraft. One of the main KPIs therefore deployed by aircraft (component) MRO providers, from the perspective of the customer, is the Service Level, being the percentage of on-time deliveries of certified serviceable components to customers. This requires availability of these components. Based on empirical data of the organisation used for this study, i.e. KLM E&M, over a period of 12 months, 47% of all orders were delivered too late. This amount equals 12,545 components. Often this is the cause ponderous repair lead times, which delay the re-stocking of components. This can either be at external repair vendors, on which KLM E&M has little power, or due to disturbances or overload of the in-house shops. Approximately half of all considered services are outsourced. The in-house shops are often not the cause of considerable delays. Nearly 80% of the internal MRO services are dispatched on-time. However, this is still not the 95% KLM E&M aims to. Outsourced repair is more often not performed as desired, compared to the target that is set by KLM E&M. Over 60% of the outsourced repairs are not dispatched on time. Figure 1.3 provides an initial visualisation of the differences in repair performance based on target lead times. In the figure the first five columns represent in-house workshops. The final six are repair vendors.

In addition to the repair lead times, the cost of MRO is another factor to consider. Where larger tasks, i.e. major repairs, are less costly to be performed externally, this is often remained in-house. Regardless of the fact that these so-called work scopes do not occur as often as regular inspection and minor repairs, a large share is remained in-house. Table 1.1 presents the average cost of MRO per work scope and allocation, being either in-house or outsourced. Major repair jobs are approximately four times more expensive if remained in-house, while the highest share of this work scope is performed by KLM E&M. The overhaul work scopes are better distributed in terms of share and cost. Another notable finding is the cost and share of minor repairs. The largest amount of outsourced jobs are minor repairs, whereas this type of work scope is considerably more affordable if performed in-house. The distribution of

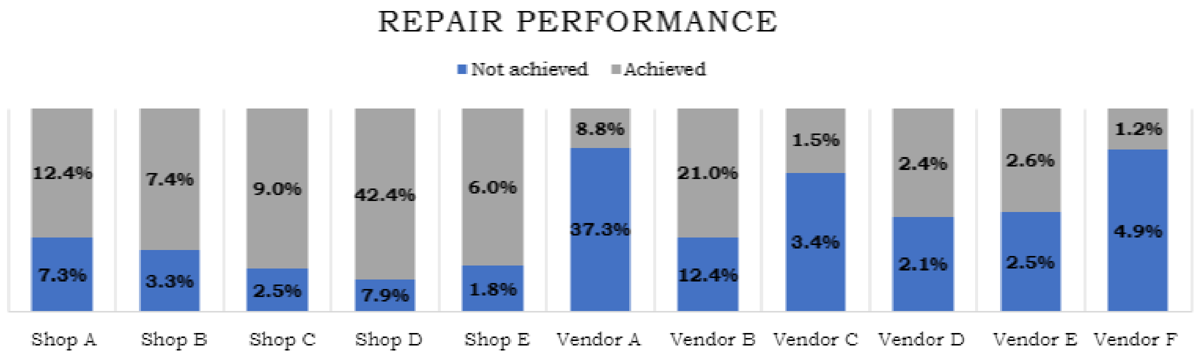


Fig. 1.3.: Repair performance of shops and vendors

MRO services compared to the respective cost results in the supposition that this, generally, performance metric is not quite considered in the decision to outsource or not.

Tab. 1.1.: Cost of MRO: outsourced and in-house

Work scope	In-house	Outsourced
Inspection	$3.198,9	$5.247,4
Overhaul	$9.272,2	$4.066,9
Minor repair	$1.042,8	$7.878,9
Major repair	$10.922,5	$8.160,1

Availability of spare parts can be improved from two perspectives defined from the MRO provider. Firstly, high work in process (WIP) buffers of spares can be deployed to ensure on-time deliveries to customers. Secondly, proper control over the entire turnaround time of the components within the closed loop supply chain (Driessen et al. 2015). This research project focuses on the latter. Currently, the control over the different departments within the system (logistics, internal repair and outsourced repair) is not integrated. In other words, these departments are, on a tactical and operational level, managed independently, whereas the activities are rather interdependent. Furthermore, the aviation MRO industry is challenged by low consumption probabilities, variation in demand, and many different parts with high inventory holding costs. Besides proper inventory policy strategies, a robust logistics strategy is desired to deal with the variances and stochastic factors in order to deploy proper control over the turnaround time (TAT) over the components in the exchange cycle, whilst also considering the cost of MRO at each respective repair shops. This allows further control and optimisation of the customer service level and inventory levels (Van Hoek et al. 1998).

1.3 Relevance of study

1.3.1 Scientific relevance

Numerous research is performed in the context of aircraft component MRO and aircraft spare parts availability. The main fields of research are demand forecasting for inventory management, scheduling of aircraft MRO, and the use of process optimisation tools and methods, often originating from the LEAN and SixSigma theories (Kashyap 2012; Massey 2005;

Vieira and Loures 2016). Generally, it aims for methods and approaches to eliminate or reduce the challenges as a result of the intermittent nature of demand of aircraft components, such as re-allocation of inventory or specific procurement decision rules. Often a single objective is considered, being predominantly holding cost and turnaround time. The most used research methods include statistical analyses, optimisation, and simulation.

This research is founded from the mean downtime of an aircraft. This period is conditional to the availability of components or spare parts. This is further elaborated on in Section 1.4. However, it is not analysed from the perspective of the availability of these components by means of proper inventory management. It takes the entire closed-loop supply chain in consideration. In other words, the replenishment of inventory is dependent on the time it takes to restore a previously used component. Moreover, it considers the administrative and logistics processes as a considerable part in this supply chain and aims to align all processes to reduce the overall time to restore. Not only is the time given due consideration, it includes the cost of certain decisions. Hence, a multi-criteria approach is established.

1.3.2 Practical relevance

KLM E&M is facing issues with the controlling of the TAT, as flow disruptions often occur at shops where no direct influence can be administered. In-house repair is preferred, for this is the least costly to the MRO provider and allows more control over the lead times, but due to their rise in customers and therefore demand as well, capacity constraints occur. Outsourcing or re-allocation of repair jobs is therefore a viable option. Currently, this is rarely deployed because data is poorly integrated between the different departments. Many complexities occur during the administration, logistics, and repair to provide MRO to unserviceable components. Previous research has predominantly focused on overcoming these complexities by means of scheduling problem solving, business process management, implementation of process optimisation theories such as Lean and Six Sigma (Choo 2004). This research project takes on coping with the complexities by redesigning the policies that align the logistics with repair. It shows the benefits of integrating data from different sources for decision-making on tactical and operational level of management (Lenzerini 2002). Research results are, in all cases, to be communicated to the industry to have a proper effect on the practice of operations (Gu et al. 2007).

1.4 Research objective

Operational availability of an aircraft is determined by the mean time between maintenance (MTBM) and mean downtime (MDT). The MDT is largely dependent on the availability of spare parts, which is, to a great extent, determined by the the time in which repair, transportation, and administrative or logistics takes place in order to re-stock these parts. Hence, the availability of spare parts can be achieved by either increasing the MTBM or decreasing the MDT (Rodrigues et al. 2000). This research focuses on the latter. The main performance indicator is the time to restore (TTR) an unserviceable component, being the time from removal due to the need of MRO until it is serviceable and re-stocked in the central warehouse. By shortening the complete TTR, chance of unnecessary grounding of the aircraft is reduced. The complete TTR can be divided in multiple different time indicators: repair lead times and administrative and logistics delays. Additionally cost are considered, being the cost to provide

MRO to a component. This depends on the component its characteristics, the type of repair required, and the respective repair facility.

Deliverables of this research project are different solution alternatives that contribute to a reduced TAT, or TTR. These alternatives are evaluated in terms of their performance, which facilitate final practical recommendations for KLM E&M. In order to obtain the research objective and the research deliverables the main research question is defined as follows:

How should MRO services of unserviceable components be allocated to various repair shops such that the time to restore and cost of MRO are taken into account?

To answer the main research questions and further structure the research sub-questions are formulated.

1. What is already known in terms of challenges and solution strategies in the context of (aircraft component) MRO?
2. What are the characteristics of the system in general?
3. What are the characteristics of the system in the case study?
4. What is the current performance of the studied system?
5. What solution alternatives can improve the performance of the systems?
6. What is the role and impact of the solution alternatives on the performance of the system?
7. What recommendations can be made regarding the alternatives?

1.5 Research outline

Figure 1.4 presents the outline of this research. The approach is predominantly based on the simulation framework by Shannon (1975). It can be divided in two main sections. The first part is the analysis phase, where literature is evaluated and data analysis is performed. Through a detailed diagnosis of the problem situation, solution alternatives are generated and tested through simulation.

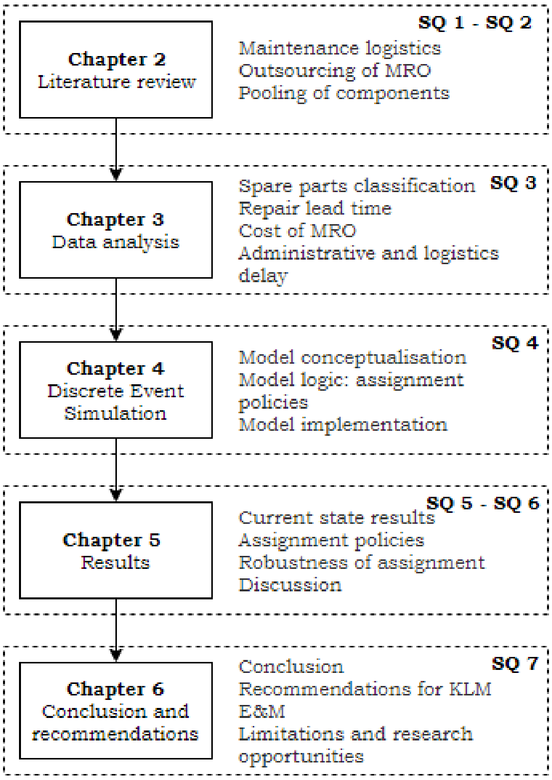


Fig. 1.4.: Research outline

2

Literature review

Operational availability of aircraft is dependent on the availability of spare parts. This can be in cases of maintenance, repair and overhaul. Driessen et al. (2015) states that the management of spare parts inventories is fundamentally different from the finished 'make and buy' products, due to their specific characteristics. These parts are not intermediate or final products to be sold to a customer (Kennedy et al. 2002). Two types of spare parts can be defined, where this research focuses on the former:

- Repairable parts: parts that are repaired rather than procured. After repair the part becomes serviceable again.
- Consumable parts: parts which are scrapped after replacement.

In this chapter a review is presented regarding the main issues in the field of spare parts management that are relevant for the problem situation at KLM E&M. In the end, a conclusion is presented of the main findings. Section 2.1 provides previous research and analyses on maintenance spare parts logistics. Additional information on performance measurement is also included here. Section 2.2 discusses previous research in the decision making on outsourcing certain services within the context of (aircraft) MRO. Both risks as well as opportunities as a result of outsourcing are presented in this section. Finally, Section 2.3 discusses the phenomenon of spare parts pooling. These three sections include topics that are applicable in the aviation MRO industry. Hence, challenges in these fields of industry are noted here.

2.1 Maintenance spare parts logistics

Macchi et al. (2011) uses further specification of spare parts are Shop Repleable Units (SRUs) and Line Replacable Units (LRUs). In the avionic sector LRUs can directly be replaced at exchange facilities, such as hangars, without direct intervention of the Original Equipment Manufacturer (OEM). For other modules, generally sub-components of the LRU, the OEM is required for support. These are the SRUs. Generally, the airline or the MRO operator batches the SRUs and LRUs that are in need of repair or maintenance to reduce the number of shipments and to control the cost of outbound logistics. The flow for the repair process starts with a failure analysis, after which the malfunction is diagnosed. The LRU is repaired, controlled/tested, and certified. A detailed process chart is presented in Appendix A.1.

The overall logistics performance is generally evaluated by measuring the Time to Restore (TTR). Specific time components encompass the logistics support to maintenance and repair activities For example, if a spare part is not retained, a supply time is needed for the delivery of the component that is to be replaced during repair. Moreover, administrative and logistics delay counts for the outbound logistics: the movement of the batch of SRUs from and to the exchange location. A long TTR negatively impacts the performance of the OEM and the service level agreed upon with the customer, as it increases the risk of Aircraft On Ground (AOG)

(Cavalieri et al. 2008). The whole TTR is visualised in Figure 2.1. As presented in the figure, the TTR is composed of three elements:

- The active repair time (ART)
- The supply time (SUT) for any spare part required for replacement
- Any administrative and logistics delay (ALD)

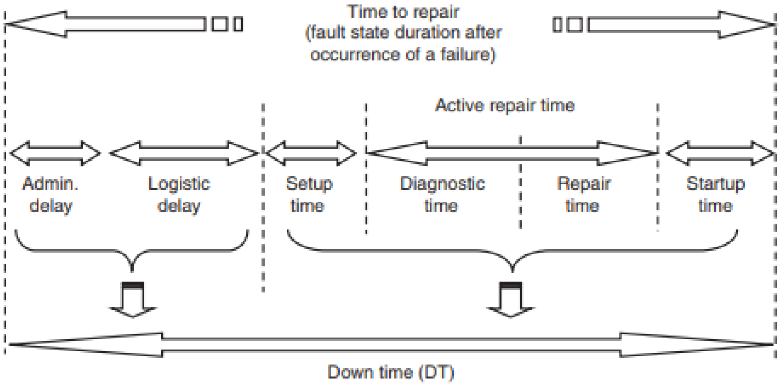


Fig. 2.1.: Time to Restore of a repairable item (Cavalieri et al. 2008)

The processes of a logistics system is linked with other processes of a company and with other parties in the supply chain. Generally, a logistics system consists of four elements: policies/processes, network structure, coordination/control, and supply chain relationships (Cooper and Ellram 1993; Huiskonen 2001). The policies/processes element described what kind of service levels are to be offered, and whether some customers are to be prioritised in specific situations. The network structure element defines the amount of inventory echelons and locations used in the system. The supply chain relationships and its management between parties considers aspects such as degree of cooperation, responsibility of control, as well as sharing risks (Cooper and Ellram 1993). The control/coordination element takes up decision making on inventory control principles, performance measurement, and incentive systems.

Four control characteristics of maintenance spare parts can be criticality, specificity, demand pattern, and value of parts. These characteristics are discussed in terms of their effects on logistics system elements network structure, positioning of materials, responsibility of control, and control principles (Huiskonen 2001). For each characteristics a control strategy can be determined. For example, for a part that is requested often, non-specific, high value, but low criticality, it would be more beneficial to push the stock back to the supplier. However, the complexity of this topic is that multiple sorts of combinations exist over the same logistics network. Generally, high criticality requires sufficient decentralised safety stocks and generous lot sizes. In case of high part values, outsourcing of the inventory would be most cost efficient. For a very high and smooth demand patterns, safety stocks can be optimised, whereas for low and irregular demand rate co-operative stock pools are more advantageous. Finally, rather user-specific parts require decentralised safety stocks, whereas standard parts do not have the need for a certain design policy. (MacDonnell and Clegg 2007)

2.2 Outsourcing of maintenance, repair, and overhaul

Al-Kaabi et al. (2007) have analysed the decision-making to outsource with focus on aviation MRO. In their research key attributes that affect the level of MRO outsourcing are determined. Additionally, the level of outsourcing for different MRO activities is ascertained. This level is evaluated in terms of its impact on the performance, measured by dispatch reliability and direct maintenance cost, of an MRO provider. The perspective of this analysis lies at the airline operator, rather then a yet existent MRO provider.

Generally, the decision to outsource can be compared to the traditional ’make or buy’ framework, as depicted in Figure 2.2 (Franceschini et al. 2003; McIvor et al. 1997). This framework follows four stages. The first stage is determining whether the service is part of the core activities that should remain under own control. Any activities that is perceived as non-core are to e outsourced. The second stage is to evaluate the level of demand for the activities or services. If demand is insufficient, outsourcing may be a viable alternative. In the context of MRO, demand is affected by several factors: fleet size, aircraft fleet mix, aircraft age and fleet utilisation, and level of leasing (Morell and Gibson 2004). Thirdly, the airline needs to assess whether it is capable of performing the MRO activities in-house. This can depend on the business models of the airline on a strategic level or whether the airline is owned by the government or privately (Backx et al. 2002). The final stage of the framework is the determination of available capacity and to what extent this is sufficient for the required in-house activities (Vieira and Loures 2016). The framework identifies four options:

1. Make and sell: MRO activity is turned into a profit centre. Excess capacity is provided to other airlines as well.
2. Make: MRO capacity is designed to solely satisfy the airline its own MRO requirements.
3. Make and buy: MRO capacity is not sufficient for all services to be performed internally. External contractors take up the support for specific activities.
4. Buy: MRO is fully outsourced.

The aforementioned outsourcing decisions can be made for five large pillars in the context of MRO: line maintenance, base maintenance, engine services, spares and rotables management, and aircraft modifications. Many airlines choose to keep line maintenance in-house, whereas the other activities are predominantly outsourced by airlines (Al-Kaabi et al. 2007). Line maintenance plays a critical role in ensuring that aircraft are dispatched according to schedule, being a core competence of airlines in general. Base maintenance and engine maintenance however, can be rather labour intensive, with low frequency of occurrence (Canaday 2005). Therefore, a certain volume is required for this activity to become cost effective. Cost reduction is also a motivation for outsourcing of spares and rotables management (Massey 2005). Airlines opt for component support solutions that are flexible, with predictable costs. Nowadays the OEM, such as Honeywell and Safran, offer equivalent programs (McFadden and Worrells 2012).

Most actual repair work that is done for either line maintenance, base maintenance, engine services, or even individual component services is performed by repair shops. According to Vieira and Loures (2016), roughly 80% of all repair shops are small to medium enterprises contracted by the MRO provider (Almeida 2005). These repair shops provide specialised skills that may not be available at the airline’s organisation. Additionally, economies of scale may

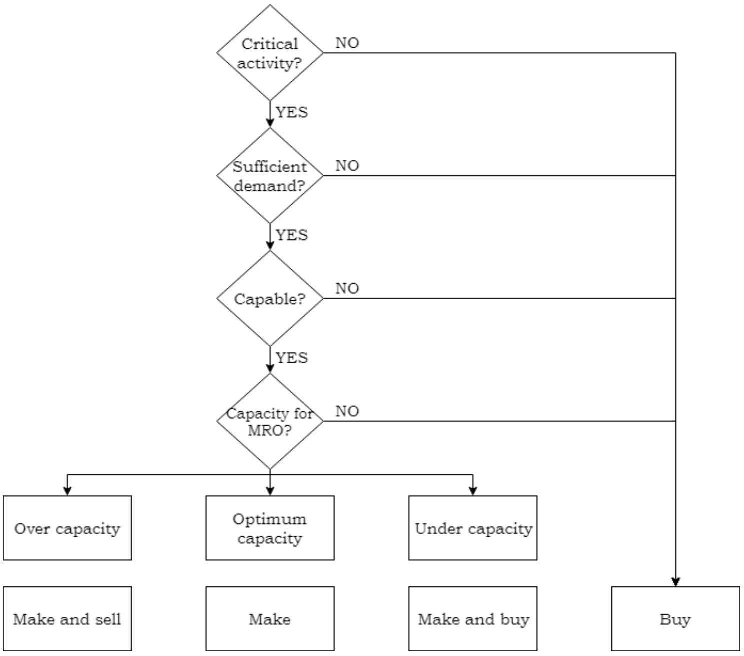


Fig. 2.2.: Make and buy framework (Franceschini et al. 2003; McIvor et al. 1997)

be generated at the creation of a hub of skilled workers, job opportunities and knowledge generation for innovation. Further outsourcing from the repair shops can be deployed when demand exceeds the baseline capacity of in-house MRO (Czepiel 2003).

When outsourcing repair to third parties, strict agreements are to be made in terms of requirements. The aeronautical industry is very complex due to required certification by airworthiness authorities. This predicament limits the options when selecting a supplier or repair vendor for new aircraft or component programs and eventually results in a lack of leverage to negotiate commercial conditions (Vieira and Loures 2016). Both internal repair shops as well as outsourced repair activities are a source of supply. The supply lead time consists of multiple elements: repair or suppliers lead time, procurement time, and picking, transport and storage time of parts (De Treville et al. 2004). When speaking of controlling the supply lead time and supply parameters, using planned lead times for internal repair is justified. However, using this logic for modelling the supply chain, one large assumption is to be made. It should then be assumed that internal repair shops meet the agreed upon lead time and that the repair shop capacity is dimensioned in such a manner that the internal due dates are satisfied (Borst et al. 2004). The decision of deploying a certain source of supply is based on several cost configurations: set-up and variable cost of the repair shop capability and resources, set-up costs of the contract, procurement or repair costs, and inventory holding costs (Rezaei Somarin et al. 2018).

According to Caniels and Gelderman (2005), the supply strategy of a company depends on the profit impact and the supply risk. These two factors are used as input for a matrix, allowing the allocation of a supplier within these two factors. Each quadrant provides recommendations, namely: form partnerships for strategic products, assure supply for bottleneck products, exploit power for leverage products and ensure efficient processing for non-critical products. These recommendations with their respective item characteristics are listed in Table 2.1. Strategic items represent a considerable value to the company and can often be purchased from only one supplier, which facilitates to the high supply risk. Bottleneck items have a moderate influence on the financial results of a company. Suppliers often have a dominant power position for these products (Kempeners et al. 1997). Leverage items can be obtained from multiple suppliers and represent a relatively large share of the product its cost price (Olsen and Ellram 1997). Finally, non-critical items usually have a small value per unit and come from various suppliers.

Tab. 2.1.: Kraljic matrix (Kraljic 1983)

Profit impact	**Supply risk**	
	Low	High
High	*Leverage items*	*Strategic items*
	Exploit purchasing power	Form partnerships
Low	*Non-critical items*	*Bottleneck items*
	Ensure efficient processing	Assure supply

Cavalieri et al. (2008) has also discussed a certain classification of parts, in which he also included supply risk and profit impact. Consumables are assumed to have a steady and continuous demand and have a vast supplier's base. Generic parts are parts that can be mounted on more pieces of equipment and are widely available on the market. Specific spare parts are designed for one particular piece of equipment and are available only through a specific supplier. Finally, strategic spare parts are assumed to be specific whose wear-out time is not foreseeable. These parts are also characterised by high supply lead times and relevant costs.

2.3 Repairable spare parts pooling

The concept of pooling spare parts is not solely deployed by the aviation MRO industry. It is a phenomenon known to multiple industries that face high inventory cost. Fundamentally, inventory pooling is an inter-'company' cooperation. Wong et al. (2005b) introduces an analytical model for determining spares stocking levels for a single-item, multi-hub system where complete pooling is permitted. In the model, a Poisson process is assumed to generate demand data. The source for demand is an infinite source. Repair times are exponentially distributed and the system has ample repair capacity. The latter assumption is based on the fact that repair work can be subcontracted when a particular repair shop has reached its capacity. Final assumptions are the negligible shipment time from the repair facilities to the hubs and no failures or repair completions can occur during shipments. Demand data is produced using failure rates of parts. The model itself allows stocking decisions whilst minimising total system cost, being the inventory holding cost, downtime cost, and transshipment cost.

Besides assuming complete pooling of spare parts, partial pooling is analysed as well (Kranenburg and Van Houtum 2009). Networks are assumed to have both central depots, as well as local inventories, where lateral transshipment is allowed. For certain case studies, the deployment of local stocks has shown a significant amount of cost savings, compared to complete pooling. These lateral shipments are predominantly described as being used by multiple companies, rather than intra-company (Wong et al. 2005a). Methods used for determining stock levels in these networks are generally analytical models, with either exact or approximate evaluation techniques.

In addition to stock level decision, another field of interest regarding inventory pooling is the cost allocation. More specifically, how to allocate and distribute the total system cost to each pooling member. In the analytical model by Wong et al. (2007) both partial and complete pooling is assumed. The former allows pooling members to satisfy their own demand from their local inventories. Whenever this inventory needs replenishment, lateral transshipment takes place. For complete pooling one company sets a positive critical stock level. Multiple cost allocation policies are evaluated using analytical models, where the system cost consists of inventory holding cost, downtime cost, and transportation cost (Karsten and Basten 2014). Concluding, all pooling members must reach consensus on the use of a single parameter value (e.g. service level or downtime cost).

2.4 Conclusion literature review: general system analysis

This Chapter provides the answers to the first two research questions. Solution strategies to certain challenges due to specific characteristics is looked for in previous research. In this concluding Section, the two research questions are answered.

The system is established in a closed loop supply chain, for parts are supplied from a central inventory, used by airlines, repaired by the MRO provider, and re-stocked in the same inventory (Wong et al. 2005b). This type of demand for spares is commercialised by MRO providers. Therefore, larger MRO providers manage pools of repairable spare parts for multiple airline customers. Demand for individual components can be rather erratic or lumpy. Pooling spare parts is therefore only economically viable once there is sufficient demand (Ghobbar and Friend 2003). Depending on the quantity of the pool and the available capacity to provide additional services, MRO to these spare parts is either deployed in-house or outsourced (Franceschini et al. 2003; McIvor et al. 1997). Generally, when demand is sufficient and excess capacity is available, MRO is turned into a profit centre. If capacity is limited, outsourcing becomes beneficial. In addition, required skill, labour intensity, and frequency of occurrence are factors that affect the decision to outsource MRO (Canaday 2005).

The performance of MRO providers is measured mostly through time and cost. The main performance measurement of aircraft MRO is the downtime of an aircraft and the accompanied cost. This downtime is largely dependent on the availability of spare parts. Most aircraft component MRO operations are deployed using exchange contracts, made possible by the pooling of these parts. The responsiveness of this type of exchange is performance from the perspective of the customer. However, the availability of the part from the perspective of the MRO provider is a result of the TTR of an unserviceable component (Cavalieri et al. 2008). The TTR starts from the moment an unserviceable component is removed from an aircraft and has entered the network of the MRO provider until the component is repaired and re-stocked in the central inventory, as depicted in Figure 2.3. It therefore includes three main processes: administration, logistics and repair. Generally administration and logistics are both considered as additional delay to the main repair processes and are therefore considered as one time factor, for travel times are assumed to be negligible compared to the entire turnaround time of component restoration (Al-Kaabi et al. 2007).

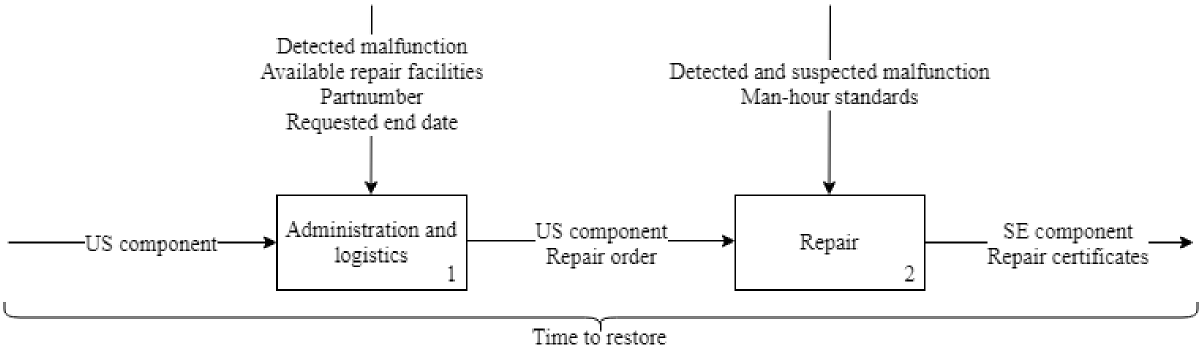


Fig. 2.3.: Time to restore (Cavalieri et al. 2008; Macchi et al. 2011)

Aircraft consist of million different parts. Therefore, research on spare part classification is used to describe the parts on a more aggregated level. From a supply perspective, which is used to determine outsourced services and procurement of parts, the profit impact and supply risk can be used to classify parts (Caniels and Gelderman 2005). By regarding the TTR to be a performance measurement, several classifications do not apply as these classications are of interest when analysing inventory optimisation and allocation (Huiskonen 2001). Specificity of components does apply, for this determines the location choices for repair. Furthermore, criticality is to a certain extent of importance. By criticality the type of service is meant, i.e. maintenance, repair or overhaul. Different skills and available resources are required for different work scopes. Moreover, the type of service is a determinant for the target turnaround time (Cavalieri et al. 2008).

System analysis

3

Following Chapter 2, where literature is used to describe the generic system in the context of component MRO, find general challenges in the context of (aircraft) MRO, performance measurements, and solution strategies for MRO management, such as the decision to outsource based on multiple attributes (Section 2.2) this chapter follows up on the case study at KLM E&M. Data from the MRO provider is used to quantify the performance measures of the system, being repair lead times, administrative and logistics delay, and cost of MRO. Furthermore, the classification discussed in Section 2.4, specificity and criticality, is applied to the part data of KLM E&M.

