MASTER

An integrated repairable spare parts management methodology
an application in the maritime sector

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An integrated repairable spare parts management methodology:

An application in the maritime sector

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Subject headings: inventory control, maritime maintenance, materials management, supply chain management, repairable spare parts, workshop scheduling, dispatching

I. Abstract

This research suggests an integrated methodology specifically for the management of repairable spare parts for complex capital-intensive organizations. This research has been conducted at the Royal Netherlands Navy. This is a capital-intensive organization with operating equipment that is highly specialized and has complex systems mounted on board. Along with this equipment the organization has a large portfolio of spare parts, a large amount of them repairable spare parts. For these parts a classification methodology, an inventory management methodology, and a repair order dispatching methodology are dynamically integrated, by sharing feedback between the elements and controlling them based on that feedback. This proposal is tested using a simulation, and shows an interesting improvement potential in regard to the relevant spare parts availability.

Keywords: inventory control, maritime maintenance, materials management, supply chain management, repairable spare parts, workshop scheduling, dispatching

II. Management Summary

Repairable spare parts management is a crucial element for capital-intensive organizations. In relation to consumable spare parts, repairable spare parts are in general high-valued, slow-moving, and important for the material availability of the equipment of the organization. The material availability of the equipment is crucial for such organizations, due to the capital invested in it. The management of the repairable spare parts can become very expensive however, when the equipment availability is maximized. Therefore a well-funded management methodology is key to obtain a good balance between capital invested in the repairable spare parts management on the one hand, and the performance regarding the availability of the equipment on the other hand.

The Royal Netherlands Navy fits exactly to the description above. With its highly specialized equipment and installations, the organization has a broad portfolio of repairable spare parts. These parts are repaired after failure to make them ready for use again. This process is called the refurbishment. Many of the repairable spare parts are repaired internally in the organizations' workshops. These workshops have a limited resource capacity, in regard to personnel and materials. Currently, the availability of the repairable spare parts is lower than desired, even when taking the limited resource capacity into account. The relevant parts for the availability of the equipment are often not available when requested. Therefore, we formulate the problem statement as follows:

"How to improve the repairable spare parts management methodology at the RNLN to increase its relevant performance, taking the limited resource capacity into account?"

Relevant scientific literature provides the insight that the best way to manage repairable spare parts is to integrate the various elements involved. This literature suggests integrating these separate elements as well as possible to achieve the best performance. Important elements suggested are a suitable repairable spare parts classification and repairable spare parts inventory management. In addition, we want to consider the element of dispatching of the refurbishment repair orders as well. Furthermore, we want to integrate the elements by making the elements interact based on dynamic information. The repairable spare parts management framework in Figure 1 is suggested.

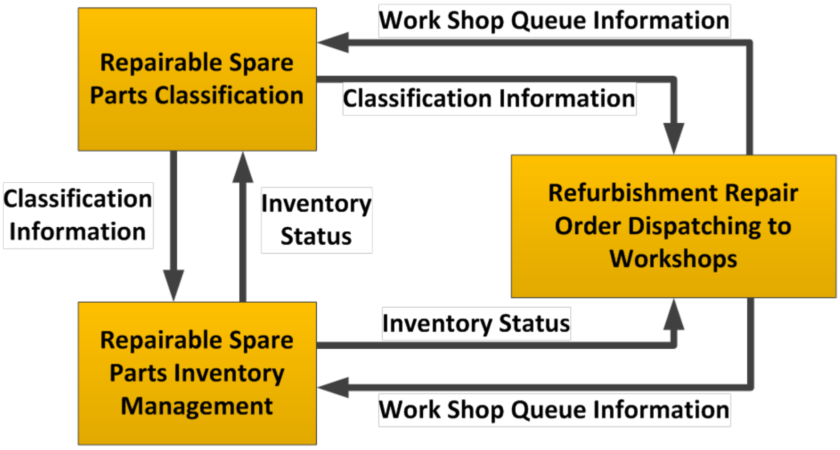

FIGURE 1: INTEGRATED REPAIRABLE SPARE PARTS MANAGEMENT FRAMEWORK

In order to validate the problem statement, the current repairable spare parts management methodology used at the RNLN is assessed, as well as the relevant performance of this methodology. The problem statement is underlined by this performance. The most relevant repairable spare parts for the equipment availability are performing worse in regard to their availability in comparison to the less relevant parts. Aspects of the current methodology used responsible for this undesired performance are the classification methodology used for the complete spare parts portfolio (including the consumable spare parts), and the inventory management policies used. The elements used in the framework are not integrated either, implicating improvement opportunities.

The first element is a classification framework that is suitable as foundation for the elements of inventory management and dynamic dispatching. After assessing potential classification criteria suggested by scientific literature, the characteristics of part criticality and procurement lead time duration are selected. The combination of these two characteristics provides a useful in the potential backorder impact in case of unavailability of the part, in regard to the likelihood of WS unavailability and the duration of that unavailability.

Using this framework as a basis, an updated form for the repairable spare parts inventory management is proposed. Because the current inventory levels for the repairable spare parts can be considered as fixed, the inventory policies focus on increasing the availability by altering the reorder policies, and by introducing a critical inventory level to influence the dynamic priority of the part. The proposed inventory policy classification framework is visible in Figure 2.

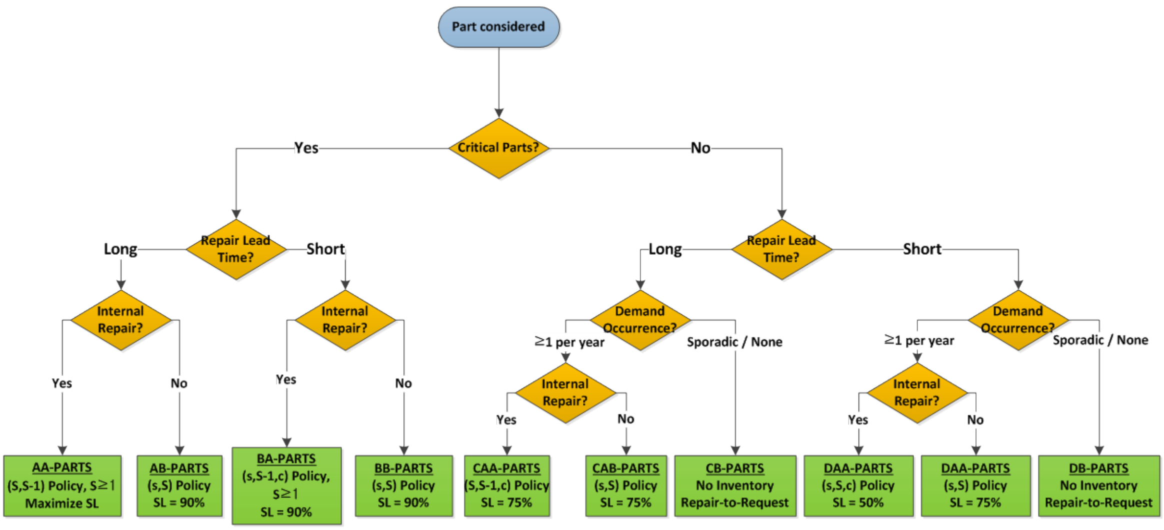

FIGURE 2: INVENTORY POLICY FRAMEWORK REPAIRABLE SPARE PARTS

Finally, a methodology for the element of workshop repair order dispatching is proposed. The dynamically determines the place in a workshop queue for the workshop repair orders (Figure 3).

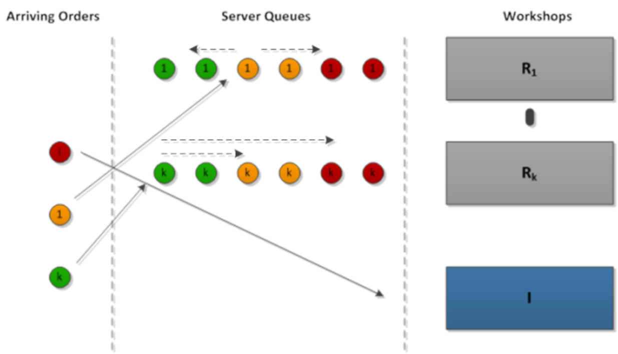

FIGURE 3: DYNAMIC REPAIR ORDER DISPATCHING FOR WORKSHOPS

In order to arrange this form of repair order dispatching for the workshops a set of dispatching rules is proposed. These rules base the position in the workshop queue on the repairable spare parts class of the part and its dynamic inventory position, resulting in its repair order priority. The dynamic integration allows for a constantly updated position, to achieve the highest relevant performance.

The complete proposed integrated repairable spare parts management methodology is evaluated by a simulation, and compared to the current methodology. The simulation input is based on historical data available regarding the repairable spare parts requests. All input is converted to the simulation environment, to assess the situation in general. The results for the simulations are visible in Table 1.

REPRESENTATIVE RNLN DATA			
Parameter	**Improvement Model**	**Reference Model**	**Difference**
RCA Requests On Time	**72.43%**	**35.47%**	**36.96%**
RCA Requests Too Late	27.57%	64.53%	
RCA Requests Fulfilled Total	100.00%	100.00%	0.00%
RCB Requests On Time	**75.25%**	**32.86%**	**42.39%**
RCB Requests Too Late	23.00%	54.18%	
RCB Requests Fulfilled Total	98.25%	87.03%	11.21%
RCC Requests On Time	**55.19%**	**56.08%**	**-0.89%**
RCC Requests Too Late	44.48%	43.92%	
RCC Requests Fulfilled Total	99.68%	100.00%	-0.32%
RCD Requests On Time	**56.13%**	**75.26%**	**-19.12%**
RCD Requests Too Late	40.12%	24.54%	
RCD Requests Fulfilled Total	96.26%	99.80%	-3.54%
Utilization Workshop	93.53%	91.37%	

TABLE 1: REPRESENTATIVE SIMULATION OUTPUT COMPARISON REFERENCE- AND IMPROVEMENT MODEL

As becomes clear in the results, the reference model is indeed able to focus on the relevant repairable spare parts in comparison to the reference model presenting the current management methodology. Sensitivity analyses performed provide additional insight in altering the control parameters and aspects of the repairable spare parts management methodology in order to obtain the desired relevant performance for the refurbishment circuit.

We conclude that the proposed integrated framework indeed results in a more desired performance for a repairable spare parts management environments, as this application within the maritime sector has shown. The integration of the elements also allows for well-funded control decisions to be made, in order to adjust the performance to the desired situation. Instead of separately trying to optimize the separate elements, this framework makes it possible to optimize the overall performance. This integrated approach to repairable spare parts management has improvement potential for other capital-intensive organizations with a comparable spare parts portfolio. Further research is desired to further investigate the applications for such an integrated framework, and the possibilities to improve it further by integrating more aspects.

III. Preface

This is the second part of my graduation thesis, in completion of the Master Operations Management and Logistics at Eindhoven University of Technology. This part succeeds a literature study, a project proposal, and the first part of my master thesis, a base line study. Most of these research deliverables have been conducted at the Royal Netherlands Navy in Den Helder. The master thesis is related to the overarching scientific MaSeLMa project (Maritime Service Logistics and Maintenance), although the contribution to that project is mainly provided by the base line study conducted (Buiting, 2014) and less directly so by this part. I would like to use this section to personally thank some of the people making this project possible.

First of all, I would like to thank my first University supervisor Tarkan Tan. Even though the time-pressure was high in many phases of the project, the meetings and discussions with him were always able to cheer me up. I really appreciate his positive approach to my project, and his flexibility and patience when these aspects were much needed. In addition, I would like to thank Engin Topan (my second University supervisor) and Sena Eruguz (my third University supervisor, albeit officious) for their helpful feedback and tips.

Second, I would really like to thank my Royal Netherlands Navy supervisors Bart Pollmann and Peter Sluijter. Next to being very helpful in regard to the contents of the research itself, above all they made my time in Den Helder a pleasure. All organizational aspects were arranged very well, my office at the Noorderkroon building had a wonderful view on the Marsdiep and Texel complete with seals swimming by, and whenever I needed to get in touch with other people within the organization the phone was immediately grabbed. Furthermore, the conversations about aspects transcending the actual research were very interesting and I really appreciated them.

Finally, all people close to me, thank you very much for all the support! The research was not always easy, but there was always someone to share my thoughts with. Most of all this is the case for my parents, you are still the best advisors I have and after 25 years I’m still learning loads from you.

Ties Buiting

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VII. List of Abbreviations and Terms Used

The following abbreviations are used throughout the document:

Thesis term	**Definition**
ASM	Inventory management
ATH	Repairable component that is offered for repair
BEVO	Process of making parts available
BO	Planned (periodical) maintenance of equipment
C4i	Maintenance area of electronical components and encryption
Consumables	Non repairable spare parts
Disposable stock	Spare components up for disposal
DMI	Directorate of the RNLN responsible for the sustainment of the equipment
DMO	The organization taking care of the development and the investment of the RNLN equipment
DOPS	Division of the RNLN responsible for the operational use of the equipment
GVU	Spare components and systems available for use
Hand-in obligation	The obligation to hand in failed replaced parts
High priority repair	Repairs given a high priority status in order to decrease their lead time
IHO	Internal maintenance order
IO	Non-planned maintenance
MG	Material availability of the WSs is an important factor for the OG
NGVU	Spare components and systems not available for use
Platform	Maintenance area of the ships' body
Redistribution	Redistribution of parts among operational equipment
Refurbishment circuit	Internal and external
Repairables	Repairable spare parts
RNLN	Royal Netherlands Navy
Specials	Maintenance area of the 'specials', special operation equipment
SWS	Maintenance area of sensors and weaponry systems
UGD	The required utmost date the maintenance request needs to be fulfilled
WS (weaponry system)	Technical term for RNLN ship
WSs (weaponry systems)	Plural of WS

1 Research Introduction

Section Abstract

The general maintenance process of the RNLN (Royal Netherlands Navy) is introduced. Extra attention is paid to the refurbishment circuit introduction. Then the main challenges for this circuit and thus the RNLN repairable spare parts management are discussed. The low service levels for these repairable spare parts are the central problem this research addresses. The broad spare parts portfolio and the repair characteristics of these parts are important element.

1.1 Maintenance at the Royal Netherlands Navy

1.1.1 General organization introduction

The RNLN is the maritime division of the Netherlands armed forces. In order to provide peace and security on various missions on water all over the world they have to be flexible and therefore they have to maximize the availability of their state-of-the-art WSs (Weaponry Systems, technical term for the RNLN ships). This requires intensive management of the maintenance of these WSs while minimizing the required expenditures to be able to operate within the available budget.

It is important to understand the RNLN is a government-funded and government-controlled organization. Therefore the RNLN is a non-profit organization. This is important to realize throughout this thesis, because this regularly results in a divergent way of decision-making compared to the literature. The goal of the RNLN is to maximize the availability of its equipment for the minimal costs. However, the composition of the fleet of WSs has to be treated as a given. This composition is based on Dutch political decisions, influenced by international treaties (the NATO).

The size of the RNLN budget comes forth from the political decisions regarding the total available budget for the Dutch ministry of defense on the national budget. This budget has to be divided over the ground forces, the air forces and the maritime forces. For many years, the total Dutch defense budget has been shrinking as a percentage of the Gross National Product (Centraal Bureau voor de Statistiek, 2011). A graph of this trend (Figure 25) is added in Appendix D (Section 9.3). As a result, for the RNLN budgets have been decreasing too, an important trend to take into account. Recently this has resulted in various reorganizations of the organization of which the most recent took place in the summer of 2013. This has also resulted in the currently executed implementation of an ERP program. This research is performed keeping this imminent implementation in mind. In order to maintain relevance for the RNLN the results are delivered in such way that they are still applicable for the organization after the implementation has been completed.

The organizational structure (Appendix 9.1) contains three directorates. This research concentrates on the DMI (directorate material sustainment) because this directorate controls the refurbishment circuit. The DOPS (directorate operations) is also part of the maintenance process (Buiting, 2014) but for this research we only consider them as the demanding party for spare parts. The organizational structure of the DMI is visible in Appendix 0. Most important for this research is the ASM division (inventory management), part of the ML division (material logistics). The ASM division is responsible for the control of the refurbishment circuit (Section 1.1.3).

1.1.2 RNLN maintenance process

The maintenance process of the RNLN has been thoroughly described in a preliminarily performed base line study (Buiting, 2014). The complete maintenance process architecture is visible in Figure 28 in Appendix 9.6.

The scope of this report lies on the refurbishment process, which is part of the BEVO (replenishment) process. The main function of the BEVO process is to have the required material resources for the required maintenance tasks to be executed available on time. Important processes for which material resources have to be provided are among others the BO (appointed maintenance) tasks and the IO (incidental maintenance) tasks. The BO tasks are a combination of scheduled large maintenance periods for the WSs (in which sometimes modifications can take place) and scheduled small (preventive) maintenance activities performed on board by the DOPS (directorate operations). The IO tasks are corrective maintenance activities performed by both the DOPS and the DMI whenever systems or components fail.

1.1.3 Refurbishment circuit

1.1.3.1 Repairable spare parts

Spare parts inventories represent an important part of the assets of the RNLN, an organization with capital intensive equipment. Part of these inventories exist of spare parts that are considered repairable. This means for these parts in case of breakdown repair instead of disposal is preferable. Because the broken part has to be replaced, in case of disposal a new part has to be purchased. Repair is therefore preferred when it is technologically possible and economically profitable, or when it is technologically obligated. From now on we will call these parts repairable spare parts.

Although simple repairs can be conducted on board of the WSs, in general broken repairable spare parts are replaced by a working equivalent and repaired. This repair is either conducted in the DMI workshops, or by outsourcing the required repair actions to the industry (either OEMs or external repair shops). After repair has been conducted the parts become available for spare parts demand. This part of the RNLN maintenance process is called the refurbishment circuit.

1.1.3.2 Description of refurbishment circuit

An overview of complete RNLN refurbishment process is visible in Figure 29 in Appendix 9.7. Certain elements involving disposal and procurement are added to complete the circle. The process involves various elements that altogether influence the performance of the circuit. Some of these elements are out of scope for this research. In Figure 4 the elements of the refurbishment circuit that are part of the scope of this research are displayed. The refurbishment circuit as considered works as follows. During RNLN both corrective and preventive maintenance tasks the option for repair-by-replacement is usually used for repairable spare parts (Buiting, 2014). Failed parts are exchanged for working equivalents in order to maintain the availability of the RNLN WSs (weaponry systems). The WSs are then obliged to hand-in the failed parts to the DMI (directorate material sustainment). The failed items first obtain an ATH status (offered for repair) after which they are assessed for their actual reparability based on technological analysis. Here we assume this assessment outcome to be positive, which means the parts obtain an NGVU status (not ready for release). Either external or internal repair is preferred for parts, based on availability of resources to conduct the repair internally. Based on the WSs demand repair orders are issued by ASM (inventory management). IHOs (internal repair orders) are addressed by DMI workshops. External repair orders are addressed by the industry, either in OEM workshops or external workshops. After the parts are refurbished (repaired to a working status) the parts obtain a GVU status (ready to release), thus making these parts available for (future) repair-by-replacement actions.

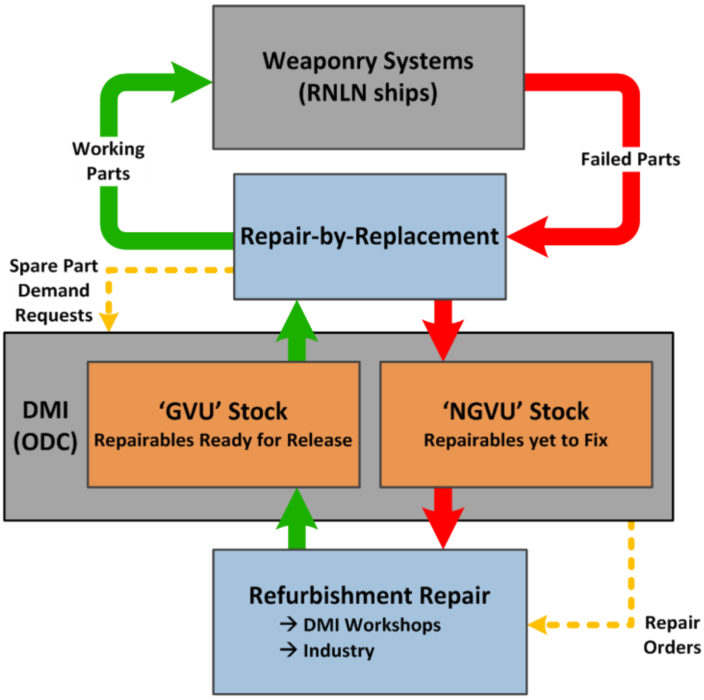

FIGURE 4: RNLN REFURBISHMENT MAINTENANCE PROCESSES

1.1.3.3 *Material - and information flows*

Several important material flows and information flows are involved in the refurbishment circuit. These flows are visualized in Figure 5. The component demands of the WSs are issued by the DOPS (directorate operations) to the DMI. Failed parts are replaced by working equivalents. These failed parts are then either repaired by external repair, expressed by 'the Industry', or by internal repair, expressed by the DMI workshops. New parts can be purchased when the available circulation stock of a certain repairable spare part type is not sufficient. Information flows accompany the part flows.

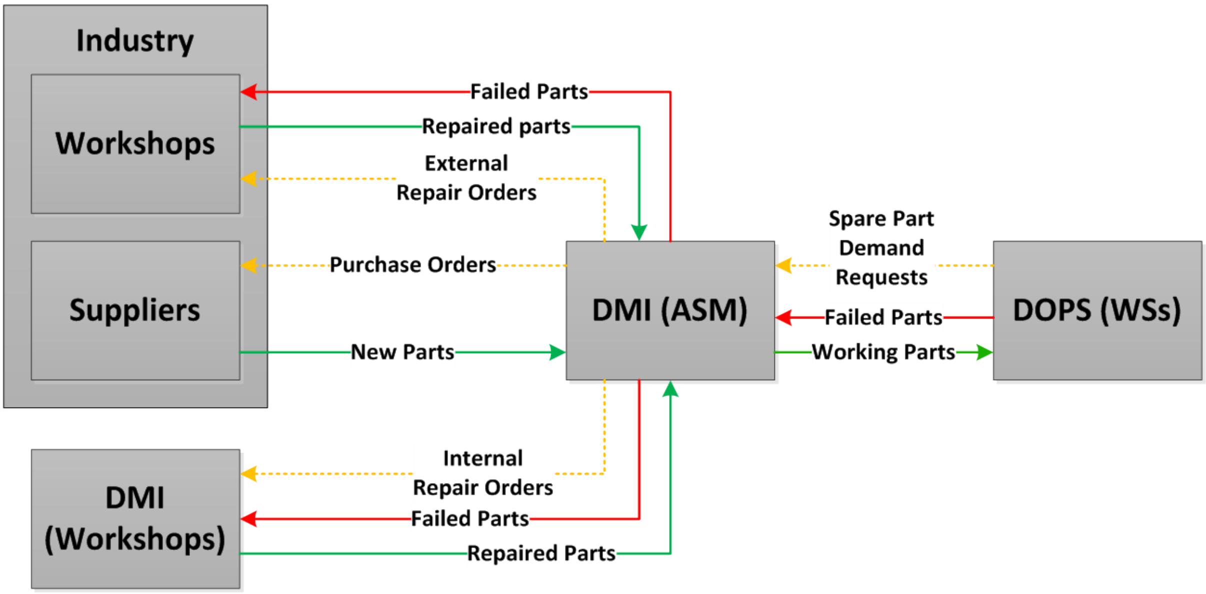

FIGURE 5: PARTS AND INFORMATION FLOWS REPAIR-BY-REPLACEMENT

1.2 Relevant Challenges

The cause for this research comes from several issues regarding the performance of the refurbishment circuit. Service levels agreements are determined for the replenishment of spare parts as a whole, so for the average service levels for repairable and consumable spare parts combined. This comes forth from the situation where the maintenance was conducted by a separate organization, the predecessor of the DMI. The service levels for the repairable spare parts are low in particular, on average only a service level of 52.56% for the previous two years. Furthermore, the value of the NGVU (not ready for release) inventory is high and parts are often slow-moving or even non-moving. The NGVU part of the inventory consists of all repairable spare parts that have failed, and have not been restored to their original state in order to (re-)obtain a GVU (ready for release) status. This means that required repairable spare parts are often not available in the GVU stock when demand for these parts occurs, because these parts are still in the NGVU inventory. To make matters worse, these repairable spare parts are in general of a more complex nature than consumable spare parts, and very important for the material availability of the RNLN WSs. Therefore unfulfilled demand for repairable spare can lead to WS unavailability for the period it takes to conduct the required (emergency) repairs to the required parts. Therefore the WS availability gets hampered by the low service levels for repairable spare parts.

The environment of the refurbishment circuit is challenging for various reasons (Buiting, 2014). The internal repair orders that are issued by the ASM (inventory management) division of the DMI all have to be executed by the DMI workshops. These workshops only have a limited resource capacity, both regarding the personnel availability and installations used for the repairs. The capacity is limited due to budget constraints, and the complexity of the resources required. This complexity regards both the personnel and its knowledge, and the repair installations. This limited capacity is shared for the various types of repair the DMI conducts, not just for the refurbishment repair. The allocation of the available capacity to the repair types is a complicated problem, since relations such as the one between allocating more capacity to preventive repairs and the reduced capacity required for corrective repairs are hard to evaluate. We will not investigate this allocation challenge, but it results in a situation where the internal refurbishment repair capacity can be oppressed by corrective repair activities or by appointed maintenance activities taking more time than expected.

The complicated repairable spare part characteristics also make the refurbishment challenging. First of all, there is a broad range of these parts. The complex nature of the repairable spare parts portfolio is caused by the composition of the WS fleet. The low numbers of the various WS types and the complexity of the equipment and its systems cause the broad portfolio of spare parts. As much as 28,222 different repairable spare part types are in use at the RNLN. These parts highly vary in regard to their value, their demand characteristics, and their criticality for the material WS availability. Parts can even have a multi-indenture structure, meaning that they have sub-parts.

These varying repairable spare parts characteristics result in complex repair management for the RNLN. Many parts have to be repaired with specific resources in a specific workshop. The lead times are long in general and can vary for similar parts. For the repair of multi-indenture items the right sub-parts have to be available, which in their turn are either consumable or repairable themselves, which means it is hard to schedule. A fraction of the parts have to be repaired externally, another fraction has to be repaired internally, and finally for a fraction both options can be used.

In conclusion, the combination of the broad repairable spare parts portfolio with highly varying characteristics and the limited capacity of the workshops available leads to a challenging situation. Therefore the repairable spare parts management of the RNLN is of a complex nature. However, the performance of this management is important for the WS availability. Having the required repairable spare parts available in order to meet the WS part demand is the main goal of this spare parts management. Both the inventory management and the repair planning of these parts are important elements for a well-performing repairable spare parts management at the RNLN.

1.3 Report Lay-Out

The outline of the report consists of several important parts (Figure 6). The research has been introduced in this section. In Section 2 more insight will be provided in the research approach to address the challenges introduced. The link to the scientific literature available will be explained, as well as the contribution of this research to it. In Section 3 the performance of the current repairable spare parts management at the RNLN is analyzed and problems are identified. Based on this analysis, Section 3.4 contains the suggested improvement methodology in order to improve the performance of the refurbishment circuit. Both the current management and the proposed improved management are then modelled in order to perform simulations to prove and quantify the potential performance gains. Section 5.5 contains the results of these simulations, as well as insight in the outcomes. Section 6 explains how the proposed repairable spare parts management methodology can be introduced at the RNLN. This leads to conclusions, and to recommendations for the RNLN, in Section 6. That section also describes the research limitations. Finally, appendices to support the research can be found in Section 9. Throughout the research references to these supportive appendices are used.

