Improving the operational availability of the ships of the Royal Netherlands Navy

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Preface

After almost eight years of studying the most exciting adventure of my life until now comes to an end. This graduation project is the final step in the Transport Engineering and Logistics (TEL) track of the master Mechanical Engineering and this report is the result of many hours of work for the last eight months.

I performed my graduation project at the Defensie Materieel Organisatie (Defence Materiel Organisation) in The Hague. The DMO is part of the Netherlands Ministry of Defence and is responsible for the development, acquisition, conservation and discard of materials for the Netherlands Armed Forces. This graduation assignment was provided by the Marine Engineering bureau within the DMO, which provides standards, regulations and advice for mechanical and electrical systems onboard the ships of the Royal Netherlands Navy.

First of all, I would like to say that I had a great time working at this bureau. I would like to thank Fred Driegen, my supervisor at the DMO, for the many hours of helpful and fun discussions and for the useful feedback he gave me. I would also like to thank Kees Posthumus, Isaac Barendrecht, Edwin van Dijk, Roel van Zwienen, Ab Blokland, Barry Hagenouw, Youri Linden and William Storey for always handing a helpful hand when I needed one and for the nice coffee breaks where I could clear my head. A thanks to Jasper Volbrandt for helping me find my way as a graduate intern at the DMO. Joris Rusman, Jeroen Boumeester and Huibert-Jan Verbaan, thanks for always listening to my struggles and helping me overcome them. I would also like to thank Maurice van Bellen from the Integrated Logistics Support bureau for contributing to my work. Thanks to everyone else at the DMO who helped me with all my questions. Furthermore, a thanks to everyone that I spoke to at the Directie Materiële Instandhouding in Den Helder for giving me insight in the maintenance process.

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Annelou van Donkelaar

Summary

The current developments in the world result in increasing tensions between different countries. This increasing tension requires a perfectly functioning defence organisation with trained soldiers and hightech and functioning materials like ships, aircrafts and vehicles. It is important that this material is available when required. Major budget cuts have resulted in the disposal of six multipurpose frigates which has reduced the total amount of frigates owned by the Royal Netherlands Navy from twelve to six (2 MFFs and 4 air defence and command frigates (LCFs)). Because of this significant reduction, a high availability of the remaining frigates and oceangoing patrol vessels (OPVs) is required. However, the availability of the frigates is not sufficient at the moment.
A suitable definition for the term 'availability' was lacking. In literature, different definitions of the term 'availability' were found. It was decided to use the term 'operational availability' as the definition of 'availability'. The operational availability is a function of the Mean Time Between Maintenance Actions (MTBMA) and the Mean Down Time (MDT), where the MDT is a function of the Active Maintenance Time (AMT), the Administrative Delay Time (ADT) and the Mean Logistic Delay Time (MLDT). The corresponding equation that expresses the operational availability as a ratio was defined as follows:

$$Ao = \frac{MTBMA}{MTBMA + MDT} = \frac{MTBMA}{MTBMA + AMT + ADT + MLDT}$$

With this equation, the required operational availability for the ships of the RNLN was calculated. This resulted in a required operational availability of 67.7% over a time period of five years for the MFFs and LCFs and a required operational availability of 73.3% over a time period of five years for the OPVs. By calculating the actual operational availability of the MFFs, LCFs and OPVs for the period 2013-2017, it was shown that the operational availability requirements are not met.

To find out which factors have a negative influence on the operational availability, the maintenance process of the frigates and OPVs was analysed by using the Delft Systems Approach [1]. The analysis showed that the lead time of the Benoemd Onderhoud (BO) process has the

largest negative influence on the operational availability of the ships. By zooming in on the BO process, a significant amount of problems were identified that cause the long lead time of this process.

The analysis showed that there is a lot of room to improve the operational availability of the ships of the RNLN. However, it is impossible to solve all the found problems at once. Therefore, it was decided to develop a continuous process improvement dashboard that can be used to improve the operational availability of the ships of the RNLN to a target value of at least 80%, by solving the found problems in an iterative way. This dashboard also needed to be useful in the design process of a new ship class to ensure the new ships achieve the target operational availability of at least 80%.
The Plan-Do-Check-Act cycle was used as a basis to develop a continuous process improvement dashboard. Every iteration of the dashboard has eight different steps that have to be passed.
The working principle of the dashboard was verified by performing a case study of one iteration. The case study examined solutions for two problems found in the BO process: the 'overhaul of repairable parts/installations problem' and the 'people flow problem'. To make the case study more manageable it was decided to look at seven installations with a long lead time. However, it is not known if these installations are situated on the critical path of the BO process. The case study showed different things:

- Only one time the results of the multi-criteria analysis (MCAs) showed that the current situation is the best solution concept.
- In different cases, the user and maintainer prefer a different solution concept than the standard setter.
- For two installations, the prefered solutions were 'no go' solution concepts for the current ships.
- The maintenance lead time of the examined installations will decrease drastically when the prefered solution concepts are implemented.
- The prefered solution concepts often imply larger initial costs but lower maintenance costs.