Firstly, Section 3.1 takes up the scope and system boundaries of this research project. It includes an overview of the entire chain of activities within the system boundaries of this study and analysis. Secondly, Sections 3.3 and 3.4 describe the repair and administrative and logistics processes respectively, including their current performance in the system. Additionally, the cost of MRO for different repair shops is included. After the process- and data analysis of the repair and logistics, in Section 3.2, the spare parts are classified through different attributes (Section 2.1). Section 3.5 provides the final KPIs used to evaluate the system performance. This chapter ends with a conclusion from the system through data analysis, which includes notable findings and enables the description of solution alternatives.

3.1 Scope case study

For the case study at KLM E&M five internal workshop and six repair vendors are assumed to limit the amount of components and their characteristics. Empirical data has shown many more repair shops and vendor. The chosen repair shops and vendors have been responsible for the majority (80%) of the overall repair services. Therefore, the other facilities are not individually considered. Furthermore, the repair vendors included in this research scope are chosen is such a way that the components being generally repaired internally can be outsourced. Additionally, the central depot consists of two different administrative and logistics processes and the main warehouse, of which the latter is past the border of the system scope.

KLM Component Services (CS), which is part of KLM Engineering & Maintenance, manages the pool of aircraft components. Customers, or operators, that have contractual agreements with this department are able to use these components. This pooling of repairable parts, the repair, and the supporting administrative processes and logistics establish a closed-loop supply chain, as presented in Figure 2.3. This research project focuses on the administrative and logistics processes, and repair, being a sub-system of the closed-loop supply chain. Therefore, the actual stocking, the accompanied inventory management and demand from customers is disregarded. These processes and where these take place within the network is presented in Figure 3.1. The administration and logistics take place within the central depot, through both outbound and inbound flows. Repair takes place at both internal as well as external/outsourced repair vendors.

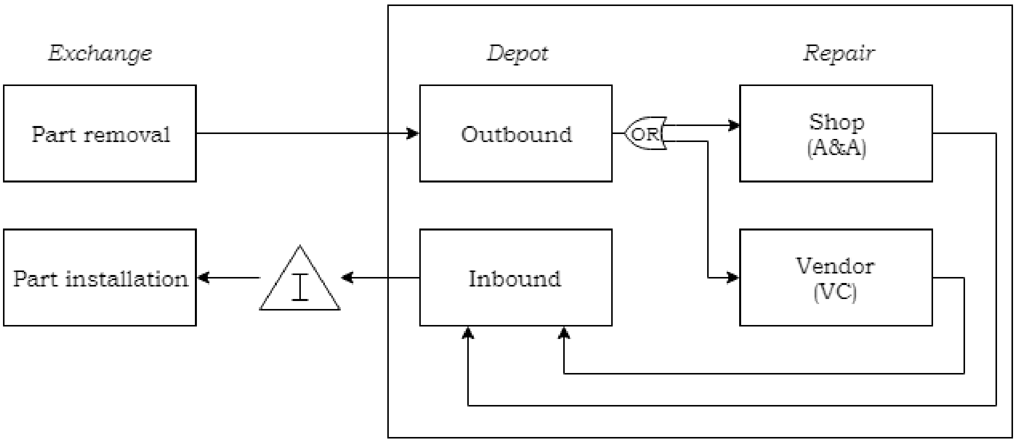


Fig. 3.1.: KLM E&M closed-loop supply chain

The process cycle starts at the central depot where requests for serviceable components are received. This can either be from hangars deployed by KLM E&M or maintenance facilities abroad. The process is as follows:

1. Request is received by customer interface and pushed forward to supply chain to check whether the part is on stock. If the part is not on stock, the request is denied or delayed.
2. Serviceable part is issued from the central depot and expedited to the customer's aircraft. After exchange of the part the customer ships its unserviceable part to the central depot.
3. Unserviceable part is received at central depot, which follows the outbound flow. This includes physical inspection, establishment of the repair order and the shipment by expedition to the respective repair facility, either internal shops or outsourced abroad.
4. Repair is initialised by administrative processes, work scope determination and planning. Assuming all documentation and certificates are correct, final repair work is performed.
5. The repaired part is generally shipped back to the central depot. If the part is highly prioritised, drop-shipments are in place. This allows the part to be shipped directly to the respective aircraft.
6. Serviceable part is received at central depot, where it now follows the inbound flow. The part is officially declared serviceable in the ERP system after which it is re-stocked in the central inventory.

As aforementioned, a part of the closed-loop chain is considered. Therefore, steps 1 and 2 are left out of scope.

3.2 Spare parts classification

As discussed in Sections 2.1 and 2.2, spare parts in the context of aircraft MRO can be characterised from two different perspectives: inventory and supply management. The control characteristics of both perspectives are somewhat equivalent. This research does not directly consider inventory management to be included as decision variable, but the control characteristic specificity is used. This determines what repair facility is capable of specific types of component MRO. Furthermore, the profit impact is analysed in terms of cost of MRO, which differs per repair work centre and component.

KLM E&M uses four different classes of components, also called 'commodity groups': interiors, exteriors, pneumatics/hydraulics, and avionics. These groups are used by KLM E&M and are commonly used to in the design of airlines operations (Overend 1979). Interiors is an encompassing term to describe products, such as power drive units, sensors, light assemblies, and battery units used inside the aircraft. Exteriors are used to control specific parts of the airframe. Components in this group are for example brake system control units, door locks, control valves for nose wheel steering and door safety. Pneumatics/hydraulics are mainly actuators, fans, and pumps. Finally, avionics include communication and navigation. Figure 3.2 presents the shares of services to the different commodity types performed either in-house or outsourced. In addition, the relative total share of commodity types is presented.

Besides commodity type, another way to describe the components is in terms of the service they require. In the context of component MRO, four different work scope types are used: repair, overhaul, minor, and major repair. This attribute is a determinant for both the repair lead times as well as the cost of MRO. Both configuration variables are further explained per shop in Sections 3.3.1 and 3.3.2. Empirical data reveals a share of 54%, 1%, 4%, and 40% for inspection, major repair, overhaul, and minor repair respectively. The relative shares over both in-house and outsourced services is presented in Figure 3.3. These shares are withdrawn from data over a one-year period. The subsequent year these shares could have changed.

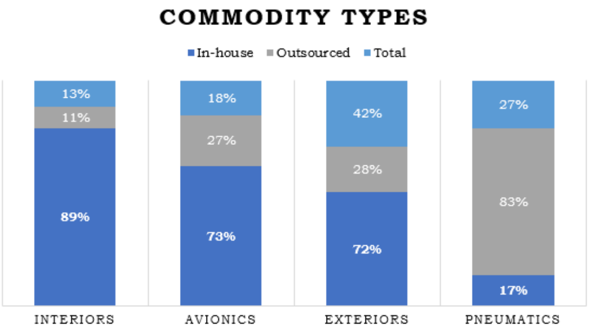


Fig. 3.2.: Share of commodity types

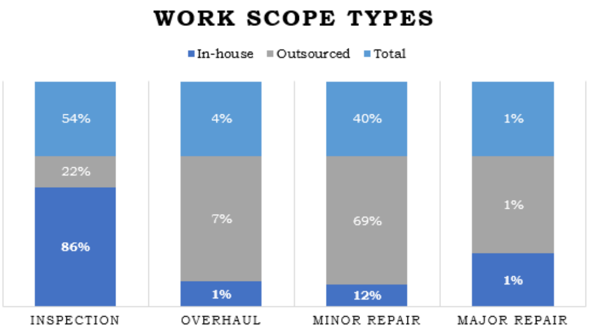


Fig. 3.3.: Share of work scope types

3.3 Maintenance, repair, and overhaul services

Considered in this research project are five internal workshops and six repair vendors, each capable of providing MRO to the components with the classifications mentioned in the previous section. Figure 3.4 provides an overview of all the considered workshops and the vendors including the commodities that can be repaired at the respective facilities. The commodity groups are: interiors, exteriors, avionics, and pneumatics/hydraulics (Section 3.2). It is assumed that outsourcing is possible if empirical data shows repair activities of the same commodity group.

Roughly half of the considered repairs over a one-year period is outsourced. Currently, the decision to outsource for KLM E&M is, to a certain extent, in line with the statements by Czepiel (2003) and McFadden and Worrells (2012), which are discussed in Section 2.2. It is dependent on contractual agreements, required skill for the service, and available resources. However, there are no exact decision rules. KLM E&M has multiple airlines under contract with a large fleet size and varying fleet mix, making it logistically challenging to perform all services in-house (Al-Kaabi et al. 2007). In the context of MRO many strategical decisions

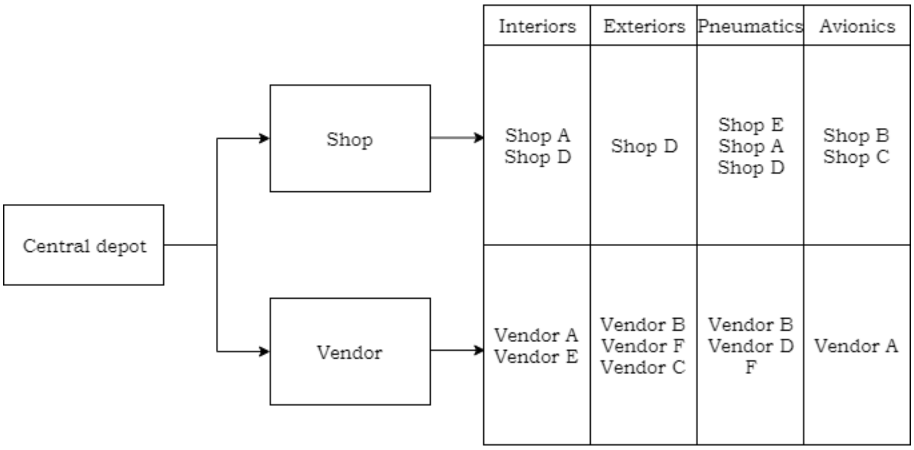


Fig. 3.4.: Considered repair shops and vendors

are to be made in terms of contracting. The further control over repair shops and vendors is primarily done using these contracts in which a specific repair lead time is agreed upon. This repair lead time differs per component and per repair facility, for this is also dependent on the available resources.

In terms of repair activities, four categories can be distinguished: inspect, overhaul, minor, and major repair (Section 3.2). The type of work scope is the most accurate predictor for the different lead times, for this reveals the lowest standard deviation in comparing means. Generally, inspection takes up the littlest time. It is assumed the ratio of active repair time is throughout the shops and vendors the same. This means that minor repair is used as reference. The ratio's used for the different work scopes is presented in Table 3.1.

Tab. 3.1.: Ratio's of active repair time for work scopes

Work scope	Ratio of active repair time
Inspection	$AvgRepairTime/1.5$
Overhaul	$AvgRepairTime * 1.9$
Minor repair	$AvgRepairTime$
Major repair	$AvgRepairTime * 2.3$

3.3.1 In-house MRO

For in-house repair five shops are considered. Figure 3.4 depicts what commodity is repaired at the respective repair cells. The repair shop generally receives the components for internal MRO. The initial phase is to determine the work scope in order to plan and assign the work order. Besides following through with the final work scope, i.e. inspection, overhaul, minor, or major repair, other situations may occur. The measurement of the repair lead time can be put down temporarily in case of exceptional cases. However, this does affect the final delivery date. These exceptional cases occur during the administrative and logistics and outsourced repair as well. These situations can be as follows:

- Part to be repaired externally
- Task to be performed by other shop
- Part removed for scrap [1]

---

[1] Scrap rates and re-purchasing from the OEM are left out of scope, as this is in lign with the conservation law of parts

- Part to be returned as-is
- Quote required
- Part removed serviceable (cannibalisation)

In-house lead times

At KLM E&M the internal repair is measured in four sequential steps: (1) pipeline, (2) CIR-IN, (3) repair, (4) CIR-OUT. Pipeline is where the component has arrived at the repair shop, but is simply waiting to be serviced. Generally, this time stamp allows insight in capacity constraints and flow disruptions at the repair shop. Thereafter, the CIR-IN process step is initiated. This step, as well as the fourth step, is performed by the Customer Interface Repair Officer (CIRO). Both CIR-processes consists of all the administrative work, such as receiving and departure paperwork and includes general work-preparation administration. Furthermore, the CIRO is also the link between the component at the repair shop and the customer. In case of quoting, the CIRO is to contact the customer. The process of quoting occurs when an additional failure in the component is determined, for which it was initially not sent for repair. This additional repair requires approval of the customer. To cope with these multiple tasks, the CIRO takes on the components in batches, which facilitate to an increased waiting time before repair (Van Rijssel 2016). Summarising statistics of each activity is presented in Table 3.2. Additionally, Figure 3.5 presents the lead times in the form of a box plot, facilitating to the identification of outliers. These outliers contribute to the rather high standard deviations in the table below.

Tab. 3.2.: In-house repair descriptive statistics per repair step in days

Shop	Statistic	Buffer	CIR-in	Repair	CIR-out
Shop A	Mean	8.1	1.2	8.4	0.4
	Std. Deviation	8.3	2.1	16.1	4.0
Shop B	Mean	6.4	1.6	8.5	0.4
	Std. Deviation	7.6	3.0	15.8	6.2
Shop C	Mean	2.9	1.4	11.2	0.3
	Std. Deviation	5.0	1.8	17.2	7.9
Shop D	Mean	6.5	1.0	4.5	0.1
	Std. Deviation	5.9	1.1	11.3	3.6
Shop E	Mean	2.7	1.6	12.6	0.4
	Std. Deviation	4.0	3.1	16.9	8.3
Total	Mean	5.3	1.4	9.1	0.3
	Std. Deviation	1.6	5.1	14.0	3.1

Different lead time elements can be used to describe the total repair time. The contracted lead time is equal to the *active repair time*, as stated in the Service Level Agreements (SLAs) with customers. This indicator solely represents the time window in which the component is repaired. However, surrounding the actual repair, other stages, such as customer interface processes and possible flow disruptions, extend the *repair lead time*. The repair lead time provides insight in the moment the repair order is created at the central depot until the repair is completed and the component is ready for dispatch. The repair lead time can be independent from the active repair time, as cases may occur where the repair of a certain component has a higher importance and the component is required as soon as possible, rather than according to the contracted time. During the establishment of repair orders at the central depot, a requested

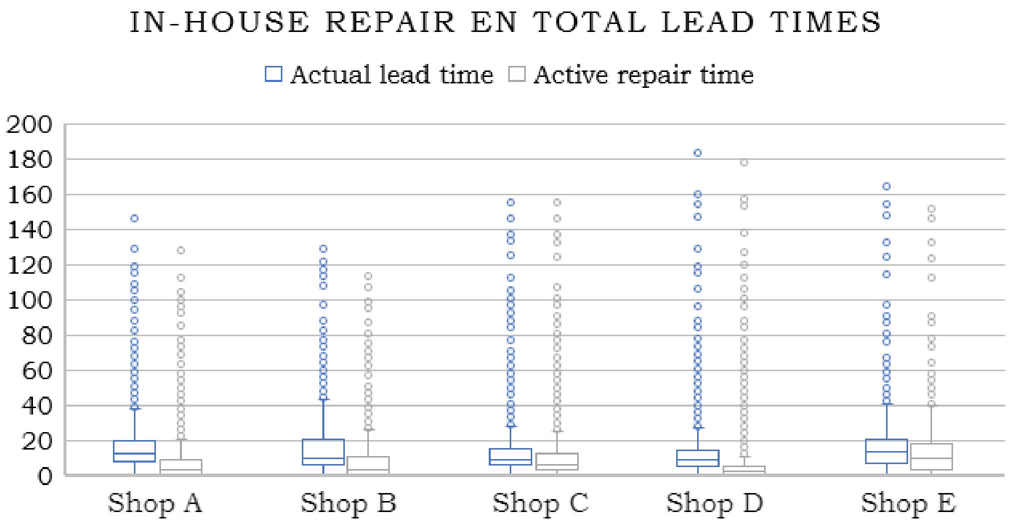


Fig. 3.5.: Spread of in-house lead times

end date is entered in the ERP system. In cases of high priority, the requested end date can differ from the active repair time.

Table 3.3 lists the active repair times for each considered repair shop and the resulting lead times. The difference between these two variables is the time the components wait for repair, are in transport, or are due for additional administrative handlings. This is largely an indicator for lack of resources in terms of manpower or material. The repair lead time is as presented in the table is measured in days, regardless of actual work hours. The shops are operated from the same work schedule five days a week from 08:00 AM - 17:00 PM. On a daily basis between 10 and 50 employees are available and scattered over the five workshops. The active repair time in hours is therefore assumed to be the repair lead time $*8$ hours. The current performance of repair lead times is currently measured over the actual time it took to repair a component, but the date of dispatch is also monitored. From the considered shops over the period of one year, 23% has exceeded the requested end date. Table 3.3 also presents the targets of the total lead time. It can be seen that the targets for the jobs where the requested end date is achieved do not differ much from the jobs where the requested end date is not achieved. Notable is the significant difference between the lead times for the jobs that have and have not achieved the requested finish date. Generally, this is caused by larger repair times. Empirical data shows buffer times are also slightly larger, but are not the main determinant for the long lead times.

In-house repair cost

The total repair cost consists of multiple configurations, which each have their own cost. Additional cost specifications, not included in this section, are vendor costs and surcharges. More on this specification in Section 3.3.2. The configurations are as follows:

- Man hours cost
- Material cost
- Surcharges material

Tab. 3.3.: In-house lead times (in days)

Shop	Target	Repair lead time	Active repair time
Requested end date not achieved			
Shop A	14	31,4	19,3
Shop B	15	33,8	25,6
Shop C	15	40,2	35,6
Shop D	16	31,0	19,5
Shop E	19	36,5	32,6
Requested end date achieved			
Shop A	14	9,8	3,9
Shop B	17	9,5	3,4
Shop C	16	9,2	6,4
Shop D	19	8,6	2,9
Shop E	20	11,7	8,9

Generally, the cost of repair depends on the defect of the material, thus work scope, and on the technical complexity of the material its configuration. Since each workshop focuses on a group of products, the average costs per work scope and workshop are used to determine mean values of repair instead of individual repairs. Table 3.4 presents the average values of the aforementioned cost specifications. The cost specifications presented in the table below are not based on the same data as Table 3.3, but it does provide proper insight in the cost of component MRO. Generally, minor repairs are least costly. The average of man hours and cost of material are the highest for major repair and overhaul, which are also the most time consuming services. Major repair also requires specific equipment and other material, which explains the high material cost. Appendix B.6 presents the cost of each work scope type per repair shop.

Tab. 3.4.: In-house MRO costs in USD

Work scope	Manhours cost	Material cost	Surcharges	Total
Inspection	$595.2	$817.5	$143.1	$1,555.9
Overhaul	$1,084.9	$1,022.7	$197.4	$2,305.1
Minor repair	$493.3	$537.6	$98.5	$1,129.5
Major repair	$2,033.9	$9,057.7	$858.1	$11,949.8
Total	$4,207.4	$11,435.6	$1,297.2	$16,940.4

3.3.2 Outsourced MRO

Based on a period of one year and considering the six largest repair vendors, a little over 45% of component services is outsourced to repair vendors. The repair vendors considered are able to perform the same, or even more, services as the in-house repair shops. Moreover, the six vendors considered, are already accountable for over 80% of all outsourced repair. As mentioned in Section 3.1, once a component is removed from an aircraft, it first passes the central depot. Here the repair location is determined by the so-called Repair Administrator (RA). The RA establishes the repair order and provides the packaging of the respective component with the proper address and prepares it for shipment. Components that are to be shipped abroad are transported by the freight forwarder Bolloré. This organisation also facilitates the custom clearances. The RA determines the repair facility for each component based on provided information on contracts and previous shops that have been responsible for services to that component. However, KLM E&M is also able to outsource services once the capacity of in-house workshops is causing constraints in performance. This is rarely done, for data on the capacity in shops is lacking or not shared properly. As discussed in Section 3.2, the majority of the pneumatics/hydraulics services is currently outsourced. This phenomena is not only due to lack of capacity, but for the majority of the cases also due to lack of specific skill. The exact processes or phases of repair at the vendors are unknown and KLM E&M has no significant power in controlling the lead times. Each repair vendor is contracted to a certain repair turnaround time or active repair time, as the majority of the airlines and other maintenance organisations do (Ghobbar and Friend 1996). The targets are also increased for outsourced repair, for it requires additional travel times and administrative activities. On the former, more in Section 3.4.3.

Outsourcing lead times

Based on the same time period as in Section 3.3.1, roughly 63% of the outsourced repairs were not completed according to contracted turnaround time. Whether this is due to capacity constraints, material shortage, machine failure, or other factors is unknown. Furthermore, the work scope is not properly monitored as it is for internal repair. Generally, the target lead time for outsourced is on average double of the target lead time for internal repair, for it requires additional administrative handling and longer transportation time. The exact touch times are also unknown to KLM E&M. The data available are: turnaround time, travel times, and total delivery time. Table 3.5 presents the repair turnaround time and the total delivery times. Figure 3.6 depicts the spread of data points per repair vendor.

Tab. 3.5.: Outsourced repair lead times in days

Shop	Statistic	Repair lead time	Total delivery time
Vendor A	Mean	39.7	42.0
	Std. Deviation	29.9	29.9
Vendor B	Mean	21.5	24.8
	Std. Deviation	21.7	22.2
Vendor C	Mean	11.9	15.6
	Std. Deviation	6.9	6.2
Vendor D	Mean	28.6	40.6
	Std. Deviation	17.2	18.2
Vendor E	Mean	43.5	58.8
	Std. Deviation	35.5	36.2
Vendor F	Mean	23.9	34.2
	Std. Deviation	24.0	25.0

From the obtained data, nearly 63% of the outsourced repairs were not according to target. Where the targets between the on-time and late repairs did not differ too much for in-house repairs (Section 3.3.1, they do for outsourced repair. Table 3.6 presents the average targets for the on-time and late outsourced repairs. These targets are based on the repair lead times and not on the total delivery time. However, since over 60% outsourced repairs did not achieve the targets, one might consider whether the targets are feasible.

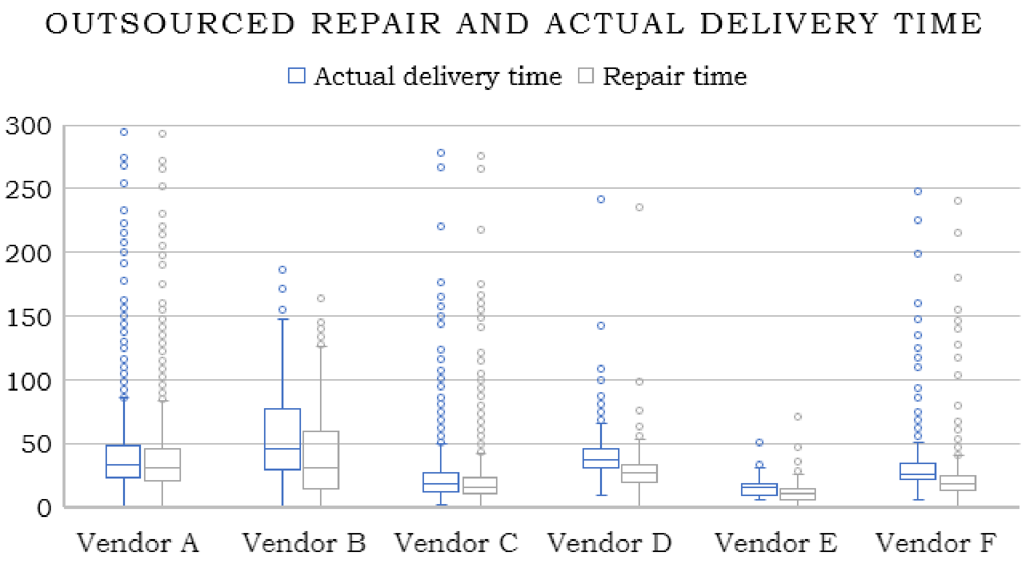


Fig. 3.6.: Spread of outsourced lead times

Tab. 3.6.: Differences in target for outsourced repair

Vendor	Target → not achieved	Target → achieved
Vendor A	17	25
Vendor B	18	21
Vendor C	9	10
Vendor D	27	25
Vendor E	22	29
Vendor F	11	24

Outsourced repair cost

The outsourced repair consists of the same cost specifications as in-house repair, but additional vendor surcharges and costs are added to the total price. Again, man hours and material are to be paid for, but are mostly covered by the vendor itself. These cost are negligible to be considered independently from the perspective of KLM E&M, as these are yet to a certain extent included in the vendor costs. Table 3.7 provides a list of average values per work scope and vendor on the vendor surcharges and general costs. The most costly work scope to outsource are minor repairs. Least costly outsourced service is inspection, with Vendor A being the most affordable vendor. Furthermore, in-house major repair costs over 10,000 USD, whereas outsourced, it would cost just over 8,000 USD on average. This rather large difference can be due to different skill sets and available resourced to provide this service.

Tab. 3.7.: Outsourced MRO costs in USD

Work scope	Surcharges vendor	Vendor cost	Total
Inspection	$873.8	$5,623.2	$6,497.1
Overhaul	$1,047.1	$6,940.9	$7,988.0
Minor repair	$1,153.7	$7,532.8	$8,686.6
Major repair	$1,034.9	$6,994.5	$8,029.4
Total	$4,109.7	$27,091.5	$31,201.2

3.4 Administrative and logistics delay

The central depot is the front door of the MRO provider. Besides the actual warehouse, other logistics and administrative processes take place here. All components and material required for internal MRO and stock replenishment for both KLM Royal Dutch Airlines as well as customer airlines initially enter the central depot. The central depot can be divided in four different processes: expediting goods, Repair Administration (RA), Inspection Incoming Goods (IIG), and warehousing. How the processes at the central depot are linked to repair as discussed in Section 3.3 is presented in Figure 3.7. Where repair is rather component-specific, the processes and handlings at the central depot are not. All the pillars in the system as presented in Figure 3.1, besides repair, contribute to administrative and logistics delays. Throughout the central depot, a distinction in flow is made with serviceable and unserviceable goods, for these are physically separated. Generally, KLM E&M aims for a lead time of one day for unserviceable components and two day for the serviceable goods within the central depot for administrative processes and supporting logistics. However, based on aggregated data over the entire central depot an average lead time of 12 days is determined (inbound and outbound). This can be the cause of several large outliers, for the median is three days. The processes within the central depot are as follows:

1. Expedition takes in all the goods and provides the components with an RFID label that allows the tracking of the component on the KLM E&M acreage. Additionally, the label includes the final location of the component within the central depot based on whether it is a consumable or rotable and if it is serviceable or unserviceable. The goods are batched onto rolling carts or are transported using forklifts, depending on the size and weight.
2. RA is done within the unserviceable lane which only processes the rotables, for consumables are not repaired. RA includes physical inspection of the components and administrative work required for repair, such as determining work scope. Here the repair order is established and the respective repair shop or vendor is determined.
3. After repair, the component, being now serviceable, follows the inbound flow. The activities of the inspection incoming goods (IIG) include confirming the permits, licenses, and certificates included in the components' package. If all is correct, the inspector officially declares the component to be serviceable with a Goods Receipt (GR) notification. After IIG, the components are generally stored in the central warehouse. In cases of high priority or low stock levels, the component is immediately dispatched to a customer.

3.4.1 Repair administration

On the exact time a component spends at the central depot before it is re-stocked, little data is available and the available data is rather unreliable. Based on previous research by Porozantzidou (2015), averages and standard deviations on the touch times and waiting times at the RA can be estimated. In this research, the RA process is divided in two steps: physical inspection and administration. The physical inspection is performed to see to which airframe the package belongs, for the RA is divided per airframe type. The processes per airframe are the same, but it simplifies contact with the respective CIRO and customers. For this research these two steps are considered as one since it is performed by the same employees.

At the central depot, the capacity and throughput per time step is solely dependent on the amount of resources and on the amount of arrivals of goods. All work is performed manually.