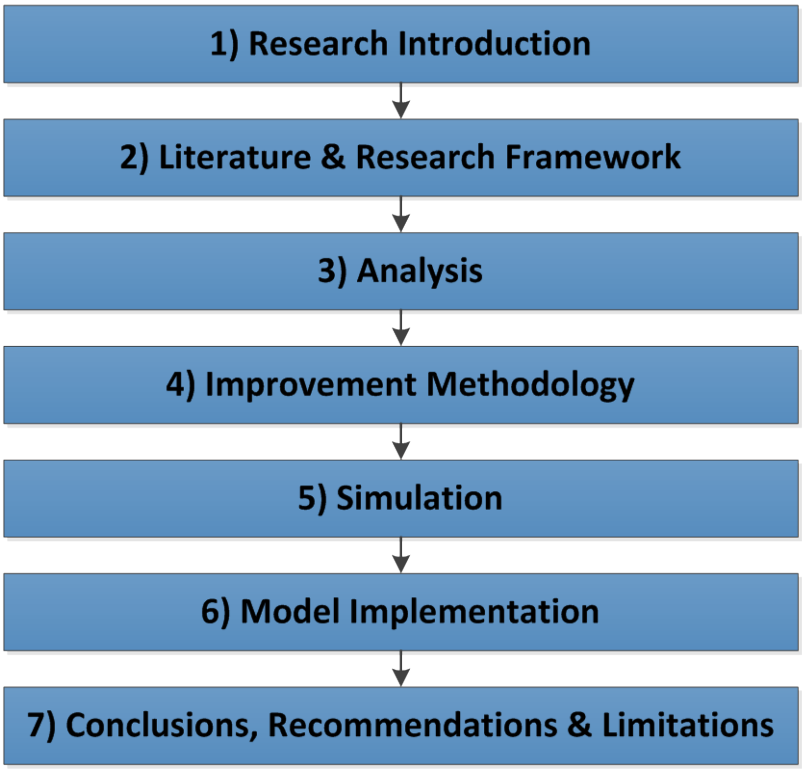

FIGURE 6: REPORT LAY-OUT

2 Literature and Research Framework

Section Abstract

This section clarifies the design and the methodology used for this research. The purpose of this particular design is to provide a generally applicable improvement design for the refurbishment circuit of the RNLN. This improvement is achieved by designing the system such that all aspects are in line with striving for improvement of the same central KPI.

In Section 2.2 the scope of this research is defined. This section aims to clarify the position of our research within the larger picture of the maintenance process at the RNLN. Within this scope we provide a problem statement in Section 2.2. The central research question is introduced and elaborated. Finally, Section 2.4 presents the research design used in this thesis of which the contribution to scientific research is proposed in Section 2.5.

2.1 Relevant Literature Insights

Spare parts inventories represent an important part of the assets of organizations with capital intensive equipment, such as the RNLN. Part of these inventories exist of spare parts that are considered repairable. This means for these parts in case of breakdown repair instead of disposal is preferable. Therefore the repair has to be technically possible and economically profitable. From now on we will call these parts repairable spare parts. We consider other spare parts to be consumable spare parts, which means repair is either technically not possible or economically not profitable. Even though repairables usually take up a smaller portion of the number of items in inventories, we should keep in mind that repairable spare parts are generally more expensive, which means that their share in the total service department is just as relevant compared to consumables (Sleptchenko, van der Heijden, & van Harten, 2002). Repairables are of particular importance for companies that are characterized by heavily utilized and relatively expensive equipment (Díaz & Fu, 2005). Repairable inventory systems are common in the military and typically composed of high cost, long-life goods that are less expensive to repair than to replace (Guide & Srivastava, 1997).

Important is that we consider the refurbishment circuit to be similar to a production environment in regard to literature, since the two are very similar.

"Repair shop environments are characterized by a greater degree of uncertainty than traditional job or assembly shop environments, and this introduces unique managerial complications" (Guide, Srivastava, & Kraus, Priority scheduling policies for repair shops, 2000). They are considerably more complicated because of a number of decisions to consider, even for a single-echelon inventory system (Guide & Srivastava, 1997). Often occurring problems and decisions to make:

1) Demand for units not balanced with returns of repairable units
2) Procurement policies of replacement units; condemnation and recoverability rates
3) The review choice of the inventory status
4) Choice of repair returns and choice of repair policies

"The repairable inventory problem is typically concerned with the optimal stocking of parts at bases (or forward locations) and at a central depot facility which repairs failed units returned from the bases while providing some predetermined level of service" (Guide & Srivastava, 1997). The objective usually is to maximize the availability of the respective equipment.

The performance of a repairable inventory system is a function of three major factors (Hausman & Scudder, 1982): 1) the target spares inventory level for the repairables, 2) the capacity to actually repair the repairables, and 3) the scheduling system used to control the flow of work in the repair shop.

These repairables have been researched extensively. The trade-off between the availability of these parts on the one hand and the inventory costs on the other hand is quite familiar within inventory management. Downtime of critical equipment can seriously influence the military efficiency (Sleptchenko, van der Heijden, & van Harten, 2002). Specifically for the repairables, which are usually low-demand high-value, usually goes that a proper optimization of this trade-off is important. This is due to the relatively large impact on the system availability on the one hand and the relatively high value of the parts and thus high inventory costs on the other hand. “To insure continuity of operations, an ample supply of spare parts must be maintained; however, this must be traded off with the cost of tying up capital in non-revenue-generating spare parts inventories” (Díaz & Fu, 2005).

When managing such systems three levels are conducted; strategic, tactical, and operational (Caggiano, Muckstadt, & Rappold, 2006). Strategic management regards supply chain design issues concerning the repair functions and facilities, tactical management focusses on enhancing policies and parameters within the supply chain design, and finally operational management regards day-to-day decision making based on the actual state of the system.

Cavailieri, Garetti, Macchi and Pinto (2008) provide a decision-making framework for managing maintenance spare parts. A stepwise decision-making path is provided using five sequential steps, with the goal to pragmatically handle the management of maintenance spare parts in a company. The path consists of part coding, part classification, part demand forecasting, stock management policy and policy test and validation. The main finding here is that it is important to have an integrated approach for the spare parts management taking the complete picture into account.

The idea of an integrated approach is further supported in other literature. It is arguably one of the main aspects affecting the overall effectiveness of spare parts management (Bacchetti & Saccani, 2012). A general view on what an integrated approach should look like is provided in Figure 7. This integrated perspective stresses the relation between the various steps of spare parts management, in order to come up with a centrally managed system, leading to better performances accordingly. The elements of spare parts classification and inventory management will be further discussed.

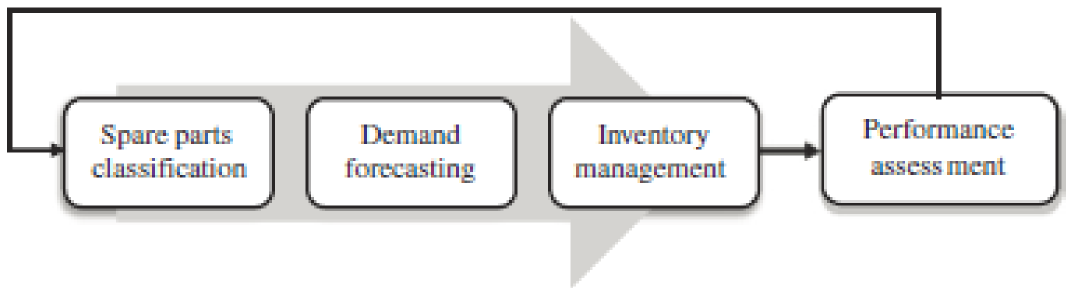

FIGURE 7: A VIEW ON AN INTEGRATED SPARE PARTS MANAGEMENT APPROACH (BACCHETTI & SACCANI, 2012)

2.1.1 Classification of repairable spare parts

In general, spare parts can be classified in three categories, according to Cavalieri et al. (2008):

1) Generic spare parts; items widely available and relevant for several equipment types
2) Specific spare parts; specific for certain equipment and/or available from a specific supplier
3) Strategic spare parts; specific spare parts with a wear-out time that is not foreseeable, and with high supply time, high costs and sporadic demand

Consumables are often of a generic nature, repairables are often of a specific or a strategic one. This empirical classification is rough and serves as a basis for subsequent classification steps.

The value of a proper and unambiguous way of classifying spare parts is explained by their highly varied nature regarding costs, service requirements and demand patterns (Bacchetti & Saccani, 2012). These characteristics are all definitely true for repairable spare parts specifically too. A proper classification of spare parts is very important for the implications to the complete aspect of spare parts management.

The issue of classification of spare parts has not received as much academic attention as would seem necessary given the implications on the spare parts management (Bacchetti & Saccani, 2012). Throughout literature concerning spare parts management various categorization criteria are used. "A classification for spare parts […] is helpful to determine service requirements for different spare parts classes, and for forecasting and stock control decisions" (Bacchetti & Saccani, 2012).

"The top three challenges are: the lack of a system or holistic perspective, the inaccuracy of service part forecast, and the lack of system integration among the supply chain parties" (Bacchetti & Saccani, 2012). They provide an overview of spare parts classification criteria suggested throughout literature and the following criteria came up; 1) part cost / value, 2) part criticality, 3) supply characteristics / uncertainty, 4) demand volume / value, 5) demand variability, and 6) others (life cycle phase, specificity, and reliability).

Furthermore, the paper looks into the classification techniques used to classify spare parts.Both quantitative methods and qualitative methods are available, and both have their benefits. Most quantitative methods are based on traditional Pareto approaches such as ABC analysis (Cavalieri, Garetti, Macchi, & Pinto, 2008). Within these approaches one to several classification drivers can be used. The combination of these drivers enables the identification of the level of spare parts criticality, based on their contribution to the annual maintenance budget or the amount of attention they require due to the downtime they cause. The FSN method is based on the moving rates of the spare parts, making it possible to identify obsolete spare parts for instance.

The qualitative methods are based more on consultation with maintenance experts. Specific characteristics regarding the usage and management of the spare parts are taken into account in VED analysis methods. However, this type of analysis might be a hard task to perform despite its apparent simplicity. Especially in the case of very large numbers of spare parts to be considered. Next to that, the task may suffer from the subjective judgments of users (Bacchetti & Saccani, 2012).

Options are to be to use technical variables such as the MTTF (mean time to failure) and the MDT (mean down time) in order to determine the parts requiring more attention, due to more frequent failures, long lasting stoppages, or both (Cavalieri, Garetti, Macchi, & Pinto, 2008). Another option is to focus on the contribution to the annual maintenance budget, by taking the annual demand and the annual purchasing costs into account. Another option is to focus on the moving rates of the spare parts. This is a useful classification in case evidence is required that parts have become obsolete (Cavalieri, Garetti, Macchi, & Pinto, 2008).

2.1.2 Repairable spare parts inventory management

"Inventory systems where units which fail are repaired at the depot, rather than disposed after use, are called repairable-item inventory systems" (Perlman, Mehrez, & Kaspi, 2001). A wide use of these inventory systems occurs in the military sector. The main problem for these systems is one of design, in regard to for instance "an optimal spares stocking policy, allocation of these spares to various locations, determination of maintenance policy, the distribution policy, etc." (Perlman, Mehrez, & Kaspi, 2001).

We have to consider the fact that the RNLN inventory system can best be assumed to be a two-echelon model. Such a two-echelon inventory model would consist of the first echelon being the bases and the second echelon being the depot (Perlman, Mehrez, & Kaspi, 2001). In our situation the WSs would serve as the first echelon and the DMI would serve as the second echelon. The benefit of this system is the fact that this structure allows for fast supply for certain parts because of the local stock, but it also allows for stock centralization to reduce holding costs (Sleptchenko, van der Heijden, & van Harten, 2002). We do only consider the second echelon to have repair capacity, since the parts considered are all parts that are not repairable at the WSs but only at the DMI (Section 2.2). "When a failure occurs, the defective part is removed, exchanged for a fresh part taken from the base stock (if such a part is available) and sent to a repair facility known as the depot, where it is repaired and held in stock, to be eventually sent down to the bases to cover another part used in repair" (Díaz & Fu, 2005).

In case of constant failure the Poisson distribution is suitable for determining stock sizes of spare parts (Cavalieri, Garetti, Macchi, & Pinto, 2008), because the demand rate in each time unit (regularly a month at the RNLN) is relatively low. Using this distribution a stock size S can be calculated for all spare part kinds based on the target level of fill rate.

Spare parts classification in combination with spare parts forecasting should be linked to stock control policies (Bacchetti & Saccani, 2012). Various papers throughout spare parts management were reviewed by Bacchetti & Saccani (2012). Next to classification possibilities the authors also looked into inventory policies used and suggested. Most papers suggested simple and well-established inventory policies, mainly continuous review policies. Both the (Q,r) policy with fixed re-order point (r) and fixed order quantity (Q), and the (s,S) policy with fixed re-order policy (s) and order-up-to level (S) were used. The latter is considered to be the best-suited technique for low and intermittent demand items. "Only few companies […] use complex and specific inventory models in practice, primarily due to the mathematical complexity that characterizes their resolution" (Bacchetti & Saccani, 2012). For the parts having smooth / erratic demand it makes sense to stick to the (s,Q) policy (van Duren, 2011). For the parts having intermittent / lumpy demand it makes sense though, to use an adjusted inventory policy to cope with these characteristics. Since the RNLN has many repairables that have this type of demand behavior the implementation of such a policy might have interesting consequences.

Dhakar, Schmidt and Miller (1994) use a base stock level determination for high cost low demand critical repairable spare parts using an (S- 1, S) policy with different modes of replenishment: normal repair orders, emergency repair orders, and the expediting of outstanding orders. A simulation is used to determine the important threshold levels: the base stock level S, the emergency level, and the expediting threshold T. This way the inventory policy has become dynamically. Even when orders are already outstanding, there status can be altered. This is a very important concept since a repairable spare parts environment is usually very dynamic. This dynamic aspect is directly related to the work shop dispatching of repair orders, "a responsive scheduling system should reduce repair times for those components which are currently in short supply while allowing less-critical components to be repaired more slowly. Priorities will change over time as different parts become critical" (Hausman & Scudder, 1982).

2.1.3 Work shop dispatching of repair orders

When it comes to work shop scheduling and sequencing in queues, there are three different solution directions mainly guided by the main performance goal of the sequencing on hand (Hopp & Spearmann, 2008). These solution directions are not conflicting and often go hand in hand, but the choice for a performance goal influences the scheduling policy. Options of goals are meeting due dates (for instance by minimizing backorders, e.g. Guide & Srivastava (1997) and Hausman & Scudder (1982)), by maximizing utilization, and by minimizing queuing parameters (e.g. flow times or WIP, for instance Guide et al. (2000)). In the first research direction, it is common to maintain an inventory of spares, such as the RNLN does. Therefore this solution direction appears to be most relevant for further research.

Within a production environment focusing on meeting due dates we can consider two types; the make-to-order environment and the make-to-stock environment (Hopp & Spearmann, 2008). The RNLN refurbishment circuit is a combination of these two environments, since some repairables are made-to-stock in order to make sure they are available on time when demand occurs, and other repairables are made-to-order, these are only ordered in case of a demand. This depends on the demand characteristics of the particular repairable.

Dispatching is the traditional alternative to scheduling. The jobs are then sorted according to a specified order as they arrive at the 'servers'. For dispatching several well-known options are available (Hopp & Spearmann, 2008); FCFS (first-come, first-served), LCFS (last-come, last-served), EDD (earliest due date), SPT (shortest process time), or based on priority schemes. The latter seems most appropriate for the RNLN, since the variability in the characteristics of the spare part demand requests arriving. Dispatching rules are myopic by default, which means they consider only local and current conditions. Therefore they do not work well all the time. Dispatching is still useful in the industry because options for scheduling realistic systems are still very limited, these problems can often be NP-hard (Hopp & Spearmann, 2008).

An overview of possible dispatching rules is provided by Hausman & Scudder (1982) and Browning & Yassine (2010). These rules are divided into three categories; 1) static priority rules, 2) dynamic rules, and 3) current shop status rules. The first category gives jobs the same priority regardless of its progress through the shop and the dynamic behavior of inventories, the second takes the jobs progress into account, the third also includes the current inventory status. However, almost all of the optional available rules do not consider the 'importance' of the components to be repaired.

Because we are considering a situation with a hierarchical product structure, we need priority scheduling rules that take this into account. Priority scheduling rules offer either better performance for a given inventory investment in spares inventory, or comparable performance with lower inventory levels and investment (Hausman & Scudder, 1982). The prioritization rules for the repairables influence the work shop scheduling. Efficiency gain is possible using repair priorities (Sleptchenko, Van der Heijden, & Van Harten, 2005). If a repair shop handles varied items with a limited capacity available, the throughput for important items can be reduced by giving corresponding repair jobs a high priority. As a consequence, the low priority items will face a longer lead time. The relevant availability can therefore be increased when adequate priority rules are introduced for the repair.

It is important to realize that the actual scheduling for work shop jobs is on an operational management level, often with an inaccuracy of demand forecasts and a lack of capacity and coordination for the repair systems. An important topic is how to "operate the system today given the inventory, repair capacity and information that is currently available?" (Caggiano, Muckstadt, & Rappold, 2006). Important is the optimal reaction to the current situation, with the resources and information available, and the maintenance design as defined on strategic and tactical level.

2.1.4 Preceding research within organization

The problems experienced in the refurbishment circuit have been there for a while, according to the interviewed personnel. Therefore, earlier conducted researches have been trying to address these problems for quite some time already. However, according to the interviewed personnel the findings and recommendations of these studies have not lead to a significant improvement of the situation. The lack of improvement implementations of these preceding researches do indicate the complexity.

2.2 Problem Statement

Basically the goal of this research is to design a strong conceptual model for the control of the repairable spare parts management at the RNLN. Parts of this conceptual model have to be supported by empirical analyses. This conceptual model combines both aspects of a tactical level and an operational level (Section 2.1). The link between the tactical aspect of enhancing maintenance management policies and parameters, and the influence and consequences for the execution of the operational management is central in this research. By focusing on integrating these two parts for the RNLN refurbishment circuit we aim to improve its performance.

The research goal of increasing the availability of the repairable spare parts has one main constraint, the budget is fixed and therefore the limited amount of available repair capacity is too. The main research problem statement is thus defined by the following research question:

How to improve the <u>repairable spare parts management methodology</u> at the RNLN to increase its <u>relevant performance</u>, taking the <u>limited resource capacity</u> into account?

This problem will be addressed in several steps before we can finally conclude on it in Section 6. The steps are defined by the following research sub questions:

1) What is the status of the current RNLN repairable spare parts management?
    a. What repairable spare parts management methodology is currently used?
    b. In what relevant performance does this current methodology result?
2) How can the RNLN repairable spare parts management methodology best be improved?
    a. What classification methodology to define, suitable for further elements?
    b. What inventory management policies to use for the defined classes?
    c. What dynamic repair dispatching rules to use for the resource allocation?
3) What is the improvement potential of the proposed methodology for the RNLN?
    a. What improvement potential does a simulation model show?
    b. How to implement the proposed methodology?
    c. What conclusions can be drawn from the improvement potential?

2.3 Scope and Assumptions

The definition of the scope is an important step for the research. As explained in Section 1.1, the focus of this research lies on the refurbishment circuit for the repairable spare parts. The position of this process within the complete RNLN maintenance process architecture is visible in Appendix 9.6 Figure 28 (Buiting, 2014). The refurbishment process is an important part of the BEVO (replenishment) process. This process can be considered to start when an ATH (request for repair) is placed by a material planner for a part with the status NGVU (not ready to release). The process ends end when the ATH is fulfilled and the part receives the status GVU (ready to release). That process has the goal to provide all required goods for the complete RNLN in time. This regards a wide range of goods, varying from materials required for maintenance and modifications, to supplies required during the operations. Within this thesis we will focus on the goods required for the maintenance of the WSs only. This regards both the IO (corrective maintenance) and BO (appointed maintenance) activities. As explained, among these parts the repairables obtain our main focus.

We specifically address the parts that are repairable internally at the DMI workshops. This means the broken parts that are returned from the WSs after repair-by-replacement has been conducted. Working parts are obtained from the GVU stock. These broken parts have to be repaired in the refurbishment circuit. For some aspects externally repaired parts are discussed, for completeness.

The RNLN has a wide spectrum of repairables used at the various WSs throughout the fleet. In the two-echelon structure relevant for the RNLN, both repair at the bases and repair at the depot are taking place. However, the only repair actions at the bases are relatively small. As described in the literature, in general items are sent to the higher echelon if the local repair shops do not have the required resources to fulfill the repair (Sleptchenko, Van der Heijden, & Van Harten, 2005). The decision where the repair is going to take place is not based on the current workload at the repair shops, but at the technical considerations named. We are only considering the base-repairs.

Finally, many repairables we are considering are usually of a multi-indenture structure. We will assume that spare part demand requests have been subject of a LORA to determine the appropriate level of repair. This means that we can consider a repair order to concern the highest only one of the items of which it consists.

2.4 Research Design

We will introduce an integrated repairable spare parts management approach, combining several important spare parts management elements into one framework, visible in Figure 8. Based on the classification and the actual inventory position in regard to the chosen inventory policy a dynamic priority rule can be determined for the refurbishment repair jobs.

Based on the main research questions to answer during this research the problem aspects and their relations are designed as in Figure 8. In addition we also need to take into account the more organizational researches and findings obtained earlier. This is assumed to provide more insight in the organizational environment in which this conceptual model is based.

The important thing about the framework is the fact that there are three important elements that are all integrated, the classification of repairable spare parts, their inventory management, and finally the dispatching of the repair jobs to the workshops. This integrated management is especially distinguishing itself in the feedback loops between the three elements named. This allows for a dynamic management of a situation that is in fact dynamic, leading to better performances.

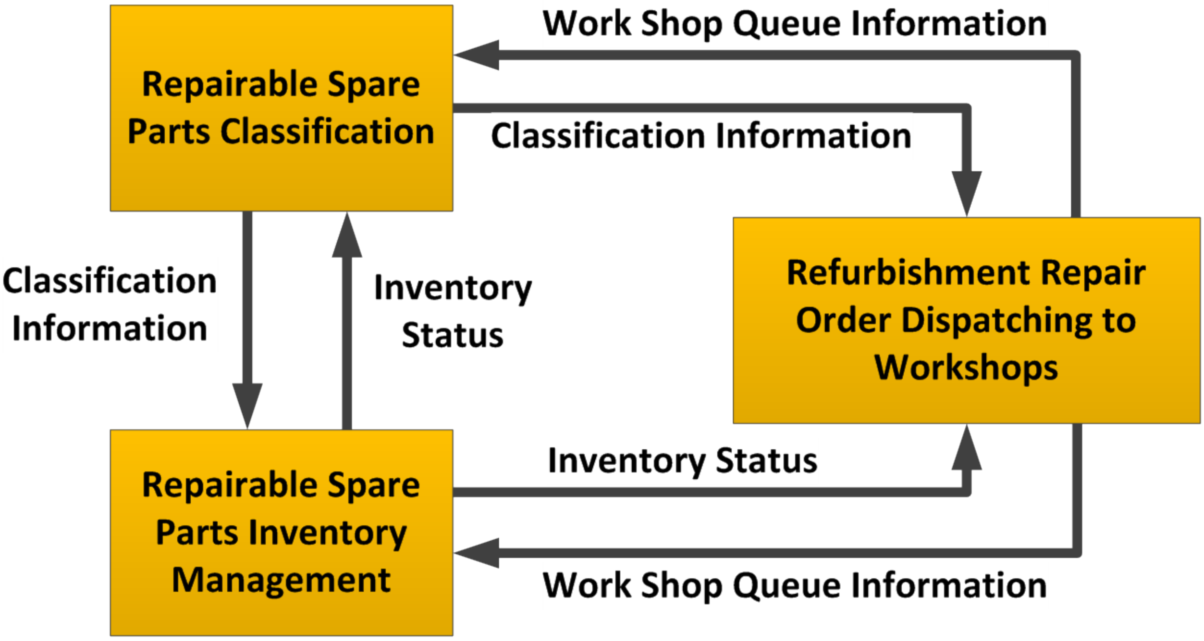

FIGURE 8: PROPOSED INTEGRATED REPAIRABLES INVENTORY MANAGEMENT FRAMEWORK

2.5 Proposed Research Contribution

Because of the high importance a well-based repairable spare parts management has for the performance of capital-intensive organizations such as the RNLN, the potential benefits of improved repairable spare parts management are very interesting. This is confirmed by scientific research, and therefore a lot of research has been performed regarding this topic.

As explained, this research combines several important elements of repairable spare parts management into one integrated approach. These elements separately have all been studied intensively, examples are provided in Section 2.1 but many similar researches exist. Approaching the elements separately allows for a very extensive analysis. Many valuable insights in the separate elements of a repairable spare parts management methodology have been obtained this way.

In reality, these elements are not isolated and therefore a more integrated approach seems to have a lot of potential. This allows for a more complete assessment of the situation, and for a study of the integration and interaction between the separate elements. This potential is underlined by the researches of Cavailieri, Garetti, Macchi and Pinto (2008), and (Bacchetti & Saccani, 2012). The idea of an integrated approach is arguably one of the main aspects affecting the overall effectiveness of spare parts management, according to these authors. These studies suggest frameworks, but they seem to be short of an extensive application of such an integrated framework.

The contribution of this research therefore consists of two important aspects. First, the definition of an integrated repairable spare parts management approach, dynamically combining a classification of repairable spare parts, their inventory management, and the dispatching of the repair orders to workshops. Especially the integration of the dynamic dispatching rules for the workshops to deal with a limited resource capacity is a potential contribution to scientific research. Second, the actual application of such an integrated framework at a capital-intensive organization representative for the field of research. These two important contributions are provided by this research.

3 Analysis

Section Abstract

This section analyzes the current performance of the refurbishment circuit. This is done by investigating the current methodologies for all elements part of the proposed integrated framework. The current refurbishment circuit performance is then analyzed. The emphasis of this analysis is on the 'relevant performance' of the circuit, which is assessed for the current repairable spare parts management methodology. Based on this analysis, the weak points of the current methodology are identified to serve as a basis for improvement suggestions.

3.1 Section Introduction

As stated in the problem statement, the performance of the RNLN refurbishment circuit is not satisfying (Section 2.2). This is expressed by the low service levels for the requested repairable spare parts (Section 3.3.1), especially for the relevant parts. The relevance of a repairable spare part is related to its influence on the material availability of the RNLN WSs (weaponry systems) (Section 4.2). The actual performance is analyzed to provide support for this problem statement. This section analyses the current repairable spare parts management methodology used at the RNLN and analyzes its influence on the performance. The weaknesses in the current methodology are identified, and serve as a foundation for the proposed improvement methodology (Section 4).

3.2 Current Repairable Spare Parts Management Methodology

The current repairable spare parts management methodology is assessed using the elements of the integrated framework from the project design (Figure 8) as a guideline. This means the current classification methodology, the current inventory management, and the current work shop dispatching methodologies are analyzed in the following sections.

3.2.1 Current classification methodology

The RNLN currently classifies its complete spare parts portfolio (both repairable and consumable spare parts) using a similar method. The classification methodology uses a combination of the value and the demand frequency of parts to group them. The overall ASM (inventory management) performance is measured by the average service level for the complete portfolio of parts. Each class has a target service level which is set in advance. To achieve the overall performance target, this target is set at a high service level for the faster-moving and lower-priced parts, while a lower service level is accepted for the slower-moving and higher-valued parts. This classification framework is visible in Figure 9. Several management characteristics applied to these classes in general are mentioned in the figure provide insight in the management methods used.

By achieving a high service level for the faster-moving low-valued parts, the overall performance improves but this provides a flawed representation of reality. The performance improves in terms of the overall service level, but these lower-valued parts are not necessarily the parts that are actually important for the availability of the RNLN WSs. Therefore a good score on this performance indicator does not necessarily lead to a performance that is actually good for the RNLN, especially in regard to the repairable spare parts. The highly specialized parts that are crucial for the operational logistic availability of the WSs are regularly higher-valued slower-moving parts. A relatively high fraction of the parts in this category is considered repairable. This means that by using the current classification method these parts are off worse. The current classification methodology thus leads to a unsatisfying performance for the repairable spare parts by default. As a result, this methodology is not applied to all repairable spare parts by the ASM material planners. However, this deviation from the general methodology is not done in an unambiguous way but for instance according to personal experience of the material planners. Therefore we conclude there is room for improvement on the aspect of repairable spare parts classification. We need a classification method that is better suited to really provide a foundation for the elements of inventory management and repair order dispatching.