The case study has shown that the continuous process improvement dashboard is a useful tool that, for a given critical path, could be used to increase the operational availability of the ships of the RNLN. Besides that, the case study showed that when the dashboard is used in the design process of a new ship, different solutions are found than when it is used for the existing ships. Therefore, the dashboard is also a useful tool in the design of a new ship. The dashboard can also be used in other issues that desire a continuous process improvement approach.

Samenvatting

De huidige ontwikkelingen in de wereld zorgen voor verhoogde spanningen tussen verschillende landen. Deze verhoogde spanning vereist een perfect functionerende defensie organisatie met getrainde militairen en hightech en functionerend materieel zoals schepen, vliegtuigen en voertuigen. Het is belangrijk dat dit materieel beschikbaar is wanneer nodig. Bezuinigingen hebben geresulteerd in de afstoting van zes multipurpose frigatten (MFFs). Dit betekende een halvering van het totale aantal fregatten van twaalf naar zes (2 MFFs and 4 luchtverdedigings- en commando fregatten (LCFs)). Door deze aanzienlijke reductie is een hoge beschikbaarheid van de overige fregatten en oceangoing patrol vessels (OPVs) nodig. De huidige beschikbaarheid van deze schepen is echter niet voldoende.
Vreemd genoeg was een definitie voor de term 'beschikbaarheid' niet voorhanden. Met behulp van andere studies en literatuur zijn verschillende definities voor de term 'beschikbaarheid' gevonden. Er is besloten om de definitie 'operational availability' te gebruiken om de beschikbaarheid van de schepen te beschrijven. Deze definitie is een functie van de 'Mean Time Between Maintenance Actions (MTBMA)' en de 'Mean Down Time (MDT)'. De MDT is weer een functie van de 'Active Maintenance Time (AMT)', de 'Administrative Delay Time (ADT)' en de 'Mean Logistic Delay Time (MLDT)'. De 'operational availability' kan worden uitgedrukt in de volgende bijbehorende formule:

$$Ao = \frac{MTBMA}{MTBMA + MDT} = \frac{MTBMA}{MTBMA + AMT + ADT + MLDT}$$

Met deze formule is de vereiste 'operational availability' van de schepen berekend. Hieruit volgde een vereiste 'operational availability' over een periode van 5 jaar voor de MFFs en LCFs van 67.7% en een vereiste 'operational availability' over een periode van vijf jaar voor de OPVs van 73.3%. Door de huidige 'operational availability' van de schepen te berekenen over de periode 2013-2017 kon aangetoond worden dat de vereiste 'operational availablity' niet wordt gehaald.

Om erachter te komen welke factoren een negatieve invloed op de 'operational availability' hebben is het onderhoudsproces van de schepen geanalyseerd met behulp van de Delft

Systems Approach [1]. De analyse heeft aangetoond dat de doorlooptijd van het Benoemd Onderhoud (BO) proces de grootste negatieve invloed heeft op de 'operational availability' van de schepen. Door daarna in te zoomen op het BO proces, is een significant aantal problemen geïdentificeerd die een oorzaak zijn voor de lange doorlooptijd van het proces.

De analyse liet dus zien dat er veel ruimte is om de 'operational availability' van de schepen van het Commando Zeestrijdkrachten (CZSK) te verbeteren. Het is echter niet mogelijk om alle gevonden problemen in één keer op te lossen. Om deze reden is er besloten om een 'continuous process improvement (CPI)' dashboard te ontwikkelen wat gebruikt kan worden om de 'operational availability' van de schepen te verbeteren naar een waarde van minstens 80%, door de gevonden problemen op een iteratieve manier op te lossen. Het dashboard moet ook gebruikt kunnen worden in het ontwerp proces van een nieuwe scheepsklasse zodat voor de nieuwe schepen een beschikbaarheid van minstens 80% gehaald kan worden.
Door gebruik te maken van de Plan-Do-Check-Act (PDCA) cyclus is een 'continuous process improvement' dashboard ontwikkeld. Elke iteratie van het dashboard bestaat uit acht verschillende stappen die doorlopen moeten worden.
De werking van het dashboard is geverifieerd door een case study van één iteratie uit te voeren. Twee problemen die zijn gevonden in de analyse van het BO proces zijn onderzocht in de case study: het 'revisie van herstelbare onderdelen/installties probleem' en het 'people flow probleem'. Om de case study behapbaar te maken is er besloten om naar zeven installaties met een lange doorlooptijd te kijken. Het is echter niet bekend of deze installaties zich op het kritieke pad van het BO proces bevinden. Uit de case study volgenden verschillende dingen:

- Slechts één keer lieten de multi-criteria analyses (MCAs) zien dat de huidige situatie de beste oplossing is.
- In een aantal gevallen prefereren de gebruiker en onderhouder een andere oplossing dan de normsteller.
- Voor twee installaties was de geprefereerde oplossing in het geval van het huidige schip een 'no go' oplossing.
- De doorlooptijd van het onderhoud aan de onderzochte installaties reduceert drastisch wanneer de geprefereerde oplossingen geïmplementeerd worden.
- De geprefereerde oplossingen brengen vaak hogere initiële kosten maar ook lagere onderhoudskosten met zich mee.