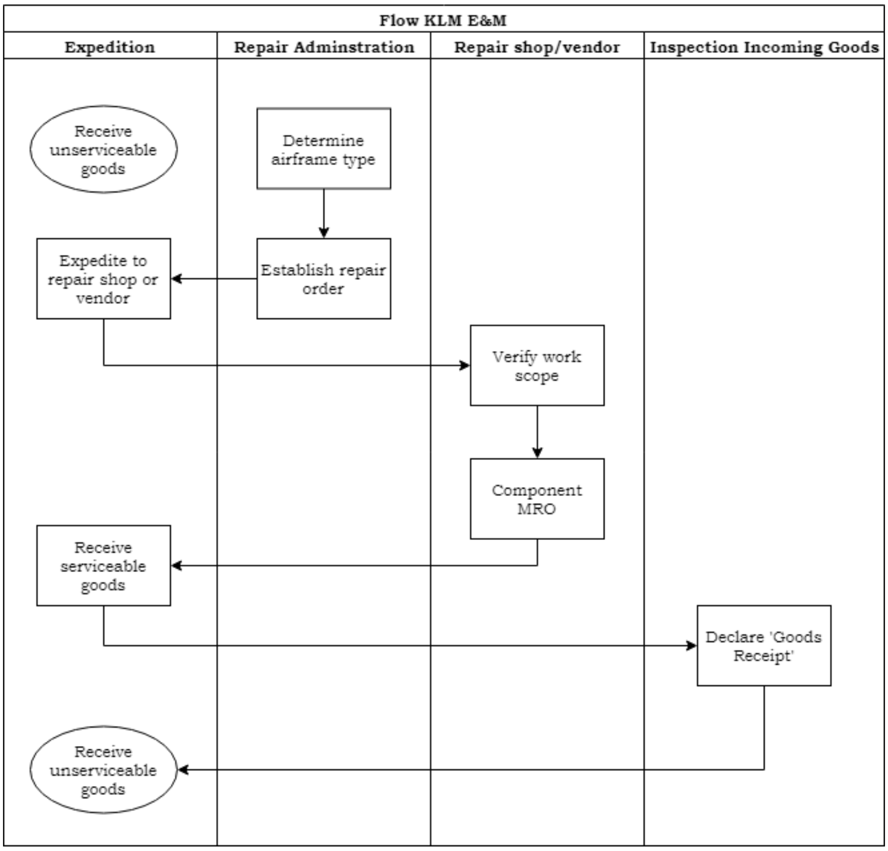


Fig. 3.7.: Function of central depot in network

Therefore, resources are assumed to be employees. Table 3.8 presents some descriptives on the capacity at the RA. Workdays are divided in two shifts of eight hours: 06:00 - 15:30 and 14:30 - 23:00. One person for both shifts is equal to one FTE.

Tab. 3.8.: Capacity repair administration

Day	Mean processed	Std. Deviation	Mean FTE
MON	25.2	8.4	4
TUE	24.6	8.6	4
WED	22.1	6.1	4
THU	21.3	3.6	4
FRI	19.5	5.2	3
Total	18.6	9.5	4

The touch times of outbound, consisting of four processes (receipt, repair administration, and distribution) are listed in Table 3.9. The actions required for these processes are rather standardised, but do reveal relatively high standard deviations. This is largely due to changes in tracking systems which has resulted in packages not being removed from the data. Between the steps WIP buffers are established. More on these waiting times is discussed in Section 3.4.3.

3.4.2 Inspection incoming goods

The process from expedition to the finishing the IIG step forms the inbound division in the central depot. The inspectors at IIG pick up the packages from the first buffer based on a

Tab. 3.9.: Time steps outbound in minutes (Porozantzidou 2015)

Step	Department	Mean	Std. Deviation
1	Expedition	96.9	153.5
2	Repair administration	39.0	15.2
3	Expedition	44.9	4.9

FIFO-policy. Initially the package and the components are visually inspected on damage and labels. Thereafter, the certificates and documents of the repair shop or vendor are inspected for completeness and correctness. If all information and physical characteristics are correct, the 'Goods Receipt' notification is established. This notification states that the component is officially declared airworthy. The inspectors place the component in its package onto the second buffer, where expedition personnel picks it up and provides it to the general warehouse employees. Table 3.10 provides information on the capacity currently available for the IIG process. Less manpower is scheduled for IIG process, which results in higher WIP buffers (Section 3.4.3.

Tab. 3.10.: Capacity inspection incoming goods

Day	Mean processed	Std. Deviation	Mean FTE
MON	19.3	9.2	2
TUE	22.1	14.5	2
WED	7.3	9.2	1
THU	24.3	11.6	3
FRI	23.1	15.5	2
Total	15.4	13.9	2

On this process, again, little reliable data is available. In recent history manual tracking was performed, which often resulted in unreliable or missing data on where the component is from expedition, IIG, and warehouse. However, since the current technology, i.e. RFID, is still in its experimental phase, the data of the previous tracking ways is used. This can be combined with the data from the freight forwarder, which includes the day when the component is received at the central depot. Finally, data of the GR notifications is used to connect the time stamps to an average and a standard deviation in minutes for IIG, which is listed in Table 3.11.

Tab. 3.11.: Time steps inbound process in minutes

Step	Department	Mean	Std. Deviation
1	Expedition	96.9	153.5
2	Inspector	37.4	36.1
3	Expedition	45.5	142.8

3.4.3 Logistics delay

In literature administrative and logistics delay are considered one time components added to the actual MRO services. However, empirical data by KLM E&M reveals some significant delays in buffers and travel times to and from repair vendors. Travel time is not treated as a configuration variable in this research project, but it is to be considered in the total time to restore a component as a fixed parameter. KLM E&M itself is based in the Netherlands, Amsterdam. Therefore, the travel times are quite as expected, with Amsterdam revealing the lowest travel time and the facilities in the United States the highest. The travel time is measured from the date the repair order is created until it is delivered at the vendor. Deviation between the average and maximum time can be explained by different flight schedules and consolidation of products. Table 3.12 lists all mean travel times.

Tab. 3.12.: Travel times to and from vendors in days

Vendor	Country	Mean travel time to vendor	Mean travel time to KLM E&M
Air Franc Industries	France	1.1	1.0
Vendor B	The Netherlands	1.0	1.1
Vendor C	United Kingdom	1.9	1.8
Vendor D	United States	5.2	4.0
Vendor E	United States	4.8	8.4
Vendor F	Unites States	4.2	4.7

Travel times to and from repair shops is negligible and assumed to be one day. Any delay occurring from the movement of components from and to repair shops is most likely the cause of excessive waiting times at the central depot. In this facility, buffers are used as switch between subsequent activities. Regarding the outbound flow, the expedition personnel initially places the component in a queue at the ’outbound lane’ within the central depot. Thereafter, the package is picked up, divided according to airframe type, and placed in the second queue.

The repair administrator picks up the component, provides the proper administrative work, establishes the repair order, and places it in the third queue where it can be picked up by expedition personnel again. All activities and picking packages from the queues are done according to a FIFO policy. Table 3.13 provides a list of times for each of the above mentioned steps. For the same reason as outbound delay, the buffers are used function as a switch between expedition and IIG and between IIG and warehousing in terms of inbound delay. The table also presents the average buffer time between expedition and the IIG and between the IIG and the depot. The manpower available at the IIG is less than at the RA, which results in higher buffer times between these two activities.

Tab. 3.13.: Logistics delay at central depot in hours

Buffer	Mean time	Maximum time
	Outbound	
1	46.0	68.9
2	4.7	112.3
	Inbound	
1	28.9	57.0
2	3.0	20.0

3.5 Performance measurement

The objective of this research project, as discussed in Section 1.4, is to improve the availability of aircraft components from the perspective of inventory to reduce the mean downtime of an aircraft. As found in Section 2.1, the time to restore a component is composed of the repair time, administrative and logistics delay, and the supply time. The supply, in terms of newly provisioned products, is not further considered in this research project due to scoping. KLM E&M does not directly use these measures as performance indicators, but does deploy activities and processes that match the two measures of active repair time and administrative and logistics delay. The objective of reducing the mean downtime from an inventory replenishment perspective can thus be further explained by these two compositions (Figure 3.8). Therefore, these measures are used as final KPIs for this research project. Furthermore, cost is generally an important performance indicator for commercial businesses. Therefore, this research project also aims to enhance the efficiency by including cost of MRO as well. This is dependent on the work scope and to which repair shop it is assigned.

The repair lead time time for a component, measured for both in-house as well as outsourced repair consists of the active repair time and delays occurring prior and post to the repair. The administrative delay is a measurement for the lead times in the central depot, including the outbound and inbound processes. Since this research project is not focused on reducing the lead times by altering the capacity and resources, the aim is to reduce the overall delay (Cavalieri et al. 2008; Al-Kaabi et al. 2007).

Besides the aforementioned KPIs, another output variable is considered to measure the performance: resource utilisation. This is not reported as a KPI, for it is correlated with the total lead time. However, it does explain either increase of decrease in lead times. Furthermore, it reveals elasticity in capacity of the shops and therefore also whether the alignment of jobs with shops is done effectively and efficiently.

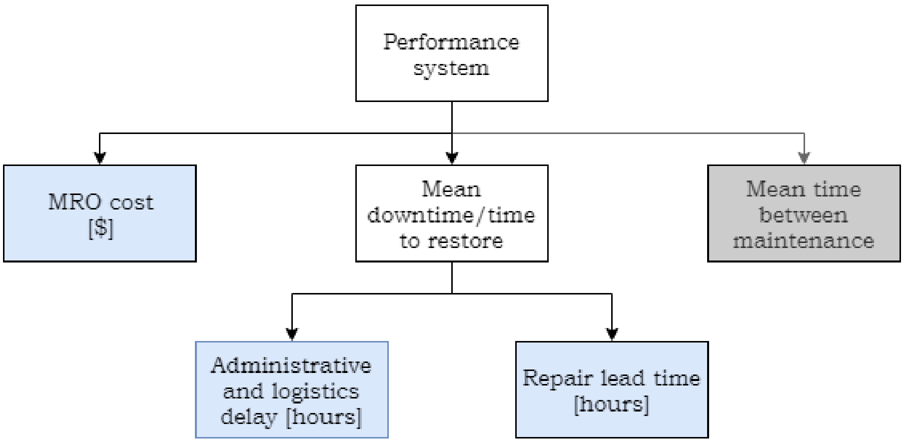


Fig. 3.8.: Key performance indicators

3.6 Conclusion data analysis

From Section 3.3 it can be concluded that large deviations exist in terms of repair lead time. This applies to both in-house as well as outsourced repair. Table 3.14 presents the lead time performance per repair shop and vendor. Two in-house repair shops over-perform, i.e. Shop C and Shop E. This is measured by the service level, i.e. the amount of times a repair job is finished on-time. Vendor C and Vendor B are vendors that approach the target lead time rather closely. The poor performance in terms of on-time dispatch of jobs of the vendors might be due to the strict targets, for over 60% of the jobs does not suffice to this performance indicator.

The table presents average lead times, but large outliers have been identified for all repair facilities, which generally cause bottlenecks for the following repair services. The decision-making for repair facility is done by the repair administrator at the central depot. Here, initial administrative work is performed. Moreover, the shares of repair jobs varies over the repair shops, whereas more shops are capable of providing services to different commodity types.

Depending on the available capacity of each shop, re-allocation of repair jobs is a viable option to reduce overall lead times. The data on load and capacity at each shop is available, but is not integrated with the data of repair administrator. When significant disruptions occur at a shop, this is communicated to the central depot, which allows them to reconsider the selection of shop for the arrived unserviceable components.

Tab. 3.14.: Lead time performance

Shop	Target time [d]	Actual time [d]	Mean service level	Share of repairs
Shop A	14	17.9	79%	11%
Shop B	16	17.1	97%	6%
Shop C	16	16.1	98%	6%
Shop D	18	12.2	151%	28%
Shop E	20	13.9	112%	4%
Vendor A	18	42.0	46%	11%
Vendor B	20	24.9	93%	9%
Vendor C	9	12.0	79%	2%
Vendor D	26	40.7	91%	5%
Vendor E	26	58.9	59%	11%
Vendor F	14	34.3	57%	7%

The second large attribute contributing to the MDT are the administrative and logistics delay (Section 3.4). Within the central depot, the majority of the administration takes place, for this the location where all components and material are entered in the system. The physical flow is divided in serviceable and unserviceable goods. The former is processed by IIG, where the component is declared airworthy and prepared for re-stocking. The unserviceable components are handled by RA. Here the repair order is established and the respective repair shop or vendor is determined. Thereafter, the components are expedited to the proper location. The administrative delays for unserviceable components, if all processes are continuous, would be approximately 3 hours on average. However, more aggregated data shows an average lead time of 12 days within the central depot. This would mean that a component is waiting nearly 8 and 9 days at the central depot until further processing. This can either be at expedition, waiting to be transported, or waiting at intermediate buffers in between processes or due to lacking information or IT system failures.

When the objective is to achieve the overall lowest cost, all component services should be performed in-house. However, due to lack of material, skill, or contractual agreements, outsourcing is done to repair vendors. This comes at a cost, depending on the work scope and the respective vendor. For major repairs, outsourcing could be more feasible, but for smaller work scopes, such as inspection and minor repairs, in-house services are least costly. Table 3.15 provides a concise summary of averages of the current performance based on the data used in the analyses performed in this chapter. Generally, the repair vendors lead time is longer than in-house lead time and cost of MRO are higher, but since the demand pattern for component MRO can be characterised as rather erratic or even lumpy, different scenario's can establish in which it is cheaper or faster to outsource. Moreover, Figures 3.5 3.6 reveal several significant outliers. Currently, contractual agreements and historical assignments are the leading predictors of the choice for repair facility. In few exceptional cases, shops and vendors communicate to KLM E&M whenever capacity constraints or other resource limiting situations have occurred. This aids the repair administrator to choose a different repair facility.

Tab. 3.15.: Summary mean current performance

KPI	In-house	Outsourced
Lead time [d]	14.7	35.3
Cost [USD]	$ 3.277.626,7	$ 13.949.423,2
Administrative and logistics delay [d]	4.1	7.9

Model synthesis

4

The simulation model enables the evaluation of the base case as well as the performance of solution alternatives and pursues a reduction in the TTR. The TTR starts from the moment a component has entered the outbound division in the central depot and ends at the moment of re-stocking. The reduction in TTR is tested upon whether it assures a better performance in terms of time and cost for different repair facilities are accompanied by different cost of MRO and repair lead times.

The simulation model that is used to represent the system is a Discrete Event Simulation (DES) model. A DES model is one in which the state of the model and its objects only change at a discrete set of simulated points in time, i.e. events (Schriber et al. 2014). For implementation the software Simio is used, which is built on object oriented principles. The choice for DES modelling can be substantiated by the fact that it enables manipulation to the system in a relative small period of time and for low cost. Additionally, it expedites the speed at which an analysis can be performed (Fishman 2013). This research regards changes in operating rules, making simulation a suitable method to assess the performance as a result of these changes. Instead of implementing these changes in the actual system, with risk of causing flow disruptions, simulation facilitates experimentation with an abstraction of the system (Carson and John 2005). Finally, the use of simulation has proven its efficiency in stochastic environments, as it allows the use of probability distributions rather than exact data. A conceptualisation of the simulation procedure is presented in Figure 4.2.

The main objective of the simulation model is to evaluate different design alternatives in terms of the performance measures. The performance measures, or KPIs, are the lead times, cost of MRO at repair shops, and administrative and logistics delay. Additionally, resource utilisation is considered an important output variable, since this describes possible overload of jobs to repair shops and vendor. To obtain this objective, different sub-objectives are to be accomplished. These sub-objectives encompass the evaluation of the current situation and facilitate to the stochastic environment of aviation MRO. These objectives are as follows:

1. Quantify the base case performance as reference scenario
2. Evaluate different alternatives in the solution space
3. Test the performance of the alternatives through experimental design

4.1 Model conceptualisation

In order to model the system properly, an initial conceptualisation is made. This conceptualisation provides the scope of the model and therefore facilitates insight in the model input, output variables and which assumptions are in place. Furthermore, conceptual model logic is described such a manner that the solution alternatives can be generalised over different DES systems.

4.1.1 Model scope

The entire system consists of four modules: demand, administration, logistics, and repair. The scope of the model is yet depicted in Figure 3.1 where the exchange and the storage of components are left out of scope. Availability is assumed to be provided once a component has been re-stocked. The model is initialised with the arrival of components with different attributes at the central depot. Here the components are moved to the repair administration to prepare the repair order. This repair order is made according to the repair shop or vendor where the component is to be repaired. The component is thereafter expedited to the respective repair facility where the component is repaired. After repair, the component is dispatched back to the central depot, where it is declared serviceable and re-stocked in the main warehouse. A visualisation of the physical flow as modelled is presented in Figure 4.1.

Some configurations are not considered as decision variables and are therefore not modelled in thorough detail. These configurations are modes of transport, use of specific equipment, and transport schedules are not included in the model. These configurations are assumed to be a black box, for the in- and output is considered, but internal logic is not elaborated on (Holzinger et al. 2017).

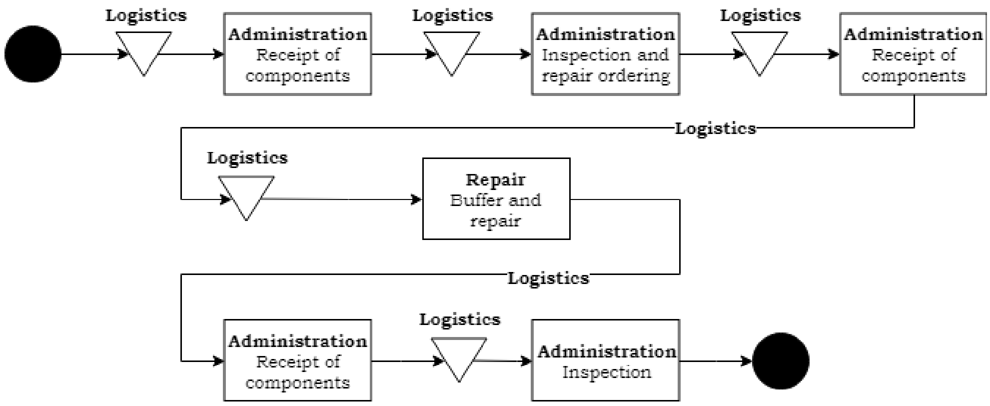


Fig. 4.1.: Scope of simulation model

4.1.2 Model assumptions

Modelling the system requires assumptions. A proper level of aggregation is assumed that allows modelling the problem definition. However, by scoping too narrow, false results can be rendered and incorrect understanding of the actual system can be established (Jefferys and Berger 1992). For this reason assumptions are checked during the validation of the experimental plan. The assumptions made in this research project are:

1. **Demand for MRO**: the aviation industry, and especially in the context of MRO, is characterised by erratic or lumpy demand patterns (Kilpi et al. 2009). This characterisation accounts for individual components. However, from a more aggregated perspective, the total demand over a longer period (i.e. month or year) is rather continuous. To follow the empirical demand pattern, an exponential inter-arrival time is opted for, as used in the majority of simulation studies (Adan and Kulkarni 2003). However, seasonality does occur in the context of MRO. During the months May until September more flight hours are measured, which results in more demand for MRO in the following months. The data

used to model the system contains data of one complete year is thereafter smoothed into the average exponential inter-arrival rate.

2. **Work schedules**: demand is generated 24/7, but the different servers are not available continuously. Different work schedules, based on empirical data, are used as input to determine the available capacity. Standard work days from 8:00AM - 5:00PM are used for the repair facilities. The central depot has longer operational hours: 7:00AM - 11:00PM. Both repair and logistics are not available during the weekends.
3. **Secondary resources**: no additional resources, such as equipment, headcount, and tools are added to the model. It is assumed all resources are covered with the capacity provided in the work schedules.
4. **No downtimes**: since secondary resources are not included in the model, no machine failure or downtime are present in the model. Possible delays in case of flow disruptions are assumed to be inherited in the processing time distributions.
5. **Transportation**: components arrive from all over the world at the central depot. Transportation to and from this facility is performed via truck and aircraft. However, the exact schedule of transportation is not considered. It is assumed that no significant difference in overall performance is measured if a continuous dispatch and receipt of components is modelled using solely average travel times (Sahay 2012).
6. **Amount of repair facilities**: a selection of repair facilities is made to limit the amount of components and their characteristics. Empirical data has shown many more repair facilities, but these have been responsible for a negligible amount of repairs for the considered commodity types, and are therefore not individually considered. Furthermore, the repair vendors included in this research scope are chosen is such a way that the components being repaired internally can be outsourced.
7. **Operational availability**: operational availability is assumed to be provided once a component is re-stocked in the main warehouse. Inventory management strategies and responsiveness of both KLM E&M as well as customers, is not considered in this research project.
8. **Processing times**: the processing times of the repair facilities are assumed to be location dependent rather than component dependent. A repair shop or vendor is able to repair specific commodity types. Therefore, the processing time based on the component is already inherited to a large extent.
9. **Physical capacity**: no physical capacity constraints are assumed in this study. This applies to the repair facilities as well as the central depot.
10. **Capacity at repair vendors**: the exact capacity in terms of personnel is unknown for the repair vendors. KLM E&M employees were able to estimate the relative size of these facilities (Appendix D). The capacity is determined in such a way that resource utilisation is not below 75% for the vendors that have a relative high share of jobs (> 5%).

4.2 Model logic

The simulation model is used to evaluate solution alternatives. Alternatives are proposed as a result of Chapters 2 and 3. The alternatives focus on the aggregated repair lead time by assigning repair shops based on the criteria cost, priority, and time, whilst accounting for load.

As concluded in Chapter 3, the assignment of repair is currently primarily done by contractual agreements, previous assignments, and required skill. In case of disruptions and in case this is communicated to KLM E&M its central depot, re-allocation of jobs to other shops is possible but is done rarely. Figure 4.2 describes the model logic as is specified in the DES model.

A classification, including the work scope, and commodity type of components is yet provided in Section 3.2. How these classifications are notated in the algorithms is listed in Table 4.1. A certain percentage of the components owns each of these attribute classes. Each component is therefore assigned certain attributes based on probabilities from a discrete distribution. These attributes are workscope and commodity type. The components are processed at the outbound department within the central depot. There the assignment of repair facility is determined. Four different assignment policies are tested: random, time based, cost based, and a mix of cost and time. The assignment policies where cost and time are used as objective are evaluated with different weights for shop load to avoid the accumulation of buffers. The base case is not described in an algorithm, as this is modelled through link weights that mimic the share of components running through specific servers (Table 3.14). This is equal to the actual allocation of components over the repair facilities in the system. The logic of this allocation at KLM E&M is is rather ambiguous and restricted to SLAs with several exceptional decision rules.

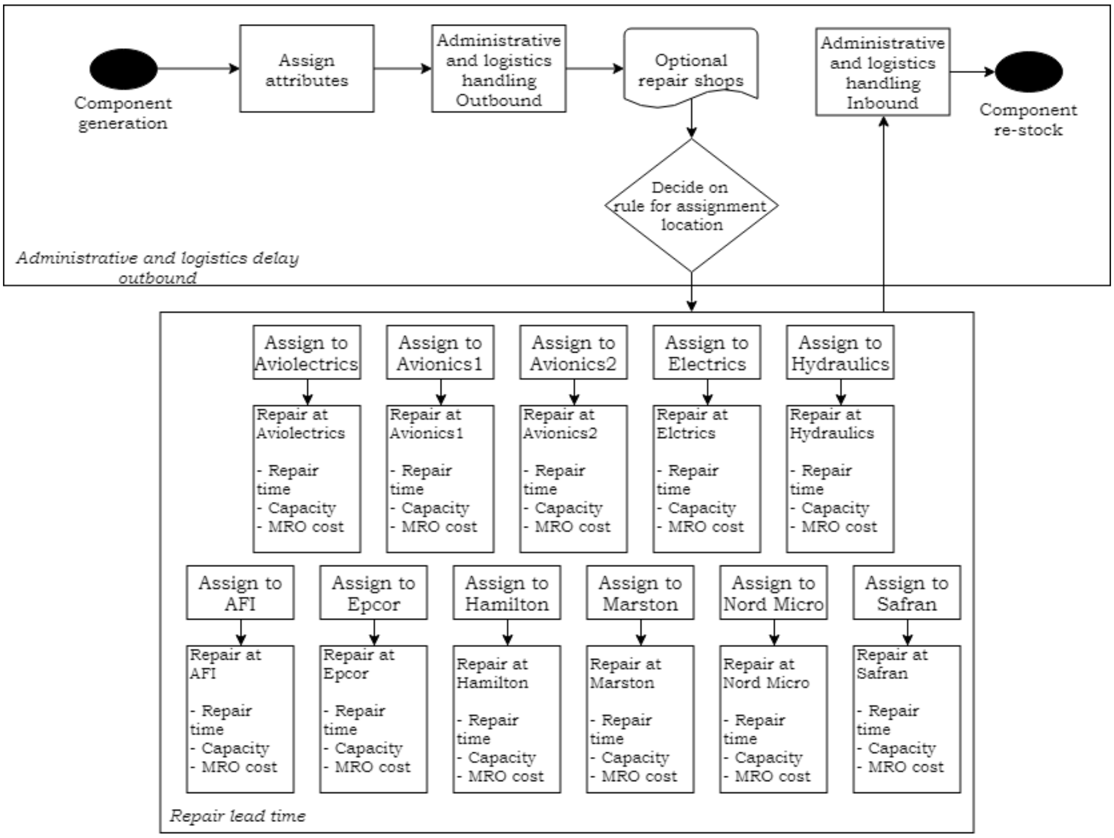


Fig. 4.2.: Model logic

4.2.1 Shop-task assignment

As part of the solution alternatives, multiple assignment policies are tested where different attributes are included. Moreover, the different assignment policies aim to reduce these attributes. It is no optimisation, but a decision for the smallest value as a result of the selection expression. Within this expression aspects such as time and cost are included. The classic assignment problem can be denoted as follows:

$$
\begin{aligned}
Minimise \ & \sum_{i=1}^{n}\sum_{j=1}^{n} c_{ij}x_{ij} \\
Subject\ to: \sum_{i=1}^{n} = 1 & \qquad j = 1, ..., n, \\
\sum_{j=1}^{n} = 1 & \qquad i = 1, ..., n, \\
& \qquad x_{ij} = 0\ or\ 1,
\end{aligned}
$$

where x_{ij} = 1 if agent i is assigned to task j, 0 if not, and c_{ij} the cost of assigning agent i to task j. The first set of constraints ensures that every task is assigned to one agent and the second set ensures that each agent is assigned to at least one task. The objective now aims to minimised cost of task assignment. In this study other aims are also pursued. Different assignment problems are acknowledged in previous research, such as the balanced assignment, minimum deviation assignment, semi-assignment, categorised assignment, and multi-criteria assignment (Pentico 2007). For each assignment policy a different objective is determined and possibly also changes in constraints.

The KPIs are either time- or cost-related. Therefore, the objectives, or selection expression, is focused on these two performance indicators. In addition to the aim of reducing time and cost a random assignment is included as well, primarily for the sake of experimentation. The random assignment is elaborated on in Section 4.2.2. The policies focusing om time are discussed in Section 4.2.3. The first policy is a naive policy, for limited information is used in the selection expression. It is assumed that this information, such as shop load, can become available, whereas other information on type of arrivals at the central depot (i.e. demand forecasting) is not. This is assumed due to the stochastic nature of MRO demand, the current work procedures and instructions. The former makes it challenging to make accurate forecasts and the latter is a managerial implication for the implementation. The same reasoning is applied to the cost-based policies in Section 4.2.4. The final policy is a mix between both aims and therefore pursues a multi-criteria objective selection. This facilitates to the comprehensiveness of this research project. Both cost and time are included in the objective relative to the load of the candidate server. Different weights are applied to both attributes for experimentation. Finally, the policies are elaborated with the inclusion of priority based on the task size, which is more often included in work-flow modelling (Shen et al. 2003).

The developed assignment policies, or heuristics, are described in pseudocode. The notations used in the algorithms are described in Table 4.1.

Tab. 4.1.: Summary of notations

Shop attribute		Component attribute	
$r \in R$	Set of repair facilities	$p \in P$	Set of components
$t \in T$	Set of repair lead times	$d \in D$	Set of commodity types
$s \in S$	Set of available skill	$w \in W$	Set of workscope
$n \in N$	Set of available resources		
$c \in C$	Set of cost of MRO		

4.2.2 Random assignment (R)

In the majority of studies where the assignment problem is addressed a random assignment is proposed (De Koster et al. 2007). The random assignment is the simplest extension of the original assignment problem. A probability is drawn from the uniform distribution, which then represents the share of components being repaired at each repair facility (Bogomolnaia and Moulin 2001). The heuristic as implemented in the simulation model is presented in Algorithm 1

Initially, a list L_c^r is constructed where the attributes of a repair shop are included. These attributes are expected service time and cost of MRO {r, E_r, C_r}. Thereafter, a random shop is drawn from that list as a result of randomly drawn link weights from the uniform distribution varying between 0 and 1. This list differs for different commodity types, for a repair shop is not able to repair all sorts of commodity types. The work scope attribute is added to the components, but is not further considered in the assignment to repair shops. The list for random assignment is presented in Appendix B.1. For the random assignment, no shop load is considered. In other words, a random shop is selected from the list and there is no rule for destination selection.