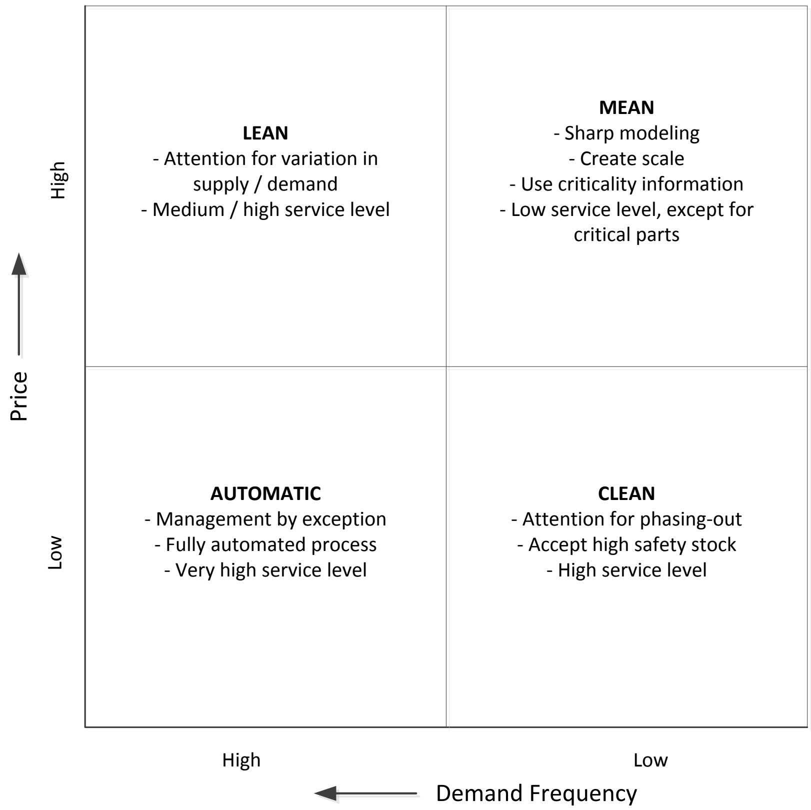

FIGURE 9: CURRENT RNLN SPARE PARTS CATEGORIZATION METHODOLOGY (GORDIAN LOGISTICS)

3.2.2 Current inventory management methodology

The RNLN currently uses an (s, S) policy for the inventory management of their complete spare parts portfolio, including the repairable spare parts. A standard calculation method is used by the DMI material planners, we will explain this method for the repairable spare parts.

The reorder level $s_{k,n}$ for part type n repaired at workshop k is determined as follows:

$$s_{k,n} = Expected\ Usage\ n_k\ during\ Repair\ Lead\ Time + Safety\ Stock\ n_k$$
$$s_{k,n} = Demand\ Rate\ n_k * Average\ Demand\ Size\ n_k * Repair\ Lead\ Time\ n_k + Safety\ Stock\ n_k$$
$$s_{k,n} = \lambda_{k,n} * \mu_{k,n} * \theta_{k,n} + Safety\ Stock\ n_k$$

$$Safety\ Stock\ n_k = Safety\ Factor\ n_k * Standard\ Deviation\ Usage\ n_k\ during\ Repair\ Lead\ Time$$
$$Safety\ Stock\ n_k = x_{n,k} * \sigma_{\lambda_{k,n} * \mu_{k,n} * \theta_{k,n}}$$

This finally leads to (1 for determining the reorder levels for repairable spare parts:

$$\boldsymbol{s_{k,n} = \lambda_{k,n} * \mu_{k,n} * \theta_{k,n} + x_{n,k} * \sigma_{\lambda_{k,n} * \mu_{k,n} * \theta_{k,n}}} \quad \textbf{(1)}$$

The order-up-to level $S_{k,n}$ for part type n repaired at workshop k is determined as follows:

$S_{k,n} = s_{k,n} + Expected\ Usage\ n_k\ during\ RepairLead\ Time$

Therefore we have (2 for the order-up-to level $S_{k,n}$ of the repairables spare parts.

$$\boldsymbol{S_{k,n} = s_{k,n} + \lambda_{k,n} * \mu_{k,n} * \theta_{k,n}} \quad \textbf{(2)}$$

Finally the repair order size $Q_{k,n,\tau}$ for party type n repaired at workshop k at time is determined according to the real time inventory level $I_{k,n,\tau}$ at the moment of reordering τ, which is not always the same as the reorder level due to for instance limited repair capacity reasons, or because of material planners deciding to postpone the repair. This means we obtain (3.

$$\boldsymbol{Q_{k,n,\tau} = S_{k,n} - I_{k,n,\tau}} \quad \textbf{(3)}$$

One important aspect regarding this calculation method is that it uses a normality assumption type of calculation, since the safety factor (k-factor) is based on a standard normal distribution. This safety factor is set to 0.67 by default, which matches a 75% left-sided probability interval. Although this method could be well-suited for the more fast-moving parts which are more prone to behave according to a normal distribution regarding their demand, this assumption does not hold for the more slow-moving parts with their specific demand characteristics (Section 4.2.1.3). Therefore this method is another example of the current repairable spare parts management of the RNLN not being adapted to meet the specific characteristics of these parts.

This standard calculation method is integrated in the inventory management IT system, in order to inform ASM material planners when the reorder level is reached. There is a possibility for material planners to manually overrule the calculated values. The most important reason to do this is the fact that the repairable spare parts amount in the refurbishment circuit for a certain part type is already determined at the acquisition of new WSs and systems, which makes it close to impossible to decide about the order-up-to level. Furthermore, this can be done in a case where for a certain part type the standard inventory management policy results in a situation where the part is often unavailable when requested. Another reason to overrule these values is when the amount of parts to reorder is higher than the NGVU parts available for repair for the specific part type requested. In order to overrule the system, the material planners can then decide to insert their own calculated or even manually determined parameter values into the system. There is no ambiguous way of doing that though, often this is done in a reactive manner.

3.2.3 Current dispatching methodology

There are various relevant component- and information flows (Section 1.1.3.2, Figure 5) leading to the current dispatching methodology used within the DMI. After a component fails on a WS component demand arises. After this component demand has been fulfilled, the failed part will be returned to the DMI and will obtain the status ATH (offered for repair). If the part is accepted and suitable for repair, it will be stored in the NGVU stock of the ODC. An repair order will be ordered if the material planner requires the part for the BEVO (replenishment) of maintenance activities. This repair order can either be an IHO (internal repair order) or an external repair order. After repair these items are placed in the GVU stock of the ODC. It is important to realize that currently repair orders are mainly placed in reaction to demand occurring, instead of proactively to maintain a healthy inventory position for all components. This situation has been caused by the limited repair capacity available in the workshops, so that no time is spend on repairing items that are not demanded. This often results in requested parts not being available in the GVU stock (Section 2.2) so that incidental repair is required, often under time-pressure.

Currently, there is no official dispatching methodology for the refurbishment orders used but in general it comes closest to a FCFS policy with priority influences in case of Prio1 (highest priority) or Prio2 (one-but-highest priority) refurbishment orders.

The workshops are not unambiguous in sequencing the refurbishment orders. There is a set of guidelines though when it comes to assigning a sequence of processing the orders.

1) **High priority orders first**
    a. **High priority determined by the ASM material planners**
    b. **Determined by the mission status of the WS requesting the components**
2) **External orders are outsourced fast because of dependency on planning industry workshops**
3) **Remainder of sequence determined based on the requested due date**
4) **Long lead time items are sometimes processed first, especially when they are dependent on subcomponents (disposable or consumable) that have to be obtained from the industry**
5) **In certain specific occasions orders are batched whenever a specific resource is required**

These guidelines lead to a general approach of processing orders based on the requested due date, where the orders with the closest requested due date are processed first. Only the high priority (Prio1) orders are treated independently of that general rule, since these orders are always addressed with absolute precedence in relation to the other outstanding repair orders. The differences between the various types of repairables are not taken into account, except for the repair lead time in rare occasions. Because this is not done unambiguously for all articles and workshops we conclude there is no official rule for that though. The same goes for the batching of repair orders. A part of the repair orders is batched for technological reasons, for instance because a specific test installation is required to conclude the orders. However, for this batching no unambiguous guideline is available, furthermore it is not clear which orders are batched.

3.3 Current Refurbishment Circuit Performance

Using the proposed static classification framework as a foundation, we will assess the relevant performance of the refurbishment circuit for the period of March 22, 2012 until March 21, 2014. We have used the classification methodology that is explained further on in Section 4.2 to maintain the scientific structure of this research. However, the proposed classification methodology provides a useful foundation for analyzing the current relevant performance of the refurbishment circuit.

3.3.1 Service Levels Repairable Spare Parts

Table 2 shows the service levels (in red) that have been achieved during the last two years regarding the repairable spare parts for the ASM of the DMI. The service level is determined by considering the fraction of demand requests fulfilled on time, not taking into account the demand requests that are still pending, meaning the demanded due date has not come to pass yet. The overall service level is low (52.56%) which indicates that the refurbishment circuit is indeed not working well. The fractions of demand requests repaired externally and internally are almost equal. The service level for the externally repaired parts is lower (42.02%) than for the internally repaired parts (62.54%). Both of these service levels are quite low compared to the overall target service level (80%) set.

ALL REPAIRABLE SPARE PARTS		
PENDING	927	10.51%
ON TIME	4149	47.04%
NOT FULFILLED	708	8.03%
LATE	3037	34.43%
TOTAL	8821	52.56%

EXTERNALLY REPAIRED SPARE PARTS		
PENDING	407	9.59%
ON TIME	1613	37.99%
NOT FULFILLED	234	5.51%
LATE	1992	46.91%
TOTAL	4246	42.02%

INTERNALLY REPAIRED SPARE PARTS		
PENDING	520	11.37%
ON TIME	2536	55.43%
NOT FULFILLED	474	10.36%
LATE	1045	22.84%
TOTAL	4575	62.54%

TABLE 2: CURRENT SERVICE LEVELS REPAIRABLE SPARE PARTS

For further assessment of the relevant performance the service levels for the various repairable spare parts classes divided over external and internal repair are visible in **Error! Reference source not found.** and **Error! Reference source not found.**. It becomes clear that where it concerns the externally repaired spare parts, the service levels are very similar for the various classes, but all very low. This is an interesting fact, given that for the internally repaired spare parts, the service levels are varying much more. For the classes that were considered as critical (A and B) the service levels are notably lower than for the non-critical classes (C and D). This indicates that the relevant performance of the refurbishment circuit is actually lower than the overall performance. We would rather have a situation with higher service levels for the critical classes instead, since this would reduce the likelihood for unavailability of (a part of) the WS.

Furthermore, we notice there are no striking differences between the service levels for classes with a procurement lead time items classified as long (A and C) and the classes with short lead times (B and D). In the desired situation, service levels would be higher for the long lead time parts since in case of a backorder the period of unavailability of (a part of) the WS will then be reduced.

EXTERNALLY REPAIRED CLASS A PARTS		
PENDING	136	31.70%
ON TIME	109	25.41%
NOT FULFILLED	36	8.39%
LATE	148	34.50%
TOTAL	429	37.20%

EXTERNALLY REPAIRED CLASS B PARTS		
PENDING	232	14.64%
ON TIME	547	34.51%
NOT FULFILLED	146	9.21%
LATE	660	41.64%
TOTAL	1585	40.43%

EXTERNALLY REPAIRED CLASS C PARTS		
PENDING	18	3.26%
ON TIME	218	39.49%
NOT FULFILLED	16	2.90%
LATE	300	54.35%
TOTAL	552	40.82%

EXTERNALLY REPAIRED CLASS D PARTS		
PENDING	21	1.25%
ON TIME	739	43.99%
NOT FULFILLED	36	2.14%
LATE	884	52.62%
TOTAL	1680	44.54%

TABLE 3: SERVICE LEVELS EXTERNALLY REPAIRED SPARE PART CLASSES

INTERNALLY REPAIRED CLASS A PARTS			INTERNALLY REPAIRED CLASS B PARTS		
PENDING	266	23.67%	PENDING	224	13.92%
ON TIME	470	41.81%	ON TIME	770	47.86%
NOT FULFILLED	144	12.81%	NOT FULFILLED	257	15.97%
LATE	244	21.71%	LATE	358	22.25%
TOTAL	1124	54.78%	TOTAL	1609	55.60%

INTERNALLY REPAIRED CLASS C PARTS			INTERNALLY REPAIRED CLASS D PARTS		
PENDING	14	1.62%	PENDING	16	1.63%
ON TIME	627	72.74%	ON TIME	669	68.27%
NOT FULFILLED	23	2.67%	NOT FULFILLED	50	5.10%
LATE	198	22.97%	LATE	245	25.00%
TOTAL	862	73.94%	TOTAL	980	69.40%

TABLE 4: SERVICE LEVELS INTERNALLY REPAIRED SPARE PART CLASSES

The outcome of this analysis of the service levels for the repairable spare parts indicates that indeed the relevant refurbishment performance gets hampered by the current spare parts management method. Exactly the repairable spare parts that have the most important influence on the material availability of the WSs (the most important performance goal of the RNLN) are performing notably worse than the parts that are less relevant for this material availability. Furthermore, there are no differences between the classes with the long and short procurement lead times, meaning on average the duration of the unavailability periods could theoretically be reduced.

3.3.2 NGVU Inventory Sizes Repairable Spare Parts

Table 6**Error! Reference source not found.** provides an indication of the inventory characteristics for the RNLN repairable spare parts. As becomes clear here, the inventory for the non-critical parts (class B and C) is much higher than for critical parts (class A and B), both regarding the amount of parts in inventory and their total value. This is not surprising since the non-critical part classes are larger in size. The average value per part in inventory is higher for the critical parts though.

	# of parts		value	
	GVU	NGVU	GVU	NGVU
All Repairable Spare Parts	100.00%	100.00%	100.00%	100.00%
Class A Parts	1.20%	6.41%	7.42%	23.31%
Class B Parts	4.35%	12.59%	5.41%	21.31%
Class C Parts	21.33%	31.15%	44.91%	23.31%
Class D Parts	73.12%	49.86%	42.27%	32.07%

TABLE 5: DISTRIBUTION OF NUMBER OF PARTS AND VALUE OVER CLASSES

A more interesting difference between critical and non-critical parts can be found in the NGVU/GVU ratio. Where for the non-critical parts the main part of the inventory consists of GVU stock, for the critical items the main part of the inventory consists of NGVU stock. This is an important indication that the refurbishment circuit is underperforming. It also indicates the refurbishment circuit is congested and is not able to cope with the repairable spare parts demand.

The differences between long procurement lead time parts (class A and C) and the short procurement lead time parts (class B and D) are also small, whereas better inventory performance for the long lead time items would lead to a better performance of the refurbishment circuit since the average duration of reduced availability per unfulfilled part request of the WSs would be decreased.

	# of parts		value	
	GVU	NGVU	GVU	NGVU
All Repairable Spare Parts	78.79%	21.21%	55.83%	44.17%
Class A Parts	40.98%	59.02%	28.68%	71.32%
Class B Parts	56.22%	43.78%	24.29%	75.71%
Class C Parts	71.79%	28.21%	70.90%	29.10%
Class D Parts	84.49%	15.51%	62.49%	37.51%

TABLE 6: NGVU/GVU RATIO NUMBER OF PARTS AND VALUE FOR REPAIRABLE SPARE PARTS CLASSES

3.4 Conclusion

After conducting the analyses of both the current spare parts management and the performance of the refurbishment circuit as a result of that management we can conclude that our problem is relevant and indeed needs to be addressed. The parts that are actually relevant for the material availability of the RNLN WSs have low service levels compared to the average. Furthermore, the GVU stock sizes (ready for release) are low compared to the NGVU stock sizes (parts to repair) for these relevant repairable spare parts classes. This means there is need for a better-suited repairable spare parts management methodology that is capable of dealing with the dynamic aspects of the refurbishment circuit. This is required to improve the relevant performance of the ASM, as expressed by the availability of relevant spare parts.

An important outcome is that this is true for both the externally repaired parts and the internally repaired spare parts. This research mainly addresses the internally repaired spare parts because of data-availability and a lack of influence on the management of externally repaired spare parts in regard to the dispatching of repair orders. However, this is an important finding because these parts are really downgrading the performance of the refurbishment circuit as well.

The reasons for the unsatisfying performance can be found in the current repairable spare parts management, or better put, the lack of an actual repairable spare parts management at the RNLN. The repairable spare parts are generally managed according to methods not suited for such parts. In cases where material planners differ from these methods this is not done in an organization-wide unambiguous way. Therefore we can conclude that a more well-suited method is required for the repairable spare parts management of the RNLN.

4 Improved Repairable Spare Parts Management Methodology

Section Abstract

This section suggests an improved repairable spare parts management methodology based on the previous sections. First, a suitable method for classifying the repairable spare parts is determined. Then, an improved method for the determination of the stock sizes of repairable spare parts is suggested, based on that classification. Important is the decision to focus these policy on the availability of relevant parts, while taking the current inventory sizes as a given.

Finally, dispatching rules to use for processing refurbishment repair orders through the workshops are provided. The dispatching rules are based on the priority classification of repairable spare parts and the dynamic position in regard to the proposed inventory policies. The dispatching rules have the goal to fulfill the required high service levels for the most relevant parts is fulfilled, while still achieving a reasonable service level for the less important repairables. The most important restriction is the limited resource capacity available.

4.1 Section Introduction

This section suggests an improvement methodology for the RNLN repairable spare parts management. The improvement suggestions are based on the weak points in the current repairable spare parts management, as identified in Section 3. All elements of the integrated framework proposed in Section 2.4 are treated for improvement suggestions.

4.2 Repairable Spare Parts Classification

Using this relevance as a guideline, the DMI has the ability to improve its repairable spare parts management and thus the performance of the refurbishment circuit.

In order to be able to obtain a useful assessment of the performance for the refurbishment circuit, we have to come up with a suitable classification methodology. This methodology has to divide the repairable spare parts into groups based on their importance for the RNLN WS availability.

Currently there is no unambiguous way to express this concept of relevance of the parts (Section 3.2.1). Therefore relevant parts do not receive a special treatment compared to less relevant parts in an unambiguous way. Instead a target value for the overall service level of the parts delivered by the DMI is maintained. In order to achieve this target performance a classification methodology is used that focusses on relatively cheap and fast-moving parts. In general, this hampers the performance of the repairable spare parts that are in general relatively expensive and slow-moving (Section 1.1.3.1). The goal is to come up with a specific and relevant repairable spare parts classification. This classification will allow for a proper analysis of the current refurbishment circuit performance.

Various ways of classifying spare parts are available in the scientific literature. Important for these classifications are the selection criteria and the technique used for the classification within these criteria (Bacchetti & Saccani, 2012). Main suggestions for spare parts classification criteria are the part value, the part criticality, the part supply characteristics, the part demand volume, and the part demand variability. The techniques used for classification can either be quantitative or qualitative.

The RNLN has a wide portfolio of repairable spare parts (Section 1.1.3.1). This large portfolio has to be categorized into groups that are representative for the repairable spare part importance. The goal of this classification is to provide a ground for a relevant analysis of the ASM performance for the repairable spare parts. This allows for an assessment of the current service levels of the repairable spare parts that are actually important to have available when demanded. Furthermore, the classification has to serve as a suitable foundation for improving the repairable spare parts management methodology of the RNLN.

4.2.1 Review of potential classification criteria

We focus this review on the spare parts classification criteria suggested by the research of Bacchetti & Saccani (2012) (Section 2.1.1). These criteria are reviewed for the RNLN repairable spare parts, except for the criteria rated as 'others', since these criteria (life cycle phase, specificity, and reliability) are rarely suggested by scientific literature as useful for a classification, and because quantitative information regarding these criteria was not available for all parts considered.

For the analysis of all classification criteria it is important to note that only parts with an active status (ART-STATUS = 1) and with an refurbishment criterion (HERST-CRIT = H) are taken into account. Furthermore, articles without a recorded value (PRS-MAG = €0) are excluded from the analysis. Next to that, a set of capital replacement sets is removed (articles not listed for commercial reasons), since these sets are not comparable to components on lower levels due to parameters such as value and repair times. Most importantly though, they do have their own refurbishment design because of its repair duration. Finally, only a selection of ASM (inventory management) categories (Table 7) is used because of the different characteristics for excluded sets such as the one containing munition.

ASM Section	ASM Category	Description
SWS	B	Surface
SWS	C	C4i (a.o. communication, encryption)
SWS	Q	Submerged
SWS	Z	Ship Safety
MTP	E	Common Electronics
MTP	H	Common Engineering
MTP	S	Ship Engineering
MTP	W	Engineering/Electronics

TABLE 7: OVERVIEW OF ASM CATEGORIES USED FOR ANALYSIS

4.2.1.1 Spare part value

Since we are only considering the repairables, the differences between prices are large. Figure 10 provides insight in the differences in prices between spare parts. As becomes clear, the differences in the price of repairables are enormous. It is important to note however, that both complete systems and subcomponents are in this analysis, since it depends on an LORA (level of repair analysis) which part is sent down for repair. Usually this is not the complete system, but only a smaller component off it.

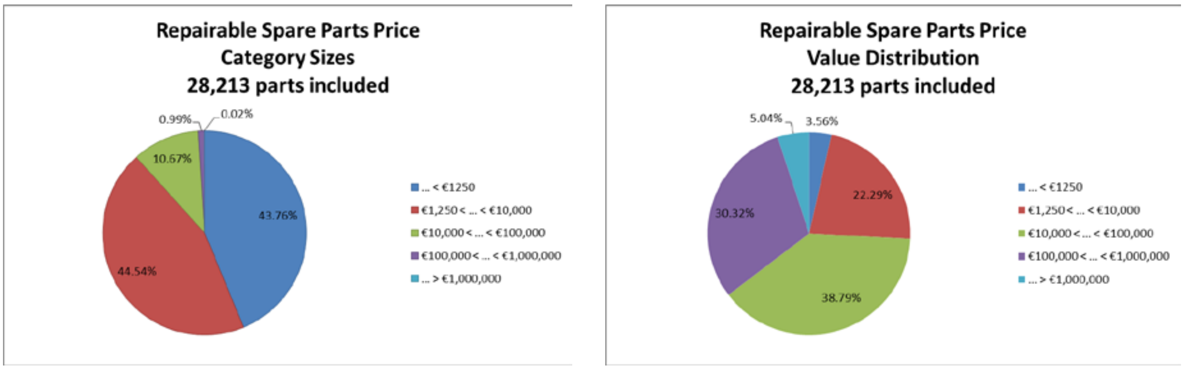

FIGURE 10: REPAIRABLES PRICE CHARACTERISTICS BASED ON AMOUNT AND VALUE

The large variety in the value of the repairable spare parts is visible in Figure 10. It also becomes clear that the majority of the parts (just under 90%) is only responsible for a relatively small fraction of the total value distribution of the repairable spare parts (just over 25%). The majority of the value of the repairable spare parts comes forth from the parts with a value of over €10,000. Because the amount of parts in the refurbishment circuit for each of the part types has not been taken into account, this does not mean that the same effect is found for the total inventory value.

4.2.1.1.1 Spare part criticality

Within the RNLN currently there is no unambiguous way to determine the criticality of the repairable spare parts. Ideally the criticality of a part would be based on the likelihood of a WS becoming materially unavailable when the part demanded is unavailable, in case of component failure. Another option would be to combine various variables as to come up with a construct to 'determine' the criticality of a part. The most important part of determining the criticality, is the fact that it needs to be done in an unambiguous way for all components.

The static priority could be determined based on the criticality of the repairables for the WSs. Together with the DOPS (directorate operations) in the role of operators of the equipment several parts are classified as requiring a priority-status, which means they can be added to the ASM priority database. This occurs whenever a component reaches a critical status for the RNLN according to the DOPS and the DMI, because the unavailability of a part is leading to a crucial reduction of the required material availability of a WS. Parts that have been assigned as either Prio1 or Prio2 in recent years are candidates for a static criticality status, Prio3 and Prio4 parts to a lesser extent.

The second option is to consider the k-factor that the parts have been assigned in the determination of the ON (order-up-to level) of the parts. The k-factor is used in this calculation (Section 3.2.2). The k-factor can be increased manually above the default value of 0.67 (equal to a service level of 75%) whenever a part is important for the availability. Therefore the parts having a k-factor higher than 0.67 are also candidates for a static criticality status.

Both of these criteria do not fulfill the requirement of unambiguousness which is vital for a correct and useful classification of the repairables. Both increasing a components' k-factor or adding a component to the priority database are measures that are taken in a reactive manner, instead of the pro-active manner of classification we would prefer to implement. Nevertheless, these two concepts currently provide the best ground for assigning a criticality to parts. Therefore the criticality of repairable spare parts is expressed using those criteria. With that construct for criticality, there are 2,692 parts that can be considered 'critical' due to either having a k-factor > 0.67, an appearance in the priority database, or both.

4.2.1.2 Procurement lead time

The second spare parts characteristic is the procurement lead time. In the case of a backorder that leads to decreased availability or even unavailability of the WSs, the procurement lead time determines the duration of that decreased availability. The fact that the ASM of the DMI has various options when it comes to procurement has to be taken into account.

In case of a part failure two main phases occur, namely a delay phase and a phase in which the actual repair takes place (Cavalieri, Garetti, Macchi, & Pinto, 2008). The delay phase is caused by for instance resource unavailability. During these phases a system on a WS of which the part was a can become unavailable. In case the system is crucial for the WS availability the complete WS might even be materially unavailable during the phases. Speeding up the delay phase by acquiring additional spare parts for a prompt availability is a possibility, but this obviously leads to higher inventory holding costs. In case important demand cannot be fulfilled, the delay phase is also speeded up. In that case ASM wants to consider all possible ways of obtaining the spare parts (Buiting, 2014), as recorded in the data management of the RNLN. We purposely do not consider the option of redistribution though, since this would harm the material availability of another WS. Therefore the following construct is used for the procurement lead time in case of item failure:

$$Procurement\ Lead\ Time = Minimum\begin{Bmatrix} LeadTime_{Acquisition} \\ LeadTime_{Refurbishment} \end{Bmatrix}$$

Based on the lead times obtained from this construct we obtain the distribution between long and short lead times. Long is defined as $> 5\ months$ because this makes it hard to fit the refurbishment repair within an appointed maintenance window which usually has a size of 6 months. Figure 11 shows the distribution, 34.58% of the repairable spare parts have a long procurement lead time.

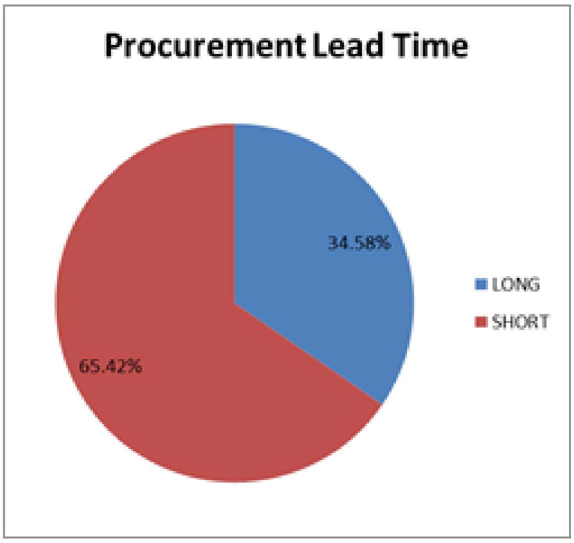

FIGURE 11: DISTRIBUTION PROCUREMENT LEAD TIME DURATION

4.2.1.3 Demand volume and variability

An important aspect regarding the demand characteristics is the fact that within the RNLN there is no general (only for small sets of parts) availability of failure information, nor is there usage- and operating information generally available. The demand information can therefore only be based on the historical demand data available. The variability has to be based on this information too. For almost all components the demand is too low to use statistical information to fit a distribution upon. Therefore we assume the demand requests arrive according to a Poisson process.

In Figure 12 the information regarding the demand occurrences for the various parts is visible. As becomes clear, the large majority (over 80%) of the repairable spare parts has not been demanded in the two years with historical data that were considered. Most of the other parts (just under 20%) are also slow-moving with an average demand occurrence less than every month. Only a very small fraction (less than 1%) of the repairable spare parts is requested on a regular basis.