De case study heeft laten zien dat het ontwikkelde CPI dashboard een bruikbare tool is die, voor een gegeven kritiek pad, gebruikt zou kunnen worden om de 'operational availability' van de schepen te verhogen. De case study heeft ook laten zien dat wanneer het dashboard gebruikt wordt in het geval van een nieuw schip andere oplossingen worden gevonden dan wanneer het gebruikt wordt in het geval van de bestaande schepen. Daarom is het dashboard ook een bruikbare tool in het ontwerp proces van een nieuw schip. Daarnaast kan het dashboard ook gebruikt worden om andere problemen binnen de organisatie aan te pakken die een 'continuous process improvement' aanpak vereisen.

List of abbreviations

AAW	Anti-Aircraft Warfare
ADT	Administrative Delay Time
AHP	Analytic Hierarchy Process
AM	Assisted Maintenance
AMT	Active Maintenance Time
Ao	Operational Availability
ASOL	A-Standaard Onderhoudslijst
ASUW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
BE	België
BO	Benoemd Onderhoud
BSMI	Basis Standaard Materieel Indeling
BVO	Beproevingen Voor Onderhoud
CBM	Condition-Based Maintenance
CDC	Commando Dienstencentra
CDS	Commandant der Strijdkrachten
CI	Consistency Index
COTS	Commercially of the Shelf
CPI	Continuous Process Improvement
CR	Consistency Ratio
DA	Deelactiviteiten
DLM	Depot Level Maintenance
DMI	Directie Materiële Instandhouding
DMO	Defence Materiel Organisation
DMP	Defence Materials Process
DNV	Det Norske Veritas
DSA	Delft Systems Approach
FRISC	Fast Raiding Interception and Special Forces Craft
GO	Skill Level
GSP	Gereedstellingsplan
GVT	Gemiddelde Verwervingstijd

HA	Hoofdactiviteiten
HAT	Harbour Acceptance Test
HEM	Hoofd Elektromotor
ILM	Intermediate Level Maintenance
IMM	Integrated Mast Module
IP	Instandhoudings Programma
JSS	Joint Support Ship
KPI	Key Performance Indicator
LCF	Luchtverdedigings- en Commando Fregat
LLI	Long Lead Items
LR	Lloyds Register
LRU	Line-Replaceable Unit
MATLOG	MaterieelLogistiek
MB	Marinebedrijf
MCA	Multi-Criteria Analysis
MDT	Mean Down Time
MFF	Multipurpose Frigate
MG	Material Readiness
MLDT	Mean Logistic Delay Time
MOU	Memorandum of Understanding
MTBMA	Mean Time Between Maintenance Actions
NATO	North Atlantic Treaty Organisation
NL	Nederland
NLMARFOR	Netherlands Maritime Force
NSE	Nadere Specificatie van Eisen
OEM	Original Equipment Manufacturer
OG	Operational Readiness
OJP	Operationeel Jaarplan
OLM	Organic Level Maintenance
OPV	Oceangoing Patrol Vessel
PDCA	Plan-Do-Check-Act
PG	Personnel Readiness
PID	Project Initiatie Document
PLF	Platform
PMP	Project Management Plan
PROPER	Process Performance Model
RCI	Random Consistency Index
RHIB	Rigid Hull Inflatable Boat
RNLN	Royal Netherlands Navy
SARC	Safety and Readiness Check
SAT	Sea Acceptance Test
SEWACO	Sensors Weapons and Control
SoFa	State of Failure
SoFu	State of Functioning
SOL	Standaard Onderhoudslijst
SRU	Shop-Replaceable Unit
TSM	Technical System Management