Algorithm 1 Random algorithm

```
procedure INITIALISATION
    for all components $p \in P$ do
        Assign attributes to component $p \in P$: commodity type $d \in D$, workscope $w \in W$
    for all repair shops $r \in R$ do
        Assign attributes: skill set $s \in S$, cost of MRO $c \in C$, active repair time $t \in T$, resources $n \in N$
procedure SHOP ASSIGNMENT(R)
    $L_c^r \leftarrow$ Construct lists of repair shops $r \in R$ based on skill set $s \in S$
    for all repair shops $r \in R$ in the order of list $L_c^r$ do
        Compute $u$ for link weights
        Assign components $p \in P$ to shops $r \in R$ according to $u$
```

4.2.3 Time based assignment (N&SL)

Repair lead time is an important performance indicator. In stead of constructing an order list based on solely the required skill set, the expected repair time is used. This attribute includes the time configurations for repair, which includes the CIR-processes as presented in Table 3.2. The buffer measurement is calculated by the process logic as a result of the available capacity $n \in N$ and repair lead time $t \in T$ at the repair shops. The heuristic is initialised at the central depot after processing the packages at the outbound department. Here the expected operation time of the shops and vendors is calculated and based on this time, a repair facility is assigned for each component. This type of task assignment policy is often referred to as 'Shortest-Line' task assignment (Harchol-Balter et al. 1999). The heuristic is presented in Algorithm 2.

Two types of selection expressions are evaluated in this assignment policy to deal with possible lack of data. Initially, the tasks are assigned based on solely the active repair time of the candidate servers. This is in the 'extreme' case where no information is available on the load at the respective shops (Equation 4.1). Hence, this is further described as the *Naive* policy. Thereafter, a policy is tested where information on the load is available (Semchedine et al. 2011). This is multiplied by the active repair time to compute the remaining flow time in the shop before the component can be serviced here (Equation 4.2). The load includes the entities being processing, waiting in the buffer, and on the link directed to the server. Otherwise only one shop would be chosen and queues would accumulate. The active repair time is linked to the load and capacity, as this results in an accurate estimate for total lead time. The formula used to define the expected lead time as selection expression, and is used to construct the list L_r^s is as follows:

$$E^{t(N)} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} x_{ij} \tag{4.1}$$

$$E^{t(SL)} = \sum_{i=1}^{n} \sum_{j=1}^{n} t_{ij} x_{ij} l_j \tag{4.2}$$

Algorithm 2 Shortest algorithm

```
procedure INITIALISATION
    for all repair shops $r \in R$ do
        Assign attributes: skill set $s \in S$, cost of MRO $c \in C$, active repair time $t \in T$, and resources $n \in N$
    for all components $p \in P$ do
        Assign attributes to component $p \in P$: commodity type $d \in D$, workscope $w \in W$
procedure SHOP ASSIGNMENT(N/SL)
    $L_c^r \leftarrow$ Construct lists of repair shops $r \in R$ in increasing order based on $E^{t(N/SL)}$
    for all repair shops $r \in R$ in the order of list $L_r^s$ do
        Assign commodities $p \in P$ to shops $r \in R$
```

4.2.4 Cost based assignment (C)

Besides the lead time, cost of MRO is also considered a KPI. Therefore, assigning jobs to the shop where the services are least costly is another viable option. As stated in Section 3.3.2, major repair is cheaper when it is outsourced. However, for the other types of work scopes, in-house services are generally more affordable. When assigning jobs to shops, which deploy these services for the lowest cost, the cheapest repair shop server in the simulation seizes all jobs. This results in an unstable system where resource utilisation quickly rises to 100%. At this point, buffer start to accumulate to such an extent a steady state cannot be reached. Therefore, the load in each shop is accounted for by means of additional logic to the selection expression. This logic is as follows:

$$E^{t(C)} = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} x_{ij} l_j \tag{4.3}$$

$E^{t(C)}$ accounts for the load that is repaired at that point, waiting in the buffer, or is transported to that specific candidate shop. It therefore computes the actual cost of jobs at that specific point in time, but also the future cost. Every time an entity, or component, enters the repair administration server, a list L_r^c is made with the candidate shops and their C^t. The objective is then to assign the shop with the lowest value of C^t. This way, the assignment gains a multi-criteria approach where also the least remaining work is included for (Harchol-Balter et al. 1999).

Algorithm 3 Cheapest algorithm

```
procedure INITIALISATION
    for all repair shops $r \in R$ do
        Assign attributes: skill set $s \in S$, cost of MRO $c \in C$, active repair time $t \in T$, and resources $n \in N$
    for all components $p \in P$ do
        Assign attributes to component $p \in P$: commodity type $d \in D$, workscope $w \in W$
procedure SHOP ASSIGNMENT(C)
    $L_r^c \leftarrow$ Construct order of repair shops $r \in R$ in increasing order based on $E^{t(C)}$
    for all repair shops $r \in R$ in the order of list $L_r^c$ do
        Assign commodities $p \in P$ to shops $r \in R$
```

4.2.5 Mixed assignment (CS)

Full comprehensiveness on the output of the assignment policies is obtained by mixing both cost and time in the objective expression. Different weights are applied to these two attributes and multiplied by the load to account for resource utilisation. This way a multi-criteria single objective is obtained. Both cost and time are to be reduced (Pentico 2007). The expression is depicted in Equation 4.4. Algorithm 4 denotes the pseudocode of the mixed algorithm. It is rather similar to the CL and SL algorithms. The sole difference is the selection expression of which the List $L_r^c s$ is constructed for each component at the repair administration. The list consists the output of Equation 4.4 for each candidate shop and is then constructed in increasing order of value. As previously mentioned in Section 4.2.1, the different weights are not sensitive due to the different units and size of the attributes. In the equation the weights are denoted by β_S and β_C for time and cost respectively. Three scenarios are considered in terms of weights:

1. β_C = 0.5, β_S = 0.5
2. β_C = 0.7, β_S = 0.3
3. β_C = 0.3, β_S = 0.7

$$E^{t(CS)} = \sum_{i=1}^{n} \sum_{j=1}^{n} (\beta_C * c_{ij} + \beta_S * t_{ij})(x_{ij} l_j) \tag{4.4}$$

Algorithm 4 Mixed algorithm

```
procedure INITIALISATION
    for all repair shops $r \in R$ do
        Assign attributes: skill set $s \in S$, cost of MRO $c \in C$, processing times $t \in T$, and resources $n \in N$
    for all components $p \in P$ do
        Assign attributes to component $p \in P$: commodity type $d \in D$, workscope $w \in W$, time entered $T_{in}$, and time re-stocked $T_{out}$
procedure SHOP ASSIGNMENT(CS)
    $L_r^c s \leftarrow$ Construct order of repair shops $r \in R$ in increasing order based on $E^{t(CS)}$
    for all repair shops $r \in R$ in the order of list $L_r^c s$ do
        Assign commodities $p \in P$ to shops $r \in R$
```

4.2.6 Priority assignment (P)

Within the system and model four work scope types are generated: inspection, overhaul, minor repair, and major repair. By assigning these types without the consideration of their accompanied cost and repair time, bottlenecks may occur. Therefore, the classification of criticality is applied in this heuristic to be the main decision variable to decide on the assignment of repair jobs to shops. The components are batched at the repair administration in the central depot. The physical inspector is then to provide information on the work scope to the repair administrator, who then is able to select a shop for the components with larger work scopes first. The priority of the work scopes is based on both time and cost. Major repair services are more expensive when performed in-house and generally take the longest. The assignment of priority is thus provided from the perspective of KLM E&M in-house services.

This assignment is applicable to the previous two heuristics and for the base case. Therefore, this assignment policy is evaluated as a scenario for the previous assignment policies. The heuristic in pseudocode is presented in Algorithm 5, for the assignment procedure Algorithm 2 is used. The difference lies at the priority assignment, which physically takes place at the repair administration and thereafter at the expedition.

Algorithm 5 Priority algorithm

```
procedure ASSIGN PRIORITY(P)
    for all components $p \in P$ do
        Determine work scope $w \in W$
        if work scope = major repair then
            priority = 1
            if work scope = overhaul then
                priority = 2
                if work scope = minor repair then
                    priority = 3
                    if work scope = inspection then
                        priority = 5
procedure SHOP ASSIGNMENT(S)
    $L_r^s \leftarrow$ Construct order of repair shops $r \in R$ in increasing order based on $E^{t(SXX)}$
    for all repair shops $r \in R$ in the order of list $L_r^s$ do
        Assign commodities $p \in P$ to shops $r \in R$
```

4.3 Model implementation

The model is implemented in Simio. It is an object oriented simulation software based. It supports the use of multiple modelling paradigms including, event, process, object, and agent-based modelling. This study assumes the components and resources in the servers to be passive and active respectively (Thiesing and Pegden 2013).

This section also elaborates on the verification and validation of the model. Verification and validation is crucial when modelling a problem situation. Verification takes on whether the model is correct and whereas validation checks whether it is the right model. For verification several checks and runs are performed to certify correct relations between in- and output. Generally, occurring errors have been corrected in the model. To validate the model, simulation results are compared to empirical data. This enables substantiation for the utility of the model to the actual system (Carson and John 2002).

4.3.1 Model input

The model is built by combining objects representing physical configurations of the system. An object is further defined by its properties, states, events, and logic. Properties are parameters, such as service times. States are dynamics values that may change as the model executes. Events are configurations that the object can 'fire' at selected times.

Two types of input can be distinguished for simulation modelling. Firstly, fixed parameters are used to specify the model logic. These are obtained through literature review and data analysis from the case study. Secondly, input data is used to generate entities in the model.

Fixed parameters

The model includes 16 servers total, of which five are located in the central depot, five internal repair workshops, and six repair vendors. The standard properties of the servers include capacity type, work schedule, ranking rule, process type, processing times, and financials in terms of capital costs and resource costs. For some servers, additional process triggers are added to broaden the process logic of the servers. These additional process triggers can occur before, during, or after processing at that specific server, on run initialised and run ending, and on entity entered and exited the server module. A list of the fixed parameters used in the model is presented in Table 4.2. The logic of a general server module in Simio is visualised in Figure 4.3.

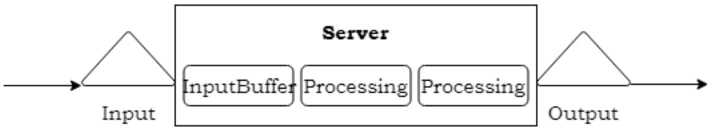


Fig. 4.3.: Server module

Central depot
The first three servers represent the outbound division in the central depot. The process logic of the physical inspection and repair administration contains an initial capacity of 4, as determined in Table 3.8. The servers and their processing time within the central depot are all modelled through an exponential distribution. After repair administration the components are expedited. The fifth server, being part of the central depot, is the inbound division. The process logic of this module is rather similar to the outbound servers in terms of a processing time from the exponential distribution, but is deployed by an independent capacity source, following the FTE from Table 3.10.

Repair shops and vendors
The simulation consists of 11 repair servers: Shop A, Shop B, Shop C, Shop D, and Shop E, Vendor A, Vendor B, Vendor C, Vendor D, Vendor E, and Vendor F. As input for processing time, solely the active repair time is used. The simulation facilitates to the establishment of queues based on this active repair time and available capacity.

The buffer times in Section 3.3.1 are based on empirical data. To mimic this logic, work schedules are included during weekdays. It is assumed that no work is performed during the weekends. Internal data of KLM E&M has enabled the input of capacity for each in-house work shop. However, this slightly deviates due to holidays and sickness. Therefore, the capacity is modelled by means of a uniform distribution, that allows some margin in resources. The capacity of repair vendors is also modelled by means of a randomly drawn value from the uniform distribution. The values used as mean are based on estimated guesses by KLM E&M employees. The exact values used are depicted in Appendix B.4.

Tab. 4.2.: Fixed parameters

Parameter	Value	Property
	Central depot	
Resources per Server	1, 3 Uniform	Initial Capacity
Resources per Server	2, 4 Uniform	Initial Capacity
Service time Expedition In	100 [min] Exponential	Processing Time
Service time Expedition Out	60 [min] Exponential	Processing Time
Service time RA	60 [min] Exponential	Processing Time
Service time IIG	60 [min] Exponential	Processing Time
Work order	First Come First Serve	Ranking Rule
	Repair facilities	
Resources	Appendix B.4 Uniform	Capacity Type
Active repair time	Appendix B.5 [h]	Processing Time
Repair cost	Appendix B.6 [$]	Resource Cost
Work order	First Come First Serve	Ranking Rule
Travel time	Table 3.12 [days]	TimePath

Input

One type of entity is created. Using state assignments, commodity types and workscope are added to these entities. This is done by means of probabilities. for the exact amounts are not static over time. Each entity is provided two real states varying from one to four, each representing a commodity type and workscope. These values are randomly drawn from the discrete distribution with cumulative probabilities of each attribute. The arrivals are computed according to an exponentially distribution inter-arrival time, based on empirical data.

The entities are destroyed at one sink module, representing the main warehouse where all the repairable components are re-stocked. No additional properties are given to this module, since the inventory management strategies are not included in this research project. Therefore, no input buffer is established at this object.

4.3.2 Model output

Three different KPIs are used to determine the performance of the system and to evaluate the solution alternatives. These KPIs are the cost of MRO, additional delay due to administration and logistics and the repair lead time. The cost are simply measured by including resource cost to the repair shop servers. After the runs these are summed and described using descriptive statistics, such as average, maximum and minimum, and half width. The administrative and logistics delays are measured from the two modules: inbound and outbound. The total delay is the time spent processing and waiting in the buffers. The repair lead time is a sum of the processes presented in Figure 4.3. The final TTR is the total flow time of an entity in the system.

4.3.3 Verification

To ensure that the conceptualisation of the system is specified with sufficient accuracy, the model is verified (Robinson 2006). This also ensures the system specification and implementation of the conceptual model is correct (Sargent 2009). Different techniques are used to verify the model, through both static as well as dynamics analysis. In other words, the model is analysed by means of the static source code and through model execution respectively. This category of model verification is opted for as this is rather effective whilst relatively simple to do (Whitner and Balci 1989).

- **Consistency checking:** consistency checking verifies whether the model description does not contain contradictions and that data elements are manipulated properly. This includes data assignment to variables, data within computations, and data representation. Most consistency checking is accomplished by using the documentation produced by the expressions, which is already presented in Table 4.2 and further elaborated on in Section 4.1. Balance checking is part of this technique, where at the end of each run the amount of entities created, destroyed and yet in system are checked for balance.
- **Event tracing:** event tracing is part of dynamics testing and allows the researcher to follow each step of each entity and each accompanied processes it follow. This enables a complete understanding of the model logic and whether it is in line with the conceptual model. Simio has such a function already built in. This technique is also possible for each individual object.
- **Run time visualisation:** statistics and tables are continuously used to see whether output is computed as expected. Some examples of these statistics are average time in buffers, number of components in the repair shop, and capacity utilisation.
- **Bottom-up testing:** sub-models are tested to evaluate relations in in- and output. Thereafter, these are implemented in the overall model. This is especially of importance when using probability distributions as input.

4.3.4 Validation

Validation of the model aims to answer whether or not the model is able to present the specific purpose of that model (Sargent 2009). The validation substantiates "the applicability of a computerised model to a specific domain and whether is possesses a satisfactory range of accuracy consistent with its objectives (Balci et al. 1997). Regardless of the type of system, several common validation techniques can be used for all types of modelling, which is comparing the simulated and real world data through statistical tests.

Three types of validation are performed. Firstly, the data used as input in the model is validated by means of statistical validation. This is mostly relies on the goodness of fit of the used stochastic distributions. The majority of the data the model is built upon are the active repair times, which are implemented by means of these distributions. The Kolomogorov-Smirnov test is used to test the goodness of fit of the estimated distributions. The results of this test is presented in Appendix B.5. The test is based on the maximum difference between empirical and a hypothetical cumulative distribution, as modelled in the simulation (Massey Jr 1951). Secondly, structural validation is used to measure the work- and data-flow and to what extent it is according to the actual system (Qudrat-Ullah 2005). The steps, as presented in Figure 4.2, is discussed with experts of KLM E&M. A summary of the information provided by these experts is presented in Appendix D. Finally, performance validation is in place. The KPIs considered in the study are therefore compared to the KPI values as determined in Section 3. These will be further explained.

Repair lead time

The processing time, or the active repair time, is one of the determinants for the total repair lead time. The other determinant is the capacity. The exact available capacity at the repair vendors is unknown to KLM E&M. Therefore, rough estimates drawn from the uniform distribution are used as parameter for capacity (Appendix B.4). Table 4.3 presents the results of total lead times both modelled as well as actual values withdrawn from empirical data. These values include the travel time as well. As previously mentioned, the capacity of the repair vendors was rather unknown and was therefore matched to the repair time, the known delivery time, and estimated resource utilisation from experts. There is no specific rule to when a model is valid in terms of the allowed difference between model and actual system. All differences in lead times are lower than 25% and will be further tested through a higher amount of replications, sensitivity and scenario analysis in Section 5.2.

Tab. 4.3.: Modelled and actual lead times (in days)

Shop	Actual lead time	Model lead time	Difference Model/Actual
Vendor A	42.0	48.7	14%
Shop A	17.9	20.3	12%
Shop B	17.0	17.9	5%
Shop C	16.0	19.5	18%
Shop D	12.4	12.1	-3%
Vendor B	24.9	22.0	-13%
Vendor C	15.7	15.3	-3%
Vendor D	38.8	35.2	-10%
Vendor E	58.9	51.6	-14%
Vendor F	34.3	33.2	-3%
Shop E	17.3	21.6	2%

Administrative and logistics delay

As concluded in Section 3.6 the supporting services to repair is a grey area for KLM E&M in terms of data. Currently, the company is in transition of data collecting technology which increases the unreliability of data even more. The relative delay in the model is less than the actual delays of the amount of waiting and processing times is slightly different than in the actual system. However, on a more aggregated level, the average delay approaches the actual delay well. The KPI is further analysed through sensitivity analysis in Section 5.2.4. The only, relatively more reliable, data that is available for the administrative and logistics delay is an average of 12 days. The maximum modelled values for both inbound as well as outbound are also presented. According to the project manager direct support (2018) (Appendix D), these values are valid. Several outliers occur, but these are not modelled to a detailed extent. For example, in case of lacking information provided by the customer, a component is put on hold before pushed forward to either the inventory or repair. Depending on the responsiveness of the customer, this can take months.

Tab. 4.4.: Modelled administrative and logistics delay (in days)

Flow direction	Statistic	Model	Actual	Difference Model/Actual
Inbound	Average	5.9	-	-
	Maximum	10.5	-	-
Outbound	Average	7.0	-	-
	Maximum	23.5	-	-
Total delay	Average	12.9	12	-8%

Cost of MRO

The cost of MRO services is dependent on the share of work scope types, i.e. inspection, overhaul, minor and major repair, and on the repair shop these services are deployed. Appendix B.6 presents the average cost per service of different shops for each work scope. These values are used to evaluate the average cost per item, which are presented in Table 4.5. Additionally, the same metric is added to this table as a result of the simulation of the base case. Some deviation is as expected, for the amount of work scope types is also dependent on the total amount of entities generated. Nevertheless, no deviation > 25% is revealed in terms of average cost of MRO services.

Tab. 4.5.: Modelled and actual cost of MRO per item (in USD)

Shop	Actual cost per item	Model cost per item	Difference Model/Actual
Vendor A	€ 3,392.3	€ 4,174.0	20%
Shop A	€ 1,208.7	€ 1,502.0	10%
Shop B	€ 1,737.7	€ 1,927.2	8%
Shop C	€ 3,337.8	€ 3,612.5	5%
Shop D	€ 658.3	€ 695.8	14%
Vendor B	€ 7,410.3	€ 7,410.3	19%
Vendor C	€ 13,555.0	€ 14,939.5	7%
Vendor D	€ 2,113.8	€ 2,280.8	9%
Vendor E	€ 10,263.3	€ 10,771.5	7%
Vendor F	€ 2,905.5	€ 3,360.5	5%
Shop E	€ 4,521.8	€ 5,276.2	14%

4.4 Conclusion model synthesis

A DES simulation model is built to represent a simplification of the studied system. It contains three main components: arrival, administration and logistics, and task assignment. The servers in the model are presumed to be the active objects, whereas the components are passive. In other words, the servers seize and release requests based on different attributes. A demand is generated, which is initially handled through administrative and logistics tasks. Thereafter, a decision is made on where to send the components for repair based on different task assignment policies. The task assignment each cover either the KPI of time or cost. The configuration of work load is also included in the assignment policies, to restrict the resource utilisation. This way a steady state is aimed for in each policy. Administrative and logistics delay is further affected by these assignments, but is not included in the decision. Furthermore, the attributes of work scope and commodity type are included in the assignment policies, as these limit the amount of candidates.

5

Results

The main deliverable of this chapter are the results of the current state and the assignment policies. Various heuristics are evaluated on the performance measures: repair lead time, additional delay due to administration and logistics, and cost of MRO. The model is already validated in Section 4.3.4 by means of these KPIs. Other output variables are still to be quantified that influence these KPIs. Therefore, the current situation is included in the experimental design, which is discussed in Section 5.1. Here, the setup of the experiments is further elaborated on. The setup includes aspects, such as run length, replications, and warm up period. Following the experimental setup and design are the results of the curent situation, or base case, in Section 5.2. The KPIs under the described different experimental setup are presented. Output, such as resource utilisation, is further elaborated on. This metric encompasses a large part of the time to restore. Furthermore, the base case, which is further used as reference alternative, is analysed in terms of its sensitivity through input scenario's. The results of the assignment policies are provided in Section 5.3 where these are compared to the base case results. Furthermore, the robustness of the assignment policies is tested through scenario's mainly focused on variation in demand. These results are presented in Section 5.5. The chapter ends with a concluding section, where the main and notable findings are summarised.

5.1 Experimental setup

The experimental plan for simulation studies is the art of designing experiments that yield the desired outcomes and includes determining how each of the test runs are to be executed. The run length of the model, starting conditions, correlations with output data, and valid statistical tests are to be dealt with (Shannon 1998). The system as presented in this study is a non-terminating system, as it does not end when a critical event occurs. The system is assumed to be non-stationary. In other words, the performance measures are able to change over time.

5.1.1 Run length and replications

Empirical data has shown that on average 480 components enter the system, with only considering the selected repair shops and vendors. According to Verbraeck (2019) there is no general method for determining the run length for non-terminating systems. A rule of thumb is setting the rung length as three times the longest cycle time, in such a manner rare events occur at least three times. However, in this system no 'rare events' are modelled. The data used for fitting the distributions as input for the model is nearly one third ($52/3$ weeks) of the empirical data. The run length should then be 52 weeks to validate the output. This is doubled for the experiments, leading to 2 years or 104 weeks of run length.

The most important criterion for the amount of replications is the relative width of the confidence interval relative to the mean value of the performance indicator (Verbraeck 2019).

Generally, the half width should not be lower than 5% of the KPI's average. The default number of replications in Simio are 10, however this is not enough, as the margin of error for the KPI's > 5%. Through further experimenting 50 replications were chosen to use, for this reduces the half width significantly. Not for every KPI is it below 5% of the average value, but it is kept at 50 due to high run times.

5.1.2 Warm up period

No rules are found in terms of determining the warm up period for a system such as this one. As previously mentioned, the model represents a non-terminating system. Therefore, it is solely of interest when a steady state is achieved. To achieve this steady state a warm up period is in place. Often, as well as for this study, the warm up period is used to fill up the buffers in the model as they would be in the actual system. The warm up period for this study is visually determined by modelling the number of entities in the system and is monitored over time. Figure 5.1 presents the number in system per in-house workshop. The graph starts by generating entities. After the first peaks, the first batch of components has been repaired. The buffers are established at roughly 60 days after the model is initialised. Therefore, a warm up period of 60 days is implemented in the experiments.

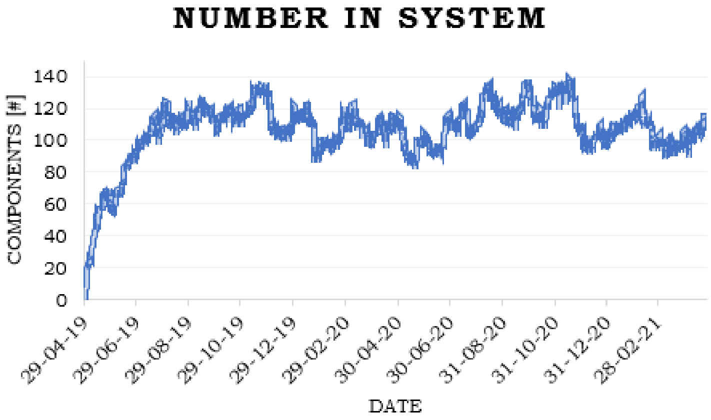
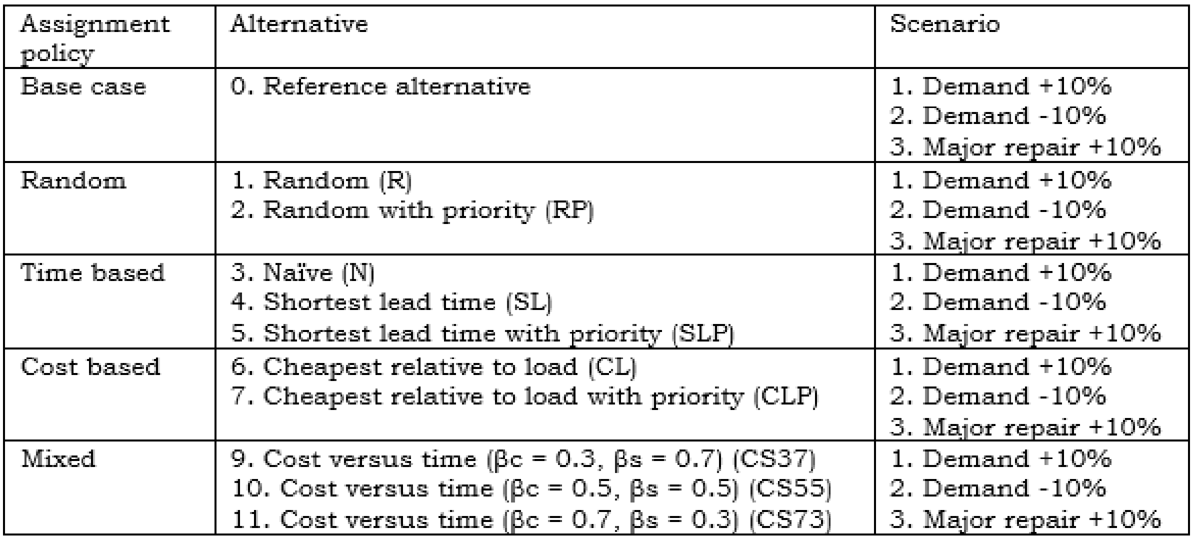


Fig. 5.1.: Entities in system

5.1.3 Experimental plan

Besides the base case, four different assignment heuristics are described (Section 4.2). Firstly, the random assignment (Algorithm 1) is evaluated with and without priority. The time based assignments (Section 4.2.3), is tested through three alternatives. Initially, solely the repair time is used as selection expression, which is therefore considered a 'naive' policy. This is then extended by the inclusion of shop load. Finally, priority assignment is included as well. Furthermore, the cost based assignment (Section 4.2.4) is tested. This assignment has two alternatives: with and without priority. Finally a mixed heuristic is tested. This includes both time and cost attributes. Three alternatives are evaluated using different weights for both cost and time. Each alternative is evaluated for three scenario's: increase in overall demand, decrease in overall demand, and additional major repair jobs. In total $14x3 = 42$ experiments are run by means of the simulation model. The experiments are summed up in Figure 5.2



Assignment policy	Alternative	Scenario
Base case	0. Reference alternative	1. Demand +10% 2. Demand -10% 3. Major repair +10%
Random	1. Random (R) 2. Random with priority (RP)	1. Demand +10% 2. Demand -10% 3. Major repair +10%
Time based	3. Naïve (N) 4. Shortest lead time (SL) 5. Shortest lead time with priority (SLP)	1. Demand +10% 2. Demand -10% 3. Major repair +10%
Cost based	6. Cheapest relative to load (CL) 7. Cheapest relative to load with priority (CLP)	1. Demand +10% 2. Demand -10% 3. Major repair +10%
Mixed	9. Cost versus time (βc = 0.3, βs = 0.7) (CS37) 10. Cost versus time (βc = 0.5, βs = 0.5) (CS55) 11. Cost versus time (βc = 0.7, βs = 0.3) (CS73)	1. Demand +10% 2. Demand -10% 3. Major repair +10%

Fig. 5.2.: Experimental plan

5.2 Results of the current situation

This section presents the results of the base case model run. The current state is set up from empirical data and expert analyses on repair lead times and capacity over the multiple repair shops. No algorithm corresponding to the current assignment of repair jobs is deployed in this model run. The distribution of jobs is modelled through link weights in the network representing the share of repairs by each considered shop. The results show the output of the performance indicators of repair lead time, cost, resource utilisation and additional delay. A share of the base case results have already been administered for in Section 4.3.4 to validate the simulation model with the actual system.