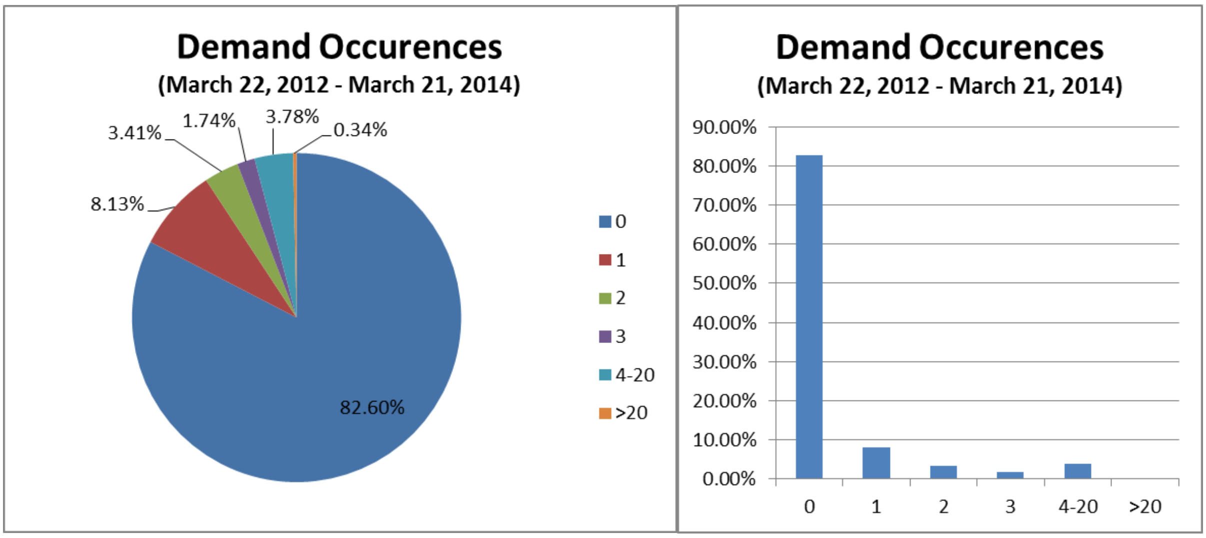

FIGURE 12: DEMAND FREQUENCY NSNs

In Figure 13 the information regarding the demand amount of parts per order is visible. Interesting information is the fact that often demand sizes are very small. In fact, in most situations (just over 80%) only one or two parts are demanded at the same time. A very small fraction (just under 1%) of the demand occurrences regards amounts higher than 50 parts at the same time.

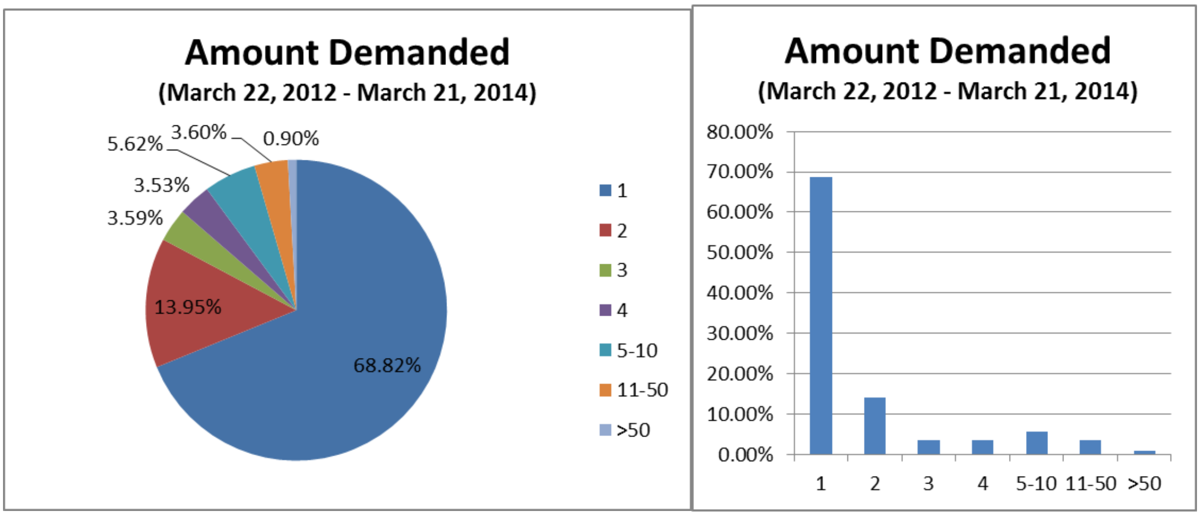

FIGURE 13: AMOUNT DEMANDED PER ORDER

4.2.2 Selection of static classification criteria

Based on the three selection criteria below the potential classification criteria are compared (Table 8). The two criteria that perform best on all aspects are selected for the classification.

1) Scientific relevance; the relevance of the criterion regarding to scientific literature.
2) Data availability; the quality of the data available for the criterion within the RNLN.
3) Research applicability; the suitability of the criterion for (indirectly) assessing the most important DMI performance indicator, the WS availability.

	Scientific Relevance	Data Availability	Research Applicability	Selected
Repairable Spare Part Value		XX	X	
Repairable Criticality	XX	X	XX	X
Repairable Spare Parts Procurement Lead Time	XX	XX	XX	X
Repairable Demand Volume	X	XX	X	
Repairable Demand Variability	X		X	

TABLE 8: SELECTION OF STATIC CLASSIFICATION CRITERIA

We choose to categorize the repairable spare parts based on a combination of the criticality for the WSs and their repair lead time in case of a backorder. The data availability regarding the criticality of the repairable spare parts is not ideal in regard to its unambiguousness (Section 4.2.1.1.1) but there is enough data available for the purpose of this research. These criteria reflect the impact of a backorder well. Both the likelihood for the unavailability of (a part of) the WSs and the duration of this unavailability during the procurement lead time for the demanded part are taken into account. We will treat these criterions as explained in Section 4.2.1.1.1 and Section 4.2.1.2.

4.2.3 Classification framework

The static classification framework obtained is based on an ABC analysis categorization method. A categorization based on conditions for the repairable spare part characteristics is best suited in regard to the data we have available. The cutoff conditions are as mentioned; an appearance in the RNLN priority database or a K-value above 0.67 indicates a critical part, a procurement lead time longer than 5 months indicates a long lead time part. This way the framework in Figure 14 is obtained for the static repairable spare part classes. The classes each obtain a letter for further reference throughout this research. The framework is applicable for internal and external repair.

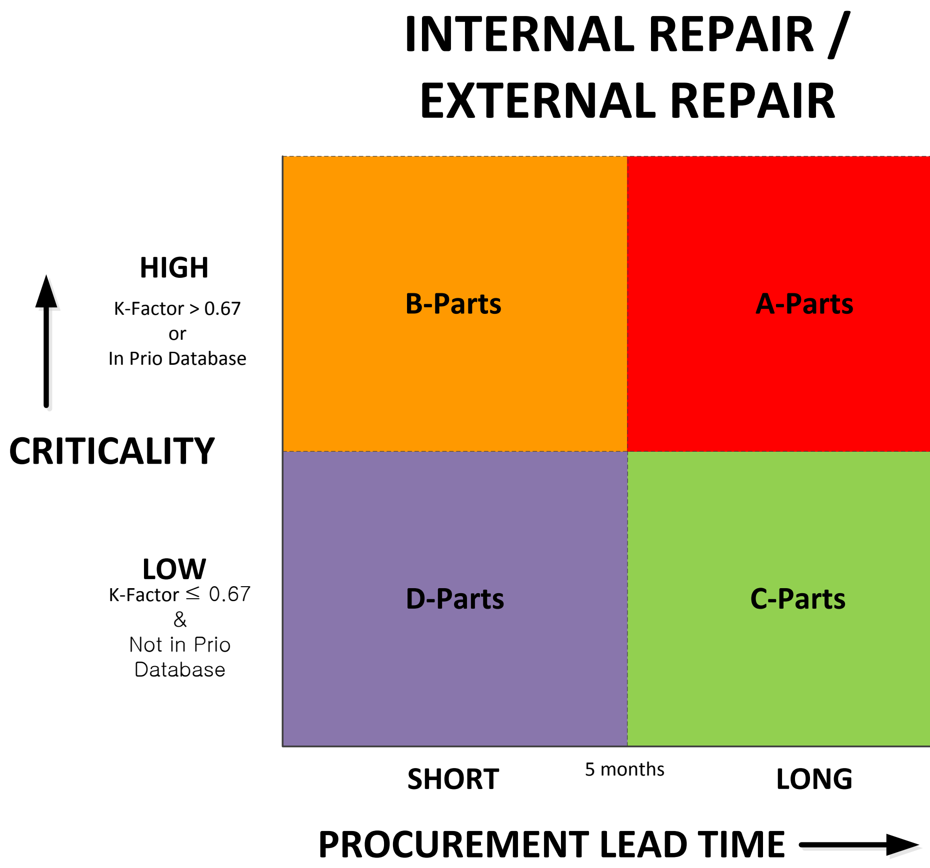

FIGURE 14: PROPOSED STATIC CLASSIFICATION FRAMEWORK RNLN REPAIRABLES

4.3 Inventory Management

4.3.1 Section introduction

An important part of integrated repairable spare parts management is the inventory management. In order to be able to fulfill the performance goals of the RNLN WSs the inventory management has one important performance target, the service level for the repairable spare parts requests. However, the RNLN is working with a resource set that we consider to be fixed, due to the fixed budget size and allocation for the DMI (directorate material sustainment). Furthermore, values have been set for some important inventory parameters such as the amount of spare parts per part type. Therefore inventory management has the goal to optimize the availability along relevant constraints.

4.3.2 Proposed inventory management methodology

Based on recent research (van Duren, 2011) we know it might be better to use varying stock policies for classes of repairables with varying characteristics, such as determined in Section 4.2.1. Based on the characteristics of these groups and the findings within literature, we will use a selection of inventory policies. However, an important note to make here is that we have to treat the current repairable spare part inventory sizes as fixed. The decisions about the inventory sizes are made at the acquisition of new WSs and or systems on board of them. Because of the specificity of the parts and therefore the lack of procurement options at the market, in combination with the high value of these parts whereas the budget of the RNLN is fixed, it is not possible to increase these inventories. Therefore our proposed inventory management methodology will only focus on the availability of the repairable spare parts, instead of analyzing the optimal inventory levels.

4.3.3 Stock policy setting framework

Spare parts classification in combination should be linked to stock control policies (Bacchetti & Saccani, 2012). Based on the inventory policy chosen for the repairables category the desired stock levels can be determined. Initially we will use the inventory levels determined by the RNLN using an (s,S) policy. We will examine what happens when the values for these levels are changed in a sensitivity analysis to further assess the options of increasing the service levels (Section 5.6). The policies deferring from the policy settings explained in Section 3.2.2 are explained in the following sections. As explained, the values of the inventory settings will not be altered. However, for further improvement it is definitely useful for the RNLN to investigate the inventory parameter values at the moment of acquisitioning new WSs and or systems, in order to further improve performance.

Figure 15 shows the inventory policy classification framework.

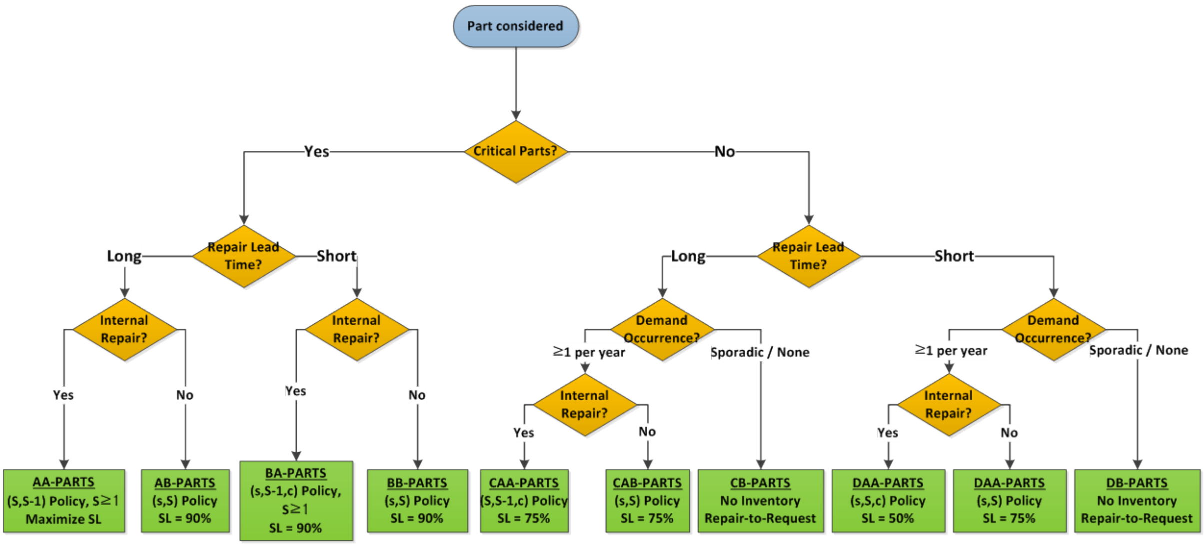

FIGURE 15: INVENTORY POLICY CLASSIFICATION FRAMEWORK

4.3.3.1 Inventory policies used

Often repairable inventory optimization problems experienced are solved by also taking the availability costs and inventory holding costs into account. However, in the case of the RNLN the unavailability of the equipment is impossible to express in costs since the WSs do not provide any profit when available. Furthermore, since the inventory holding costs of the RNLN can be considered as being the capital invested in components, it does not matter whether these are in the NGVU or in the GVU stock. Therefore the following policies are solely based on a required component availability.

The (s,S) policy with fixed re-order policy (s) and order-up-to level (S) were used is considered to be the best-suited technique for low and intermittent demand items. “Only few companies […] use complex and specific inventory models in practice, primarily due to the mathematical complexity that characterizes their resolution” (Bacchetti & Saccani, 2012). However, because we are assessing internal orders without ordering costs, we will extend this policy for the various repairable spare parts classes, based on increasing the availability of the relevant repairable spare parts. Therefore all policies described below use the equations from Section 3.2.2 (1), (2) , and (3) as a foundation.

4.3.3.1.1 (s,S,c) Policy

We use the base-stock policy currently used for the ASM of repairable spare parts as a foundation (Section 3.2.2). The level for the order-up-to level is fixed as explained. The way the reorder-level is calculated Equation (1) is maintained for the parts with the shorter procurement lead-time that are not-critical. These parts results in a shorter period of unavailability for (parts of) the WS. Therefore we can accept this non-optimal methodology.

The dynamic inventory position is important in addition to the static priority classification of the repairables (Section 4.2.3). It is required for a clear and unambiguous insight to provide a sound ground for decision-making regarding the dispatching of orders. Whenever the inventory level reaches a critical threshold c, the criticality of the product group can be increased to a higher level, giving the actual production of this product group more priority. How this is performed will be explained in Section 4.4.2. The value of c will be set at 50% of the reorder level of the part type which is defined as in Section 3.2.2 in Equation (1), and 0 for class D. We will analyze deferring from this initial setting later on to find the best setting (Section 5.6).

4.3.3.1.2 (S,S-1,c) Policy

The (S,S-1) policy which is a base-stock policy where the reorder level is set at S-1, so for each request immediately a repair order is issued. This policy is used with the addition of a critical threshold c similar to the one in Section 4.3.3.1.1. A specific situation occurs for the parts with only one item in inventory, these components receive an critical status immediately according to the dispatching rules (Section 4.4.2). For the AA parts, the critical status is already reached when the inventory level reaches the S-1 level since we want to maximize the service level for these parts.

4.3.3.1.3 Repair-to-Request Policy

The RNLN has a large amount of repairables that are only sporadically ($<1\ per\ year$) requested (Section 4.2.1.3). For the non-critical components that have this demand pattern we suggest a repair-to-request policy where the risk is taken to not have the parts in GVU stock in case of a failure. Whenever demand occurs they immediately have surpassed the threshold value to increase in priority according to the dispatching rules.

4.3.4 Alternative inventory management options

In the inventory classification framework policies are proposed for the various repairable spare parts classes focusing on optimizing the availability of the important parts. However, there are other options in regard to this goal. We will propose these options here, to evaluate them in Section 5.8.1.

As explained, the availability is key but increasing this availability by using an (S,S-1,c) policy for the repairable spare parts class B might be harming the availability of the other classes. This class has a short lead time so an option is to try a (s,S,c) policy. The other way around, we could also try to use an (S,S-1,c) policy for the repairable spare parts class D.

Furthermore, the introduction of the criticality level to the inventory policies is an option, but it is interesting to see whether it really improves the performance regarding the relevant spare parts availability. This would remove the dynamic aspect, but the policies still focus on availability.

4.4 Repair Order Dispatching

4.4.1 Introduction

The scheduling of the refurbishment repair orders for the workshops is an important element. We aim for an integrated approach whereas literature often considers the scheduling in regard to KPIs such as minimum waiting time or tardiness. We propose an integrated approach, taking the determined static priority (Section 4.2) of the repairables into account, as well as the dynamic inventory level in regard to their policy and parameters (Section 4.3). This is the most appropriate method to allocate the limited available workshop capacity; it is used in the organizations' best interests.

4.4.2 Proposed dispatching methodology

The capacity allocation of the workshops is currently pre-determined. A fixed proportion of the available workshop capacity is allocated to refurbishment activities.

The goal is to develop a scheduling rule to allocate the available capacity as efficient as possible. Furthermore, we will use the dynamic inventory position based on the inventory status and the fact whether or not the critical inventory level c has been reached (Section 4.3.3.1) and the static priority classes (Section 4.2.3 Figure 14) to determine the dynamic priority of the refurbishment orders. Based on this dynamic prioritization the work schedule can be determined per work shop.

Next to that we want to determine whether the available capacity for refurbishment jobs is sufficient. If this is not the case, we are interested in the difference between the available allocated capacity and the actually required refurbishment capacity.

The following general steps form the refurbishment order dispatching decisions for repair orders:

1) **Outsource preferred external repairs**
2) **For internal repairs; determine place in resource dispatching sequence based on dynamic inventory position and part classification**
3) **Update inventory parameters after processing an order**
4) **Update dispatching sequence based on additional arriving orders**

4.4.2.1 Dispatching of refurbishment repair orders

The refurbishment process flows are visualized in Section 1.1.3.2 in Figure 5. Based on the demand of the RNLN WSs for repairables, and the inventory policy set according to the repairables classes repair orders arise to be dealt with by the different DMI workshops. Because of the limit capacity of these workshops (Section 1.2) not all of these repair orders can be addressed imminently. One of the major problems coming forth regarding the current malfunctioning of the refurbishment circuit is exactly that; orders are not processed in time leading to an unavailability of required components. In order to make the most efficient use of the limited workshop capacity available appropriate dispatching rules for the sequence to process the orders are therefore required.

A mathematical notation overview is available in Appendix 9.1. We address the dispatching of orders as follows (partially based on de Boer, Schutten and Zijm (1997)): We have K workshops R_k $(R_1, R_2, \ldots, R_K)$ available for maintenance activities. Each of these workshops groups has a number Q_k of identical resources (technicians operating equipment) which can all process one refurbishment job at the time allocated to that resource. We assume the resources are capable of processing all possible refurbishment orders arriving. Each resource has a capacity of $42 * 40 = 1680\ hours\ per\ year$ or $\frac{1680}{12} = 140\ hours\ per\ month$. Each of these resource groups has a percentage ρ_k at which they are available for refurbishment jobs, and not working on other maintenance types (Section 1.1.2). We assume that these hours are evenly distributed over the days, so that all resources have $\rho_k * 8\ hours$ available per working day.

Some refurbishment repair jobs can actually be conducted either externally or internally. Each refurbishment order consists of a characteristic d_k which refers to which workshop it should be appointed and for what duration the resource will be seized, and a characteristic d_i which provides similar information for the industry. Because for each repairable either one of the two is impossible, the refurbishment lead time for all but one d_k or for d_i is equal to ∞. are also assigned to the industry. We assume the option for either internal or external repair is based on technological characteristics, and can therefore not be influenced. The general internal/external characteristic is available in the database. For the disputable orders we assume the repairs takes place internally.

Each of the internal workshops has a set of NGVU components waiting to be processed. This is done according to the IHOs (internal refurbishment orders) that arrive according to the inventory policies set for the repairables classes (Section 4.3.3). These IHOs carry a dynamic priority that will be set by the dispatching rules as described in Section 4.4.2.2.

We have a situation with Kservers with a dispatching sequence based on the dynamic priority of the IHOs. Next to that we have the 'back-up' server I which stand for the industry. Whether these orders are processed in time is determined by comparing the UGD (requested due date) with the achieved due date. IHOs are 'on time' if $UGD \leq \tau_{achieved\ completion\ date}$ and 'too late' if $UGD > \tau_{achieved\ completion\ date}$. For each of the product classes we can determine the service level by $SL_k = \frac{On\ time_k}{On\ time_k + Too\ late_k} * 100\%$.

4.4.2.2 Dispatching rules

We have a situation with K servers. Each server has its own queue of refurbishment orders to process. These orders are Important is the fact that we want to develop a suitable sequencing rule for these queues where the orders that are most urgent for the RNLN are addressed first. The urgency of the orders is based on the repairables class and the dynamic inventory information. We assume that orders once being served by one of the internal servers R_k cannot be interrupted. Therefore the relevant problem to address is arranging the server queues for the right order. These sequences have to be updated after parameters have been changed to taken the dynamic environment in which the workshops operate into account.

Figure 16 provides an illustration of the desired situation. The arriving orders carry an allocation characteristic whether to be processed internally and at which workshop or externally determined by $\min\{d_k, d_I\}$. Furthermore, they carry a priority characteristic determining the place in the queue of that specific workshops, given by the dynamic inventory status of the component according to the rules described further on. In Figure 16 orders have an allocation characteristic (visualized by a letter or a number) and a priority characteristic (visualized by the different colors). It is important that after repair orders have been placed in the dispatching sequence, their priority can still change. The dotted arrows represent situations where either the priority increases based on the inventory position, or decreases. This represents the dynamic aspect of the dispatching rules.

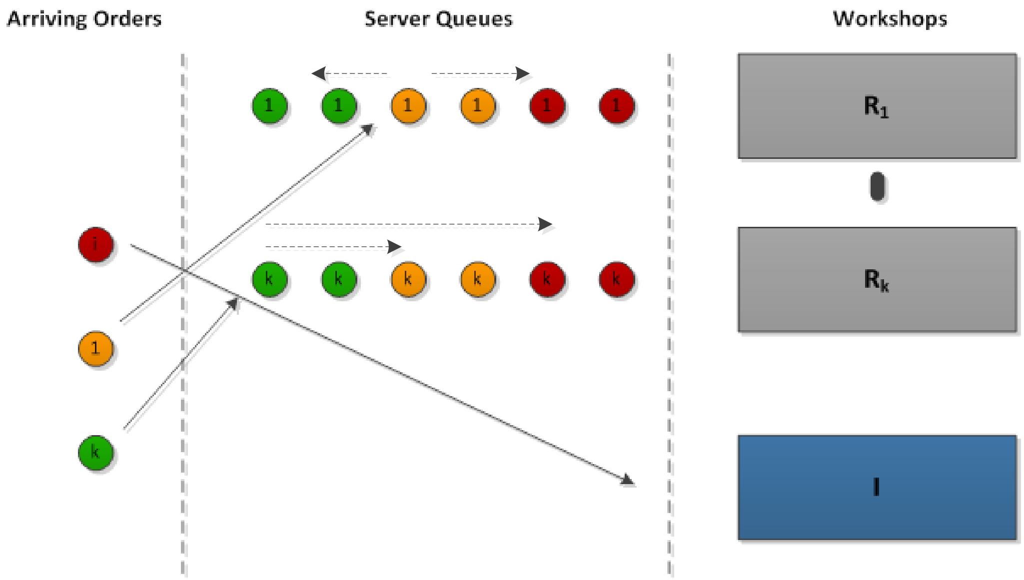

FIGURE 16: SCHEMATIC OVERVIEW OF WORKSHOP QUEUES

In order to write down the dispatching algorithm for the orders, the internal queues are split-up in three different sub queues $Q_{k,\varphi}$ $(Q_{k,1}, Q_{k,2}, Q_{k,3})$, $k \in K$, $\varphi \in \{1,2,3\}$ for each server, where the first queue has the highest priority and the third queue the lowest priority. By making the servers k, $k \in K$ (workshops) always address orders $Q_{k,1}$first and orders in $Q_{k,3}$ last the desired dispatching sequence is obtained. Each of the queues $Q_{k,p}$ is addressed in a FIFO sequence because we will assume that the due dates will be based on the current run time t. In reality the UGD is highly varying due to an unambiguous way of requesting these dates by the DOPS operating the WSs. Because we are only interested in the improvement potential of our integrated approach we can assume the UGDs to be based on the current time since both models will use similar input then.

The set of dispatching rules for the repairable classes (Figure 15) is displayed in Table 9. These dispatching rules are valid for the IHOs, the external situation is not specifically mentioned since that dispatching is done by the Industry workshops themselves.

Repairable Class	Inventory/Backorder Position	Order Position	Dispatching Queue
AA	$if\ I^+_{k,AA} = S_{k,A}$ $else\ (if\ I^+_{k,AA} < S_{k,AA})$	$No\ Orders$ $O_{k,A} = S_{k,AA} - I^+_{k,AA} + I^-_{k,AA}$	$-$ $Q_{k,1}$
AB	$if\ I^+_{I,AB} > s_{I,AB}$ $else\ (if\ I^+_{I,AB} \leq s_{I,AB})$	$No\ Orders$ $O_{I,AB} = S_{I,AB} - I^+_{I,AB} + I^-_{I,AB}$	$-$ $Industry$
BA	$if\ I^+_{k,BA} > s_{k,BA}$ $if\ \{I^+_{k,BA} \leq s_{k,BA} \cap I^+ > c_{k,BA}\}$ $else\ (if\ \{I^+_{k,BA} \leq s_{k,BA} \cap I^+_{k,BA} \leq c_{k,BA}\})$	$No\ Orders$ $O_{k,BA} = S_{k,BA} - I^+_{k,BA}$ $O_{k,BA} = S_{k,BA} - I^+_{k,BA} + I^-_{k,BA}$	$-$ $Q_{k,2}$ $Q_{k,1}$
BB	$if\ I^+_{I,BB} > s_{I,BB}$ $else\ (if\ I^+_{I,BB} \leq s_{I,BB})$	$No\ Orders$ $O_{I,BB} = S_{I,BB} - I^+_{I,BB} + I^-_{I,BB}$	$-$ $Industry$
CAA	$if\ I^+_{k,CAA} = S_{k,CAA}$ $if\ \{S_{k,CAA} \leq s_{k,CAA} \cap I^+_{k,CAA} > c_{k,CAA}\}$ $else\ (if\ \{I^+_{k,CAA} \leq s_{k,CAA} \cap I^+_{k,CAA} \leq c_{k,CAA}\})$	$No\ Orders$ $O_{k,CAA} = S_{k,CAA} - I^+_{k,CAA}$ $O_{k,CAA} = S_{k,CAA} - I^+_{k,CAA} + I^-_{k,CAA}$	$-$ $Q_{k,3}$ $Q_{k,2}$

CAB	$if\ I^{+}_{I,CAB} > s_{I,CAB}$ $else\ (if\ I^{+}_{I,CAB} \leq s_{I,CAB})$	$No\ Orders$ $O_{I,CAB} = S_{I,CAB} - I^{+}_{I,CAB} + I^{-}_{I,CAB}$	$-$ $Industry$
CB	$if\ \{I^{+}_{k,CB} = 0\ \cap I^{-}_{k,CB} = 0\}$ $else\ (if\ I^{-}_{k,CB} \geq 1)$	$No\ Orders$ $O_{k,CB} = I^{-}_{k,CB}$	$-$ $Q_{k,2}$
DAA	$if\ I^{+}_{k,DAA} > s_{k,DAA}$ $if\ \{I^{+}_{k,DAA} \leq s_{k,DAA} \cap I^{+}_{k,DAA} > 0\}$ $else\ (if\ \{I^{+}_{k,DAA} \leq s_{k,DAA}\ \cap I^{+}_{k,DAA} = 0\})$	$No\ Orders$ $O_{k,DA} = S_{k,DAA} - I^{+}_{k,DAA}$ $O_{k,DA} = S_{k,DAA} - I^{+}_{k,DAA} + I^{-}_{k,DAA}$	$-$ $Q_{k,3}$ $Q_{k,2}$
DAB	$if\ I^{+}_{I,DAB} > s_{I,DAB}$ $else\ (if\ I^{+}_{I,DAB} \leq s_{I,DAB})$	$No\ Orders$ $O_{I,DAB} = S_{I,DAB} - I^{+}_{I,DAB} + I^{-}_{I,DAB}$	$-$ $Industry$
DB	$if\ \{I^{+}_{k,DB} = 0\ \cap I^{-}_{k,DB} = 0\}$ $else\ (if\ I^{-}_{k,DB} \geq 1)$	$No\ Orders$ $O_{k,DB} = I^{-}_{k,DB}$	$-$ $Q_{k,3}$

TABLE 9: DISPATCHING RULES FOR REPAIRABLE CLASSES

The processing rules then used for the servers $k,\ k \in K$ are visible in Table 10.