WOPS	Wal Ondersteuning Patrouilleschip
WSM	Weapon System Management

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Chapter 1

Introduction

The current developments in the world result in increasing tensions between different countries. Examples are the ongoing situation in Syria, tensions between Russia and Ukraine and the provocations of North Korea towards the US, South Korea and Japan. This increasing tension requires a perfectly functioning defence organisation with trained soldiers and hightech and functioning materials like ships, aircrafts and vehicles. It is important that this material is available when required. Over the last twenty years, the Dutch defence budget has suffered major cuts: the budget as a percentage of the Gross Domestic Product has decreased from almost 2.5% to less than 1.5% [10]. One of the results of these cuts was the disposal of six out of the eight multipurpose frigates owned by the Royal Netherlands Navy. This has reduced the total amount of frigates available for deployment from twelve to six. Because of this significant reduction, a high operational availability of the remaining frigates is required. However, the operational availability of the frigates is not sufficient at the moment. It is important that the operational availability of the ships of the Royal Netherlands Navy is increased in order to be able to quickly respond to external threats, take part in peace supporting deployments and provide humanitarian aid, wherever and whenever the home state or international community calls for it.
Different studies already address problems with the operational availability of military equipment and the authors try to find solutions for this problem. For example, Verhoeff introduced two interconnected mathematical optimisation methods for flight and maintenance planning of the aircrafts of the Royal Netherlands Air Force that increased the operational readiness (availability) by up to 22% [3]. Macheret et.al. proposed two approaches for achieving and maintaining a high operational availability of military systems: overhaul and prognostics asset management strategies. The study showed that the prognostics approach led to an improved operational availability [11].

This thesis will focus on the improvement of the operational availability of the ships of the Royal Netherlands Navy by developing a continuous process improvement dashboard. This dashboard should be useable to improve the operational availability of the existing ships of the Royal Netherlands Navy. Besides that, it should also be useable in the design process of new ship classes to ensure that they achieve a satisfying operational availability in their operational lives. Based on this, the final research objective is formulated as follows:

Design a continuous process improvement dashboard that can be used by the Royal Netherlands Navy to achieve an operational availability of 80% or higher, both for the existing ships and in the design process of new ships.

Background information for this thesis is given in Chapter 2, where information on the Ministry of Defence, the Defence Material Organisation, the Royal Netherlands Navy and the ships of the Royal Netherlands Navy is given. It also discusses the initial problem description of this thesis. Chapter 3 explains the definition for the term 'operational availability'. Chapter 4 discusses the different maintenance strategies found in literature and gives a description of the maintenance process of the frigates of the Royal Netherlands Navy. This chapter also discusses the required operational availability and the actual operational availability of the frigates and OPVs of the Royal Netherlands Navy. In Chapter 5, the Delft Systems Approach is used to analyse the existing maintenance process and in this way identify the problems that cause the low operational availability. Chapter 6 defines the final research objective. In Chapter 7, the continuous process improvement tool/dashboard is developed. A case study is performed in Chapter 8 to verify the working principle of the developed continuous process improvement tool/dashboard. Finally, conclusions are presented and directions for future research are discussed in Chapter 9.

Chapter 2

Background information

This chapter provides background information to get some feeling for the subject of this thesis. First the Netherlands Ministry of Defence, especially the Defence Materiel Organisation, which facilitated this MSc research project, and the Royal Netherlands Navy will be discussed in Section 2-1. In Section 2-2 general information about the ships of the Royal Netherlands Navy will be given. With the information from Section 2-1 and 2-2 in mind, the initial research objective will be explained in Section 2-3.

2-1 The Dutch Ministry of Defence

War is of all ages. Just look, for example, at the age of the Greeks and Romans, the Middle Ages, the 1st and 2nd World War and more recently the war against ISIS. This illustrates the importance for our country to be protected against threats at all times. 185 years ago, this need for protection resulted in the formation of the Netherlands Department of War and the Department of Navy, with the goal to "protect what is close to our hearts at all times". After World War II, in 1959, it was decided to join these two departments, which resulted in the Netherlands Ministry of Defence as we know it today. Nowadays, the main three tasks of the Dutch Ministry of Defence can be summarised as follows [2]:

- Protection of our territory and that of our allies;
- Foster the (international) law and order and stability;
- Offer support in case of disasters and crises.

In this way the Netherlands Ministry of Defence contributes to freedom, peace and safety all around the world. Nowadays, the Netherlands Ministry of Defence is an organisation with approximately 60.000 employees (military and civilian). The structure of this organisation is captured in Figure 2-1. The Minister of Defence stands at the top of the organisation. The organisation can be divided into three departments: the Armed Forces, the Command

Services Centres (Commando Dienstencentra (CDC)) and the Defence Materiel Organisation (DMO). The Armed Forces are subdivided into the Royal Netherlands Navy (RNLN), the Royal Netherlands Army, the Royal Netherlands Air Forces and the Royal Netherlands Military Police. The operational control of the Armed Forces is in the hands of the Commander of the Armed Forces (Commandant der Strijdkrachten (CDS)). As already mentioned there are two other departments besides the Armed Forces: the Command Services Centres which performs supporting tasks for the Armed Forces and the Defence Materiel Organisation.