Stated in Chapter 3, the first objective of the simulation model is to quantify the base case performance. Empirical data has yet revealed the base case performance to a certain extent. However, some performance metrics are not properly connected. Furthermore, quantifying the current situation through the same simulation model as used to evaluate solution alternatives provides proper comparison to reference values.

5.2.1 KPI 1: Repair lead time

The repair lead time is configured of three time modules: travel time, buffer time, and active repair time. The active repair time is dependent on the distributions used to model the processing time and the available capacity. The repair process is initialised by transport, of which the modelled values are equal to that of empirical data and therefore do not deviate in the simulation. Thereafter, the components are placed in a buffer prior to the actual processing. The warm up period of 60 days enables the establishment of buffers at the start of the simulation run.

The repair lead time is dependent on the repair facility and the type of work scope. Major repairs and overhaul services are larger tasks and require additional man hours compared to inspection and minor repairs. Figure 5.3 depicts several descriptives on the lead time per work scope. The results are quite as expected. The performance of the assignment policies is not tested on the work scope level, as this time is not changed. However, the overall lead time remains of interest because of the fact that the policies are to account for larger tasks, especially the prioritised assignment policies.

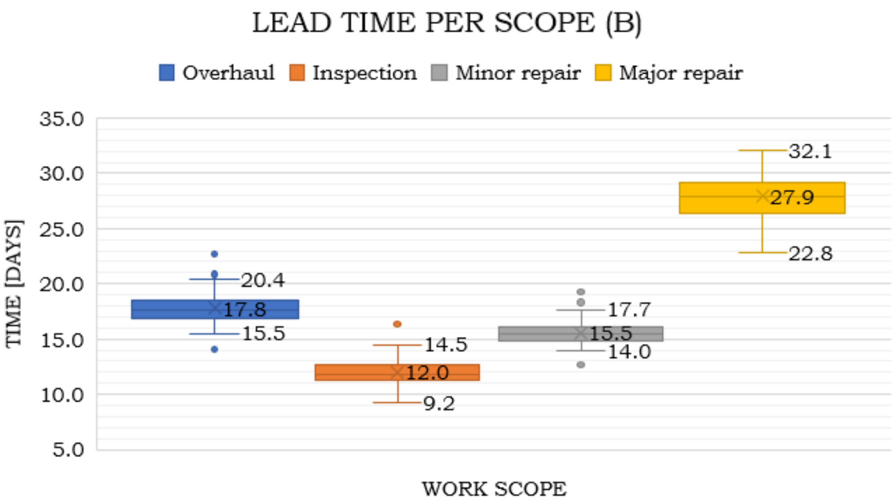
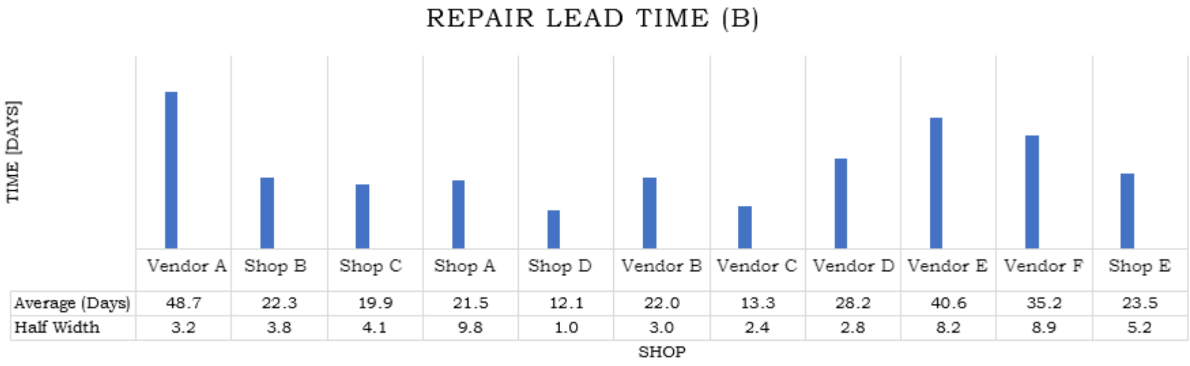


Fig. 5.3.: Lead time per work scope

Figure 5.4 presents the repair lead times as modelled for the base case over 50 replications, representing the current situation. These results are further used as a reference to compare other assignment policies. The repair lead times differ from the total lead time, as transport is not yet included in these numbers. However, this can have a significant impact on the total duration of the MRO services. For example, transport to and from Vendor E consumes approximately 13 days (Table 3.12. This especially is of importance in the decision to outsource. Regardless of the transportation, repair lead times are generally lower when performing the MRO services in-house. Vendor C is the only repair vendor (outsourced) that performs rather well in terms of lead time. However, the cost of MRO by this vendor are relatively the highest (Table 4.5). More on this KPI is discussed in Section 5.2.3.



	Vendor A	Shop B	Shop C	Shop A	Shop D	Vendor B	Vendor C	Vendor D	Vendor E	Vendor F	Shop E
Average (Days)	48.7	22.3	19.9	21.5	12.1	22.0	13.3	28.2	40.6	35.2	23.5
Half Width	3.2	3.8	4.1	9.8	1.0	3.0	2.4	2.8	8.2	8.9	5.2

Fig. 5.4.: Base case repair lead times

Following from the lead time, resource utilisation is an interesting output variable. Resource utilisation is a common variable to track in simulation models (Ingalls 2001). During the simulation resources change states from busy to idle and from unavailable to reserved. Resource utilisation defines the percentages of the time that a resource spends in each state. It therefore provides a useful statistic in measuring and analysing under-utilisation or over-utilisation (Tumay 1996). KLM E&M aims for a utilisation of 75%. A utilisation of this extent allows elasticity in differences in input. In other words, changes in amount of jobs or services would less likely influence the repair lead time. When the utilisation is 100% more resources are allocated than initially scheduled. Additional inflow of MRO services would result in exponential increase in total repair lead times, of which the majority of the time comes from large buffer holding times. Limiting the amount of jobs would be required to achieve a steady state again (Lakshmi and Iyer 2013). Figure 5.5 depicts the resource utilisation of each shop. Vendor A and Vendor F are rather large repair facilities. These organisations also provide service to many other customers besides KLM E&M. Internal communication at KLM E&M has showed difficulties in TAT for these shops. Therefore, it is assumed that a limited amount of resources are available for additional MRO services.

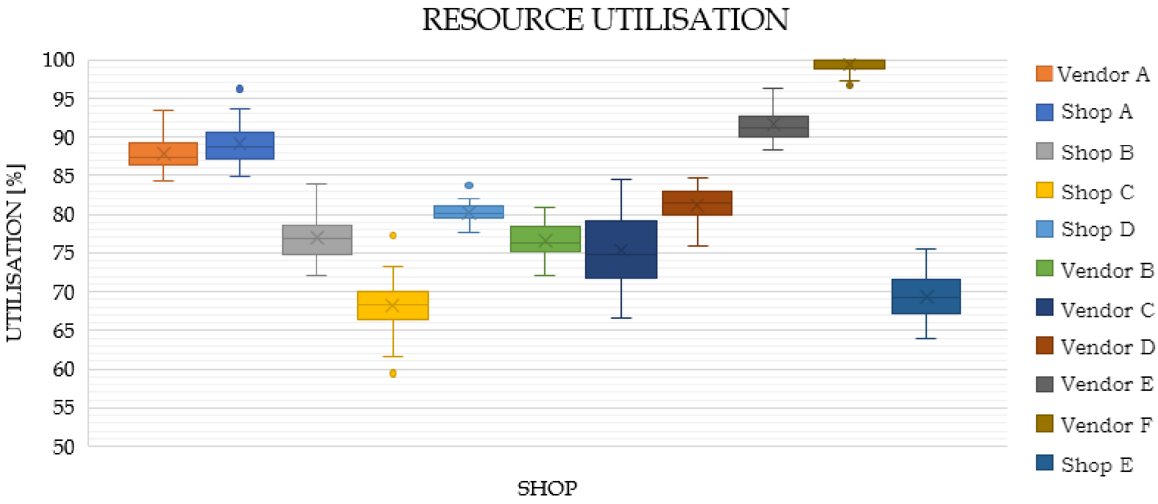


Fig. 5.5.: Base case resource utilisation repair shops

5.2.2 KPI 3: Administrative and logistics delay

Prior and post to the total lead time, additional delays are added to the time to restore. These are primarily from administrative causes. Before MRO it is a result of the outbound flow in the central depot, which includes the passage of expedition and repair administration. This 'division' in the central depot is accountable for the selection and distribution of jobs to repair shops. As concluded in Section 3.6 the repair administrator picks the shop that is responsible for repair based on contractual agreements. However, KLM E&M is allowed and able to deviate from these agreements when TAT measures are not according to target. This is done rather rarely, for the data of repair shops and vendors is not integrated with the data at the central depot. Only in extreme events, the shops and vendors inform the supply chain department at the central depot of such events. Any further communication with shops and vendors is rather inefficient, as nothing is properly documented. Due to this way of deployment, vendors often get away with surpassing the agreed upon TAT.

Outbound activities take place prior to MRO and inbound post to these services. Where this previously was analysed as administrative and logistics delay, it is now considered as additional delay. Section 3.4.3 included buffer times in the central depot and travel times to and from repair shops as logistics delay. The travel times are included in the KPI of total repair lead time. The generated buffers in the central depot are from now included in the total time in the central depot. The exact relation between the different activities in the central depot and the MRO services is yet presented in Figure 3.7. Figure 5.6 presents the built up delay for both directions of flow. Service in the figure represents repair administration in the outbound flow and the inspection incoming goods in the inbound flow. The total delay adds up to approximately 12 days.

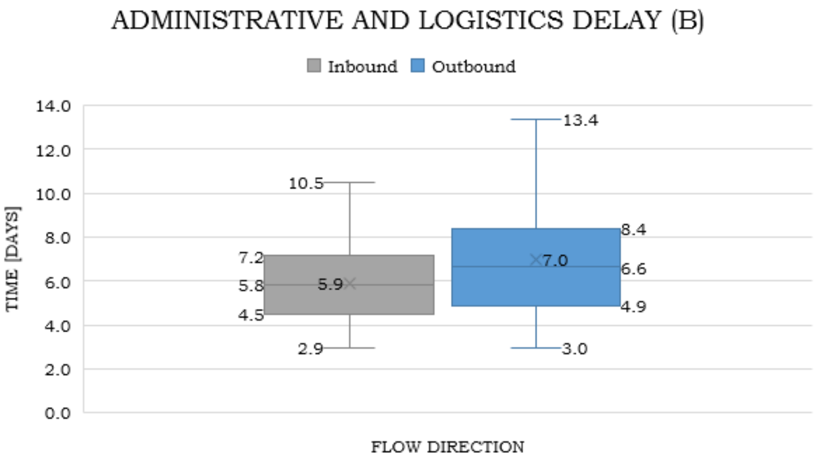
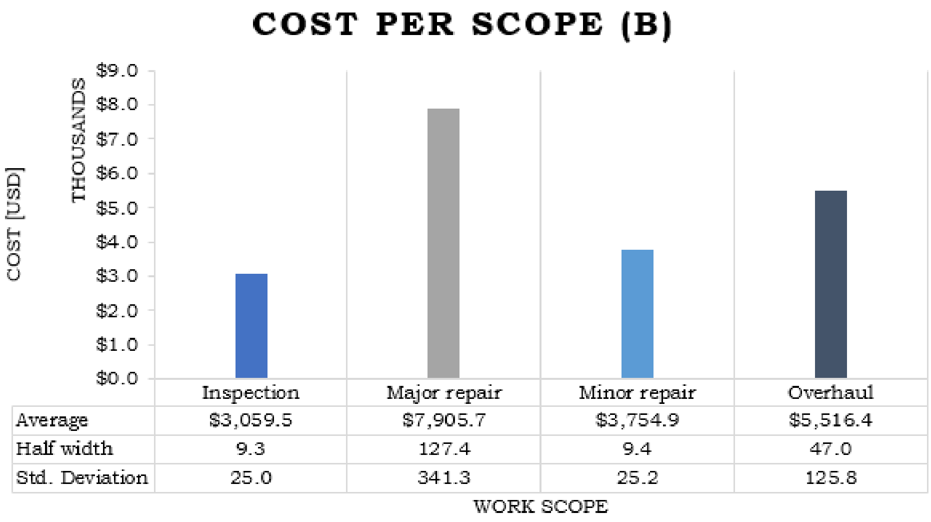


Fig. 5.6.: Base case administrative and logistics delay

5.2.3 KPI 4: Cost of MRO

The cost of MRO is dependent on the shop the service has taken place and on the work scope. For in-house services, major repair is the most costly and minor repair the least. When the services are outsourced, this ratio of cost differs. Major repair is significantly cheaper when performed by repair vendors. The share of work scope types in the system is therefore a configuration variable for both the average cost per item as well as the total cost of MRO. The total cost is also dependent on the amount of services assigned to each respective shop. The average total cost of MRO per work scope is presented in Figure 5.7. The figure depicts these cost without the distinction of in-house or outsourced repair. Regardless of the fact that major repairs are cheaper when performed externally, this task remains the most costly overall. This is largely due to the remaining in-house services for this work scope. The considerable difference in cost of major repair throughout all shops can be concluded from the standard deviation resulted in approximately 340 USD.



	Inspection	Major repair	Minor repair	Overhaul
Average	$3,059.5	$7,905.7	$3,754.9	$5,516.4
Half width	9.3	127.4	9.4	47.0
Std. Deviation	25.0	341.3	25.2	125.8

Fig. 5.7.: Base case cost of MRO per work scope

As previously stated in Section 5.2.1, Vendor C is under-utilised from the perspective of KLM E&M. This is substantiated by the high cost per item resulting from the shop its high vendor cost and additional vendor surcharges. The costs per item resulting from Vendor C its services rise above that of other shops and vendors. The shop that provides the most affordable services are Shop A and Shop B. Relative to the amount of services, Shop B provides is the cheapest to assign MRO services to. Figure 5.8 depicts both the relative and the resulting total cost per shop.

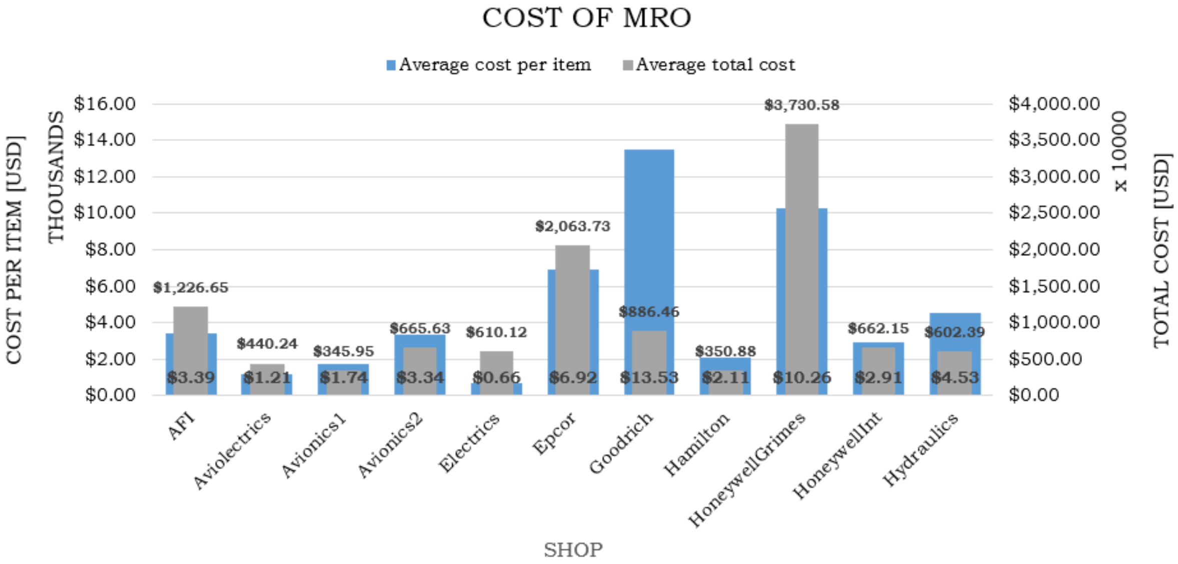


Fig. 5.8.: Base case cost of MRO

5.2.4 Sensitivity analysis

In this section two three sensitivity analyses are discussed as scenario's. Sensitivity analysis can be defined as follows: *'the study of how the uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input'* (Saltelli et al. 2004). Interesting changes in input are demand and processing times, as these are expected to have the highest influence due to the found high resource utilisation and current lead times. If more demand for MRO services is generated, resource utilisation will reach a maximum which results in additional delay. This sensitivity analysis therefore also provides knowledge on the elasticity of the capacity. The active repair time is deemed to have a high influence on the final lead time, for most active repair times exceed the daily shift hours. In stead of increasing each repair time by x percent, the share of work scope types is altered in such a manner that more major repairs are generated relatively to the total demand for MRO.

Only two KPIs are shown as a result of the different input scenario's. First the lead time is discussed and thereafter the administrative and logistics delay. The cost are not extensively discussed, for no notable results have been determined. The results of cost follow the line of expectation where it drops at the reduction of demand and rises at the increase of demand. The results are therefore presented in Appendix C.1.1.

Variation in demand

For the first sensitivity analysis the demand for MRO is increased and decreased with 10%. To provide initial insights in the aggregated performance of the system, the time to restore is compared with the base case performance. In the current state the time to restore is on average, minimum, and maximum 35.6, 28.6, and 44.5 days respectively. Figure 5.9 provides the absolute differences for the decrease and increase of demand in terms of the time to restore. The values of the averages and additional descriptive statistics are summarised in Table 5.1.

Fig. 5.9.: TTR as a result of change in demand

Tab. 5.1.: Average values in days of TTR for change in demand

Scenario	Average	Minimum	Maximum	Half Width	Std. Deviation
Base	35.5	31.8	44.5	1.1	2.8
Demand + 10%	57.3	51.6	60.4	0.9	2.3
Demand -10%	24.1	23.7	24.6	0.1	0.2

The overall time in system is rather sensitive to changes in demand. However, this is not a result of additional repair lead times, but over-utilisation in the central depot. From the additional TTR, nearly 80% is caused by additional time at both the repair administration as well as inspection incoming goods. This can be explained by their respective resource utilisation. In the base case, the utilisation already approaches the 100%. By adding 10% of demand, which is a significant increase in terms of absolute amount of packages, the utilisation rises to the 100% threshold. According to the logistics leader expedition (2019) (Appendix

D) the exact inflow in the central depot is uncertain and scheduling the correct amount of resourced is therefore challenging. A time delay of approximately 60 days is rare, but does occur due to these uncertainties and therefore accumulating queues. Furthermore, the central depot makes use of flex-workers, which are primarily employed during peak periods.

Due to the limitation in the model, which does not account for high and low demand periods, buffers accumulate once the utilisation reaches 100%. The significant addition in time for administrative and logistics delay comes from the outbound flow direction. The inbound is not necessarily influenced by the change in demand of components, for repair shops take longer to finish their services, which provides additional time for the inbound department to finalise unfinished work.

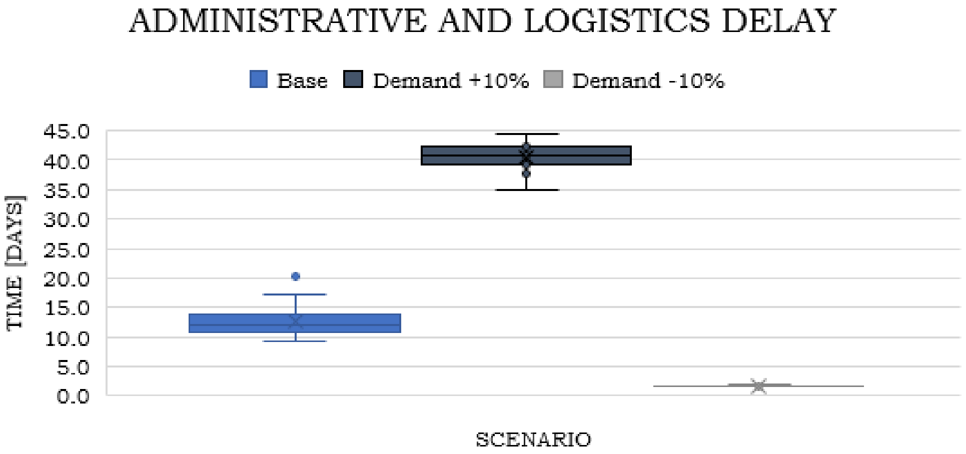


Fig. 5.10.: Administrative and logistics delay as a result of changes in demand

Tab. 5.2.: Average values in days of admin and logistics delay for change in demand

Scenario	Average	Minimum	Maximum	Half width	Std. Deviation
Base	12.7	5.9	23.1	0.8	2.2
Demand + 10%	40.5	31.6	48.5	0.9	2.5
Demand -10%	1.7	1.5	1.9	0.0	0.0

Different share of work scopes

The second scenario analysis is based around the active repair time. The simulation is built in such a manner that the processing time is delayed in case of more time consuming work scopes. As a reference, minor repair is used in the model as this takes the least amount of time. Additional relative delays are added to this reference processing time (Table 3.1) where major repair has the highest additional delay. Due to the current set up of the model using link weights, the active repair time is again also dependent on the distribution of component services. One shop generally takes longer to deploy MRO than another one.

Generally, the repair lead times are increased. However, the overall TTR is not significantly affected. The increase in major repair services does provide a positive influence on the administrative and logistics delay. Since components are delayed at the repair facilities, the inbound activities have a margin of time to finish the work that is left to be done. No shops reveal a utilisation over 100% and are thus resilient to an additional share of major repair jobs. The results of the TTR compared to the base case is presented in Figure 5.11.

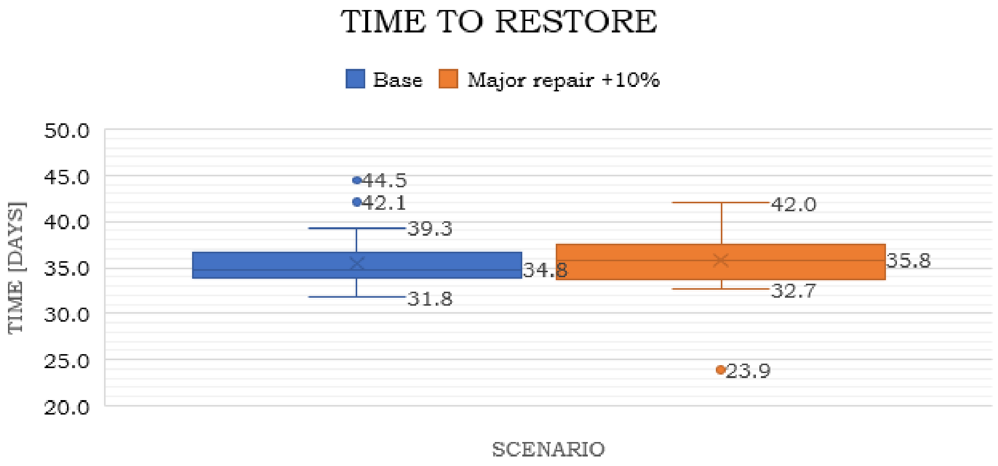


Fig. 5.11.: TTR as a result of additional major repair jobs

Tab. 5.3.: Time to restore as a result in additional major repair

Scenario	Average	Minimum	Maximum	Half width	Std. Deviation
Base	35.5	31.8	44.5	1.1	2.8
Demand -10%	36.2	32.7	42.0	0.9	2.3

In addition to the influence the change in work scope share has on delays, it also influences the cost. Notable is the difference in cost per item between the scenario's. By adding more major repair jobs. Overall, the average cost of MRO are increased by roughly 10%, the same as the increase in major repairs. Regardless of the fact that major repairs can be double the price for in-house services, they still remain cheaper when performed by a repair vendor. In the base case alternative nearly half of all MRO services is outsourced. This phenomenon explains the relatively small increase in total cost. The average values, compared to the base case results, are depicted in Figure 5.12.

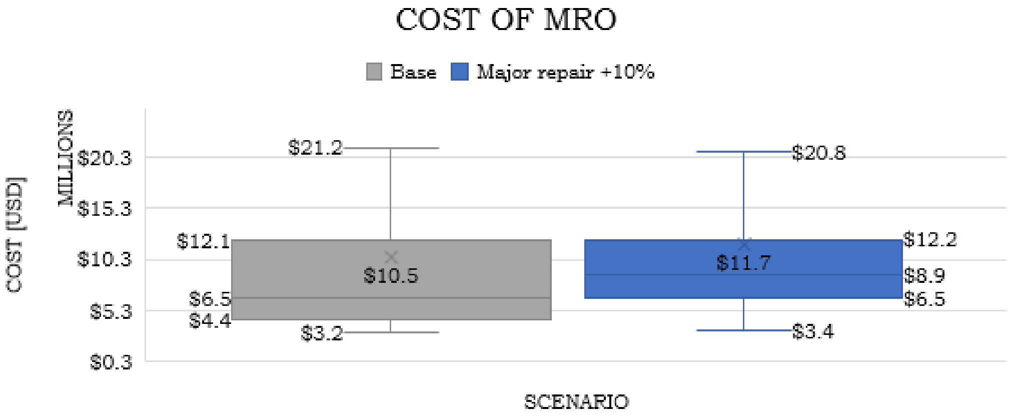


Fig. 5.12.: Total cost of MRO as a result of additional major repair jobs

Tab. 5.4.: Cost of MRO as a result in additional major repair

Scenario	Average	Minimum	Maximum	Half width	Std. Deviation
Base	$115,847,728.6	$111,546,985.0	$120,696,605.0	77176.03	$206,704.41
Major repair + 10%	$128,896,995.6	$122,962,661.0	$134,481,403.0	101343.07	$271,432.21

5.3 Results of the assignment policies

The previous section elaborated on the current state, which is further considered as the base case, and where the room for improvement lies. It is seen that large differences in resource utilisation is measured. Base on these differences, the accompanied cost and lead time, a re-alignment of MRO jobs to repair shops and vendors is beneficial in terms of all KPIs. In this section the value of the assignment policies is discussed by means of the model results. The KPIs as presented in Section 5.2 are also presented for each assignment policy. Here it was found that the share of repair jobs is assigned to several large repair shops. This has led to the establishment of buffers, for resource utilisation is brought to a maximum. This section presents the results of re-aligning jobs to shops based on several attributes, which are not considered in the current situation. All experiments are run according to the experimental setup as described in Section 5.1 to provide results within a 95% confidence interval with a small half width. This section does not include the prioritised assignment results. These are presented in Section 5.4.

The section is divided over the three KPIs: repair lead time, administrative and logistics delay, and cost of MRO. The main and notable findings are presented in these sections and compared to the base case. More elaborated results are reported in Appendix C. The overall performance metric is the time to restore (TTR), which includes both the administrative and logistics delay as well as the total repair lead time. This is not considered a KPI, for it depends on the two time configurations. It does provide a global comparison on the different assignment policies. Figure 5.13 reveals initial descriptives on the TTR including that of the base case and of the assignment policies. The TTR is reduced as a result of most of the policies. The assignment policies focusing on cost result in roughly the same time measurements. The Naive assignment causes a significant increase in TTR.