Server	Queue Condition	Processing Orders from Queue
$k, \quad k \in K$	$if\ NQ_k(Q_{k,1}) \geq 1$ $if\ \{NQ_k(Q_{k,1}) = 0 \cap NQ(Q_{k,2}) \geq 1\}$ $if\ \{NQ_k(Q_{k,1}) = 0 \cap NQ(Q_{k,2}) = 0 \cap NQ(Q_{k,3}) \geq 1\}$ $else\ (if\{NQ_k(Q_{k,1}) = 0 \cap NQ(Q_{k,2}) = 0 \cap NQ(Q_{k,3}) = 0\}$	$Q_{k,1}$ $Q_{k,2}$ $Q_{k,3}$ $-$
I	$Industry$	$Industry$

TABLE 10: PROCESSING RULES FOR SERVERS

4.4.3 Alternative dispatching options

Similar to Section 4.3.4, we provide alternative dispatching options that will be evaluated in Section 5.8.1. The dispatching rules suggested can be changed slightly to see what this does to performance.

The proposed dispatching methodology favors the long lead time classes over the short lead time classes. However, the criticality aspect is important for the material availability, so it is interesting to see what happens if we consider both A and B class parts to be of similar importance. This means the long lead time RCA parts are no longer favored over the short lead time RCD parts.

Furthermore, an interesting approach is to reserve capacity for orders with a critical inventory status, regardless of what static priority they have. This means that class A, B, C, and D are considered to be just as important when their critical status has been reached.

5 Simulation

Chapter Abstract

This chapter provides numerical insights in the improvement potential of the proposed repairable spare parts management methodology for the RNLN, as discussed in Section 4. The simulation method is explained, as well as all simulation input used. The results of the simulations representative for botch the current and the improvement methodology are provided. Sensitivity analyses are conducted to further investigate the improvement potential of the methodology.

5.1 Section Introduction

The proposed improved repairables spare parts management methodology (Section 4) is assessed to evaluate the improvement potential for the performance of the RNLN refurbishment circuit. In order to do this a simulation is performed using the data available as input. A simulation is performed for a representation of the current methodology, and for a representation of the improved methodology, both processing similar representative input data. This allows for an assessment of the improvement potential obtained by implementing the proposed methodology.

The simulation model is validated and verified (Sections 5.6 and 5.7), to make sure it is indeed applicable to the RNLN repairable spare parts environment. Additionally a sensitivity analysis (Section 5.8) tests the stability of the improvement methodology, and identifies its limitations. This is important for understanding the applicability of the methodology for the RNLN and for comparable repairable spare parts environments.

5.2 Simulation Environment

The simulation environment is a validated representation of the relevant part of the RNLN refurbishment circuit as described in Section 1.1.3. The simulation requires a founded representation of reality, although the complexity of the reality has to be reduced in regard to the number of parts classes considered. The simulation environment consists of the various modules representing complex parts of the internal refurbishment circuit. The representative input for the model modules for the period the simulation considers (March 22, 2012 – March 21, 2014) is discussed below. The model therefore runs for 730 days (after a warm-up period of 365 days), because demand requests can occur on any day. Capacity is only available during weekdays, so the model only runs for $\frac{5}{7} * 8$ hours is 5.7 hours per day. For each simulation, 100 replications are conducted to make sure the results are not influenced too much by variety. The simulations are performed using the simulation software package Arena Enterprise Suite Academic. An explanation of the compositions of the reference model and the improvement model are described in 5.4.

5.3 Simulation Input

5.3.1 Repairable spare parts classes

The simulation only assesses the four main internal repairable classes (RCs). The dispatching of external repair orders is out of the scope of the simulation, as it is conducted by the external parties which have their own scheduling methods. This means that the integrated framework can only really be applied in a simulation for the internally repaired parts. Furthermore, the repairable spare parts subclasses with sporadic demand or no demand at all (classes CB and DB, Section 3.2.2 Figure 15) have not been taken into account. The reason is the fact that the demand is so low that there is not sufficient input data for the simulation so that we are not able to provide useful insights for these classes. Due to the infrequent failures of these subclasses the simulation results will not significantly be influenced. The classes from the inventory management classification scheme (Section 4.3.3 Figure 15) used as input for the simulation are therefore AA, BA, CAA and DAA, in the simulation referred to as RCA, RCB, RCC and RCD.

5.3.2 Workshop refurbishment repair characteristics

The procurement lead times are varying between the classes, since the classes were formed based on the difference in procurement lead times (Section 4.2.1.2). However, the refurbishment repair lead times are varying from these procurement lead times, since there the option of acquiring additional spare parts is also considered. Now we are looking into the current refurbishment repair lead times for the repairable spare parts. The distributions for these lead times are visible in Figure 30 in Appendix 9.10.1, the average values are visible in . Many of these values are put in the IT system manually and the consistency is therefore lost, so they only provide insight. The refurbishment repair lead time consists of both the delay phase for parts where the repair order is issued but where the part has to wait for the actual repair, and of the actual repair phase. The delay phase is caused by resource unavailability, concerning required material- and personnel resources. For the duration of the delay phase we have no concrete values available. However, we know and observe that this phase is longer for the longer refurbishment repair lead times. Furthermore, we assume the extension is longer for the critical long refurbishment repair lead time items since these are often more complex in nature. This leads to the values in Table 11.

Category (long)	Refurbishment Repair Delay Lead Time	Category (short)	Refurbishment Repair Delay Lead Time
A	3 months	**B**	1 month
C	3 months	**D**	1 month

TABLE 11: REFURBISHMENT REPAIR DELAY LEAD TIMES

Once the orders reach the production status at the workshops only a small fraction of the repair lead time is required to repair them. Repair duration characteristics are only available for orders that have been processed recently. The averages are comparable, although class A takes slightly longer (Table 12). We only have the workshop processing time information for 1,096 out of 28,223 components. We consider this too little information to fit a proper distribution upon. Therefore we assume the workshop order processing times to be constant and equal to the averages in Table 12.

Category	Average Repair Duration	Category	Average Repair Duration
A	30.6 hours	**B**	24.7 hours
C	23.6 hours	**D**	24.7 hours

TABLE 12: ORDER WORKSHOP PROCESSING TIMES

We have to consider the fact that these values are the average repair durations for the repair orders. However, we need to consider the time the repair takes per part. Using the average repair order sizes for the different classes from Table 16 we find the workshop processing times $\theta_{k,n}$ for the repairable spare parts classes, as displayed in Table 13.

Category	Average Repair Duration	Category	Average Repair Duration
A	22.8 hours	**B**	3.8 hours
C	5.4 hours	**D**	6.9 hours

TABLE 13: PART WORKSHOP PROCESSING TIMES

Finally, the repair capacity allocated to refurbishment repair for the simulation run period (Table 14) is equal to the total amount of hours allocated to this according to the historic data for this period.

Allocated Capacity (2 years)	Average Capacity Per Part Type (2 years)
242,000 hours	242,000 / 3,999 parts = 60 hours

TABLE 14: ALLOCATED REFURBISHMENT REPAIR CAPACITY

We want to convert this to our simulation environment, where one part per repairable spare class is considered carrying the average class characteristics. This means we consider four parts in our simulation environment, meaning that we only have four times 60 hours is 240 hours of refurbishment repair capacity. We have to convert this to full available capacity for simulation purposes, so we need a factor to convert the spare parts demand request arrivals later on. In order to do this the available capacity for the refurbishment repair of 4 parts during 2 years is converted by the total capacity a full time refurbishment repair resource would have available during 2 years or 730 days, running for 5.7 hours a day like in our simulation model environment.

Available Capacity (4 parts, 2 years)	Fraction of Full Time Refurbishment Repair (4 parts, 2 years)	Convert Factor Capacity (4 parts, 2 years)
240 hours	$\frac{240}{730 * 5.7} = \frac{1}{17.4}$	17.4

TABLE 15: CONVERTING FOR AVAILABLE CAPACITY FOR SIMULATION ENVIRONMENT

5.3.3 Demand request characteristics

There are more than 28,000 repairable spare parts at the RNLN, of which around 50% are repaired internally and thus within the scope of the simulation. Because of the level of complexity a simulation using all these articles as input would result in, we have used representative demand classes. These representative demand classes are based on the selection of classification repairables classes selected (Section 5.3.1). For each of the four demand classes selected we have the repairable spare parts requests arriving according to demand distribution characteristics representative for the whole. These demand distribution characteristics are based on the historic demand request information of the DMI (Section 4.2.1.3). In Table 16 the demand characteristics for the selected repairable spare parts classes are visible, calculated with 730 days for 2 years. The mean inter arrival times for the demand classes in this table are concerning all parts within that class.

Class	Demand Occurrences (2 years)	Demand Inter-arrival (days)	Total Amount Demanded	Average Request Size
A	2,046	0.36	2,804	1.4
B	5,402	0.14	35,897	6.6
C	1,840	0.40	8,153	4.4
D	3,752	0.19	13,334	3.6

TABLE 16: AVERAGE DEMAND CHARACTERISTICS REPAIRABLE SPARE PARTS CLASSES

These demand occurrences are arriving according to an exponential distribution, as becomes clear when looking at the occurring inter-arrival times (in days) with their respective probabilities. For each of the four classes assessed, the inter-arrival times behave according to a Poisson distribution with the expected inter-arrival time of the class as expected value, as is visible in Figure 17.

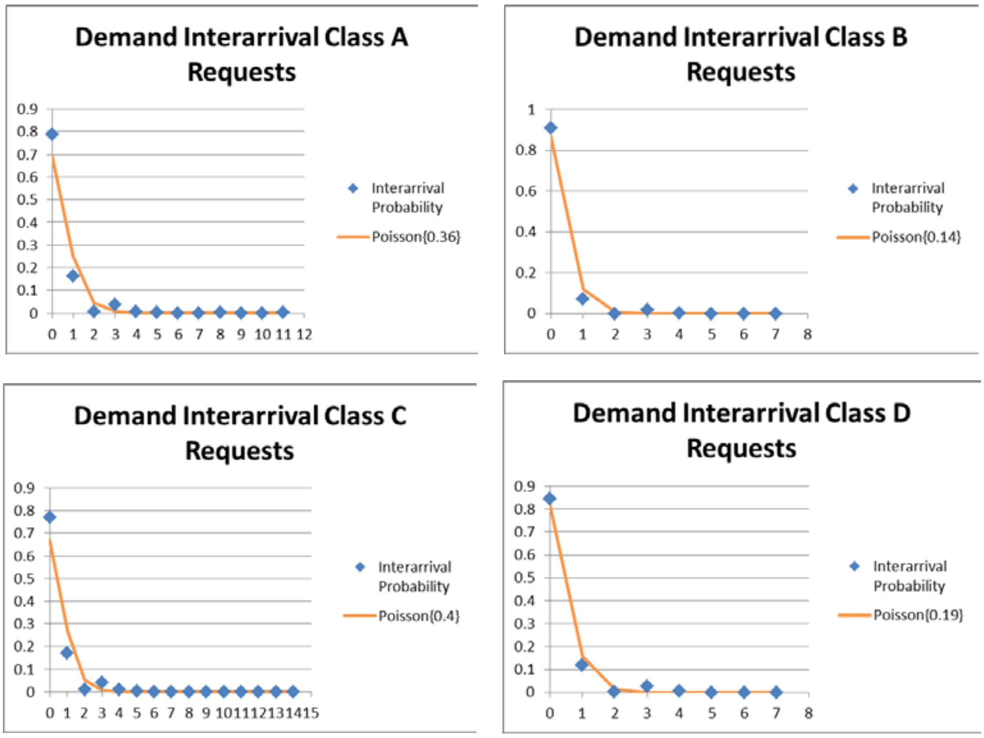

FIGURE 17: POISSON DISTRIBUTION FOR DEMAND INTER-ARRIVAL TIMES

Now that it is clear that the inter-arrivals for the demand requests are Poisson distributed, we want to convert the arrivals to simulation input. We want to convert our model to a situation where four parts are considered, one of each repairable spare parts class. Therefore we have to convert the demand to demand request arrival characteristics for an average part of each class (Table 17).

Class	Class Inter-arrival (days)	Unique Parts Requested (2 years)	Unique Part Arrival (days)	Converted Part Arrival (corrected for available capacity)
A	0.36	576	201 days	$\frac{201}{17.4} \approx 12$ days
B	0.14	963	138 days	$\frac{138}{17.4} \approx 8$ days
C	0.40	1,021	415 days	$\frac{415}{17.4} \approx 24$ days
D	0.19	1,439	261 days	$\frac{261}{17.4} \approx 15$ days

TABLE 17: CONVERT DEMAND REQUEST ARRIVALS TO SIMULATION INPUT

For the request sizes no particular distribution is particularly useful. We need discrete probabilities since we consider complete parts, and there appears to be no foundation for a fit of an existing distribution as is visible in the original request size occurrence histograms for the repairable spare parts classes (Appendix 9.10.2). The average request sizes (Table 16) are represented by assigning discrete probabilities to various possible demand sizes based on the actual request size distributions, resulting in the actual expected average request size. Table 21 shows the notation used for this.

Class	Mean Request Size	Request Sizes with Probabilities	Notation used
A	$\mu_{k,A} = 1.4$	$m_{k,A}$ 1 2 3 4 $P(m_{k,A})$ 0.8 0.15 0.0 0.05	Discrete{0.8,1; 0.95,2; 1,4}

TABLE 18: REQUEST SIZE PROBABILITY SIMULATION ENVIRONMENT NOTATION

Finally, each request is assigned a requested lead time until the desired due date. For this requested due date the behavior varies a lot, leading to an undefinable distribution of requested lead times. Therefore the average requested lead time is selected for each of the repairable spare part classes.

Based on that we define the original demand simulation input for the demand classes (Table 17).

Class	Demand Distribution	Demand Size	Requested Lead Time
A	Exp{12} days	Discrete{0.8,1; 0.95,2; 1,4}	37 days
B	Exp{8} days	Discrete(0.25,1; 0.35,3; 0.45,5; 0.75,7; 1,9)	47 days
C	Exp{24} days	Discrete{0.5,2; 0.6,3; 0.7,5; 0.8,7; 0.9,9; 1,10}	13 days
D	Exp{15} days	Discrete{0.6,2; 0.7,3; 0.85,5; 0.95,8; 1,10}	14 days

TABLE 19: DEMAND INPUT PARAMETERS SIMULATION

One important observation though, is that a very small fraction of the demand requests (<1%) is significantly influencing the demand request sizes. As is visible in (Appendix 9.10.2), only a very small fraction of the demand is high. Because these outliers are not likely to concern requests where indeed all parts need to be repaired, we also consider the situation without outliers (Table 20).

Class	Demand Distribution	Demand Size	Requested Lead Time
A	Exp{12} days	Discrete{0.8,1; 0.95,2; 1,3}	37 days
B	Exp{8} days	Discrete(0.4,1; 0.5,3; 0.65,4; 0.8,5; 1,8)	47 days
C	Exp{24} days	Discrete{0.7,1; 0.9,2; 0.95,4; 1,6}	13 days
D	Exp{15} days	Discrete{0.7,1; 0.8,2; 0.9,5; 1,7}	14 days

TABLE 20: DEMAND INPUT PARAMETERS SIMULATION - OUTLIERS REMOVED

5.3.4 Inventory characteristics

Regarding the inventory characteristics we use the current amount of repairable spare parts in the RNLN refurbishment circuit. Since we are using the averages to represent the various repairable spare part categories, the same goes for the (rounded) repairable spare parts total inventory sizes including NGVU inventory for the various classes, see Table 21.

Category	Average Inventory	Category	Average Inventory
A	7 parts (6.9)	**B**	13 parts (13.3)
C	7 parts (6.5)	**D**	13 parts (13.0)

TABLE 21: REPAIRABLE SPARE PART INVENTORY CHARACTERISTICS

For the additional inventory parameters we then have the values as displayed in Table 22 where we use the total inventory as order-up-to levels. The other inventory parameter values used in either the reference model or the improvement model are displayed.

Class	Order-up-to Level $S_{k,n}$	Reorder Level $S-1_{k,n}$	Reorder Level $s_{k,n}$	Critical Level $c_{k,n}$
A	7	6	4	
B	13	12	8	6
C	7	6	4	3
D	13		8	0

TABLE 22: INVENTORY CHARACTERISTICS SIMULATION ENVIRONMENT

5.4 Simulation Models

The environment for the simulation models, and their input data are extensively discussed in Section 5.2 and Section 5.3. The composition of the models themselves is discussed in this section. As explained we compare simulation models containing the repairable spare parts management elements. The improvement model (flowchart visible in Appendix 9.11.1) uses the integrated framework for this (Section 2.4) with the improvement methodology discussed in Section 4. The reference model uses the methodology currently used at the RNLN as discussed in Section 3.2.

For the reference model (flowchart visible in Appendix 9.11.2) the current reorder levels are used to trigger component repair. Furthermore, there is no priority, except for order that are assigned a high priority status. This happens to a fixed fraction of the repairable spare parts classes A and B part requests arriving (Table 23). These high priority orders obtain absolute precedence.

Category	Fraction High-Priority	Category	Fraction High-Priority
A	13%	**B**	12%
C	0%	**D**	0%

TABLE 23: HIGH PRIORITY REQUEST FRACTIONS CURRENT SITUATION

Both models consist of a demand management and a repair- and inventory management part, linked by inventory variables. The demand requests can only be addressed whenever the dynamic inventory position is high enough. Furthermore, the requests taking out parts from the inventories result in a trigger for the repair- and inventory management part of the simulation to start repairing parts. The criticality status for certain part classes is automatically either assigned or not after a demand request has been fulfilled, and either maintained or reset after a repair has been completed. It is important to understand that for both models the workshop resource capacity is shared, which means that the repairs all have to be conducted by the same resource, that resource cannot work on more repair orders simultaneously.

5.4.1 Demand management

The demand management setup for both the improvement simulation model and the reference simulation model is similar, and visible in Figure 18. The values for the input named are provided in Section 5.3 where all simulation input is extensively described. As explained, the demand management is related and linked to the repair- and inventory management for both simulation models by the shared variables for the inventory status and characteristics.

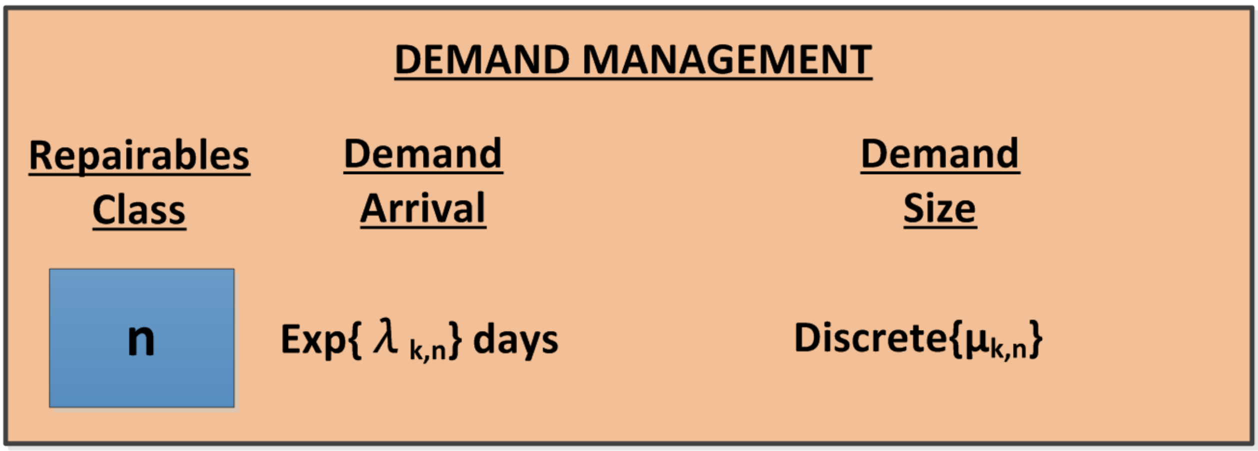

FIGURE 18: SIMULATION SETUP DEMAND MANAGEMENT

5.4.2 Repair and inventory management

The inventory management is different for both models, since the improvement model used the dynamic inventory status and the static classification to determine the next order to spend refurbishment repair capacity on. The repair- and inventory management setup for the simulation is visible in . The rules for increasing the criticality of the parts are based on the critical inventory levels (Table 21). The rules for the release of repair orders to the actual workshop refurbishment repair resource are the rules introduced in Section 4.4.2.2.

IMPROVEMENT MODEL – REPAIR- AND INVENTORY MANAGEMENT

Repairables Class	Order Signal	Increase Criticality Status	Processing Time Per Part	Release Order to Workshop Condition
A	If $I_{k,A}^{+} < S_{k,A}$	-	$\theta_{k,A}$	If $\{WIP_{k,A} = 0\}$
B	If $I_{k,B}^{+} < S_{k,B}$	If $I_{k,B}^{+} \leq C_{k,B}$	$\theta_{k,B}$	If $\{NQ_{k,A} = 0 \cap WIP_{k,B} = 0\}$ Or If $\{I_{k,B}^{+} \leq C_{k,B} \cap WIP_{k,B} = 0\}$
C	If $I_{k,C}^{+} < S_{k,C}$	If $I_{k,C}^{+} \leq C_{k,C}$	$\theta_{k,C}$	If $\{NQ_{k,A} = 0 \cap NQ_{k,B} = 0 \cap WIP_{k,C} = 0\}$ Or If $\{I_{k,C}^{+} \leq C_{k,C} \cap NQ_{k,A} = 0 \cap WIP_{k,C} = 0\}$
D	If $I_{k,D}^{+} \leq S_{k,D}$	If $I_{k,C}^{+} \leq C_{k,D}$	$\theta_{k,D}$	If $\{NQ_{k,1} = 0 \cap NQ_{k,2} = 0 \cap WIP_{k,D} = 0\}$ Or If $\{I_{k,D}^{+} \leq c_{k,D} \cap NQ_{k,A} = 0 \cap WIP_{k,D} = 0\}$

FIGURE 19: IMPROVEMENT MODEL SIMULATION – REPAIR- AND INVENTORY MANAGEMENT

For the reference model the situation is less complex. Orders are always released when the work in process is zero for that class, except for when high priority orders are processed (Figure 20).

REFERENCE MODEL – REPAIR- AND INVENTORY MANAGEMENT

Repairables Class		Order Signal	Processing Time Per Part	Release Order to Workshop Condition
A_{Prio}	B_{Prio}	If $I_{k,n}^{+} \leq s_{k,n}$	$\theta_{k,n}$	If $\{WIP_{k,n,prio} = 0\}$
A, C	B, D	If $I_{k,n}^{+} \leq s_{k,n}$	$\theta_{k,n}$	If $\{WIP_{k,a,prio} = 0 \cap WIP_{k,b,prio} = 0 \cap WIP_{k,n} = 0\}$

FIGURE 20: REFERENCE MODEL SIMULATION – REPAIR- AND INVENTORY MANAGEMENT

5.5 Results Representative Run

For all simulation runs goes that a replication with a length of two years for the period of March 22, 2012 – March 21, 2014 is performed several times to provide insightful information. First a representative run is conducted, then several optional scenarios are tested in a sensitivity analysis. For the sake of completeness, we define the service level per class n simply by Equation (4).

$$Service\ Level\ Class = \frac{Amount\ of\ Class\ Requests\ Fulfilled\ Before\ Requested\ Due\ Date}{Total\ Amount\ of\ Class\ Requests\ Received} \quad \textbf{(4)}$$

The representative run consists of two steps, first we run the simulation models for the situation including the outliers where it becomes clear the refurbishment circuit becomes unbalanced. Because of this unbalance in the system and the utilization of (close-to) 100% the waiting times will grow to infinity in the long term and the inventories will drop to zero. Thus these values are not useful as stated below, which is why they are marked in red. Then we run the slightly relaxed interpretation of the reality where the outliers in request sizes are removed. This results in a situation that is indeed congested like reality, but that is still balanced (Table 25). Here it becomes clear that the improved methodology is able to focus on the relevant performance by allowing for a better performance for the parts with a larger backorder impact, RCA and RCB.

REPRESENTATIVE RNLN DATA			
Parameter	**Improvement Model**	**Reference Model**	**Difference**
RCA Requests On Time	**66.56%**	**38.35%**	**28.21%**
RCA Requests Too Late	33.44%	61.08%	
RCA Requests Fulfilled Total	100.00%	99.43%	0.57%
RCB Requests On Time	**0.66%**	**14.84%**	**-14.18%**
RCB Requests Too Late	54.87%	24.29%	
RCB Requests Fulfilled Total	55.53%	39.12%	16.41%
RCC Requests On Time	**0.65%**	**2.87%**	**-2.22%**
RCC Requests Too Late	68.18%	86.15%	
RCC Requests Fulfilled Total	68.83%	89.02%	-20.19%
RCD Requests On Time	**1.25%**	**7.16%**	**-5.91%**
RCD Requests Too Late	66.94%	69.73%	
RCD Requests Fulfilled Total	68.19%	76.89%	-8.70%
Utilization Workshop	100.00%	97.85%	
Average Inventory Level RCA (parts)	0.7	0.4	0.3
Average Inventory Level RCB (parts)	3.7	1.8	1.9
Average Inventory Level RCC (parts)	2.7	2.7	0.0
Average Inventory Level RCD (parts)	2.0	2.3	-0.3
Avg Wait Time RCA Request (days)	30	55	-25
Avg Wait Time RCB Request (days)	294	286	8
Avg Wait Time RCC Request (days)	265	176	88
Avg Wait Time RCD Request (days)	212	168	44

TABLE 24: RESULTS RNLN REPRESENTATIVE SITUATION – ORIGINAL

Interesting results for the situation including the outliers are the improved performance for the RCA requests, and the higher total fulfillment of RCB requests. Even though the reference model performs better on the RCB service level, and for the RCC and RCD requests, it appears as if the improvement model is indeed beneficial for the performance of the classes most critical for the material availability of the WSs. The increased average inventory levels and decreased average waiting times for the RCA and RCB classes do add to that appearance. However, because of the extremely high utilization, no well-funded conclusions can be drawn yet.

REPRESENTATIVE RNLN DATA (outliers removed)			
Parameter	**Improvement Model**	**Reference Model**	**Difference**
RCA Requests On Time	**72.43%**	**35.47%**	**36.96%**
RCA Requests Too Late	27.57%	64.53%	
RCA Requests Fulfilled Total	100.00%	100.00%	0.00%
RCB Requests On Time	**75.25%**	**32.86%**	**42.39%**
RCB Requests Too Late	23.00%	54.18%	
RCB Requests Fulfilled Total	98.25%	87.03%	11.21%
RCC Requests On Time	**55.19%**	**56.08%**	**-0.89%**
RCC Requests Too Late	44.48%	43.92%	
RCC Requests Fulfilled Total	99.68%	100.00%	-0.32%
RCD Requests On Time	**56.13%**	**75.26%**	**-19.12%**
RCD Requests Too Late	40.12%	24.54%	
RCD Requests Fulfilled Total	96.26%	99.80%	-3.54%
Utilization Workshop	93.53%	91.37%	
Average Inventory Level RCA (parts)	0.7	0.3	0.4
Average Inventory Level RCB (parts)	3.4	2.1	1.3
Average Inventory Level RCC (parts)	1.7	2.0	-0.3
Average Inventory Level RCD (parts)	3.5	5.0	-1.5
Avg Wait Time RCA Request (days)	26	52	-25
Avg Wait Time RCB Request (days)	37	122	-85
Avg Wait Time RCC Request (days)	26	22	4
Avg Wait Time RCD Request (days)	35	14	21

TABLE 25: RESULTS RNLN REPRESENTATIVE SITUATION - OUTLIERS REMOVED

That changes for the results displayed in Table 25. Now we can see that the improvement model really is performing better for the most critical part classes, RCA and RCB. The performance is notably improved, whereas the performance for the less critical classes, RCC and RCD, is reduced slightly. The improved relevant performance is also visible in the higher average inventory levels for the RCA and RCB classes compared to the reference model, as well as the shorter waiting times. The opposite is true for the RCC and RCD classes. However, the gain on relevant performance is higher than the loss on less relevant performance. The simulation outcome is therefore that the proposed repairable spare parts methodology has significant improvement potential for the RNLN.