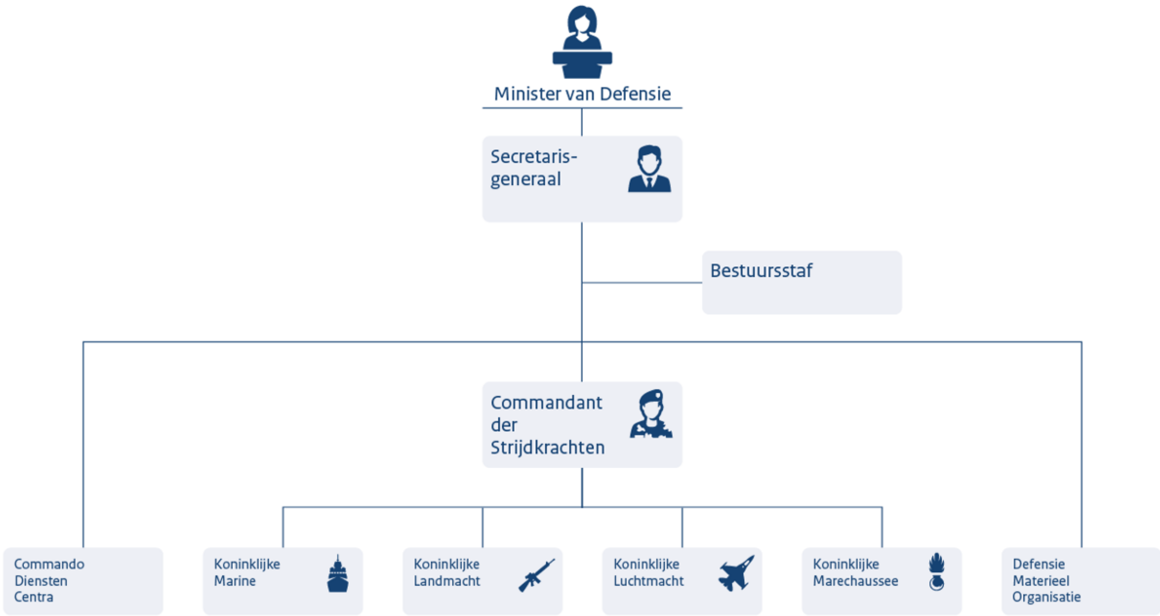

Figure 2-1: Organisation chart Dutch Ministry of Defence [2]

2-1-1 Defence Materiel Organisation

The Defence Materiel Organisation is a logistics supporting, administrative and coordinating organisation. It provides the development, acquisition, conservation and discard of materials for the Netherlands Armed Forces. The Armed Forces can in fact be regarded as a customer of the DMO. This thesis is conducted at the maritime branch of the DMO, therefore, the focus in this thesis lies on the Royal Netherlands Navy. The DMO sets the standards for the ships of the Royal Netherlands Navy. In a replacement project of a ship, the DMO has a leading role. The DMO is currently working on the replacement programs for the multipurpose frigates, submarines and minehunters.

2-1-2 The Royal Netherlands Navy

The RNLN is the oldest Netherlands Armed Forces organisation and operates from the sea. They can perform independent operations but they can also act together with other Armed Forces divisions. The tasks of the RNLN can be summarised as follows [2]:

- *Safety at Sea*: The RNLN provides safety at sea by securing seaways and nodes which enables safe transport of goods. They combat piracy, drug transports, human trafficking, gunrunning and terrorism by the use of naval ships carrying out patrols, boarding operations and making blockades. They also clean up explosives at sea and in harbours and they monitor coast waters. The submarines of the RNLN collect intel and secure worldwide sea areas.
- *Safety from Sea*: The RNLN units can be deployed ashore from the sea and independently carry out, or support, land operations. They do this by supplying soldiers, vehicles, ammunition, food and water, and by giving medical help or fire support. For these tasks a completely self-supporting base can be set up at sea. From this base the Commander can give orders for the operation.
- *RNLN in the Netherlands*: The RNLN also has an important social contribution in the Netherlands itself. They support coastguards and carry out search and rescue operations and combat terrorism. In the waters they clean up unexploded explosives (often from World War II), perform hydrographical measurements and support civil authorities.

Collaboration with Belgium The RNLN collaborates intensively with the Marine Component of the Belgian Armed Forces. This collaboration is called 'Admiraliteit Benelux'. The head of the 'Admiraliteit Benelux' is the 'Admiral Benelux', who is the Commander of the Royal Netherlands Navy. The collaboration includes, for example, trainings, operations, logistics and maintenance, however, both countries make their own political decisions about the deployment of their ships [2][10].

2-2 Ships of the Royal Netherlands Navy

To perform the tasks mentioned in Section 2-1 there is a need for high quality equipment such as vehicles and weapons and, most importantly for the RNLN, naval ships. The RNLN owns a wide variety of ships which all have different purposes and characteristics in order to perform different tasks. The ships of the RNLN can be divided into three categories:

- Groot Bovenwater Eenheden (Large Surface Vessels);
- Klein Bovenwater Eenheden (Small Surface Vessels);
- Onderwater Eenheden (Sub Surface Vessels)

The category 'Large Surface Vessels' can again be divided into the categories 'Logistic Support Ships' and 'Frigates & OPV'. This is summarised in Figure 2-2. The focus in this thesis lies on the ships of the category 'Frigates & OPV'. These ships are therefore discussed in more detail in Sections 2-2-1, 2-2-2 and 2-2-3. More information on the ships in the other categories can be found in Appendix B.