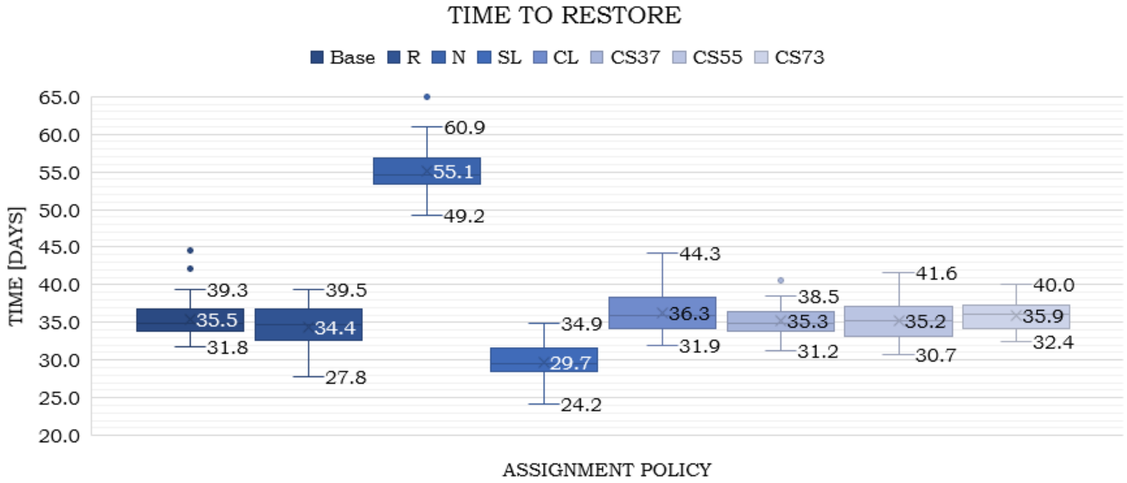


Fig. 5.13.: Time to restore as a result of assignment policies

5.3.1 KPI 1: Repair lead time

The main performance indicator is the total repair lead time. The repair lead time is assumed to be related to the Service Level from the perspective of inventory. A reduced repair lead time leads to quicker replenishment of serviceable stock, which is used to service customers with in case of exchange requests. This KPI is measured regardless of the targets KLM E&M has set for this time measurement, for the majority of the time the targets are exceeded. This research project aims to reduce the repair lead time with only the assignment decision as a variable. Other aspects, such as capacity and resources are assumed to be fixed. Figure 5.14 reveals the aggregated lead times per assignment policy including the averages. Table 5.5 elaborates on the figure with additional measures. This metric is the difference between the overall measured time to restore and logistics delay. The latter is further elaborated on in Section 5.3.2. Visualised in the figure is the improvement in performance at the implementation of the SL assignment, with nearly five days on average. Concluding from the small half widths, this is a significant reduction. The other assignment policies reveal an increase in repair lead time. As expected from the CS assignments, the CS37 policy, where time is weighed heavier, results in the lowest repair lead time compared to CS55 and CS73.

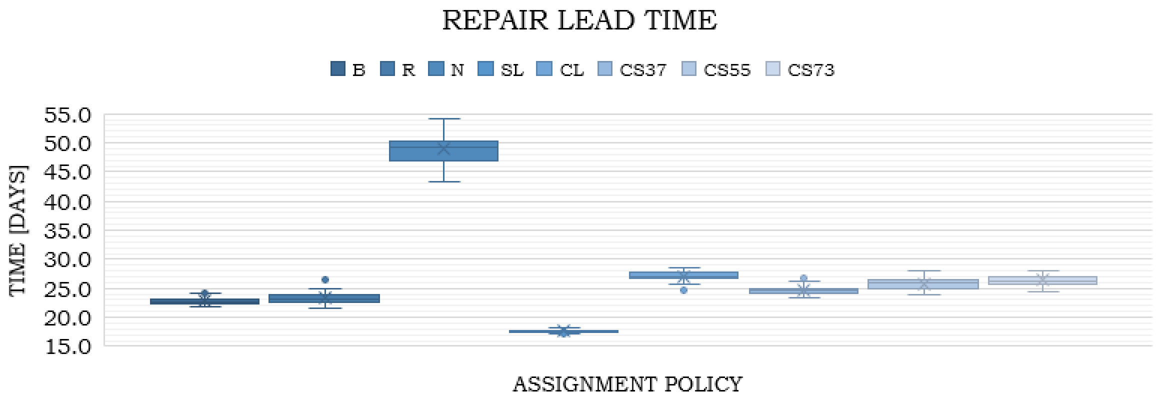


Fig. 5.14.: Aggregated repair lead time

Tab. 5.5.: Aggregated repair lead time statistics in days

Assignment policy	Average	Minimum	Maximum	Std. Deviation
B	26.1	25.2	27.6	0.6
R	26.7	24.8	29.8	1.1
N	52.3	46.7	57.6	2.5
SL	21.0	20.6	21.5	0.3
CL	30.5	28.1	32.0	0.8
CS55	28.1	26.7	30.0	0.7
CS37	29.2	27.2	31.5	1.0
CS73	29.8	27.8	31.4	0.8

To what extent the repairs are distributed over the repair shops and the results of this are depicted in Figure 5.15. This figure presents the average values of repair lead for each shop and each alternative. On average, the difference is for most alternatives not that large. However, on shop level, notable changes occur. Firstly, the N, C, and CS assignment policies do no good in terms of repair lead time. The N assignment only considers the active repair time. Shop D has the lowest active repair time and therefore seizes the majority of the jobs. The same reasoning results in shop Shop B to be overloaded with jobs. Shops such as Vendor A, Vendor E, Vendor D, and Vendor B reveal no significant difference in terms of lead time, for a lower share of jobs is seized by these servers. Therefore, the average active repair time and travel time is remained for these shops. The two assignments that include cost in their policy (CL and CS) result in higher repair lead times. This is where the classic trade-off between cost and time is clearly seen. More on the results in terms of cost of MRO in Section 5.3.3. In addition to Figure 5.15, Table 5.6 presents the overall average, min-, and max-average, of the total repair lead time overall shops. Overall the base case performs relatively well in terms of the average total repair lead time. Few assignment policies enhance the performance from this perspective. However, the maximum average, or worst-average, does improve as a result of two assignment policies (R, SL). The results within a 95% confidence interval are presented in Appendix C.2

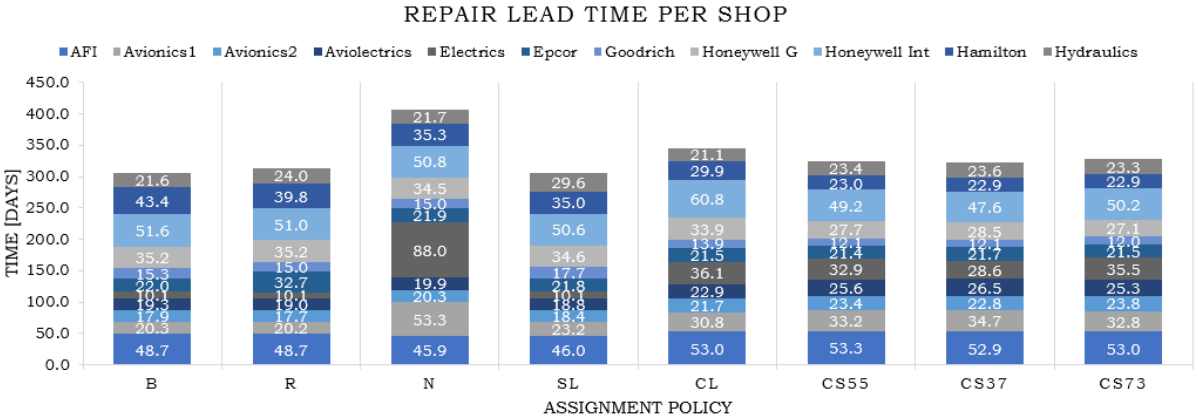


Fig. 5.15.: Total repair lead time per assignment policy and shop

Tab. 5.6.: Average values of repair lead time in days per assignment policy

Assignment policy	Average	Minimum	Maximum	Std. Deviation
B	27.8	10.1	51.6	14.5
R	28.5	10.1	51.0	14.1
N	37.0	15.0	88.0	23.4
SL	27.8	10.1	50.6	13.1
CL	31.4	13.9	60.8	15.1
CS55	29.6	12.1	53.3	13.0
CS37	29.3	12.1	52.9	12.7
CS73	29.8	12.0	53.0	13.1

5.3.2 KPI 2: Administrative and logistics delay

The administrative and logistics delay are not considered as a configuration variable. In other words, no direct measures are provided to minimise the delay in terms of capacity and other resources to speed up the processes. However, both the outbound and inbound prior and post to the MRO services are affected by the repair lead time. The capacity is presumed to be fixed in the model and already have a rather high resource utilisation approaching the 100%. In the actual system enhancement of the capacity is more flexible, for the employees are able to aid in other departments in case of high inflow of components. Furthermore, when the repair lead time is overall increased, an additional margin of time is provided to the inbound flow direction to make up for the buffers of delayed work. Figure 5.16 provides an overview of the performance in terms of administrative and logistics delay per assignment policy. Additional statistics, such as maximum, minimum, median, and half width is depicted as well. The figure is complemented by Table 5.7, providing the average values including the best and worst averages over the 50 replications.

Following up on the statement that the delay is reduced in case of longer repair lead times is substantiated by these results. The assignment policies R, N and CL show little delay, even in the maximum values. In the previous section, where repair lead times were analysed, results show that the assignment policies do not make an enormous difference in the lead time. The re-alignment of logistics and MRO and the rate of returning serviceable components, however, is rather beneficial in terms of administrative and logistics delay.

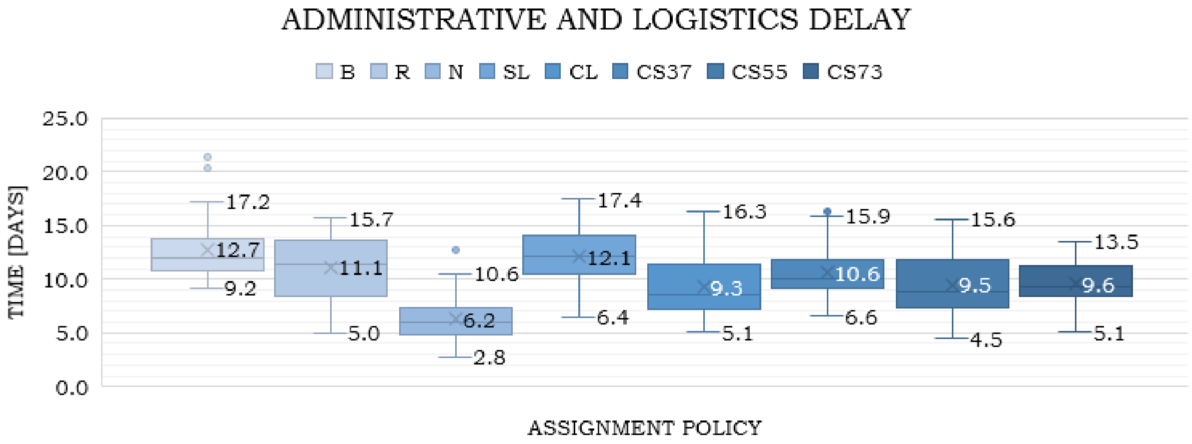


Fig. 5.16.: Administrative and logistics delay per assignment policy

Tab. 5.7.: Average values of administrative and logistics delay in days per assignment policy

Assignment policy	Average	Minimum	Maximum	Std. Deviation
B	12.7	9.2	21.4	3.0
R	11.1	5.0	15.7	3.0
N	6.2	2.8	12.8	2.4
SL	12.1	6.4	17.4	2.7
CL	9.3	5.1	16.3	2.7
CS55	10.6	6.6	16.4	2.3
CS37	9.5	4.5	15.6	2.9
CS73	9.6	5.1	13.5	2.0

5.3.3 KPI 3: Cost of MRO

The cost of MRO depend on multiple factors. The cost per item depends on the work scope and the shop to which is has been assigned to. An overview of the average cost per item for each work scope is depicted in Appendix B.6. The different cost for each work scope per shop depends on the amount of capacity available and the share of the capacity that is able to provide such services, i.e. available skill set. The components are assigned to each shop capable of providing services to a specific commodity type. In-house is generally the cheapest option for the smaller work scopes, such as inspection and minor repair. The larger scopes, such as overhaul and major repair, are often cheaper when performed by repair vendors. In other words, when these services are outsourced from the perspective of KLM E&M. This comes at a cost of lead time. Appendix C.3 provides the total cost per shop and per assignment policy.

Figure 5.17 presents the total cost of MRO per assignment policy. The minimum and maximum averages are again presented in the figure as well, but are also further elaborated on in Table 5.8. The assignment policies that include a cost attribute in the selection expression prevail as best-performing with regard to this KPI. The R and SL assignment result in high cost of MRO. The N assignment policy is improved compared to the base case. This can be explained by the fact that the shops which deploy a relatively low active repair time are also less costly. The CS assignment policies present relatively few differences in terms of their performance with different weights. Naturally, the CS73, which weighs cost the highest, results in the lowest overall cost. This can be explained by the extent of the cost compared to the lead time. Overall, the CL assignment performs best.

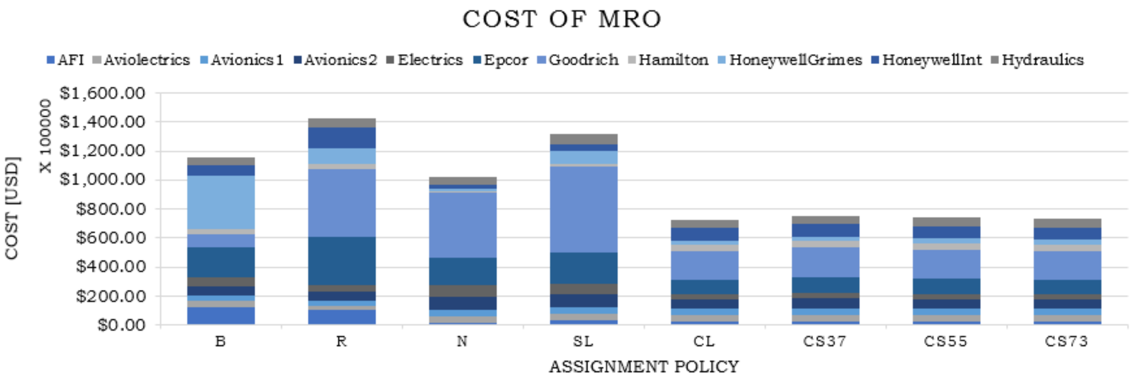


Fig. 5.17.: Cost of MRO per assignment policy

Tab. 5.8.: Total cost of MRO per assignment policy

Assignment policy	Average	Minimum	Maximum	Std. Deviation
B	$115,847,728.6	$111,546,985.0	$120,696,605.0	$206,704.4
R	$142,854,617.3	$137,469,158.0	$148,217,005.0	$240,719.8
N	$101,883,059.0	$96,850,888.0	$106,495,667.0	$213,454.1
SL	$132,106,695.9	$127,112,575.0	$136,623,291.0	$219,396.6
CL	$72,624,900.6	$68,953,961.0	$75,837,894.0	$149,015.0
CS55	$75,470,127.2	$71,536,768.0	$79,641,520.0	$177,999.9
CS37	$73,911,457.9	$70,359,348.0	$77,444,360.0	$163,216.7
CS73	$72,991,608.8	$69,499,711.0	$76,510,229.0	$158,185.0

5.4 Results of prioritised assignment policies

Additionally to the seven assignment policies (without regard for the base case) the policies are extended with the inclusion of priority (Algorithm 5). Larger tasks are prioritised over smaller tasks. In other words, major repair and overhaul are assigned before inspection and minor repairs. This priority assignment is based on the average active repair time of these work scopes. The results are presented as a comparison to their 'original' policy.

The RP and CLP assignments reveal a low difference with the original R and CL policies and are therefore not further elaborated on here. Relative changes with regard to all KPIs are < 3%. Appendix C.3 depicts more detailed results of these policies. Table 5.9 presents a summary of all assignment policies and their average results for the performance indicators. The SLP and CSP policies do reveal notable changes and are therefore further explained in Sections 5.4.1 and 5.4.2 respectively.

5.4.1 Time based with priority

The time based assignments are the N and SL policies. The N assignment policy is not further considered with the addition of priority, for this does not result in any significant improvement of the performance. It does not compete with the other policies.

Tab. 5.9.: Average results of all assignment policies

Performance metric	Time to restore	Repair lead time	Admin and log delay	Cost of MRO
R	37.8	30.1	11.1	$143,083,235.6
RP	37.8	30.4	10.7	$143,678,021.8
SL	33.1	27.8	12.1	$132,107,345.8
SLP	31.4	27.8	10.4	$131,775,679.2
CL	39.7	31.4	9.3	$72,549,019.4
CLP	39.4	31.4	9.2	$72,620,001.5
CS37	38.7	28.1	10.6	$75,393,162.4
CSP37	37.7	27.5	10.3	$74,593,252.8
CS55	38.6	29.2	9.5	$73,836,560.3
CSP55	38.9	28.7	10.2	$73,825,921.5
CS73	39.3	29.8	9.6	$72,922,505.9
CSP73	39.6	29.5	10.2	$72,982,835.7

The SLP policy considers the active repair time and the load at each possible candidate shop. This way, bottlenecks are avoided. The time to restore is reduced as a result of priority assignment. This is not a result of a reduced repair lead time, but of an improvement with regard to the additional delays at the central depot. The SL policy causes a reduction in repair lead time, which has a negative impact on the administrative and logistics processes for the return rate is increased. By considering the larger tasks first a more balanced assignment is created, increasing the returning inter-arrival rate. The average time to restore is not changed significantly, but the maximum time is reduced by 5 days.

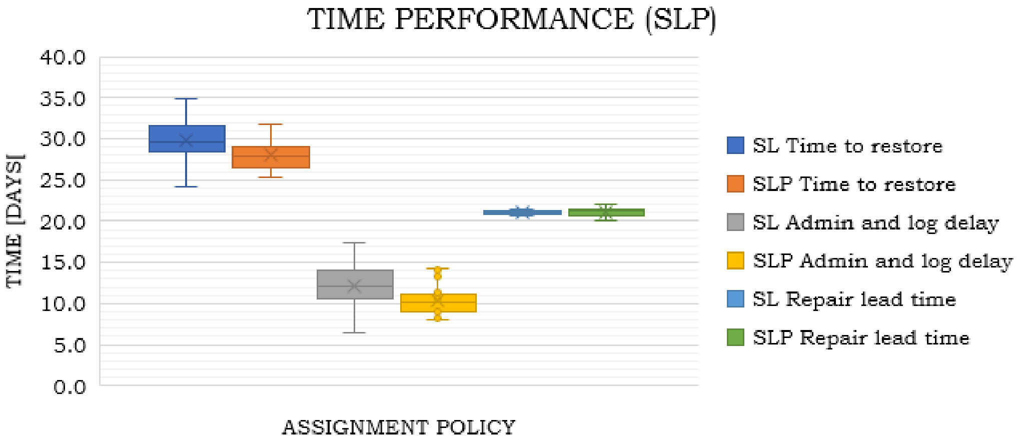


Fig. 5.18.: Time performance of SLP policy

The average total cost of MRO is reduced by over 300,000 USD, being 3% relative to the total value. The maximum of the measurements however, results in a reduction of nearly 500,000 USD. Regardless of the extent of the improvement, the SLP does perform better in terms of both cost as well as time. Including priority in the CS55 and CS73 policies does not considerably influence the performance in terms of cost.

5.4.2 Mixed with priority

Finally, three different mixed polices have been determined. Each of these is also evaluated with the addition of priority to larger tasks. Figure 5.20 depicts both the CS and the CSP policies with regard to time to restore, repair lead time, and administrative and logistics delay. The differences are not significant, but the behaviour of the results is visible. By this it is

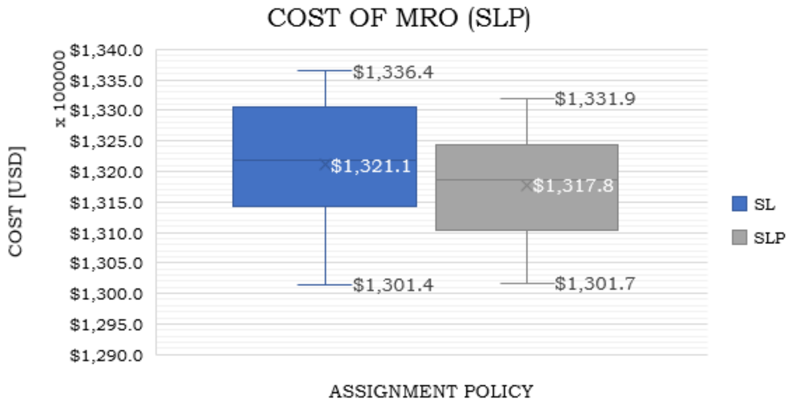


Fig. 5.19.: Cost performance of SLP policy

meant that by a decreasing weight for time, this performance measure is increased. This is primarily seen at the repair lead time, which is a cause of the increased time to restore. The addition of priority results in a reduction of 2% in repair lead time. Only the CSP37 policy results in a overall lowered TTR, for the administrative and logistics delay are also reduced. The CS55P and CS73P cause an increase of 1% in the final TTR.

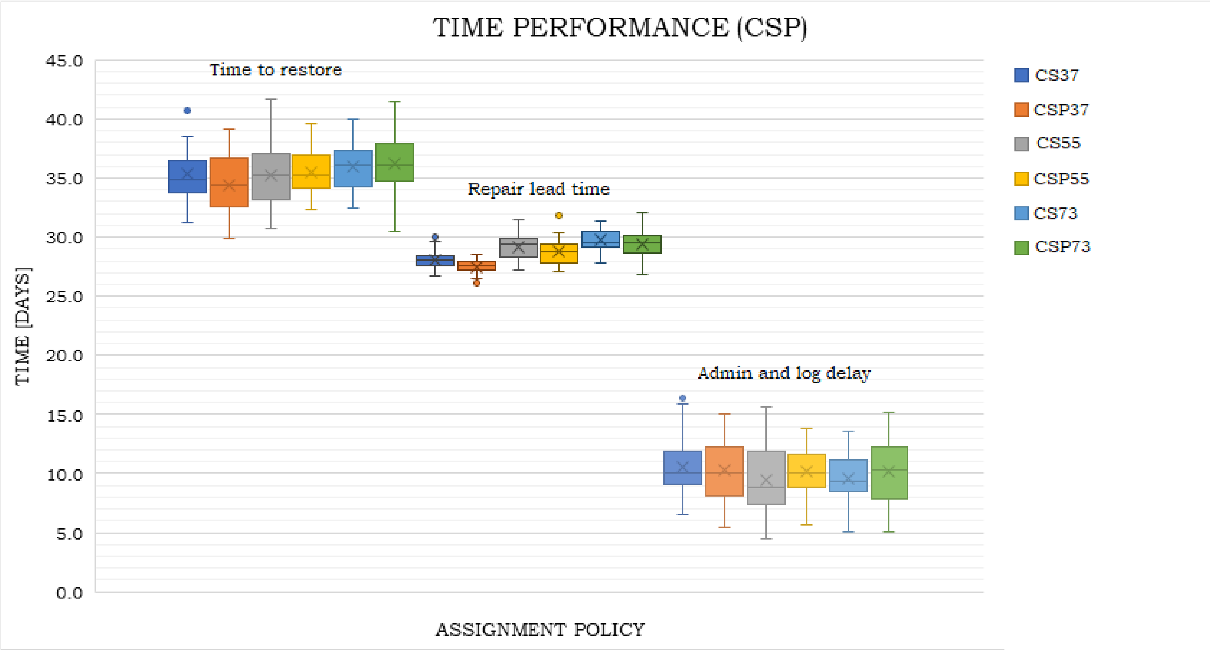


Fig. 5.20.: Time performance of CSP policy

The same behaviour as above mentioned applies to Figure 5.21, but in reversed order. As the weight for cost increases, cost of MRO is reduced. Only in the case of the CSP37 policy, the addition of priority results in a significant different result in terms of cost.

5.5 Robustness of the assignment policies

In the previous section the base case is compared to the eight defined assignment policies. In Section 5.2.4 the base case is analysed through scenario analyses. The input variables that have been altered are the demand and the share of work scopes. The major repair is then

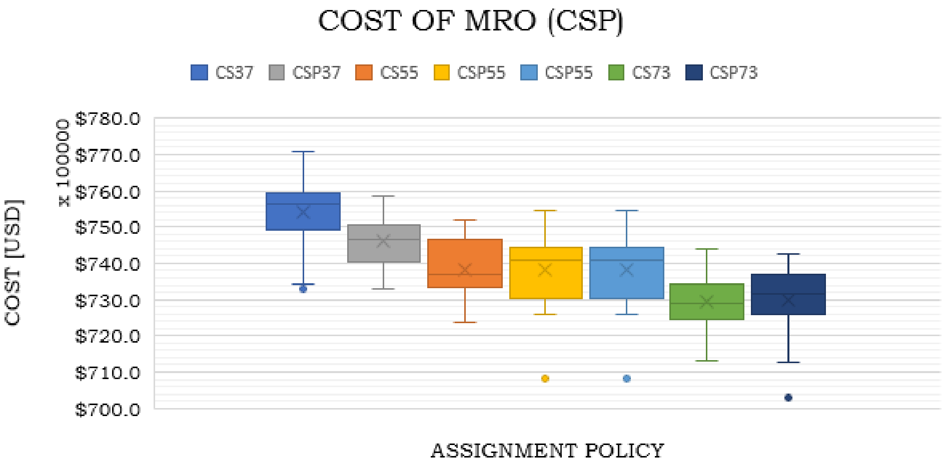


Fig. 5.21.: Cost performance of CSP policy

increased by 10% of the total share. Hence, the following percentage of inspection, overhaul, minor repair, and major repair is: 54%, 4%, 31%, and 11%. The work scope does not affect the amount of input generated, but influences the duration of the MRO activities and increases the cost per item.

The previously changed input variables to test the sensitivity of the base case model are also implemented in the evaluation of the assignment policies. By changing the input variables different scenario's are tested. Furthermore, it facilitates to conclusions on the robustness of the polices. Especially demand an work scope types are of interest, as these can change over time. Therefore, uncertainty in the system is also accounted for to a certain extent (Helton et al. 2006).

5.5.1 Change in demand

The change in demand is applied for two purposes: to test the robustness of the policy assignments and to evaluate the behaviour in case of uncertainty. As previously mentioned in Section 4.1.2, an exponential inter-arrival time is used to generate demand. Seasonality and other peaks and lows in demand is therefore not accounted for. The data used to fit the distribution is based on one year, which includes the peak seasons, as well as the seasons that generate less flight hours. The flight hours in the third quarter of the year can rise between 10% and 20% (Eurocontrol 2006). These percentages only apply to commercial aviation. KLM E&M also provides MRO services to cargo aircraft, of which the demand is more continuous. Therefore, the relative increase in flight hours is assumed to be 10%. This ratio is used to increase and decrease the demand in two scenario's.

Table 5.10 presents the performance as a result of a 10% increase in demand. The values in the table depict the relative changes to the 'base input' as provided in Section 4.3.1. For the same reason as the base case, the assignment policies are sensitive to a relatively small change in demand. This is the result of the considerable increase in administrative and logistics delay. The repair lead times, i.e. buffer time and active repair time, are barely affected. When considering the time performance metrics, the SLP is the most robust. In other words, the SLP assignment shows the least changes or even improvements when the demand is raised by 10%. The worst performing policies in this scenario are the CS policies. Generally, the prioritised assignments reveal less sensitivity than their 'original' policies.

Tab. 5.10.: Results of assignment policies +10% demand

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	+26%	-	+69%	-
R	+27%	+2%	+72%	-
RP	+36%	+6%	+85%	+2%
N	+8%	-1%	+82%	-
SL	+34%	+1%	+70%	-
SLP	+17%	-1%	+62%	+1%
CL	+38%	-	+74%	-
CLP	+30%	-7%	+69%	-
CS37	+39%	+3%	+76%	-
CS55	+38%	+6%	+73%	-
CS73	+39%	+6%	+75%	-
CSP37	+31%	+2%	+70%	-2%
CSP55	+32%	+2%	+70%	-2%
CSP73	+28%	-	+74%	-

Another scenario is tested in which the demand is reduced by 10%. Generally, this is less relevant with regard to the robustness of the assignment policies or on how to deal with uncertainty in demand. The results within the same lay-out as Table 5.10 is depicted in Appendix C.5. The TTR is reduced, mainly due to reduction in administrative and logistics delay. All the average values are 1.7 days, which is approximately equal to the min-average with the current amount of resources and processing times. The largest reduction with regard to the repair lead time is 11% in the N assignment. In absolute numbers this is 32.5 days, rather than 36.2 days with unchanged demand generation.

5.5.2 Additional larger work scope jobs

In addition to the increase in demand, another scenario is tested that influences the active repair time and the repair cost without changing these configuration variables. This scenario is also evaluated for the base case in Section 5.2.4. The assignment policies take the work scope into consideration and therefore aim to assign the MRO service to the shop with the smallest value of respective active repair time and cost of MRO. Regardless of this aim, the average repair lead times do increase, for the active repair time is approximately doubled in comparison to the most frequent minor repair jobs. The cost will not increase as much as the repair lead time, as a result of the fact that the ratio of cost to work scope differ per repair shop. A reduction of major repair is not tested. The share of major repairs in the current situation is only 1%. It is assumed that over a period of two years (run time) this does not become less.

Table 5.11 depicts the result of increasing the work scope major repair by 10%. It is assumed that the minor repair jobs are then decreased by 10%. The aforementioned claim on the probable increase of repair lead time and cost is substantiated by the results. Notable is the fact that the base case (B) actually is quite robust to the increase of major repair jobs, in terms of all performance indicators. Besides the base case, the CS37 presents the most beneficial results in terms of cost and the SL policy reveals the best performance in terms of time. The latter results in a limited increase in repair lead time and is also able to distribute the MRO services in such a manner that the administrative and logistics delay are even reduced. This is also the case for the R assignment, but this is caused by a larger increase in repair lead time. The N assignment policy performs the worst and is overall the most sensitive to the increase in work scope type. For this scenario, the average results are again presented in the Appendix C.4.