5.6 Model Validation

When we compare the results of the results for the situation without the outliers for the repair request quantity we find results alike the outcomes of our analysis of the historical data (Section 3.3). The service levels for the critical classes are lower than for the non-critical classes. There is a deviation from the analyzed service levels though. However, because of the limited size of the deviations, the similar service level performance characteristics, and the well-founded input data (Section 5.3) used based on the historical data we conclude that our model is useful for further use. Furthermore, in our analysis we have not added the pending requests to the unfulfilled orders, whereas we do that in our models. Especially for class A and class B where the fraction of pending orders are higher this would bring the results closer. In addition, the deviations in the outcomes that are present are caused by our interpretation of the historical data and the assumptions made about this data, and will therefore also be used as input for the improvement model. Both models will relatively be influenced evenly by our data input. We conclude our model is valid.

Category	Service Level Class Analysis	Service Level Class Simulation Model	Deviation
A	54.78%	35.47%	19.31%
B	55.60%	32.86%	22.74%
C	73.94%	56.08%	17.86%
D	69.40%	75.26%	5.86%

TABLE 26: COMPARISON IT SYSTEM AND SIMULATION REFURBISHMENT REPAIR LEAD TIME

5.7 Model Verification

In order to verify that our models behave according to expectations we test them using some extreme settings. First of all, we want to make sure that extremely high arrival rates lead to service levels of close to 0%, whereas we expect extremely low arrival rates to lead to close to 100% service levels. Furthermore, we expect an extreme increase of resource capacity also to lead to close to 100% service levels. Finally, we expect the results to be better when the repair delay is removed.

Scenario	Reference model Average Service Levels	Improvement Model Average Service Levels
Extremely high arrival rates (1000%)	0%	0%
Extremely low arrival rates (10%)	100%	97%
Extremely high resource capacity (1000%)	100%	100%
Removal of delay	88.5%	83.5%

TABLE 27: MODEL VERIFICATION

As becomes clear in Table 27 the models behave very much according to the expectations. The extreme scenarios also lead to extreme results in regard to the service levels achieved. Notable is the result for the removal of delay scenario where the reference model appears to perform better than the improvement model. However, this is not a weighted average so the better performance on class B tunes down the total performance of the improvement model compared to the reference. We can conclude our models are verified an behave according to expectations.

5.8 Sensitivity Analysis

The results show a situation that is indeed very much congested, similar to the results of the analysis performed. It is clear that the improved model is performing better since the performance is more balanced. However, we want to identify the extends to which this is true by performing sensitivity analyses on the various parameters part of the model. This will provide more useful managerial insights than just the representation of the reality.

5.8.1 Alternative methodology aspects

We test the possible alternatives suggested in Section 4.3.4 and in Section 4.4.3, to see what influence decisions made regarding the elements of inventory management and repair order dispatching have on the performance of the RNLN refurbishment circuit. We only consider the changes in service levels compared to the improvement model, since the average inventories and the average waiting times behave correspondingly to the changes in service levels.

In case of an (s,S,c) policy for the RCB articles the results are not varying much compared to the original settings Table 28. This can be explained by the fact that even when internal repair orders are batched in the reorder, they can still be processed individually due to the dynamic rules. However, the increases in the RCA, RCC and RCD performance are hampering the RCB performance, so this alternative is not better than the originally proposed methodology.

Parameter	(s,S,c) policy class B	Original Settings	Change
Service Level RCA	72.59%	72.43%	0.23%
Service Level RCB	73.71%	75.25%	-2.04%
Service Level RCC	55.52%	55.19%	0.60%
Service Level RCD	56.76%	56.13%	1.12%

TABLE 28: (S,S,C) POLICY RCB

When an (S,S-1,c) policy is used for the RCD items, with a c of 0, we obtain the results in Table 29. Actually, this policy leads to an improvement of the performance of all repairable spare parts classes. However, we know that an (S,S-1,c) results in extra activities for both ASM and the workshop planners. Whereas this might be beneficial for the critical- and long lead time parts because of their potential impact on the WS availability in case of backorders. Therefore we choose not to use this policy for repairable spare parts class D. Nevertheless, it is interesting to find that the implementation of an (S,S-1,c) policy for class D would actually benefit the performance for all classes, due to a higher utilization of the resources.

Parameter	(S,S-1,c) policy class D	Original Settings	Change
Service Level RCA	72.59%	72.43%	0.23%
Service Level RCB	76.48%	75.25%	1.63%
Service Level RCC	56.17%	55.19%	1.77%
Service Level RCD	61.33%	56.13%	9.27%

TABLE 29: (S,S-1,C) POLICY RCD

In case of increasing the short lead time RCB parts priority level so that it matches the priority of class RCA, we obtain the results in Table 30. As expected we obtain better results for RCB. These improvements only slightly decrease the RCA performance. However, the RCC and RCD performance are decreased more significantly by this alteration. Which scenario is best is based on what performance is preferred. We choose to stick to our logic of prioritizing long lead time parts.

Parameter	Increase priority RCB	Original Settings	Change
Service Level RCA	72.10%	72.43%	-0.45%
Service Level RCB	79.08%	75.25%	5.09%
Service Level RCC	52.92%	55.19%	-4.11%
Service Level RCD	53.64%	56.13%	-4.44%

TABLE 30: INCREASE PRIORITY RCB

In case of allowing absolute priority for critical status items we obtain the results from Table 31. The results are actually very good. Even though this slightly decreases the performance of the RCA items, the overall results are very good. The results can be explained by the slightly increased utilization and the increased efficiency of the resource in addressing repairs that prevent part requests from arriving late. This is a very useful insight in the potential value of the critical inventory level and the dynamic change in status of the priority for the parts from the various classes this results in. However, we would still not suggest providing absolute priority for the RCC and RCD classes, even when the critical inventory level is reached. Because for instance repair duration variability has not been taken into account, this could have undesired effects on the service levels for the higher criticality parts, which we would still suggest to benefit at the cost of the lower criticality parts.

Parameter	Increase priority critical levels	Original Settings	Change
Service Level RCA	71.94%	72.43%	-0.67%
Service Level RCB	87.62%	75.25%	16.44%
Service Level RCC	66.23%	55.19%	20.01%
Service Level RCD	52.60%	56.13%	-6.29%

TABLE 31: INCREASE PRIORITY FOR CRITICAL STATUS

The optimal alternative seems to be one wherein both the absolute priority is granted to items reaching their critical inventory status, in combination with adding an (S,S-1,c) policy for RCD parts. The results displayed in Table 32 are indeed displaying improvement compared to the original settings. Even though these optimal settings might not be applicable in all cases for the reasons stated at this particular alternatives, it is definitely interesting to see that the performance can even further be increased compared to the reference model displaying the current repairable spare parts management methodology.

Parameter	Optimal Settings	Original Settings	Change
Service Level RCA	72.10%	72.43%	-0.45%
Service Level RCB	88.17%	75.25%	17.17%
Service Level RCC	66.23%	55.19%	20.01%
Service Level RCD	57.59%	56.13%	2.60%

TABLE 32: OPTIMAL SETTINGS

5.8.2 Allocated refurbishment repair capacity

The refurbishment repair capacity is a fraction of the total repair capacity. The amount allocated to the refurbishment repair is an interesting parameter for the sensitivity analysis. Figure 21 shows that allocating additional capacity to the refurbishment repair activities results in higher service levels, allocating less capacity in lower service levels. Interesting to see is that the influence of this capacity allocation change results in different responses for the different classes. This is interesting information for the managerial insight in the proposed repairable spare parts methodology.

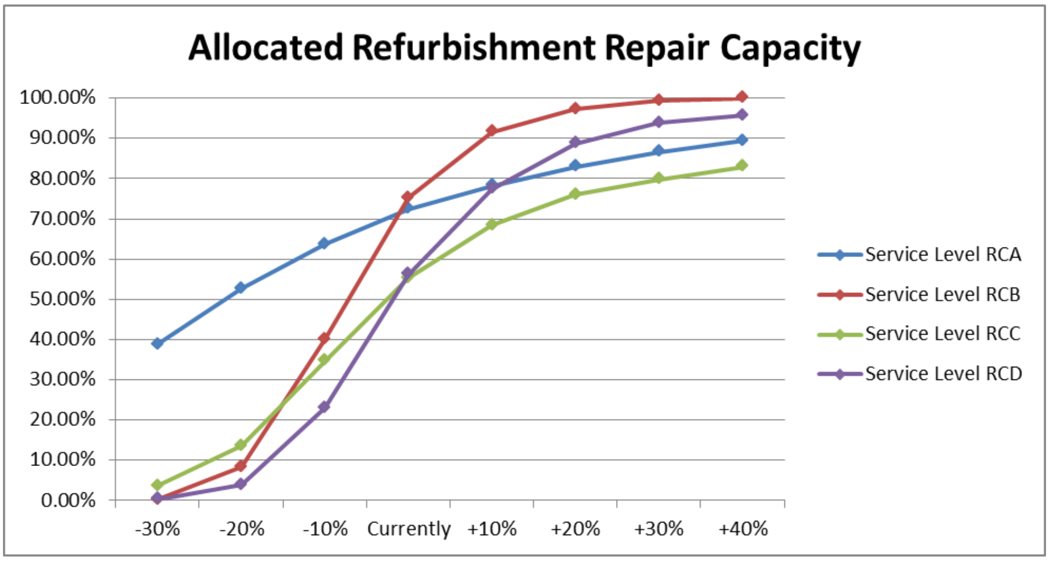

FIGURE 21: ALLOCATION REFURBISHMENT REPAIR CAPACITY

5.8.3 Inventory levels

When the total inventory levels (order-up-to levels) are changed, we obtain the results from Figure 22. The effects on the service levels appear to be straightforward, but provide additional insight.

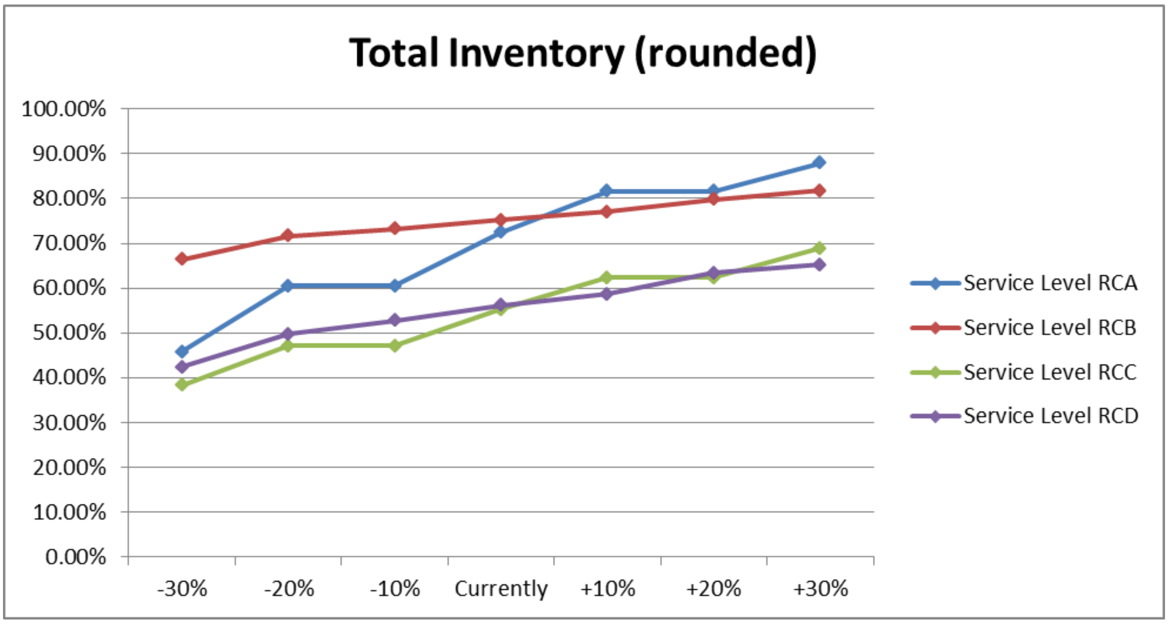

FIGURE 22: TOTAL INVENTORY

When the critical inventory level of RCB is changed, the results visible in Figure 23 are obtained. It becomes clear that the higher the critical inventory level is in comparison to the reorder level, the higher the service level for that class becomes. This is decreasing the service levels of the classes influenced by the additional repair capacity allocated to the increased priority order, RCC and RCD.

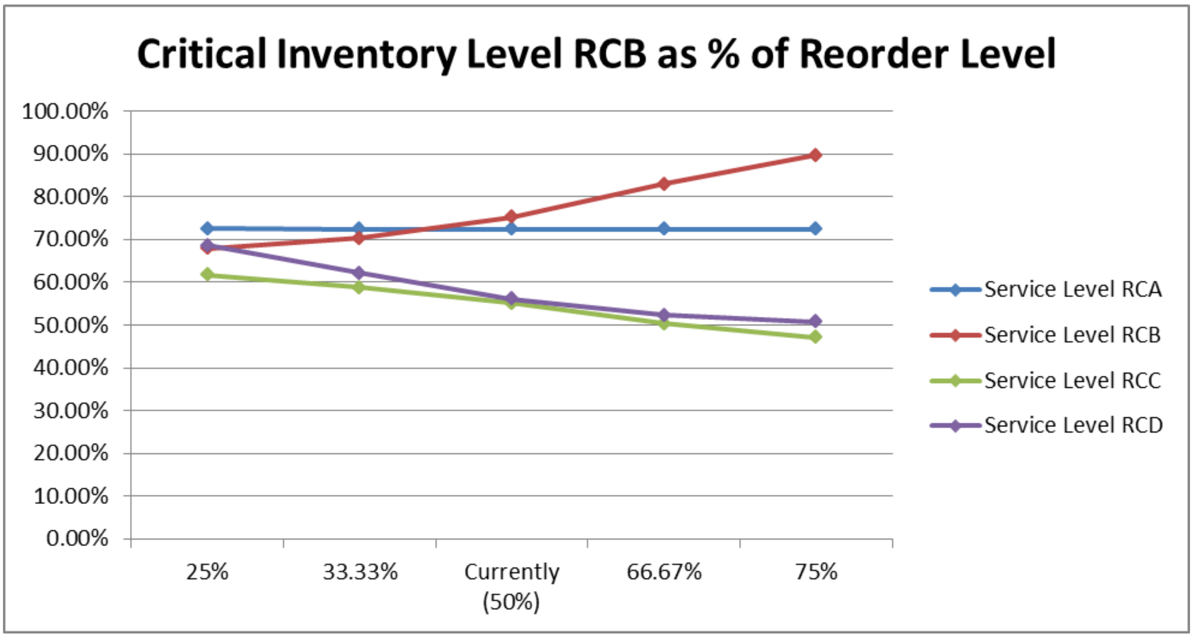

FIGURE 23: CRITICAL INVENTORY LEVEL RCB

5.8.4 Requested lead times

Increasing the requested lead times for the long lead time items, so effectively changing the request behavior of the DOPS operating the WSs results in the changes of performance visible in Figure 24. The results are most notable for the high priority items.

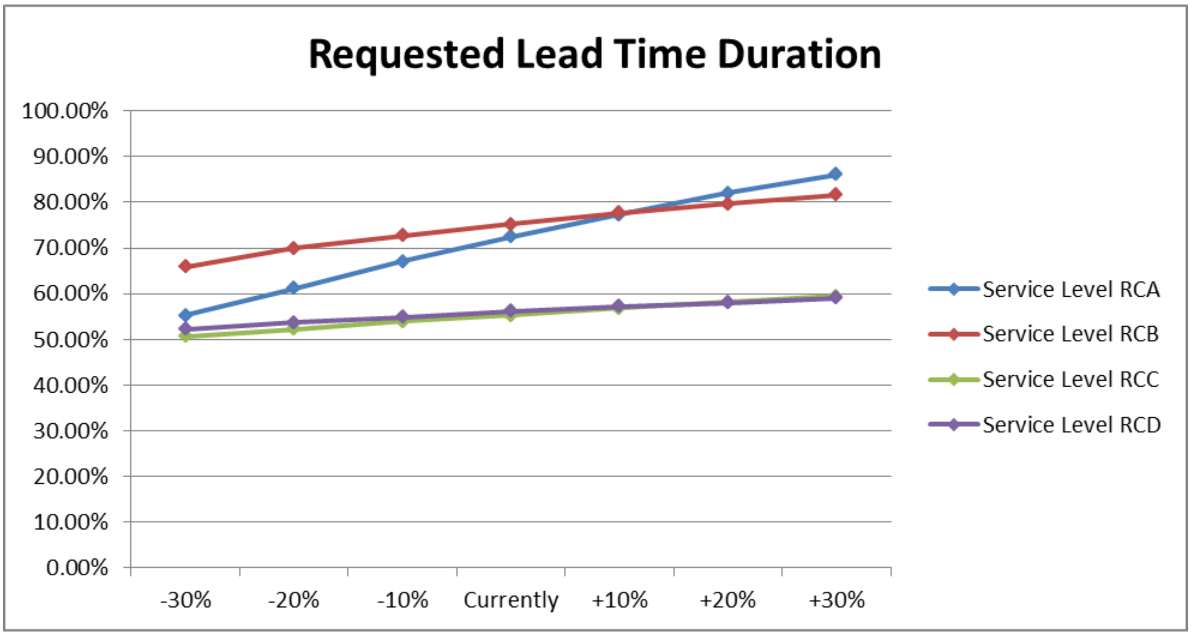

FIGURE 24: INCREASED REQUESTED LEAD TIMES

6 Implementation

Chapter Abstract

This section contains information regarding an actual implementation of the proposed improved repairable spare parts management methodology for the RNLN. Both recommendations for the organization as well as organizational aspects for an actual implementation provide a guideline.

6.1 Recommendations to the RNLN

Based on the insights obtained from this research we have several important recommendations for the RNLN, with the goal to improve the performance of the refurbishment circuit. It is important to reassess the complete repairable spare parts list by people with operational insight and knowledge about the WSs and installations currently in use. Based on that the repairable spare parts currently in the inventory that are not used anymore should be removed from the inventory. Furthermore, it is important to constantly evaluate whether the parts really deserve the status 'repairable', whenever low-valued parts are costly to repair and available at the market for instance. For new parts about to obtain a repairable status this assessment should be performed right away.

After the composure of the inventory of repairable spare parts has been reassessed and validated, the classification methodology suggested in this research should be implemented specifically for the repairable spare parts of the RNLN. This implementation is easy since it is a matter of assigning a part to a repairable spare parts class based on the parts' quantitative characteristics. After this implementation the people working at ASM should verify whether the parts within their responsibility indeed obtained the correct status, especially in regard to their criticality for the WS availability. As explained in this research, the RNLN currently has no unambiguous concept for the determination of this criticality. We would recommend the RNLN DMI to investigate the possibilities for finding an unambiguous construct for the component criticality, since it is vital for the selection of the right inventory policies for the right components. By making both the people responsible for the ASM of the parts and the people operating the WSs responsible for assigning a suitable criticality for the repairable spare parts this issue can be resolved.

The allocation of the limited repair capacity should be assessed. This limited repair capacity is shared which leads to a situation where only a fixed amount of repair capacity is available for refurbishment repair activities. The remainder of the capacity is used for both appointed maintenance activities, and for incidental or corrective maintenance activities. In the latter category regularly heavily resource-consuming repairs are required. For instance because the repair has to be conducted at an external location which requires resources to be shipped (both people and material resources), or under a lot of time-pressure. A large fraction of these resource-consuming repairs occurs because the requested GVU repairable spare parts are not available, which is a direct result of the refurbishment circuit not functioning properly. Allocating more of the available resource capacity to the refurbishment repairs leads to a better availability of the relevant repairable spare parts as explained and proved. This extra allocated capacity can be reduced from the capacity allocated to the incidental maintenance activities due to the higher availability of the requested parts.

Furthermore, it is important for the material planners of the DMI and the workshop refurbishment repair planning personnel to actually stick to the order policies as determined for the complete organization, since the options for the overruling of these policies and the accompanying parameters and parameter values are too easily accessible. By providing proper instruction and education of the people working with the methodology, this issue can be resolved.

6.2 Organizational Aspects Implementation

In line with the implementation strategy there are several relevant aspects for the implementation of the proposed repairable spare parts management methodology at the RNLN. An overview of the important aspects of these phases and the resources required per implementation phase is provided in Table 33. The implementation is based on a timely implementation, related to the imminent implementation of a new IT system at the ASM and other organizational parts of the RNLN. We see options to use this IT system implementation work as an opportunity to implement the proposed methodology simultaneously. Therefore the implementation is assumed not to take longer than one year, this time window is used. FTEs are therefore expressed for a duration of one year in total. We consider an FTE to be equal to 42*40 = 1680 hours.

Even though some of the aspects of the methodology can be implemented separately and will even lead to an improvement of the performance, we would strongly suggest to implement the complete methodology. The strength of the methodology lies in the integration of the generally separate elements of the repairable spare parts management methodology. Important is to realize that the financial gains are not expressed, as currently the budget and refurbishment resources available are considered to be fixed. The gains are therefore considered to be increased service levels for the relevant repairable spare part requests, leading to an increases availability of the RNLN WSs. The expected gains are expressed by the simulation results in Section 5.5. Another option would be to achieve the current performance by allocating less capacity for the refurbishment repair.

ASPECT	REQUIREMENTS	EXPLANATION
INITIAL IMPLEMENTATION PHASE (1 year window)		
1) Spare parts classification implementation		
Assessment of spare parts classified repairable	1 FTE (divided over ASM planners for various ASM groups)	Spare parts currently expressed as repairable need to be assessed for their actual reparability. Only a small disputable will take time.
Assigning an unambiguous criticality value to repairable spare parts	1 FTE (divided over ASM planners for various groups)	Assign the criticality value based on DOPS experience and backorder impact. Binary and possibility to use current constructs, so this phase can and should be completed fast.
Application of proposed classification methodology	0.5 FTE (divided over ASM planners for various ASM groups) 0.5 FTE (implement rule in IT system)	The spare parts classified as repairable are assigned to a repairable spare parts class. This can be done by applying a quantitative rule to the IT system, but the outcomes have to be verified by the ASM material planners.
2) Inventory management implementation		
Application of proposed inventory management methodology	0.5 FTE (divided over ASM planners for various ASM groups) 0.5 FTE (implement	The spare parts classified as repairable are assigned with an inventory policy, based on their classification and their demand frequency. This can be done by applying a quantitative rule to the IT system, but the outcomes have to be

	rule in IT system)	verified by the ASM material planners.
3) Dynamic dispatching implementation		
Education of workshop repair planning personnel	4 FTE (divided over planning personnel) 1 FTE (divided over ASM personnel giving the instruction)	The dynamic dispatching implementation is the crucial step for the success of the methodology. The people about to use the methodology should therefore be educated in the reasoning and the usage of the methodology. This requires time from both the educated personnel and the instructors.
Application of proposed dynamic workshop dispatching management methodology	1 FTE (divided over workshop planners for various workshops) 2 FTE (implement rule in IT system)	The repairable spare parts classes obtain their , based on their classification and their demand frequency. This can be done by applying a quantitative rule to the IT system, but The outcomes have to be verified by the ASM material planners.
TOTAL **Implementation Phase**	**12 FTE for aspects named above** **2 FTE for two project leaders, 1 ASM and 1 Workshop Planning**	**In total for the initial implementation phase 14 FTE are required. Important is that the project is supported from both sides of the equation, therefore two project leaders are required. Important is the integration of the methodology in the IT system which is currently implemented to allow real integration and the best performance.**
FOLLOW-UP PHASE (window with rolling horizon – no FTE estimations)		
Continuous evaluation of performance improvement		The actual relevant performance achieved by the improvement methodology should be continuously tracked, and information about the improvements mad should be spread.
Updating methodology elements and aspects		Based on the performance improvements and analyses, the methodology should continuously be evaluated and updated when required.
Instructing personnel		(New) personnel should be instructed on the methodology and its logic, to make them aware of the gains achieved by its correct usage and implementation.
Applying methodology to new acquisitions	Simulation Software (e.g. Arena)	If the methodology is implemented correctly, it can be used to optimize the spare part purchase decisions for the acquisitions of new WSs and systems, using a simulation.

TABLE 33: IMPLEMENTATION PHASES REPAIRABLE SPARE PARTS MANAGEMENT METHODOLOGY AT THE RNLN

7 Conclusions, Recommendations, and Limitations

Chapter Abstract

The conclusions that can be made from the preceding sections suggest that the proposed integrated repairable spare parts management methodology indeed has interesting and significant improvement potential for the RNLN. Furthermore, the integration of the elements for such a methodology has interesting insights for repairable spare parts management in general, and contributes to the current literature. However, the research also has limitations, due to the complexity of the environment in which the repairable spare parts management has to take place. Based on this, further research is suggested. This section also provides recommendations for the RNLN in order to make concrete steps in improving the refurbishment performance.

7.1 Conclusions

The most important conclusions obtained throughout this research are discussed in this section. These conclusions all serve to answer the main research question as formulated in Section 2.2 (also stated below) and the sub questions relevant for answering that question.

"How to improve the repairable spare parts management methodology at the RNLN to increase its relevant performance, taking the limited resource capacity into account?"

The conclusions can be addressed in two sections, using the main sub questions as a guideline.

7.1.1 Repairable spare parts management methodology

The current repairable spare parts management methodology used at the RNLN results in an unsatisfying performance regarding the availability of relevant repairable spare parts. We have found a way to express this relevance of repairable spare parts by coming up with a suitable classification for the RNLN parts (Section 4.2). Using this classification in our analysis, indeed the performance is low for the parts that we deem to be most relevant for the WS availability (Section 3.3). Furthermore, we can actually show that the low performance is related to the current methodologies, as these methodologies have a beneficial influence on the availability of the less relevant parts at the cost of the availability of the relevant parts. The most important weaknesses in the current methodologies were found to be the current classification methodology and the pre-determined service levels based on that classification, the repair-ordering policy for the slow-moving high-valued repairable spare parts, and the current dispatching rules not taking the backorder impact of the unavailability of the requested spare parts into account when dispatching repair orders to the DMI workshops (Section 3.2).

Based on this analysis we have come up with an improved repairable spare parts methodology to increase the relevant performance of the refurbishment circuit. We have focused on the weak parts of the current methodologies. First this resulted in a classification methodology that has the aim to benefit the parts that have the highest backorder impact, so the parts that result in the longest decreased material availability of the WSs because of their criticality and their procurement lead time (Section 4.2). This classification methodology serves as a basis for the repairable spare parts inventory management. Because of the fact that the current inventory sizes for most repairable spare part types are fixed, we have focused on an improvement of the reordering policies used by increasing the reorder interval for the most relevant parts (Section 4.3). Furthermore, we have introduced a dynamic aspect by adding a critical order level to the policies for most repairable spare parts. Based on this dynamic aspect that takes the real time inventory position into account the priority of the parts can temporarily be altered, which is in line with the feedback between the repairable spare parts management elements in our project design (Section 2.4). Based on both the classification and the dynamic inventory position, the dynamic dispatching rules are defined (Section 4.4). These rules take into account which parts are most relevant for the availability of the WSs, and based on that they determine the dispatching sequence for the repair orders at the DMI workshops. Dynamically, the inventory position is updated according to the processing of the orders. This results in feedback to the first two elements, in order to rearrange the part relevance (and thus its repair order priority) for the WS availability when the inventory position allows for this.