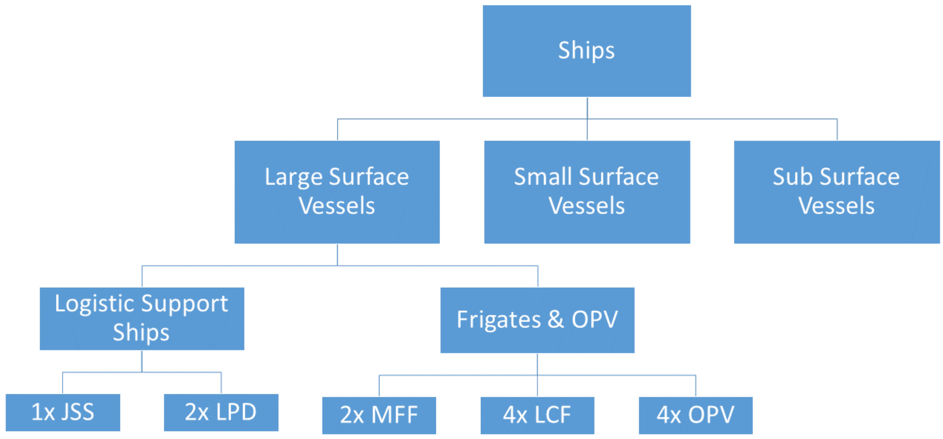

Figure 2-2: Ships of the Royal Netherlands Navy

2-2-1 Multipurpose frigates

The multipurpose frigates (MFFs) of the Karel Doorman class are the oldest frigates of the RNLN fleet. Originally, eight MFFs were owned by the RNLN but six of them were sold to other countries because of cuts in the defence budget. The frigates were sold in pairs to Portugal, Chile and Belgium. The two frigates that were sold to Belgium are still maintained by the RNLN. Zr. Ms. van Amstel (Figure 2-3) and Zr. Ms. van Speijk are the MFFs that are still owned by the RNLN. Table 2-1 shows all MFFs and their commissioning dates, decommissioning dates and the lands that the frigates were sold to [2][10].

Table 2-1: Multipurpose frigates [2][10]

Name	Commisioned	Decommissioned	Sold To
Zr. Ms. Karel Doorman	1991	2006	Belgium
Zr. Ms. Willem van der Zaan	1991	2007	Belgium
Zr. Ms. Tjerk Hiddes	1993	2006	Chile
Zr. Ms. Van Amstel	1993	-	-
Zr. Ms. Abraham van der Hulst	1993	2004	Chile
Zr. Ms. Van Nes	1994	2008	Portugal
Zr. Ms. Van Galen	1994	2009	Portugal
Zr. Ms. Van Speijk	1995	-	-

Tasks & Operations As the name of this frigate already implies, it is all-round deployable. The most important task of the MFFs is Anti-Submarine Warfare (ASW), but they are also built for Anti-Aircraft Warfare (AAW) and Anti-Surface Warfare (ASUW). They can be deployed in high and low threat environments [2][10]. The MFFs are deployed for different kind of operations in the waters all over the world. They can be deployed for operations with an increased threat of war, counter drugs operations, anti-piracy operations and humanitarian help operations after, for example, a hurricane [2][10].

Figure 2-3: Zr. Ms. Van Amstel [2]

2-2-2 Air defence en command frigates

The most advanced frigates of the RNLN are the air defence and command frigates (Luchtverdedigings- en commandofregatten (LCFs)). The LCFs are the top of the bill compared to other frigates around the world. Table 2-2 shows that the RNLN owns four LCFs [2][10]. Zr. Ms. Evertsen is shown in Figure 2-4.

Table 2-2: Air defence and command frigates [2][10]

Name	Commisioned
Zr. Ms. De Zeven Provinciën	2002
Zr. Ms. Tromp	2003
Zr. Ms. De Ruyter	2004
Zr. Ms. Evertsen	2005

Tasks & Operations The LCFs can protect a Task Group of Vessels against enemy threats from land (ASUW), from in the sea (ASW) and, most importantly, from the air (AAW). Furthermore the Netherlands Maritime Force (NLMARFOR) can lead large scale operations from the LCFs. Like the MFFs, the LCFs can be deployed in high and low threat environments [2][10].

Figure 2-4: Zr. Ms. Evertsen [2]

2-2-3 Oceangoing patrol vessels

The oceangoing patrol vessels (OPV) are (besides Zr. Ms. Karel Doorman) the newest four ships of the Royal Netherlands Navy (Table 2-3) [2][10].

Table 2-3: Oceangoing patrol vessels [2][10]

Name	Commisioned
Zr. Ms. Holland	2012
Zr. Ms. Friesland	2013
Zr. Ms. Zeeland	2013
Zr. Ms. Groningen	2013

Tasks & Operations The OPVs are designed for low threat environments like law enforcement and humanitarian tasks. They perform coastguard tasks at the North Sea and in Caribbean Areas [2][10]. The OPVs are deployed for counter terrorism and counter piracy operations. They can also be used for counter drugs operations [2][10].