Tab. 5.11.: Results of assignment policies +10% major repair jobs

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	2%	8%	-15%	10%
R	7%	15%	-38%	7%
RP	6%	15%	31%	6%
N	15%	13%	15%	16%
SL	6%	10%	-6%	14%
SLP	5%	9%	-6%	14%
CL	4%	18%	7%	5%
CLP	7%	18%	13%	5%
CS37	6%	23%	4%	4%
CS55	7%	24%	3%	4%
CS73	8%	22%	14%	5%
CSP37	6%	24%	-4%	5%
CSP55	10%	25%	6%	4%
CSP73	5%	24%	-2%	5%

5.6 Discussion on results

Two types of random policies are implemented. Both are based on the lists of shops that have the required skill set to provide service to at least one of the four commodity types. The first policy is based on a system where all servers in the model, i.e. shops and central depot (inbound and outbound) work according to the FCFS policy. The second one is where the FCFS policy is altered to a more prioritised processing system. A priority is provided in increasing order from major repair to inspection. Often systems are evaluated where the priority is given the other way around. In other words, where the smaller jobs are prioritised over the more time consuming and more costly services, such as the *Shortest Remaining Processing Time* assignment (Semchedine et al. 2011). The idea of this policy is to pre-empt the large task and switch to the smaller task. However, a limitation of this policy is the fact that large tasks are likely to be continuously pre-empted, generating additional delay in the processing of large tasks. In this research project it is looked at from a different perspective. The probability of a larger task following up on smaller ones is accounted for. This policy is therefore a mix between the aforementioned one and the *Least-Flow-time First-SIZE* assignment, where a priority is given to a certain task size. Resulting from this policy is a decrease in delay caused by large tasks. The difference in this research project is that no priority queues are formed. Generally, performance of a completely random assignment is deemed to be poor due its process logic (Harchol-Balter 2000). The results of the R and RP assignment are not as extreme as often referred to in literature (Harchol-Balter et al. 1999). This is due to the fact that the workloads in this study are not heavy-tailed, as they are in the respective studies. In this case, the R and RP assignments even result in an improved TTR compared to the base case.

The following tested assignment policies aim to minimise the repair lead time. The policies are tested in steps in order to evaluate the added value of additional data integration. Initially, the active repair time is used, which is already known to KLM E&M. It is a size-based policy. In other words, the repair administration searches for the smallest value of active repair time in the candidate shops for the specific work scope. This policy is rather limited, for it does not account for load. Shops that have a generally low active repair time are therefore chosen for the majority of the cases, which results in the accumulation of buffers. The second policy, which focuses on lead time, includes the load at each repair shop and is multiplied by the expected active repair time. Generally this provides a better insight in the actual flow time remaining from the repair administration (Semchedine et al. 2011). This policy approaches the *Least-Flow-Time Remaining* policy, which also aims to balance the load over the shops. Finally, the addition of priority is included in the SLC policy, where the FCFS ranking rules are changes to a prioritised system.

The following two assignment policies are focused on the cost of the task. However, for the same reason as the N assignment, solely assigning tasks based on cost results in large buffers. Therefore, the load is added in a similar way as the SL assignment. A load-balancing assignment based on cost is established, with and without the implementation of prioritising larger tasks. In the research by Lo (1988) a best-first search algorithm is set up of which the selection expression of a candidate server includes both cost and time relative to the load. The CS assignment policies come close to this approach, by mixing both a time and cost attribute. The different weights suggest the importance of both of the components in the expression. These weights have been selected to provide general results of the behaviour of the output. Hence, there is no underlying modelled logic to these weights.

5.7 Conclusion results

This chapter examines the current state results, the values of the heuristics, and evaluated their robustness. Furthermore, the results are concisely discussed with regard to previous research. From the analyses and results in Section 5.2 it can be concluded that there is room for improvement. MRO jobs that are outsourced generally lead to long repair lead times. Furthermore, several repair vendors reveal rather high resource utilisation, whereas the in-house shops are less utilised. There is a trade-off to be made regarding time and cost, for the time consuming and rather costly work scopes are outsourced better of than remaining them in-house. The sensitivity analyses show that the current situation is quite robust in terms of time and cost with regard to the shops. The activities at the central depot for both the inbound as well as the outbound flow direction, however, are not. The model is limited in portraying seasonality, in which possible overload is set to rights. It can be stated that the central depot is more sensitive to changes in demand, as buffer holding times of 10 days does occur, but to an extent of 20 days on average is less likely.

Section 5.3 presented the main output of the evaluation of the heuristics. The heuristics, as well as the base case, are run in the simulation model through 50 replications and a warm up period of 60 days. When looking at the aggregated performance indicator of time to restore (TTR), the majority of the assignment policies perform better than the base case. The SL and SLP policies, which aim to reduce the repair lead time, result in a time saving of 5 days on average. However, the cost of MRO are then increased by 7%. Regardless of the quicker return rate of serviceable components, the administrative and logistics delay are kept rather stable. In case of the SLP policy, this period is even reduced further with approximately 2 days. Therefore, the SL and SLP policies also perform best in terms of total time to restore. On average, this performance indicator is improved by nearly 7 days. On the other side of the spectrum cost of MRO is considered a KPI. The policies that aim to account of cost based on shop attributes and required work scope of the component are the CL and CLP policies. These are also the ones that perform best in terms of cost. On average, the cost of MRO over a period of 104 weeks is reduced by 37%. However, this comes at a cost of time. The time to restore is then increased by 1 day, being 2% of the total value.

A trade-off is to be made in terms of time and cost. Figure 5.22 presents a Pareto front of both performance measures. The N, R, RP, CS73, and CSP73 assignments do not compete with the other policies. The Pareto front depicts the set of non-dominated solutions. In other words, no objective can be improved without compromising at least one other objective. A solution alternative can be deemed as dominated by another solution alternative if, and only if, the other is equally good or even better with respect to all performance indicators. (Reddy and Kumar 2015). The figure also depicts a linear trend line including the corresponding equation. However, by assessing each alternative individually, the savings and cost compared to the base case are as follows:

- SL: 1 day reduction in TTR cost 6,012 USD/day
- SLP: 1 day reduction in TTR cost 4,650 USD/day
- *CSP37: 1 day reduction in TTR saves 4,013 USD/day*
- CS55: 1 day reduction in TTR saves 856 USD/day
- CSP55: 1 day increase in TTR saves 201 USD/day
- CLP: 1 day increase in TTR saves 2,344 USD/day
- CL: 1 day increase in TTR saves 3,545 USD/day

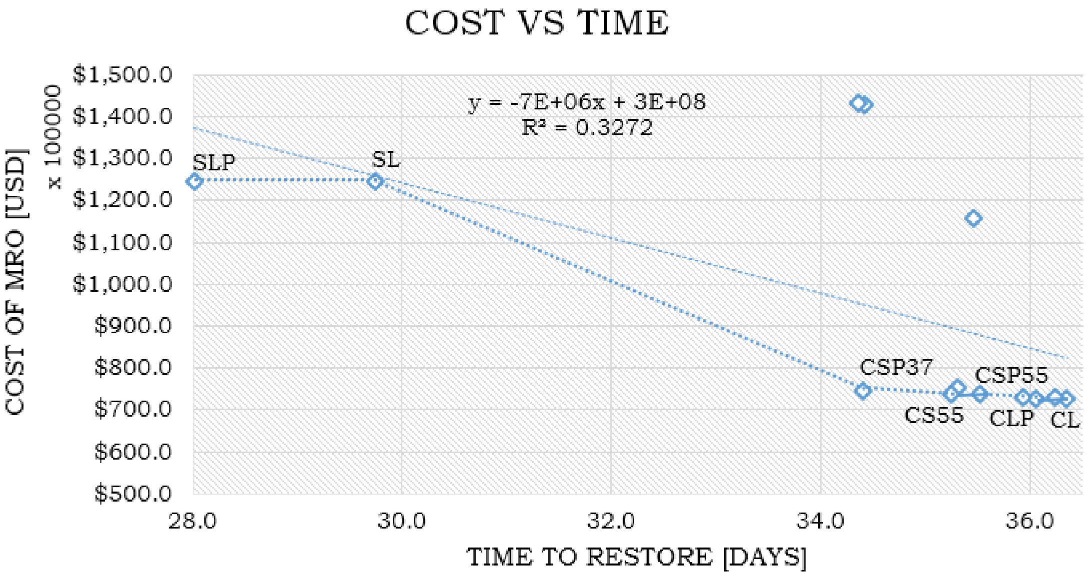


Fig. 5.22.: Pareto front of time to restore and cost of MRO

Section 5.5 elaborated on the robustness of the assignment policies. Notable are the fact that the inclusion of priority provides in robust assignment policies, compared to their 'original' policy. By adding priority to the assignment policies, the delay of larger tasks, such as overhaul and major repair, is avoided. The order of the Pareto frontier changes under different circumstances. In all cases, the SLP remains in the first place with the highest cost and lowest time. Where the CL policy provided the lowest cost and highest time in the base case, the CLP policy takes the final place in the frontier for changes in demand and in share of major repairs. In the base case, the CSP37 and CS55 policies show both improvement in terms of cost and time. By an increase of 10% in demand, none of the policies perform that well. By reducing the demand by 10%, the CS37, CSP55, CS73 and CSP73 are reduced in both time as well as cost. Finally, adding 10% of major repair jobs causes the set of policies to be non-dominating again.

Conclusion and recommendations

6

6.1 Conclusion

Multiple sub-questions are set up to address the main research question in a sequential order. The sub-questions will therefore be first discussed after which the answer to the main question will be provided. In Chapter 1 the seven sub-questions are introduced. The last sub-question is answered in Section 6.2.

Sub-question 1: ***What are the characteristics of the system in general?***
The chain of activities with regard to aircraft component MRO is different from the classic 'make-and-sell' supply chain. Components are initially provisioned, used for an x amount of flight hours, restored, and re-stocked. The larger MRO organisations not only provide serviceable components but also the actual MRO services.

The system consists of a central depot, in-house workshops, external MRO shops, and possibly smaller local inventories. Customers of the MRO provider can request a component. This is then shipped to all over the world, depending on where the exchange of components take place. The unserviceable component is shipped back to the MRO provider, which then provides services such as inspection, overhaul or repair. This can either be in-house or external (outsourced), depending on the size of the customer base, capacity, and available skill set of the MRO provider. After these services, the component is re-stocked. The latter phenomenon is called 'pooling'.

Sub-question 2: ***What is already known with regard of challenges and solution strategies in the context of (aircraft component) MRO?***
The aviation industry is often characterised by high cost and small margins, which reflects onto the demand of the MRO services. High dispatch reliability is expected from the MRO providers. Furthermore, MRO providers face several challenges in controlling and optimising inventory due to the established closed-loop supply chain. Moreover, these challenges are increased as a result of the erratic or even lumpy demand for individual components. The amount of components and heterogeneity with regard to their demand and physical characteristics determine the required capacity, skill, and labour intensity to provide MRO services. Outsourcing of these services becomes a viable option if any of these factors is limited.

Another challenge is the classification on components. Previous research took on this issue by classifying the components from different perspectives. From the supply perspective, which is mainly of interest with regard to the procurement of components, the profit impact and supply risk is often used. From the perspective of inventory and its allocation specificity, criticality, demand size, and value of components are predominantly used.

Sub-question 3: ***What are the characteristics of the system of the system in the case study?***
The case study is performed at the Dutch KLM Engineering&Maintenance, being one of the world's largest aircraft (component) MRO providers. The characteristics of this system is

quite similar to the general system descriptions in literature. KLM E&M deploys by means of one central depot, which includes the pool of aircraft components, and multiple in-house workshops. Within the scope of this study one large repair shop is included, being divided into five workshops, each specialised in a specific commodity type. This is where the first component classification is used. Specificity is often used as a way to classify inventory, but can also be used to describe the supply chain of a class of components. The commodities in terms of their specificity are: avionics, exteriors, interiors, and pneumatics/hydraulics. Furthermore, the classification criticality is used to describe four types of work scopes: inspection, overhaul, minor repair, and major repair.

Regardless of the available in-house workshops, nearly half of all considered MRO services at KLM E&M is outsourced. Available skill and labour intensity is restricted to such an extent outsourcing has become an option for the MRO provider. Naturally, different cost and lead times are accompanied by this decision. In this study six vendors are considered, for these are responsible for nearly 70% of all outsourced services and are able to facilitate MRO to all four commodity types. The assignment of jobs to shops is not done dynamically. In other words, based on the available capacity and resources at one point in time agreements are established with vendors to provide a certain share of services to them. If the vendor its capacity has become restricted to such an extent it can not provide its services, this is communicated to KLM E&M which has then the flexibility to re-assign shops to tasks.

Sub-question 4: *What is the current performance of the system?*
The performance is measured in terms of time and cost. For time the performance metric the *time to restore (TTR)* is used. The TTR is divided in two time configurations, which are considered as KPIs, and are as follows: administrative and logistics delay and MRO/repair lead time. The former is measured both prior and post to the MRO services and consists of establishing the repair order and verifying proper certificates respectively. The repair lead time is measured as the total time a component is away for repair. From internal data it is determined that currently the overall performances with regard to repair lead time is measured to be at 87%, which represents the percentage of on-time repair dispatches of all workshops and vendors. KLM E&M aims for 95% performance. The data obtained from internal sources of KLM E&M is used to develop a simulation model. The performance as a result of the model is validated to this data. Due to the use of probability distribution for demand generation and processing times, the results from the model differs slightly from the internal data. However, no significant differences are determined.

Outsourcing generally results in longer lead times, which is partially explained by the travel times. Several vendors are located in the United States, resulting in a travel time of approximately 9 days. Where in-house repair is on average 20 days, whereas outsourced services are measured to take roughly 38 days. This period includes transportation, buffer time, and active repair time. The lead time is dependent on the work scope, shop and its respective resource utilisation. Shops such as Vendor F Int, Vendor A, and Shop A have a high utilisation. Additional jobs in these shops therefore result in increased buffer times. Contrary to to the large repair lead time for outsourced services, larger tasks are cheaper when performed externally. Notable is the combination of repair lead time and share of repairs for certain vendors. The share of repair jobs is rather high, whereas the services take quite long here. The in-house repair shops, however, provide a higher service level, but have completed fewer repair jobs. The distribution of MRO services or tasks to repair shops and vendors is unjustly unbalanced.

The exact performance of the administrative and logistics delay is quite uncertain. An average of 12 days is assumed from the little (reliable) available data, whereas the touch times at the repair administration and inspection incoming goods take are a matter of minutes. Poor data integration between the different organisations in the closed-loop supply chain results in situations where components are simply pushed to the next work stations regardless of the available capacity. Based on the most occurring capacity, the model is able to provide an average total delay of 13 days of which the outbound and inbound flow takes 7 and 6 days respectively.

Three scenario's are evaluated. The first two are a change of demand. The central depot is most sensitive to changes in demand due to its high resource utilisation. In the actual system aspects such as seasonality and the deployment of flex workers make the averages outcomes less likely. However, not impossible. The second scenario includes an increase in major repair jobs, which affects the active repair time and cost. Due to longer repair lead time, the delay at the central depot is reduced. Hence, the TTR is only slightly increased. The cost however is increased by 10%, almost linearly to the increase in larger tasks.

Sub-question 5: *What solution alternatives can improve the performance of the system?*
Due to the unbalanced share of repair jobs and the resulting service levels and cost of MRO, task assignment policies are tested to re-align the logistics with MRO. Fourteen policies are evaluated. The first two are based on a random assignment. The only attribute considered here is the required skill set to provide service to a specific commodity type. The second assignment is an addition to the initial random assignment, where priority is provided for the larger tasks. In other words, major repair and overhaul are prioritised over minor repair and inspection. The prioritisation takes place at the repair administration, which is first to assign shops to the higher priority tasks. The following three assignment policies aim to reduce the overall repair lead time. The first assumes only active repair time. Therefore, this policy is considered as the *Naive* policy. This is followed up by the addition of shop load of each candidate repair shop. Finally, the assignment of priority is also included to these time based assignment heuristics. Thirdly, cost based policies are developed, which include a cost and shop load attribute in their selection expression. These are again elaborated with priority. Finally, to assure full comprehension a multi-criteria policy is created that includes both cost as well as time attributes. Different weights are included to test the heuristics to their full extent.

Sub-question 6: *What is the role and impact of the solutions alternatives on the performance of the system?*
The fourteen assignment policies can be categorised in four classes: random, time based, cost-based and mixed. The random assignments (R and RP) are solely beneficial to the administrative and logistics delay. The improvement however, is negligible. The time based assignments include a naive policy where only the active repair time. This policy also only reveals improvement in the administrative and logistics delay. This is a result of long repair lead times, as the TTR is 20 additional days on average. The SL and SLP policies result in an improvement of 7 days in terms of TTR compared to the current situation. This is both caused by a reduced repair lead time but also due to shortened administrative and logistics delay. The heuristics are able to allocate to jobs to shops in such way that the returning rate is more balanced. However, this comes at a cost. The total average cost of MRO is increased by 12%. The cost based assignment policies (CL and CLP) aim to reduce the cost of MRO whilst considering the shop loads. The TTR is maximally increased by 2 days on average. The cost are then decreased by 36%. By combining cost and time in the selection expression a

comprehensive set of solutions is established. The behaviour of the results is respective to the weights. CS37 reveals higher cost and lower TTR then CS73.

The results of TTR and cost of MRO facilitate to the trade-off between cost and time. The N, R, RP, CS73, and CSP73 do not compete with the other policies when establishing the Pareto frontier. When plotting the time and cost against each other the first policy found is the SLP policy, which results in the lowest TTR and highest cost. At the other side of the spectrum the CL assignment is found, which reveals the lowest cost and highest TTR. In the middle the CSP37 assignment shows improvement in both TTR as well as cost of MRO. This trade-off presents the choices an organisation can make in terms optimisation of performance.

Due to the stochastic nature of demand for MRO, the demand is slightly changed as input to test the robustness of the assignment policies. Notable here is that the inclusion of priority to larger tasks enhance the robustness of each respective policy. The most robust policy in terms of time is the SLP assignment, showing the least deviation in TTR, repair lead time, and administrative and logistics delay when demand and share of larger tasks should increase. However, this assignment policy is more sensitive to changes with regard to cost. Generally, the policies which include the assignment of priority are more robust than their 'original' policies

Main research question: ***How should MRO services of unserviceable components be allocated to various repair shops such that the time to restore and cost of MRO are taken into account?***
This research project takes multiple repair shops and vendors providing service to a variety of component types as an example to improve the performance of task assignment to these facilities by performing 42 experiments on different sets of assignment policies under various demand levels and demand types. The case study is performed in collaboration with KLM Engineering&Maintenance. The performance of the different assignment policies is measured through time and cost. The former is divided in two time configurations: administrative and logistics delay and repair lead time. The former delay occurs at the central depot, where repair orders are established and returning components are inspected. The latter is the time between these two activities. The cost is measured as the cost of MRO. Both the cost of MRO and repair lead time depend on the type of work scope of the component. Fixed attributes in this study are the commodity types and corresponding skill set at repair shops and capacity of both central depot and repair facilities. By means of Discrete Event Simulation with Simio, results show that different assignment policies have various outcomes on the three performance indicators.

The allocation of MRO services to repair shops is studied by means of task assignment policies. All policies, except for the random and naive policies, include both time and cost to a certain extent. The policies which are solely aimed at reducing either repair lead time or cost include shop load in their selection expression. The comprehensive set of solutions is established by evaluating 'mixed' policies that are not restricted to cost or repair time. The best policy to opt for with regard to implementation depends on the importance of either cost or time. A Pareto front can be established where time and cost are weighed against each other. A mixed policy with focus on time provides both a decrease in time as well as cost and can therefore be considered as Pareto efficient. However, this improvement is not an optimum for either one of the performance indicators.

Generally, the performance depends on the system characteristics. However, this study has resulted in interested findings. Firstly, including the task size (work scope) in the decision for repair shop has proved to be beneficial, for different work scopes are accompanied by different lead times and cost. By prioritising the larger tasks over the smaller ones, the assignment to shops becomes more robust. This is especially of interest in the context of aircraft component MRO, for the demand of individual components can be erratic of nature. From the set of assignment policies couple policies do not compete with other in the scoped system characteristics. These are the random policies, the naive policy, and mixed policy with highest weight for the cost attribute.

6.2 Recommendations

This study is based on several assumptions due to scoping and simplification of the problem definition. This results in the fact that results in general may become less reliable. Nevertheless, important insights can be implied as learning points for operations of the company and the field of aircraft component MRO. This section first discusses the recommendations for KLM E&M in Section 6.2.1. Thereafter, limitations and thus recommendations for further research are discussed in Section 6.2.2

6.2.1 Recommendations for KLM E&M

This section discusses recommendations for KLM Engineering&Maintenance, which can be captured with the following sub-question:

Sub-question 7: ***What recommendations can be made regarding the solution alternatives?***

- This study is primarily based on the available data, acquired from different data sets. The most used data source is the balanced scorecard KLM E&M deploys. This source has provided all the information on repair shops, in-house shop capacity, repair lead times, commodity types, and work scope types. The data of which the cost are withdrawn is not included in this source. Data on the logistics and administrative processes neither. The first recommendation to the company is to aim for a more integrated data source, where all aspects of the closed-loop supply chain are taken into account. A model such as established in this research, where different data sources are used, also allows the withdrawal of other statistics and measures, such as resource utilisation. Proper analysis can be performed over a large part of the supply chain, which facilitates decision-making on multiple levels of management. This information can be implemented by means of dashboards for example. At the central depot, real-time information and statistics on the performance of the repair shops helps with the allocation of jobs.
- Furthermore, it is recommended that this is deployed throughout all the different parties within this supply chain. Currently, the balanced scorecard is updated daily. By optimising the tracking systems for logistics, measurements on the duration of components in transit and in the central depot can be monitored more accurately. This allows further control on the lead times prior and post to the actual MRO services. By obtaining proper control over the lead times, other performance indicators from the perspective of the customer can be optimised such as service level. Furthermore, inventory control strategies can be revised. A reduced time to restore results in a higher replenishment rate

of inventory. Hence, inventory can be reduced or be used for other purposes such as loan or other commercial means such as selling.

- It is recommended to revise the contractual agreements with the repair vendors and shops to accommodate for additional flexibility in allocation of services. Currently, penalties in case of late deliveries are not pursued, whereas this provides proper control over the lead time. Additional knowledge on the load at the vendors enables even more insight on the expected lead time. The other way around, where the vendors receive data on the status of components at the central depot and in transit, allows them to schedule the services properly. The different assignment policies then have the potential to efficiently allocate services to jobs. In order to do so, the addition of work scope is endorsed, for this reveals the most robust results under changes in demand.
- The decision on choosing the repair facility for a specific work scope and commodity type is not solely based on a binary decision: outsourcing or in-house. Multiple repair vendors and shops are able to provide services to multiple commodity types. By assuming all the facilities in the decision and consider cost and/or time for specific work scopes as the basis of selection, an overall reduced turnaround time or considerably reduced cost can be achieved.

With the results as they are from this research further optimisation through innovation can be acquired. As basis the established Pareto set can be used. Naturally, this depends on the system characteristics. However, the following steps are to reduce the surface underneath the front in Figure 6.1. The above mentioned recommendations are to be interpreted as choices for the company. On the short term, only applying priority assignment is beneficial, especially during periods with increased demand. However, including the shop load in the selection of repair facility has proven to be of significant improvement to the TTR and cost of MRO. Generally, a policy such as the CSP37 has led to both a reduction in cost as well as time, but whether the effect is as desired remains a choice. If KLM E&M is willing to give up a few days in TTR for a considerable reduction in cost, this would be possible by applying a policy such as the CL or CLP. If the cost are of less importance, a policy such as the SL or SLP can be implemented to acquire the best results for the TTR.

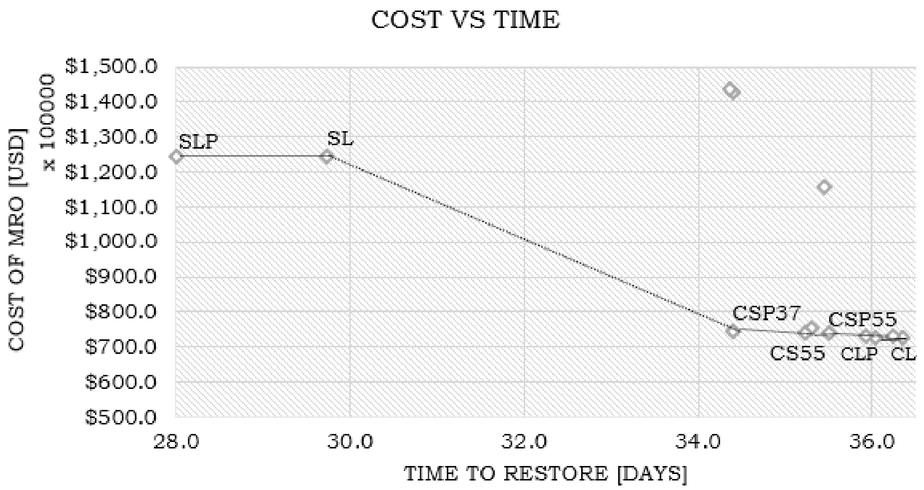


Fig. 6.1.: Pareto set of alternatives

6.2.2 Limitations and recommendations for further research

There are some limitations in this research, which are discussed in this section. Each limitation is described with potential future research opportunities.

- **Data availability**: data on in-house MRO services is largely available at KLM E&M. However, this is automatically updated and contains unlikely outliers. Data on the logistics and outsourced repair is rather limited. To what extent vendors can exchange information without having the impression of compromising its position in the market is opportunity for future research. Furthermore, a proper implementation plan of tracking systems is recommended. This can include the physical location of the trackers but also determine what information should be monitored.
- **Demand pattern**: the demand pattern is determined over the period of one year. An exponential inter-arrival time is used to generate data. This probability distribution is fitted on one-third of the data an validated over the remaining two-third. Phenomena such as seasonality are therefore limited included. Slight changes in demand is considered for each assignment policy. However, stronger deviations or a stronger stochastic component in demand should be examined more thoroughly.
- **Influence of transport schedules**: in this study transport is considered for individual components. However, in the actual system the lead time is dependent on specific transport schedules. This applies to both internal transport on the KLM E&M acreage to in-house shops as well as flight and trucking schedules to and from vendors. The assignment policies are based on lead times and consider transport as an additional fixed attribute. Many repair vendors are located in the United States for which an average transportation time of 9 to 13 days is measured. By including the transportation schedules in the assignment policies, the distribution of jobs over the shops will change.
- **Flow disruptions**: During repair, administrative, and logistics processes, disruptions may occur. This study assumed a continuous flow consisting of stochastic distributions as processing times. Large outliers are takes in consideration during the fitting of the distributions. However, to what extent the elimination or proper averting of these flow disruptions has an influence on the final TTR will result in more detailed control in the supply chain. This may be done by including the probability of specific types of flow disruptions and including them in the selection of shops or by implemented re-assignment policies in case of the occurrence of a significant disturbance. Another option is to design organisation processes to limit the effects of these disruptions.
- **Candidate shops and commodity types**: a selection of candidate shops is analysed and evaluated using the assignment policies. In the actual system, over 200 shops have been responsible for services in a certain point in time. The inclusion of a wider variety of shops which are also able to provide services to additional commodity types provides more encompassing insights on the amount of candidate shops. Other commodity types could be engines or wheels.

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APPENDIX

Literature review

A.1 Maintenance spare parts logistics

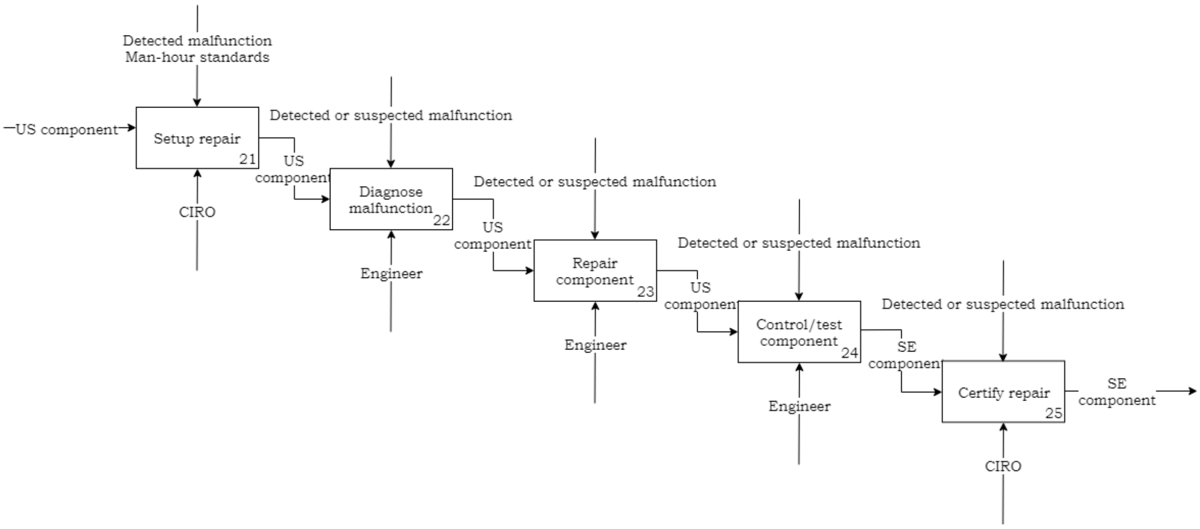

Fig. A.1.: Repair process (Cavalieri et al. 2008; Macchi et al. 2011)

Model synthesis

B

B.1 Model logic

B.1.1 Random assignment

Table B.1 depicts an example of the random order list. The simulation selects any destination for each component randomly in each replication.