7.1.2 Improvement potential of proposed methodology

Using representative historically funded input data (Section 5.3) and simulation models (Section 5.4) to compare the current methodology to the proposed improvement methodology we find that it indeed seems to prove that integrating the elements according to the suggested framework leads to better results. The availability for the parts that were deemed most relevant for the WS availability increases significantly, by allowing for a slightly lower availability for the less important parts (Section 5.5). Using the more pro-active approach when restocking these actually relevant parts results in a higher availability in case of peeks in the demand requests for these parts, as found in the demand characteristics for the spare parts. Furthermore, the proposed classification methodology allows for a better insight and more control when managing the spare part repairs and the allocation of the available workshop capacity. Findings from the sensitivity analysis (Section 5.8) even further increase the insight in controlling the circuit according to our improvement methodology. Finally, all research findings result in an implication suggestion (Section 6).

7.2 Limitations and Recommendations for Further Research

Due to the complexity of the repairable spare parts management in general the research has limitations. These limitations serve as a foundation for recommendations regarding potential further research to be conducted in order to further improve the repairables spare parts management performance of the RNLN and for organizations with a similar spare parts portfolio in general.

As explained, often repairable spare parts have a (complex) structure with multi-indenture characteristics. An important limitation regarding the repair of repairable spare parts is that we have considered a LORA (level-of-repair analysis) was conducted up front, as to identify the correct level to conduct the repair on. In reality, this LORA in itself takes time too, furthermore the results are not always perfect leading to an incorrect estimation of the repairs to be conducted and the spare parts required. In addition, the assumption that there is always one component only that causing the failure is limiting and should be relaxed in the future. This can result in a repair that requires several steps, for instance in different workshops. Extension to a job-shop type of model to account for the specific routings in workshops that some repairables have to follow. Furthermore, this might ask for a required combination of specific available workshop resources required for the refurbishment job. Repairables only require one job for one resource (personnel and equipment) in this research, in practice the complete repair enhances multiple steps, sometimes on multiple machines and with multiple persons involved. This obviously increases the complexity of the situation intensively. In addition, repairables sometimes turn out to be unrepairable, so that they are consumed whenever repair is not possible after usage, due to economic or technological reasons. Instead, repairs are perfect in this model and always succeed, so the actual state of the part is not taken into account.

Similarly, as stated earlier in this research, for a fraction of the parts there is actually an option for both internal and external repair. This means that based on the dynamic real time information a choice can be made to either conduct the repair order internally, or to outsource the repair. An optimization of this choice between external repairs and internal repairs is a point for further research. This optimization should involve the elements of potential savings, the influence on the parts availability, and the available refurbishment repair capacity. If all this information is available using the actual status of the system, this increases the flexibility and control for the management. Other aspects should also be investigated for the optimization of the dynamic integration of the management elements. The change of importance of outstanding repair orders based on the actual inventory position is a good start, but even the inventory policy could be up for a change based on dynamic information, or at least its parameter values. This definitely has potential for further research, as the improvement potential for an integrated framework is shown in this research.

This research uses the assumption that there is only one central stock keeping inventory. In reality the WSs also carry a (limited) inventory of repairables. This would in reality influence the inventory position of the repairables and the availability of parts. In fact, the network has a two-echelon structure where the WSs can be considered to serve as bases. For purposes of avoiding unpractical complexity we have assumed our problem to only be of a single-echelon structure. Furthermore, the repairables have to be repaired at the central location anyway, for almost all repairable spare parts this is impossible at the WSs. Therefore we have treated the requests for parts that are added to the inventories on board of the WSs as regular part requests. This two-echelon like structure is more regularly found in repairable spare parts management, so this limitation is interesting for further research. The other way around it is important to consider the fact that the WSs also store failed parts for a while. Whenever a failure occurs, the equivalent working parts are usually immediately requested to conduct a repair-by-replacement. However, the ship might be in a position where it is not possible to also immediately hand-in the failed parts. This can result in a situation where the requested parts cannot be repaired because the failed parts are still out on several WSs because they were not able to hand these parts in yet. Currently, the return policy of failed repairables is not working optimally. We have not researched this influence. This might however be an interesting approach for further research, because it has implications for the dispatching of repair jobs to the workshops. Furthermore, Section 4.3.2 only suggests relatively straightforward inventory policies since these policies can already lead to significant improvements for the RNLN. However, further extensions such as a replenishment delay to create a $(S-1,d,S)-policy$ or an $(s,d,S)-policy$, as suggested by van Duren (2011), could possibly lead to even further improvements. Finally, it is important to realize that even though we have showed that the service levels of relevant spare parts was increased, and thus the availability of the WSs, the latter one is still an indirect effect and hard to express. Furthermore, the effect of the improved repairable spare parts management performance on the reduction of incidental (emergency) repairs required is not calculated.

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9 Appendices

9.1 Interview overview

An alphabetical overview of RNLN employees who have contributed to this research is visible in Table 34. Most of these people have been interviewed in order to gather information and data, or in order to validate certain constructs and concepts within the research.

	Name	Department	Function / Subject
Cora	Altena	Material Techniques / SWS / Engineering	Engineering / ISS Contracts
Frans	Boeije	Maritime Logistics / Inventory Management	Assortment Manager MTP
Dirk	Egmond, van	Maritime Logistics / Inventory Management Support	Advisor Internal Logistic Matters
Hans	Garstenveld	Maritime Techniques / SWS	Senior Work Planner
Thijs	Gijn, van	Maritime Maintenance	Head Maritime Maintenance
John	Huig	Supply Chain Management	Data Management
Hidde	Hylarides	Material Maintenance / System Management	System Manager Big Grey
Henk	Jansen	Maritime Techniques / SWS / Support	Head Support (shared)
Paul	Kense	Maritime Techniques / SWS / Engineering	ILS
Hans	Kootkar	Maritime Techniques / SWS	Work Planner
Sander	Leeuwen, van	Material Maintenance / System Management	System Manager LCF
Jelle	Loosman	Maritime Maintenance	Gas Turbine maintenance
Richard	Middelbos	Programming / Analysis	Advisor
Frits	Nieuwerf	Maritime Maintenance / Maintenance Analysis	Senior Maintenance Analyst
Kees	Linden, van der	Maritime Maintenance / Coordination	Head Coordination
Bart	Pollmann	Maritime Logistics / Inventory Management	Senior Assortment Manager
Peter	Porto, de	Material Maintenance / Maintenance Management	Portfolio?
Lieuwe	Rienstra	Maritime Logistics / Inventory Management	Material Planner
David	Ruiter, de	Material Logistics / Supply Chain Management	Senior Supply Chain Manager
Peter	Salzberger	Maritime Maintenance / Maintenance Management	Senior Portfolio Planner
Theo	Schouten	Maritime Maintenance	CBM
Peter	Sluijter	Maritime Logistics / Inventory Management SWS	Assortment Manager SWS
John	Uijthof	Maritime Techniques / SWS	Senior Work Planner
Nico	Ursem	Maritime Techniques / C4i and New Units	Work Planner
Tom	Vries, de	Maritime Techniques / SWS / Support	Head Support (shared)
Arnout	Wevers	Tromp / Technical Service	Head Technical Service
Danny	Wielens	Maritime Maintenance / Submarines	Senior System Engineer
Kees-Jan	Woltjer	Maritime Techniques / Central Support	Analysis / Data
Annet	Zuidberg	Material Logistics / Supply Chain Management	Supply Chain Manager
Michal	Zulawinski	Material Maintenance / System Management	System Manager Submarine

TABLE 34: INTERVIEW OVERVIEW

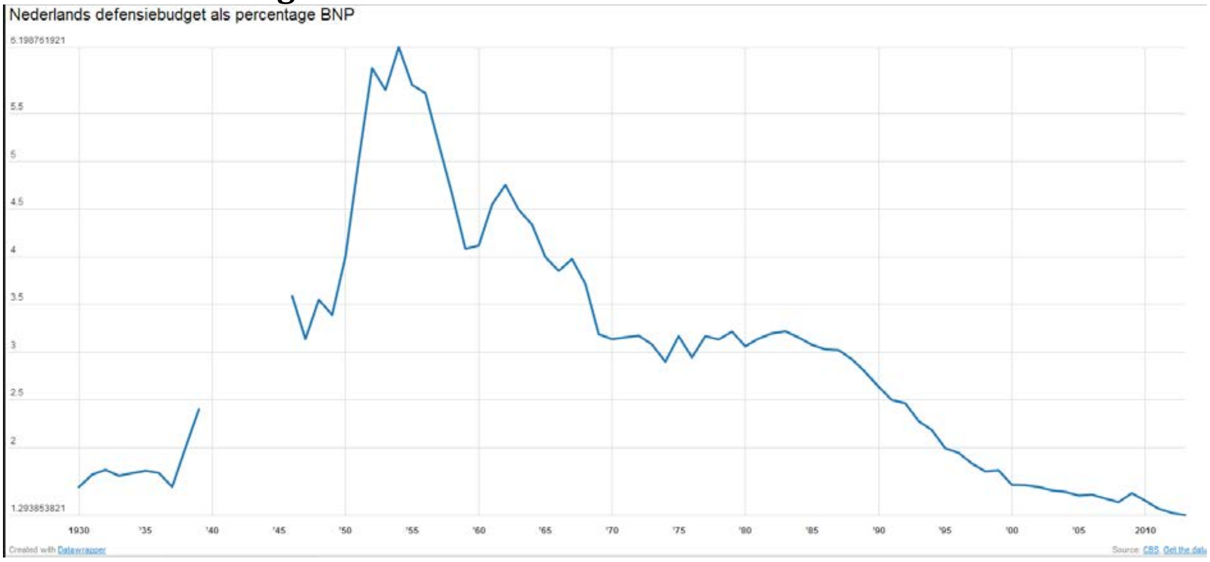
9.2 Mathematical notations for inventory policies and dispatching rules

The following parameters are used in regard to this position for the items:

	Workshop Characteristics	
k		$DMI\ Workshop\ Type$
K		$Set\ of\ DMI\ Workshops$
R_k	$k \in K$	$Number\ of\ Resources\ k$
φ	$\varphi \in \{1,2,3\}$	$Dynamic\ Priority\ Position\ in\ Queue$
$Q_{k,\varphi}$	$k \in K;\ \varphi \in \{1,2,3\}$	$Sub\ Queue\ \varphi\ for\ k$
$NQ_{k,\varphi}$	$n \in N;\ k \in K;\ \varphi \in \{1,2,3\}$	$Number\ of\ Orders\ in\ Sub\ Queue\ k,\varphi$
$WIP_{n,k}$	$k \in K$	$Work\ in\ Process\ k$
I		$Industry\ 'Workshop'$
	Repairable Component Characteristics	
N		$Set\ of\ Repairable\ Classes$
n_k	$n \in N;\ k \in K$	$Class\ n\ Repairable\ Item\ Repaired\ at\ Workshop\ k$
$\theta_{k,n}$	$n \in N;\ k \in K$	$Repair\ Lead\ Time\ n_k$
$\theta_{I,n}$	$n \in N$	$Repair\ Lead\ Time\ n\ at\ n_I$
	Repairable Component Inventory Characteristics	
β_n	$n \in N$	$Inventory\ Price\ Fraction\ n$
$S_{k,n}$	$n \in N;\ k \in K$	$Determined\ Order\ Up\ To\ Level\ for\ n_k$
$S_{I,n}$	$n \in N$	$Determined\ Order\ Up\ To\ Level\ for\ n_I$
$s_{k,n}$	$n \in N;\ k \in K$	$Determined\ Reorder\ Level\ for\ n_k$
$s_{I,n}$	$n \in N$	$Determined\ Reorder\ Level\ for\ n_I$
$c_{k,n}$	$n \in N;\ k \in K$	$Critical\ Stock\ Level\ for\ n_k$
$Q_{k,n,\tau}$	$n \in N;\ k \in K$	$Repair\ Order\ Size\ for\ n_k\ at\ time\ \tau$
$x_{k,n}$	$n \in N;\ k \in K$	$Inventory\ k - factor\ for\ n_k$
$I^+_{k,n}$	$n \in N;\ k \in K$	$On\ Hand\ Inventory\ for\ n_k$
$I^+_{I,n}$	$n \in N$	$On\ Hand\ Inventory\ for\ n_I$
$I^-_{k,n}$	$n \in N;\ k \in K$	$Amount\ of\ Outstanding\ Backorders\ for\ n_k$
$I^-_{I,n}$	$n \in N$	$Amount\ of\ Outstanding\ Backorders\ for\ n_I$
	Repairable Component Demand	
$\lambda_{k,n}$	$n \in N;\ k \in K$	$Demand\ Rate\ for\ n_k$
$\lambda_{I,n}$	$n \in N$	$Demand\ Rate\ for\ n_I$
$\mu_{k,n}$	$n \in N;\ k \in K$	$Mean\ Demand\ Size\ for\ n_k$
$\mu_{I,n}$	$n \in N$	$Mean\ Demand\ Size\ for\ n_I$
	Simulation	
τ		$Current\ Time\ (in\ hours)$

TABLE 35: OVERVIEW OF MATHEMATICAL NOTATIONS

9.3 Defense budget trend



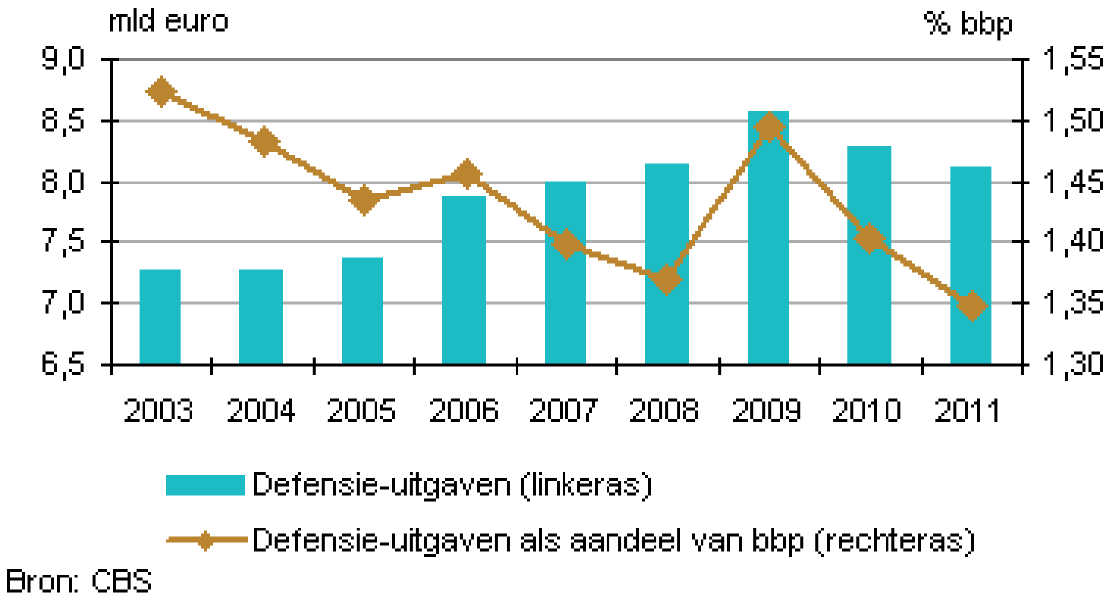


FIGURE 25: DUTCH DEFENSE BUDGET TREND (CENTRAAL BUREAU VOOR DE STATISTIEK, 2011)

9.4 Organizational Structure RNLN

The Royal Netherlands Navy has the following general (simplified) structure:

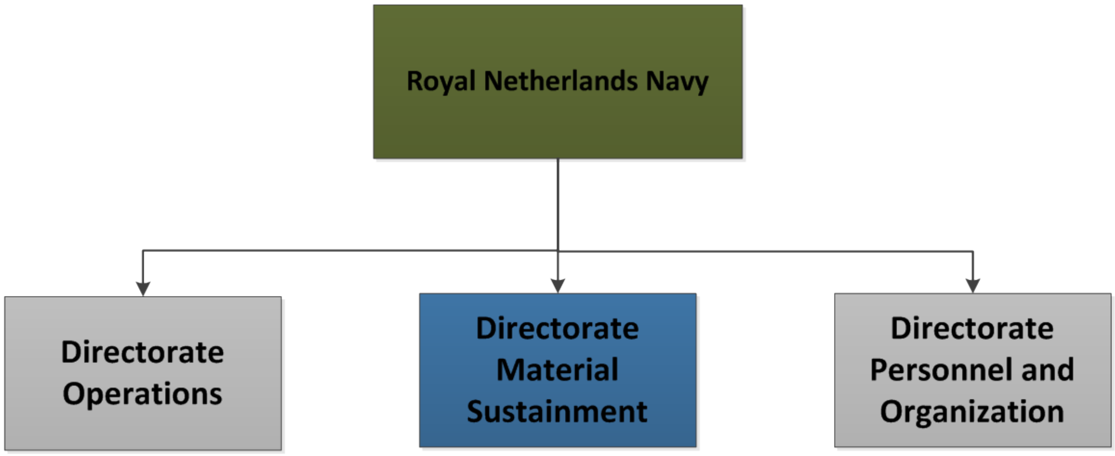


FIGURE 26: RNLN ORGANIZATIONAL STRUCTURE

9.5 Organizational Structure DMI (Directorate Material Sustainment)

The most important directorate for this thesis has the following organizational structure:

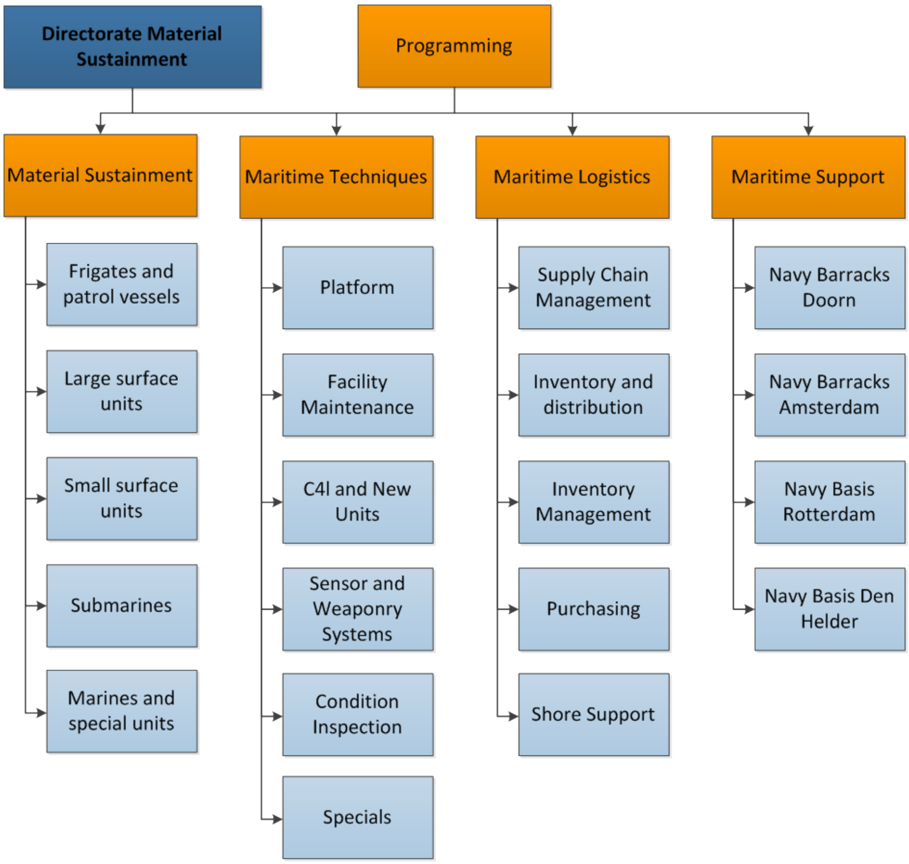


FIGURE 27: DMI ORGANIZATIONAL STRUCTURE

9.6 Maintenance process architecture RNLN

The following figure provides the maintenance process architecture of the RNLN as determined in the base line study (Buiting, 2014):

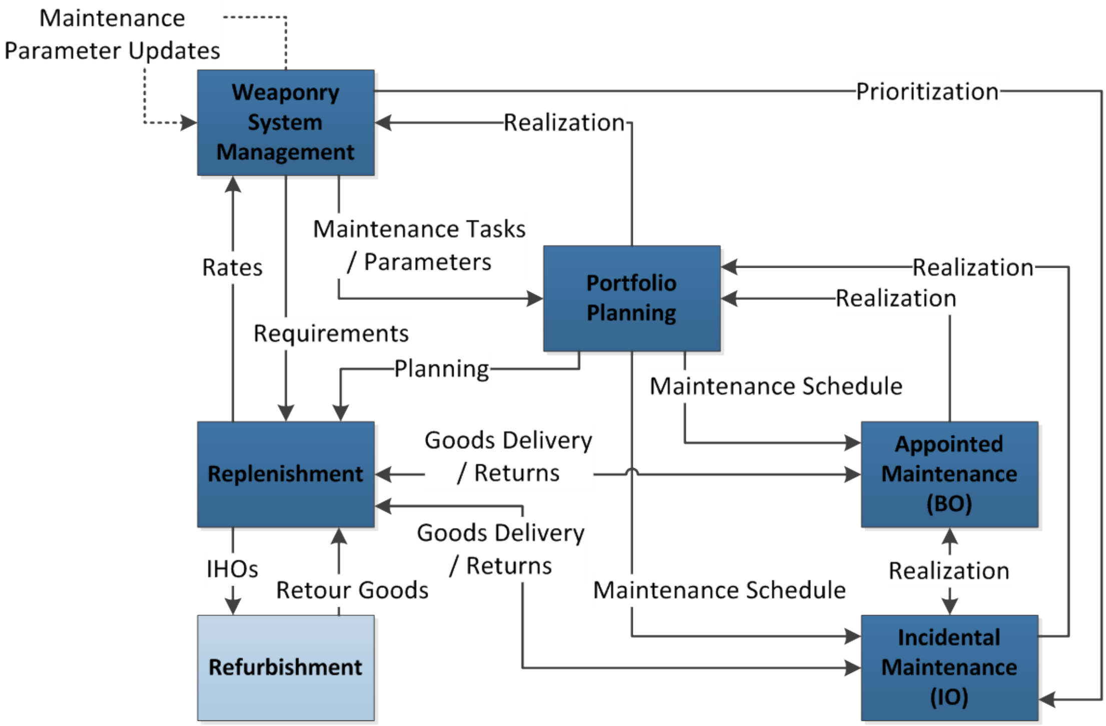


FIGURE 28: RNLN MAINTENANCE PROCESS ARCHITECTURE

9.7 Refurbishment circuit architecture

The following figure shows the architecture of the refurbishment circuit.

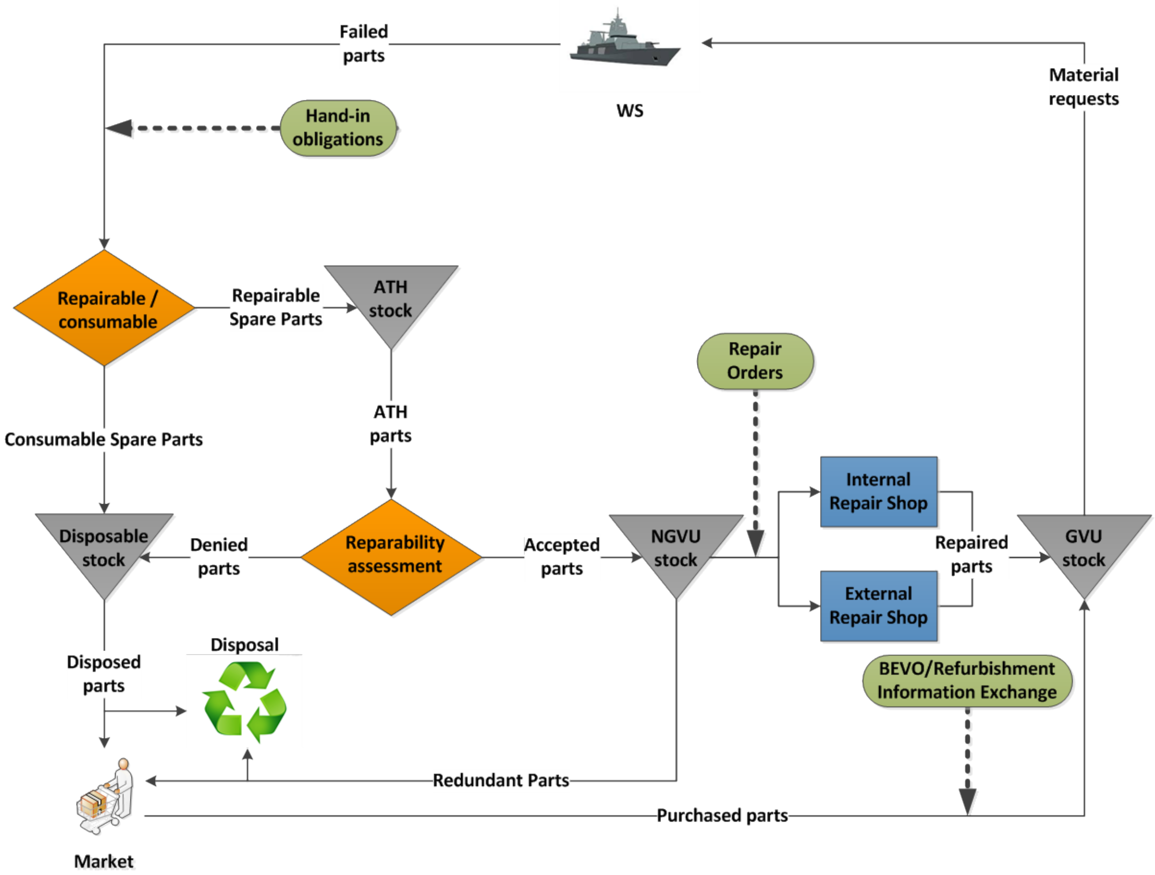


FIGURE 29: RNLN REFURBISHMENT CIRCUIT

9.8 RNLN maintenance processes explained (Buiting, 2014)

Process architecture of the DMI

In addition to the already quite complex overall RNLN service supply chain, the DMI has a complicated maintenance processes architecture involving all facets of the organization. Appendix 9.6 provides an overview of the most important maintenance processes and their interaction. This overview is a simplified version of the real situation, since in practice many other (sub)processes are involved. However, in regard to clarity this overview is more useful. An interesting note is that the RNLN is implementing their ERP system much in line with this simplified overview.

The remainder of this section describes the various parts and their interactions within the maintenance process in more detail. These sections provide clarification on the arrows displaying the process interactions in the figure above.

Weaponry system management (WSM)

The WSM (weaponry system management) function is important within the ILS (integrated logistic support) concept. In the current situation mainly decisions regarding the maintenance during the operation & maintenance phase WS life cycle are made by the WS manager. The concept of ILS is explained further later on, this section only considers the process of WSM.

Basically, WSM has knowledge of relevant maintenance tasks that need to be conducted in order to sustain the WSs. This knowledge is obtained from ILS managers and from DMO information based on the designs of the WSs. Furthermore, the WSM process has the input of the rates for the required materials and other resources from the replenishment process and the maintenance parameters provided. Based on this input and the available budgets, the WSM process decides which maintenance tasks will be conducted to which WS in which period, taking the missions to be conducted into account. Per WS type the required maintenance tasks to be conducted are provided to the portfolio planning process so that these tasks can be scheduled. Also, the tasks to be conducted are communicated to the replenishment process so that the required materials and other resources can be provided in time.

Whenever the required tasks cannot be conducted during the BO process there is a possibility to conduct the tasks during the IO process. Furthermore, whenever unforeseen maintenance tasks are required due to system or installation failures, the IO process is also required. In the case a conflict arises due to a shortage of resources such as work capacity, budget and materials, the WSM process can prioritize between the maintenance tasks on hand based on an optimization on a higher level.