Crew There is a central control room on the OPV from which the ship can be controlled and guarded by only one person. Because of this and the relatively simple maintenance of the different systems in the Integrated Mast Module (IMM), a crew of only 50 persons is found sufficient. The OPV is the first ship of the RNLN with such a crew reduction [2][10].

Figure 2-5: Zr. Ms. Holland [2]

2-3 Initial problem description

At the moment, replacement programs are taking place for different ship classes of the RNLN because within the next 15 years, they have reached the end of their useful life. As presented in Table 2-1, the current MFFs were commissioned between 1991 and 1995. In the years between 2010-2015, the Dutch and Belgian MFFs got a mid-life modernisation which extended their life to around 2025. Consequently, the MMFs should be replaced around 2025 and the DMO has already started with the replacement program of these ships.
Large military projects like this replacement project have to pass the Defence Material Process (DMP). The DMP consists of five phases, namely [12]:

1. DMP-A: In this phase the requirements for the new ships are defined.
2. DMP-B: In this phase the requirements defined in phase A are translated into functional and technical requirements. Besides that, a market study is performed and different alternatives are investigated and evaluated. Furthermore, a start is made for setting up the requirements (Nadere Specificatie van Eisen (NSE))
3. DMP-C: The requirements are extended and a 'short list' of the best alternatives is created. Then the development trajectory is started.
4. DMP-D: A product (ship) and supplier are selected in this phase.
5. DMP-E: The project and the product are evaluated.

The first task for the DMO during this process is to write a DMP-A letter which is sent to the Minister of Defence. The DMO is momentarily writing the DMP-A letter for the future MFFs which includes the capabilities of the new frigates on a functional level. This letter will be discussed in the Netherlands Second Chamber this year, after the formation of the new cabinet. There is the intention to buy four new ships together with Belgium (two for the Netherlands, two for Belgium). Therefore, on 30 November 2016 a 'letter of intent' was signed by the Dutch and Belgian Ministers of Defence [2]. This letter states that the Netherlands and Belgium are going to replace the current MFFs and the minehunters together. This letter provides a free path for the Netherlands and Belgium to exchange sensitive information for the design of the new ships.
At the moment, the DMO is conducting studies to explore the technical possibilities for the new frigates. For example, they are conducting research in the propulsion area to explore the possibilities of electrical propulsion for low speeds. Furthermore, there will be more automation (at least comparable to the OPVs) on the new frigates and the crew will be reduced from approx. 150 to 100 persons.

A problem with the current frigates and OPVs is that their availability is too low. It is important that the ships are as much available as possible, because when the need is there, the CDS should be able to deploy a ship immediately. At the DMO, there is a substantial feeling that the low availability of the ships has something to do with the current maintenance concept of the ships. Until now, the way of maintenance of the ships and corresponding logistics are an underexposed subject during the design of the ship. The budget-driven design leads to less clever choices in these areas, which results in longer maintenance periods and higher exploitation costs. At the DMO they all have the feeling that it could be done a lot 'better', but the question is how. Therefore, the initial research goal for this thesis is the following:

Determine the current availability of the ships of the Royal Netherlands Navy, identify the reasons for not meeting the availability requirements and find solutions for the found problems so at least the required availability can be achieved for the new multipurpose frigates.

It will take up to 10 years before the new ships are finished, therefore, completely new concepts can be set up. Everything is possible.

Chapter 3

Availability

Section 2-3 states that the availability requirements are not met by the ships of the RNLN, but what does the term *availability* imply? That will be explained in this chapter. Section 3-1 first explains the term 'operational readiness' that is used by the RNLN to express the availability of their ships. This section also questions the suitability of the 'operational readiness' to express the availability of the ships. Therefore, Section 3-2 gives a definition of availability that appears to be better suitable to express the availability of the ships.

3-1 Operational readiness

When the people at the DMO and the RNLN are asked to explain the term availability different answers are given, but most of the people refer to the term *operational readiness*. NATO defines the operational readiness as follows [13]:

"The capability of a unit/formation, ship, weapon system or equipment to perform the missions or functions for which it is organised or designed. May be used in a general sense or to express a level or degree of readiness."