Tab. B.1.: Random order list

Avionics	**Pneumatics**	**Interiors**	**Exteriors**
Shop B	Vendor B	Vendor A	Shop D
Shop C	Shop A	Shop A	Vendor B
Vendor A	Shop D	Shop D	Vendor F
	Vendor F	Vendor E	Vendor C
	Shop E		

B.1.2 Shortest assignment

Tab. B.2.: List of shops in increasing order based on repair time

	Avionics	**Pneumatics**	**Interiors**	**Exteriors**
1	Shop B	Shop D	Shop D	Shop D
2	Shop C	Shop A	Shop A	Vendor C
3	Vendor A	Shop E	Vendor E	Vendor B
4		Vendor B	Vendor A	Honewell International
5		Vendor D		
6		Honeywell Int		

B.1.3 Cheapest assignment

Tab. B.3.: List of shops in increasing order based on cost of MRO

	Avionics	**Pneumatics**	**Interiors**	**Exteriors**
1	Shop B	Shop D	Shop D	Shop D
2	Shop C	Shop A	Shop A	Honeywell Int
3	Vendor A	Vendor D	Vendor E	Vendor B
4		Honeywell Int	Vendor A	Vendor C
5		Shop E		
6		Vendor B		

B.2 Model implementation

B.2.1 Shop capacity

Tab. B.4.: Repair capacity drawn from uniform distribution

Shop	**Parameters**
In-house	
Shop A	$\alpha = 30, \beta = 40$
Shop B	$\alpha = 10, \beta = 30$
Shop C	
Shop D	$\alpha = 10, \beta = 30$
Shop E	$\alpha = 10, \beta = 30$
Outsourced	
Vendor A	$\alpha = 100, \beta = 150$
Vendor B	$\alpha = 40, \beta = 60$
Vendor D	$\alpha = 40, \beta = 60$
Vendor E	$\alpha = 100, \beta = 150$
Vendor F	$\alpha = 40, \beta = 60$
Vendor C	$\alpha = 10, \beta = 20$

B.2.2 Repair lead times

Tab. B.5.: Parameters and distributions for repair lead times (*$\alpha = 0.01$)

Size	**Parameters**	**Distribution**	**Kolmogorov-Smirnov**
In-house			
Shop A	$\sigma = 1.25, \mu = 3.14$	Log-Normal	0.161
Shop B	$\alpha = 0.78, \beta = 50.37$	Weibull	0.148
Shop C	$\alpha = 1.68, \beta = 29.83$	Log-Logistic	0.066*
Shop D	$\alpha = 0.80, \beta = 21.37$	Weibull	0.013*
Shop E	$\sigma = 1.04, \mu = 3.83$	Log-Normal	0.077
Outsourced			
Vendor A	$\alpha = 2.88, \beta = 140.65$	Log-Logistic	0.022*
Vendor B	$\alpha = 2.21, \beta = 66.43$	Log-Logistic	0.052
Vendor D	$\alpha = 2.18, \beta = 135.21$	Weibull	0.060*
Vendor E	$\sigma = 0.87, \mu = 4.86$	Log-Normal	0.079*
Vendor F	$\alpha = 2.92, \beta = 80.07$	Log-Logistic	0.071*
Vendor C	$\alpha = 2.30, \beta = 56.10$	Weibull	0.076*

B.2.3 Repair cost

Tab. B.6.: Repair cost per workscope and facility

Facility	Inspection	Overhaul	Minor Repair	Major Repair
Shop A	$1,011.69	$3,541.77	$1,173.95	$1,283.36
Shop B	$1,290.73	$1,483.52	$7,217.01	$1,573.60
Shop C	$3,093.20	$3,235.57	$5,056.10	$3,066.05
Shop D	$822.38	$399.47	$1,216.17	$346.99
Shop E	$3,652.04	$2,529.50	$13,337.59	$4,225.61
Vendor A	$2,030.53	$9,615.51	$4,523.82	$4,702.43
Vendor B	$5,893.63	$7,510.54	$8,209.15	$8,029.46
Vendor C	$8,509.93	$10,790.76	$20,402.82	$20,057.78
Vendor D	$1,910.65	$2,435.38	$2,347.92	$2,431.56
Vendor E	$10,501.69	$13,389.54	$9,654.41	$9,542.23
Vendor F	$2,065.78	$3,565.92	$3,933.73	$3,879.16

C

Results

C.1 Results of the current situation

C.1.1 Scenario analysis cost of MRO

The sensitivity of cost is lower when demand is increased compared to the decrease in demand. How the averages fit within a 95% confidence interval is visualised in Figure C.1, which presents a box plot the cost KPI. Additionally, Table C.1 reveals the sensitivity of cost per repair shop and vendor. The differences in average cost of MRO depends on the spread of cost per work scope for each repair shop. For instance, Vendor A has proven to provide services for relatively little deviating cost. Changes in demand do therefore not impact the average cost considerably.

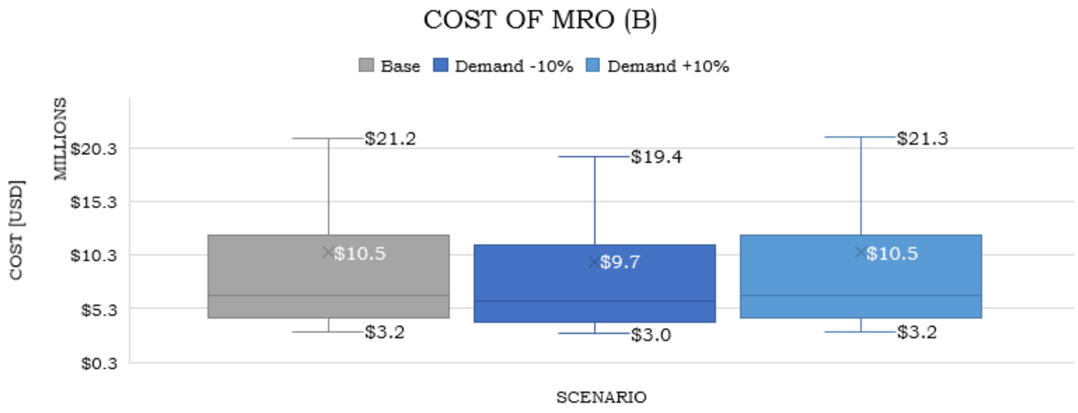

Fig. C.1.: Differences in total cost of MRO

Tab. C.1.: Average total cost of MRO per shop for change in demand

Shop	Base	Demand +10%	Demand -10%
Vendor A	$12,277,728	$12,318,339	$11,345,739
Shop A	$4,403,033	$4,405,748	$4,040,074
Shop B	$3,461,103	$3,446,758	$3,163,557
Shop C	$6,657,470	$6,624,053	$6,089,916
Shop D	$6,102,379	$6,110,036	$5,610,930
Vendor B	$20,601,707	$20,589,934	$18,920,435
Vendor C	$8,874,277	$9,020,275	$8,312,334
Vendor D	$3,498,007	$3,489,359	$3,209,282
Vendor E	$37,269,908	$37,293,829	$34,328,265
Vendor F	$6,615,547	$6,644,230	$6,203,833
Shop E	$5,994,727	$5,990,284	$5,548,575

C.2 Results of the assignment policies

C.2.1 Repair lead time

The average repair lead times for all assignment policies is presented in Table C.2. The confidence interval (95%) is also depicted here. The overall lead time is the average of each shop its individual mean lead time. Again, the SLC assignment reveals the lowest lead time and the S assignment the highest. Every half width is < 5% of the KPI its average. This justifies the amount of replications.

Tab. C.2.: Repair lead time (CI=95%)

Assignment policy	Average	Begin CI	End CI
B	27.8	21.9	33.7
R	28.5	23.5	33.6
N	37.0	29.2	44.9
SL	27.8	21.4	34.3
CL	31.4	24.6	38.2
CS55	29.6	21.3	37.9
CS37	29.3	22.1	36.5
CS73	29.8	21.9	37.7

C.2.2 Resource utilisation

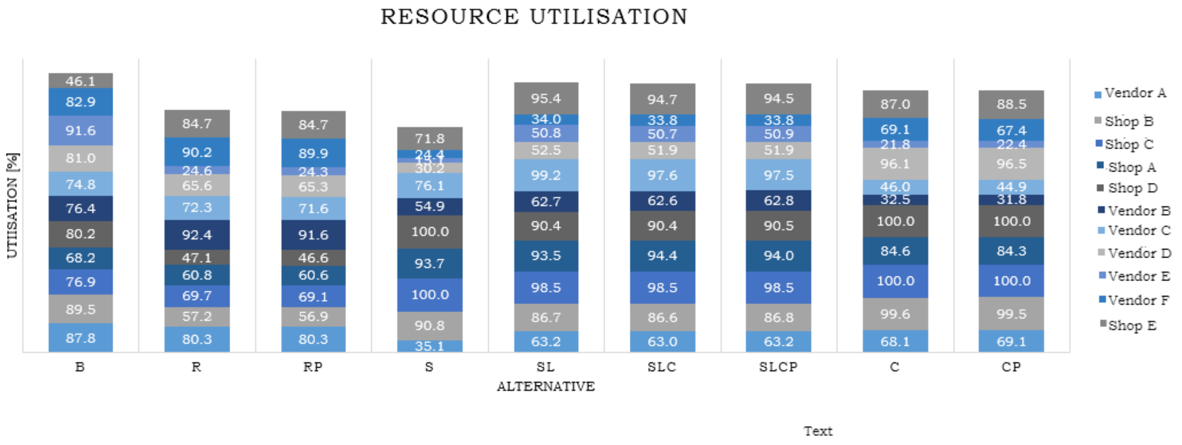

Fig. C.2.: Resource utilisation per alternative

C.2.3 Cost of MRO

Tab. C.3.: Average total cost of MRO per assignment policy and shop

Shop	B	R	N	SL	CL	CS37	CS55	CS73
Vendor A	$12,266,489.07	$10,314,308.60	$1,450,112.07	$3,378,758.43	$2,504,038.33	$2,502,776.43	$2,495,973.20	$2,487,572.73
Shop A	$4,402,431.73	$3,092,423.57	$4,515,659.53	$4,288,294.33	$4,735,093.33	$4,745,652.90	$4,737,936.83	$4,695,847.73
Shop B	$3,459,456.13	$3,450,254.93	$4,456,751.83	$4,380,141.67	$3,919,460.57	$3,903,702.83	$3,947,929.17	$3,946,974.43
Shop C	$6,656,295.77	$6,647,666.83	$9,328,913.10	$9,303,037.90	$6,780,394.07	$7,516,008.93	$7,028,839.37	$6,826,816.70
Shop D	$6,101,218.07	$3,966,042.27	$7,635,727.33	$7,018,174.40	$3,384,490.07	$3,525,551.20	$3,437,111.07	$3,409,136.53
Vendor B	$20,637,250.90	$33,198,597.20	$18,735,361.43	$21,263,317.33	$10,101,501.60	$10,724,294.33	$10,452,798.07	$10,213,891.67
Vendor C	$8,864,596.47	$47,058,053.33	$45,384,149.70	$59,379,660.93	$19,604,301.40	$20,407,175.60	$20,009,435.07	$19,726,044.67
Vendor D	$3,508,816.60	$3,164,829.40	$436,741.00	$2,277,791.67	$4,479,260.73	$4,421,249.27	$4,445,587.90	$4,485,433.23
Vendor E	$37,305,843.27	$11,033,159.67	$2,501,155.97	$8,370,444.00	$2,667,218.17	$3,468,781.20	$2,992,158.40	$2,796,596.63
Vendor F	$6,621,463.63	$14,193,207.90	$2,062,522.90	$4,883,680.37	$8,854,375.83	$8,254,888.40	$8,607,539.50	$8,739,768.33
Shop E	$6,023,867.00	$6,736,073.60	$5,375,964.17	$7,563,394.83	$5,594,766.47	$6,000,046.13	$5,756,149.30	$5,663,526.17

C.3 Results of prioritsed assignment

C.3.1 Random with priority

The RP assignment, i.e. random with priority, is tested for the time, and cost based performance indicators. The time performance is depicted in Figure C.3, which includes the time to restore, administrative and logistics delay, and repair lead time. Generally, no significant difference in found in terms of these performance indicators. The average values remain rather equal. Solely differences < 1 are measured. The largest differences can be found in the maximum results. However, the largest difference is < 4 days.

Fig. C.3.: Time performance of RP policy

With regard to the cost, again little changes are found. The average total cost of MRO is increased with nearly 600,000 USD over the run time of 104 weeks. Relatively to the total cost this is an increase of 0.4%. When analysing the changes on shop level, the same size of results are found. The largest increase in repair lead time is 0.9% and the largest decrease 1.0%. The aggregated results are depicted in Figure C.4.

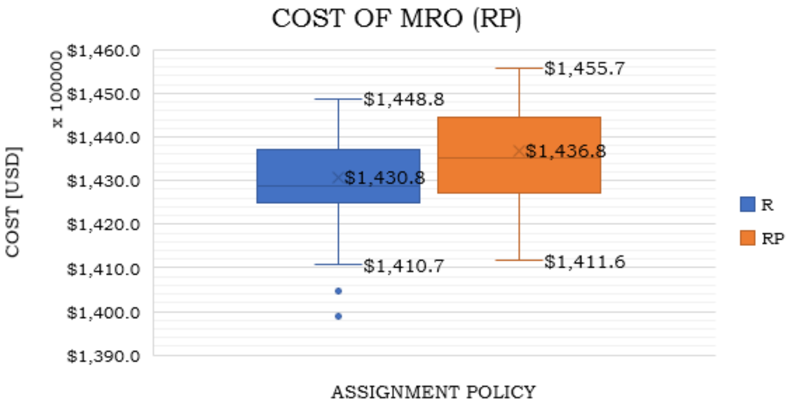

Fig. C.4.: Cost performance of RP policy

C.3.2 Cost based with priority

The third aim of assignment is based around the expected cost of MRO, dependent on the work scope. The load is again included, for another naive assignment does not compete. Figures C.5 and C.6 depict the time and cost as a result of the addition of priority respectively.

Both cost as well as time (time to restore, repair lead time, administrative and logistics delay) are not significantly changed as a result of the priority assignment. Where both performance measures have been reduced for the RP and SLP policies, cost of MRO is now ever so slightly increased. However, this reduction is rather negligible with the current system characteristics (demand and active repair time).

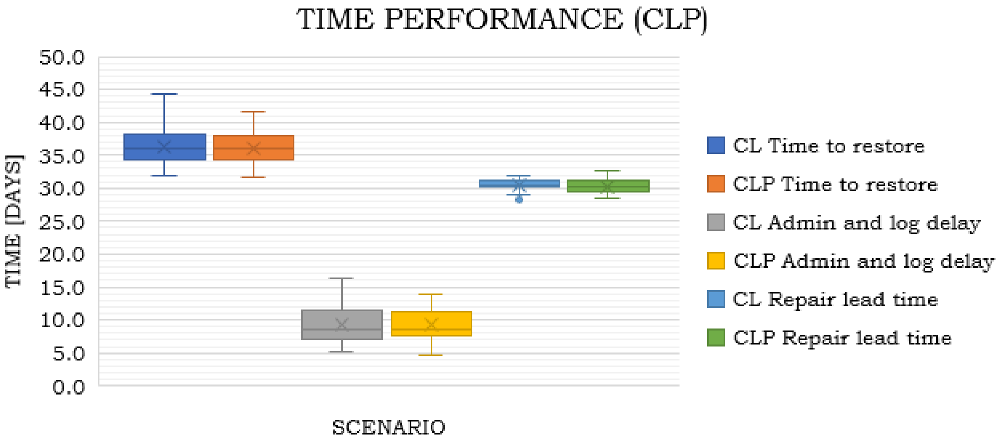

Fig. C.5.: Time performance of CLP policy

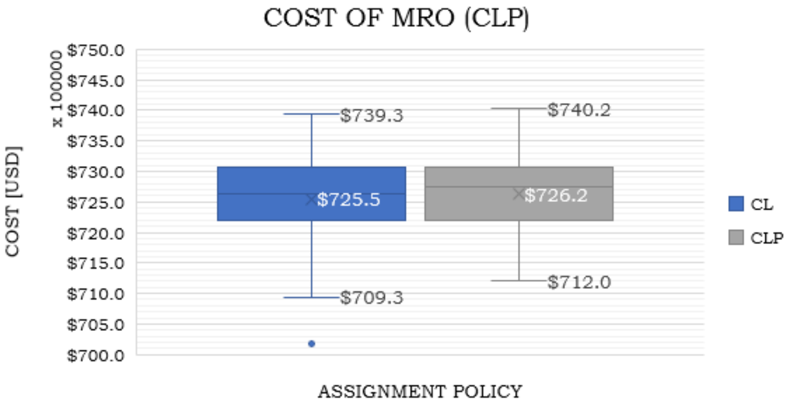

Fig. C.6.: Cost performance of CLP policy

C.3.3 Average values of all performance indicators

C.4 Robustness of the assignment policies

C.4.1 Change in demand

Table C.4 presents the average results per performance indicator and assignment policy as a result of a 10% increase in demand.

Tab. C.4.: Average results of assignment policies +10% demand

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	47.7	27.70	40.5	$115,915,084.0
R	47.4	29.00	40.1	$143,017,285.6
RP	54.1	30.40	34.7	$145,836,151.6
N	59.9	36.80	35.0	$96,901,628.2
SL	44.9	28.00	40.9	$124,800,600.3
SLP	33.9	27.60	27.0	$125,992,656.0
CL	58.9	31.40	35.6	$72,590,206.3
CLP	51.1	29.30	29.4	$72,559,617.7
CS37	57.7	30.60	40.1	$75,500,713.4
CS55	58.0	31.10	39.2	$73,875,501.6
CS73	58.5	31.50	39.1	$73,285,558.9
CSP37	51.0	29.90	34.6	$73,279,570.4
CSP55	50.9	29.70	34.3	$72,708,954.5
CSP73	50.4	29.60	39.5	$73,056,744.4

Table C.5 presents the results per assignment policy for each KPI. Generally the time to restore is reduced as a result of a lower repair lead time and less administrative and logistics delay. The latter is assumed to have reached a certain minimum in a steady state. The aim for two days for administrative and logistics delay is thus possible, but only with a reduced inflow of components. Where the prioritised policies were robust to deal with an increase in demand, they do not particularly for a decrease in demand. The results among the policies are spread and no single policy stands out in terms of its performance. The CS37 is relatively the best performing with regard to all KPIs. In addition to the relative changes, Table C.6 also depicts the actual average values per performance indicator and policy.

Tab. C.5.: Results of assignment policies -10% demand

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	-47%	-3%	-649%	-8%
R	-49%	-6%	-549%	-8%
RP	-27%	-6%	-212%	-8%
N	-37%	-14%	-317%	-2%
SL	-57%	-3%	-613%	0%
SLP	-49%	-3%	-517%	0%
CL	-48%	-7%	-449%	-12%
CLP	-46%	-7%	-452%	-13%
CS37	-54%	-2%	-474%	-17%
CS55	-54%	-1%	-526%	-14%
CS73	-50%	-2%	-477%	-13%
CSP37	-52%	-1%	-507%	-15%
CSP55	-46%	-	-511%	-15%
CSP73	-52%	-2%	-519%	-14%

Tab. C.6.: Average results of assignment policies -10% demand

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	24.1	26.9	1.7	$106,820,060.7
R	23.2	27.0	1.7	$132,867,864.6
RP	27.1	27.1	1.7	$132,369,925.2
N	40.1	32.5	1.5	$94,595,662.0
SL	18.9	27.0	1.7	$124,675,279.5
SLP	18.8	27.0	1.7	$124,496,765.2
CL	24.5	29.4	1.7	$64,558,425.9
CLP	24.6	29.4	1.7	$64,119,496.4
CS37	22.9	28.9	1.7	$64,700,132.8
CS55	23.4	28.9	1.7	$64,759,754.2
CS73	23.7	29.1	1.7	$64,328,683.5
CSP37	23.1	29.0	1.7	$64,780,189.5
CSP55	23.5	29.0	1.7	$64,392,208.5
CSP73	23.9	29.1	1.6	$64,212,033.9

C.4.2 Additional share of major work scopes

Table C.7 presents the average values of the performance per assignment policy as a result of a 10% increase in major repair jobs.

Tab. C.7.: Average results of assignment policies +10% major repair jobs

Policy	Time to restore [days]	Repair lead time [days]	Admin and log delay [days]	Cost of MRO [USD]
B	36.8	30.3	11.1	$128,896,995.6
R	36.8	33.4	8.0	$152,808,591.5
RP	64.8	33.6	7.7	$153,271,270.9
N	31.7	42.4	7.3	$114,479,554.3
SL	29.6	31.0	11.4	$144,120,687.3
SLP	37.7	30.4	9.7	$144,272,285.4
CL	38.6	38.4	10.0	$76,762,815.4
CLP	37.4	38.5	10.6	$76,677,328.4
CS37	38.5	38.5	9.9	$78,417,265.5
CS55	38.6	38.6	10.9	$77,282,684.8
CS73	37.4	38.3	11.2	$77,125,664.1
CSP37	38.4	38.6	9.9	$78,376,119.3
CSP55	38.0	38.6	10.8	$77,022,900.0
CSP73	5%	38.7	10.0	$76,996,335.4

D Interviews

The data and processes described in Chapter 3 is reviewed by multiple employees of KLM E&M within the department of Logistics&Support.

D.1 Logistics Leader Expedition - 19 November 2018

The logistics leader expedition explained the different ways the packages are tracked throughout the supply chain and provided the reasons that data integrity for logistics measurement is currently rather low. The activities performed to receive and dispatch packages via different transportation modes are explained. The travel times used in this research project are therefore validated.

Can you explain the general working of the closed-loop supply chain?
KLM E&M has one large warehouse (Magazijn Logistiek Centrum) from which we service customers from all over the world. This warehouse contains rotables. These are components that can be restored after a certain amount of flight hours or in case of defects. Once a customer requests a component, this is shipped to them. The component we provided is then exchanged for their unserviceable component which shipped back to us. We then make sure the component is restored to a serviceable status and airworthy. After that, it is checked for proper documentation and re-stocked in the warehouse.

What are the first steps when a package has been collected from the docks?
It depends on the origin of the package. If the package had to go through customs, Bolloré collects it from the docks and provides clearance verification and such. If the package is sent from relative close distance we collect it. We use mobile scanners to register the entrance of the package and to see what its location is within the central depot. If this is *Shop VC* it goes to the repair administration and if it is *VC(2000)* the component or material is serviceable and is brought to the inspection incoming goods. We check whether each package has an RFID label. If not, we provide it, so it can be traced from there on.

What would you consider as main challenge in your work?
It is difficult to schedule employees. Since recently data of Bolloré is collected and displayed on a large screen so we can see what is coming. Additionally, AOG (Aircraft On Ground) requests are visible here as well. However, this data is quite unreliable. For instance, today it says that 56 packages are expected, but halfway through the day already 70 have arrived. This issue also applies to the other departments (RA, IIG). We do not know what inflow is expected which makes it difficult to anticipate on it. Besides the expected goods, smaller practical issues occur. For instance, the mobile scanners do not always operate as desired or customers placed labels on top of ours. Regardless of directives we send to them, often information is lacking or not properly provided.

I see large buffers at both the RA and the IIG lanes. During these peak periods, how long can it take before they have been processed? That can take quite long. It is no exception that a package waits for two weeks at either one of the lanes. In extreme cases, nearly two months can even be the case. Generally, two to four employees are available at both divisions, but during peak period flex workers are hired or we at expedition aid in some administrative work. It also depends on whether all information provided with the package is correctly and completely filled in. If this is not the case, the packages are placed in a quarantine buffer.

How long does it take for a component to be received by the repair shops and vendors?
That depends on to which shop or vendor it is shipped of course. For internal transport, every half hour a shuttle bus arrives to transport the components to the in-house shops or the hangars. Some of these shuttles also deliver components to Schiphol Airport, depending on the size of the shipment. Otherwise, larger trucks are deployed, mainly from DHL. From there the total travel time depends on the schedule of KLM Cargo. Many vendors are stationed in the US, this can take from 4 to 10 days before it actually is picked up by the vendor. Most components going to repair vendors are supplied via air. Transport to and from Vendor B and Vendor A is provided via truck.

D.2 Project manager Direct Support - 11 December 2018

A walk through the central depot was supervised by the project manager direct support. The function of the multiple workstations and its respective employees were explained. Here, the process described in Section 3.4 was explained. The distinction between serviceables, unserviceables, rotables, and consumables was elaborated. Ronald Barbé also keeps track of the productivity of the RA and IIG and was therefore able to validate the times that are estimated for administrative delay.

What distinctions are made within the central depot in terms of material and component characteristics?
At the expedition a label is printed with the final destination on it within the central depot. Generally, this is Shop VC or VC(2000). The former is the repair administration, in which only unserviceable components are processed. This is performed in separate workstations, depending on the airframe type the component belongs to. This distinction is made to reduce the communication lines with the Customer Interface and thus the customers. VC(2000) is the lane in which all serviceable goods are processed. These can either be rotables or consumables. Rotables are newly procured components or components that are returned from the repair shop or vendor.

What happens with the components that are finished with administrative processes?
They are placed in the so-called *squares*, which function as a buffer between processes. A couple of times a day an expedition employee drives by these squares to pick up everything and transport them to the subsequent location within the depot. This is most often the export side of the expedition or the warehouse. Depending on the size and quantity of the components in these squares either a forklift is used or simply a rolling cart. However, the exact location of these squares and what to put there changes regularly. Because of these changes often both serviceable and unserviceable goods are placed in the same place. This does not necessarily lead to problems, but requires more time to sort them out.

D.3 Leader Direct Support - 4 March 2019

The leaser direct support, currently working on a control tower project, provided additional insights to what the desired future state is of the closed loop supply chain in terms of time performance. Rough time estimates were mapped out and included at multiple links within the network, such as 14 days for repair, 1 day for inbound, and 1 day for outbound. Additional information was also given about the performance that is expected of customer airlines, however this is out of scope for this research project.

Can you elaborate on the logistic control tower?
The control tower is a support system, basically a source which includes real-time data of all time steps in the supply chain. It includes repair, transportation, and logistics time and service level performance data. The idea is to see what the lead time at a repair shop is based on their load and capacity. If the shop is overloaded by work, we can make a decision to outsource the job or not. Additional information of AOG deliveries is also monitored. This is currently a vision, for data of logistics is practically non-existent. Repair data is available, but is not linked to the activities before and after the MRO services.

I hear you only talk about the internal workshops. Do you only consider in-house services in the control tower?
Initially that is the idea. Vendors are often reluctant to share this type of data and information. We would then use historical data to make an estimate of the expected lead time. Of course this data can be obtained from different sources. Furthermore, it is still unclear to what detail we will search for the average lead time. Do we also consider the work scope of the job? The period in time? And so on.

What is the target for in-house repair jobs in terms of lead time?
This differs per commodity type and work scope. We want to aim for 14 days for the total time before the goods are either re-stocked or directly shipped to the customer. This means that 12 days are reserved for repair and two days of supporting processes in the central depot. This does not apply to engine services, which has a supply chain on its own.

Are you able to decide on outsourcing if this is desired with regard to contractual agreements?
Yes, we have quite some flexibility when it comes to remaining jobs in-house or to outsource. Nowadays the same shop and vendor are chosen based on historical data. The repair administrator sees where it was repaired previously and selects that facility for the subsequent services on that component. Generally, KLM E&M would like keep all services in-house, but due to capacity this is not possible. The repair administrator does not know how what the expected lead time is for other vendors or shops. Neither does he know about the cost. The supply chain planners and specialists have more insight in these factors. In cases where it is opted for to outsource a job that is normally performed in-house they are consulted.