Based on the realization information of the execution of the required maintenance tasks during the BO process and during the IO process the relevant maintenance parameters can be updated. This is done in cooperation with ILS managers and technical engineers. Notice the fact that the arrow displaying this process in Figure 28 *is dotted. This is purposely done in order to show that this process is not always occurring the way it should be.*

Portfolio planning

The RNLN is working according to a concept called portfolio planning to make sure the input of all required maintenance activities as determined by the WSM process fit within the available capacity. Input for this process is the vessel operation and training schedule which is made by DOPS taking the DMO and WSM prescribed appointed maintenance periods into account. Based on this schedule the long term planning of the WS maintenance is made for all WS types. The portfolio planning process *uses an horizon of six years. Three planning levels are used, macro, meso and micro. As BO activities come closer and their planning becomes more specified they move from the macro level towards the meso level, and finally towards the micro level.*

As the maintenance tasks move down the line the planning gets more detailed and the planning is agreed upon in cooperation with the other actors required within the DMI such as the workshops. The required resources are determined and requests for these resources are spread out at the meso level, for instance to the replenishment process and the appointed maintenance process. Finally the actual official maintenance orders and suborders are placed at the micro level. Note that capacity buffers are left over for extended durations of the BO process and for occurrences of the IO process.

The actual realization of the BO process and the consequences for the realization of the IO process are looped back to the portfolio planning process. Based on this information the realization of the planning process can be send back to the WSM process, so that the planning norms can be updated for planning for upcoming activities. As stated in the previous section, the updating action of the maintenance parameters is not standardly performed, but this regards the desired situation.

Appointed maintenance (BO)

The BO process uses the planning from the portfolio planning process as its main input. The maintenance activities to be conducted during the BO process come forth from this process. Finally, requests for incidental maintenance that are still unattended due to a lower priority at the time of the request are added to the BO maintenance list.

All required material resources to conduct the required BO maintenance activities are provided by the replenishment process. For maintenance on installations and components during the BO process goes that whenever it is possible to complete all required activities within the available BO window a repair-by-repair strategy is used. In cases where this is not possible (e.g. the goalkeeper installation, a last-resort defense systems against incoming missiles) a repair-by-replacement strategy is used, these installations or components will enter the refurbishment circuit.

The main output of the BO process regards the realization of the maintenance activities conducted. This regards both the actual level of completion of the required maintenance activities, and the relevant information about the execution of the conducted activities such as the extent to which resources are consumed. Whenever required maintenance activities are not completed the BO window has to be extended, or these activities can be moved on towards the IO process. The realization information flows back to the portfolio planning process in order to enable relevant information updates.

Incidental maintenance (IO)

The process of IO has the realization of the BO process and the required incidental maintenance tasks as determined by the portfolio planning process as input. In addition the required material input is coming from the replenishment process. The maintenance tasks conducted by the IO process are based on the important pending requirements of the WSs. Usually this regards failures of installations with a certain amount of criticality for operational use of the WS, negatively affecting the material availability and thus the operational availability. Often these failures need to be addressed on a short term, which means the IO process is subject to high variability input.

The output of the IO process contains the realization information for the portfolio planning process much like the equivalent for the BO process described earlier. Furthermore, output of the required IO *tasks not conducted due to a low priority or a proximity of a BO window, making it more efficient to postpone the tasks, goes out to the BO process.*

Replenishment (BEVO)

The replenishment (BEVO) process has the goal to provide the required parts for the required maintenance activities in time. This partially enhances procurement, but also guaranteeing stocked resources are available when required. The main input is provided by the WSM process and the portfolio process. This input regards the expected required material resources to be delivered by the BEVO process later on. The WSM provides a long term expectation of required material resources based on the ILS information coming forth from the DMO and the maintenance parameters available. The portfolio process provides the more short term planned demands for the actually planned maintenance activities during both the BO and the IO process. The final input for the BEVO process comes from the latter two processes actually demanding the material resources, but the main part of the BEVO process has already been complete at that time.

The required output mainly regards the material rates for the WSM process in order to be able to optimize the usage of the available budget, and the material deliveries to enable the BO and IO processes. Accompanying these deliveries is the delivery information regarding the actual delivery dates and the order acceptance. Output is also provided to the refurbishment process (special sub-process of the BEVO process) as to which installations and components need to be refurbished at what due date in order to be enable the timely output to the BO and IO processes.

Refurbishment

The process of refurbishment is basically a sub-process of the BEVO process. However, it is an important process for two reasons. First, many installations and components are repairable and are therefore subject to the refurbishment process. Second, the refurbishment circuit will be subject for further study during the second part of this thesis.

The main input for the refurbishment process is obtained from the BEVO process, namely the IHOs placed by this process based on the portfolio planning process input in order to guarantee timely delivery to the BO and IO processes. The main output regards the returned goods that are refurbished by the process and made available to the BEVO process for delivery. The process is executed mainly by the internal DMI workshops, but a part of the work is also outsourced.

Additional processes

Several additional processes are also influencing the maintenance processes and therefore the process architecture as provided by Figure 6. However, these processes are not considered central and are therefore not included. This regards the following processes:

- *The dock & elevator planning process; this process is additional to the portfolio process and regards the planning of the large installations required to make the WSs available for the BO process and possibly the IO process.*

- *The modification process; this process is conducted whenever due to structural failures, an extension of the operational life of a WS, or obsolescence of installations and components modifications are required.*

- *The technical advice process; this process is indirectly already adopted in the process architecture above and regards the transferring of realization information from the maintenance* *processes to the WSM process and providing technical advice regarding the execution of maintenance the other way around. Furthermore, via analysis techniques such as for instance root cause analyses they provide advice to the WS managers regarding for instance modifications to deal with recurring failures. It is an important process but since this report focusses more on the operational and logistic concepts it is not treated as a separate process.*

9.9 RNLN Standard Inventory Policy with RNLN Terms

This section shows the current notation used within the RNLN for the inventory management for the spare parts portfolio.

- An (s,S)-inventory model for
    - s = ON (order level)
        - ON = PRVB * (GVT + BC) + PRGB * (GHT + GRT + BC) + OVLN
        - Usage during procurement time + usage during repair time + order safety level
        - OVLN = k * (1.25 * GAD - VB) * √(GHT + GRT) + k * (1.25 * GAD-GB) * √(GHT + GRT +BC)
        - Uncertainty of usage during procurement time + uncertainty of usage during repair and retour time; keeping the desired service level in mind
    - S is based on the PRGB and PRVB for a determined time-period
        - This is a minimum order quantity
        - There is also a desired order quantity which is higher
    - Automatically there is an (S-1,S)-inventory model for the slow moving parts
        - An (s,S)-model with Q equal to 1
        - Q=HSH/ASH=1
    - PRVB and PRGB are calculated based on calculations of usage in the past three months in combination with smoothing methodologies
    - GAD is determined using the recent request data (only the previous months)
    - k is inserted by default on a service level of 75%, so equal to 0.67

The HSH (amount to be ordered) is the minimum of the PRGB * HERSTEL-PER and VU-MHG.

9.10 Additional insight in spare part characteristics for simulations

9.10.1 Repair characteristics

The distributions for the refurbishment repair lead times of the various repairable spare parts classes of the RNLN.

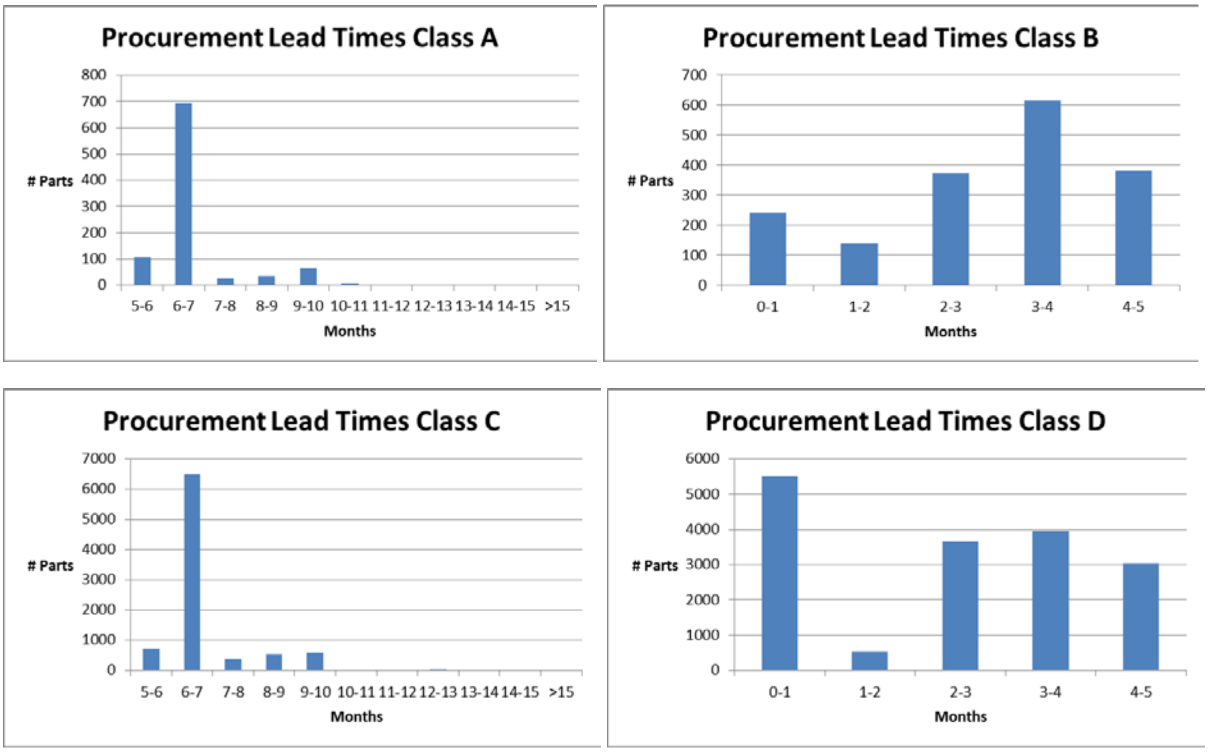


FIGURE 30: REFURBISHMENT REPAIR LEAD TIMES CLASSES

The average refurbishment repair lead times as stated in the current IT system of the RNLN are visible in Table 36.

Category	Average Refurbishment Repair Lead Time	Category	Average Refurbishment Repair Lead Time
A	7 months	B	4.5 months
C	7.3 months	D	4.5 months

TABLE 36: REFURBISHMENT REPAIR LEAD TIMES

9.10.2 Demand characteristics

The original occurrence frequency histograms for the repairable spare parts request sizes for all classes are visible in the figures.

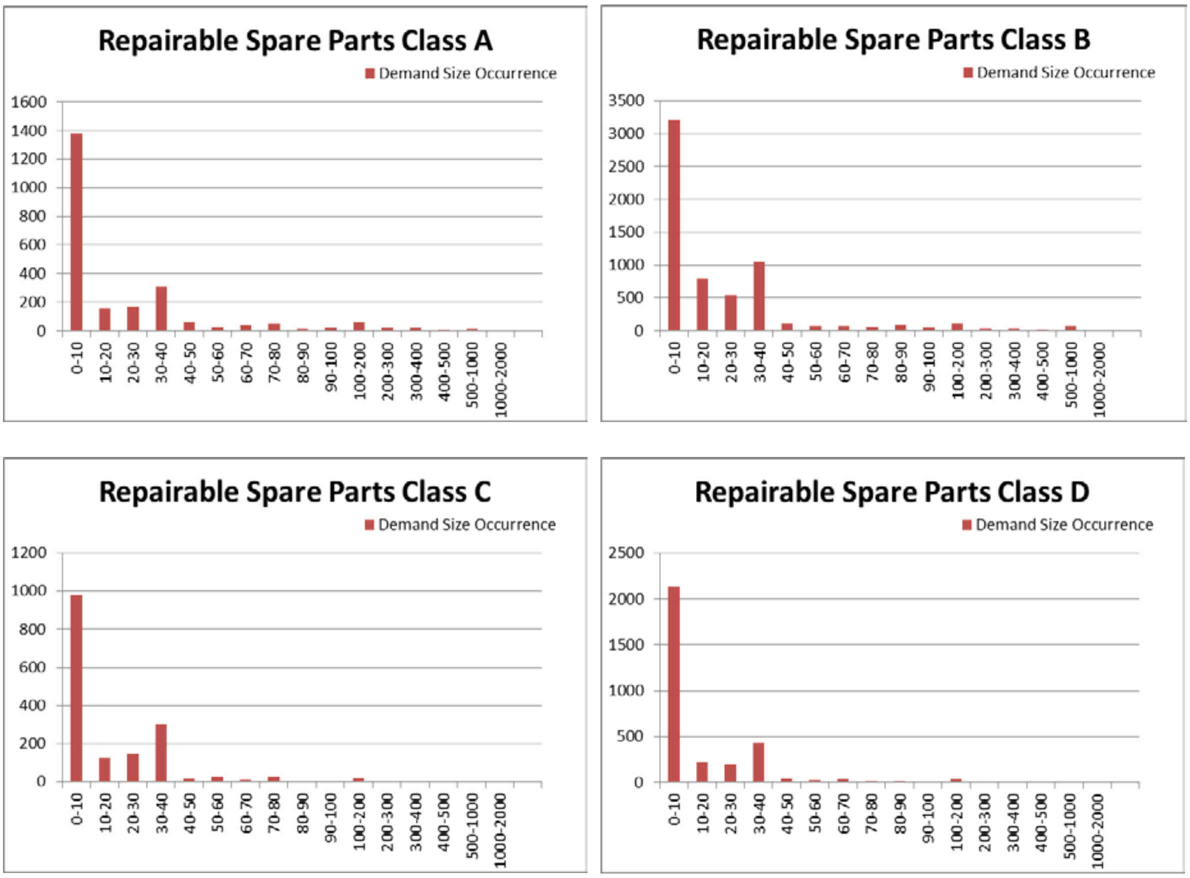


FIGURE 31: DEMAND SIZE OCCURRENCE FREQUENCIES

9.11 Simulation models

9.11.1 Improvement model (all improvement concepts applied)

The improvement model consists of both an inventory management part and a demand management part.

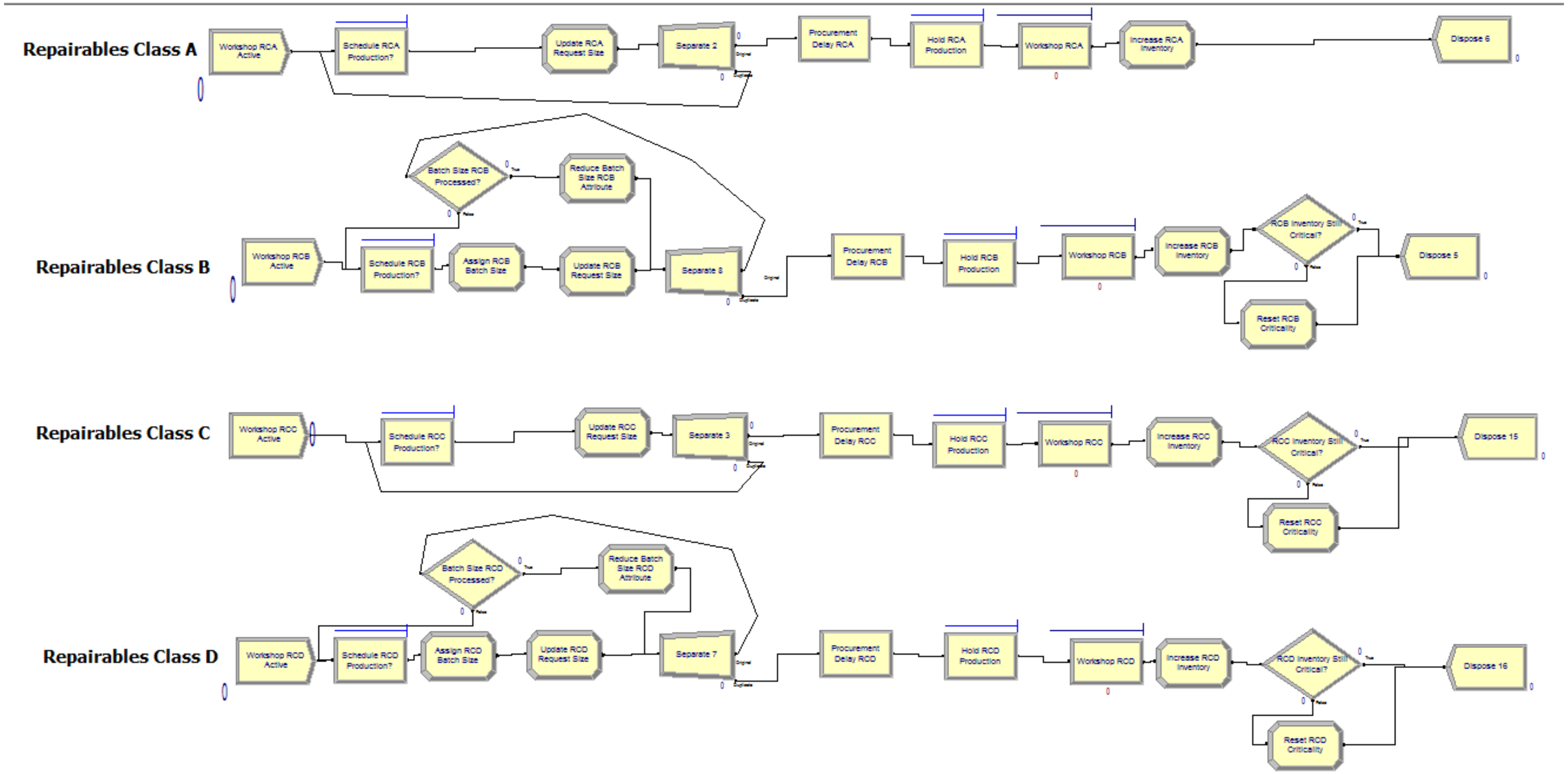


FIGURE 32: IMPROVEMENT MODEL INVENTORY MANAGEMENT

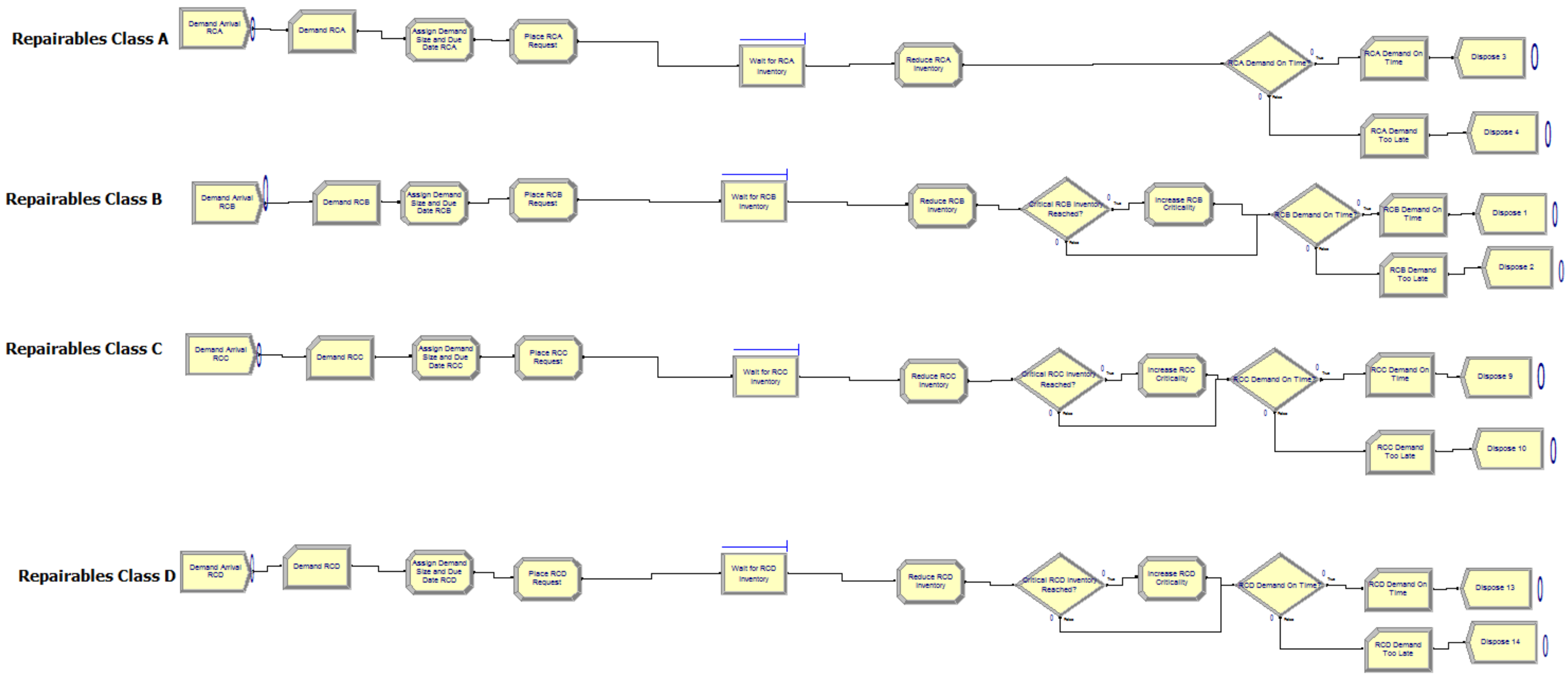


FIGURE 33: IMPROVEMENT MODEL DEMAND MANAGEMENT

9.11.2 Reference model (current situation at the RNLN)

The reference model consists of both an inventory management part and a demand management part.

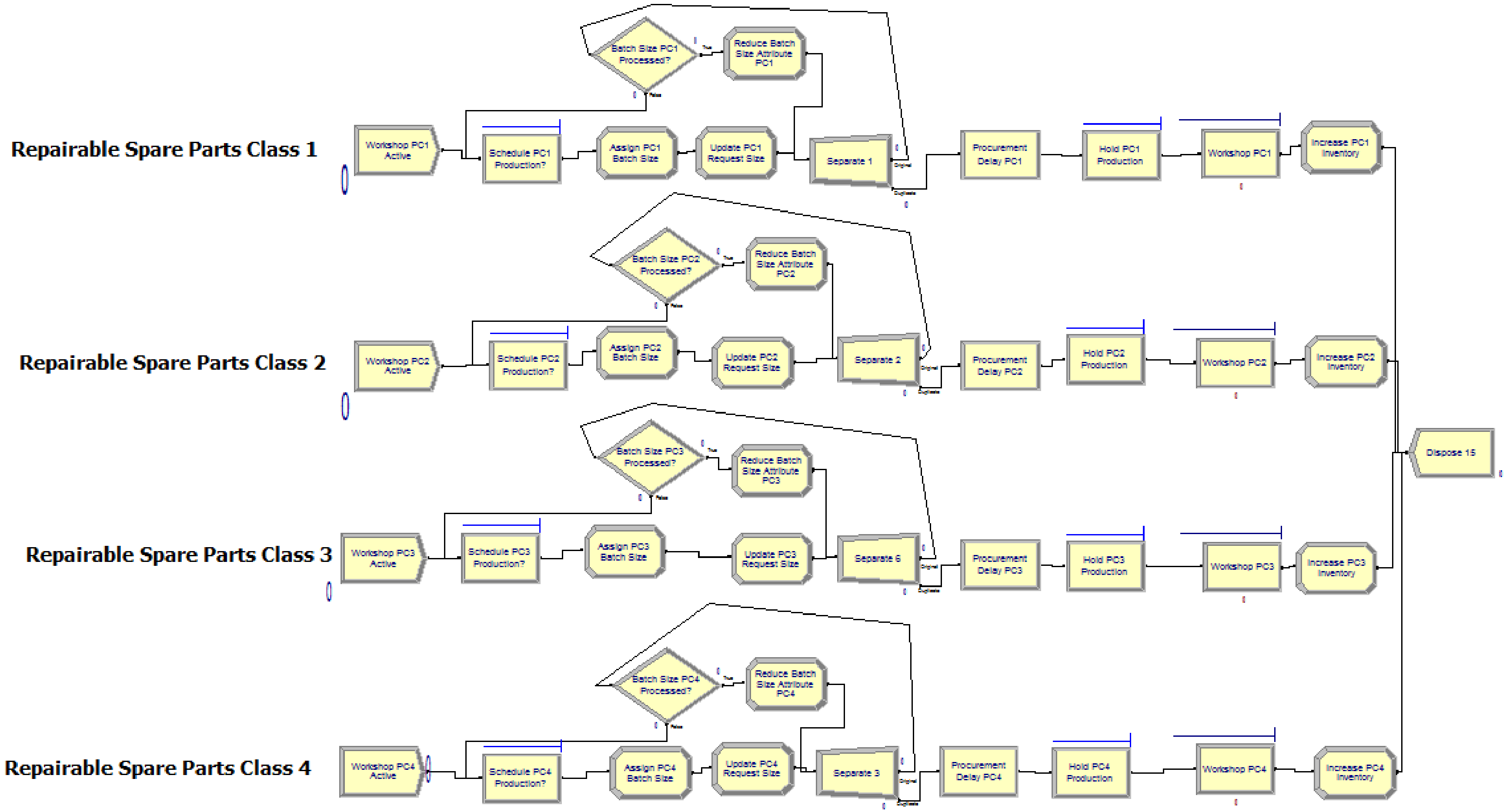


FIGURE 34: REFERENCE MODEL INVENTORY MANAGEMENT

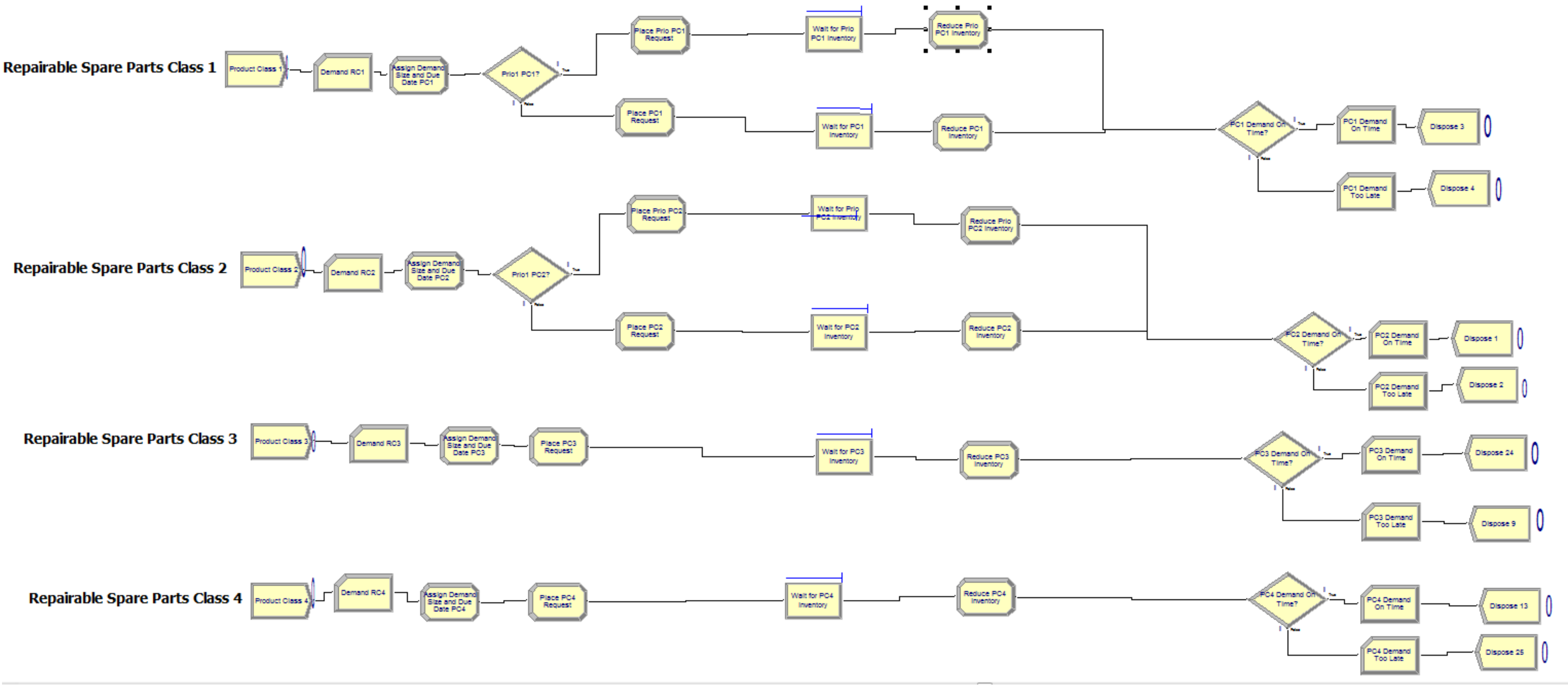


FIGURE 35: REFERENCE MODEL DEMAND MANAGEMENT