The 'Rapportage Operationele Gereedheid' states that the *operational readiness (OG)* depends on the *Material Readiness (MG)*, *Personnel Readiness (PG)* and *Skill level (Geoefendheid (GO))* [14].
The MG, PG and GO are defined as follows [14]:

Material Readiness: *"The degree in which the material of a unit is available and suitable for the execution of the commissioned tasks of the unit."*
Personnel Readiness: *"The degree in which the military personnel of a unit is available and suitable for the execution of the commissioned tasks of the unit"*
Skill level: *"The degree in which a unit practised the commissioned tasks and thereby showed sufficient level of task control.*

For this thesis the MG is the most interesting because the MG describes the availability of the ship (without personnel). The MG of the whole ship is calculated on the basis of the availability of the individual installations on the ship. As one can imagine, the M-Frigates consist of a lot of different installations. To get some order in this large pool of installations the RNLN uses a certain system that categorises these installations. This system works with so-called 'Basis Standaard Materieel Indeling (BSMI)' indices which are numbers with four digits (sometimes five). The diesel engines, for example, have BSMI 1212. A further explanation of the BSMI indices can be found in Appendix C. Some installations have a bigger impact on the total MG than other installations. One can imagine that broken diesel engines have more impact on the MG than a not working goalkeeper because the ship cannot sail without diesel engines but it can without a goalkeeper. However, for a deployment in a high threat environment, the goalkeeper is also essential. Appendix D gives a list of installations that are required for the ship to operate. If one of these installations does not work properly the ship certainly cannot have the status 'Materieel Gereed'. The availability of the different installations is summed up according to certain rules which results in a measure for the MG of the whole ship. An MG of 100% means that all systems on the ship are completely available. The requirements for the MG for a ship are the following [14]:

- $MG \geq 80\%$: The ship gets the status MG (green).
- $70 \leq MG < 80$: The ship might be able to perform certain missions (yellow)
- $MG < 70$: the ship is not MG (red).

The type of deployment is not taken into account in the MG. The measurements are performed for the highest threat environment and not for the other deployments. For example, if a ship is on a counter drugs deployment, other installations are essential than when a ship has to go on a deployment in a high threat environment.

The MG of the MFFs and LCFs of the last 8 years is shown in Figures 3-1 and 3-2.

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Figure 3-1: Material Readiness of the Dutch MFFs

Figures 3-1 and 3-2 are constructed by measuring the value of the MG on a quarterly basis (3 months) and then a line is drawn between these points. When the ship is having an extended

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Figure 3-2: Material Readiness of the LCFs

maintenance period (which will be explained later) the MG is not measured which explains the interruptions of the lines in the graphs of the MFFs and LCFs. When looking at the values of the MG in the periods when the ship is not in maintenance, there seems to be no significant problem. Most of the times the ships have an MG above 70%. However, this is a distorted image caused by the fact that the MG is not measured during the extended maintenance periods. It is possible that the length of the extended maintenance periods is longer than originally planned but the MG is only measured when the ship is not in an extended maintenance period. This means that the MG does not take into account the performance of the maintenance process of the ships. A measure of time is lacking in this definition of availability because the MG does not take the performance over a period of time into account.

3-2 Operational availability

To also take into account the performance of the maintenance processes on the ships of the RNLN, it would be nice to be able to express the availability of the ships over a period of time. In literature this availability over time is often referred to as the *operational availability* of a system. Different definitions for the operational availability of a system can be found. Isola et.al. defines the operational availability as follows [15]:

"The probability that a system/equipment at any instant in the required operating time operates satisfactorily under stated conditions where the time considered includes operating, corrective and preventive maintenance, administrative and logistic delay time."

Another definition was found in the work of Verhoeff [3]:

"The ability of an item to be in a state to perform a required function under given conditions at a given instant of time over a given time interval, assuming that the required external resources are provided."

Verhoeff explains the operational availability by considering the functionability profile [3]. The functionability can have two different states, the *state of functioning* (SoFu) and *state of failure* (SoFa). When the system is in SoFu, it is capable to perform its intended function and is thus called functionable. In our case functionable means that the frigate is capable to perform a mission. On the other hand the system is not functionable when it is in SoFa which means that the frigate is down for maintenance (corrective or preventive). Figure 3-3 shows this graphically.

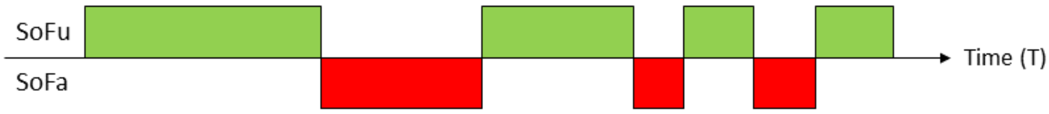

Figure 3-3: Functionability profile of a restorable system. Adapted from [3].

Verhoeff states that the availability is a function of the following three factors [3]:

- Reliability: *"Reliability is the inherent characteristic of an item related to its ability to maintain functionability when used as specified."* [3]
- Maintainability: *"The concept of making it easier to detect failures (or potential failures) and to replace failed components at reasonable costs." [3]* or similar *"The ease with which scheduled or corrective maintenance can be performed on an item" [16]*
- Supportability: *"Supportability is the inherent characteristic of an item related to its ability to be supported by the required resources for the execution of the specified maintenance task."* [3]

Figure 3-4 shows that the reliability determines the duration of the state of functioning and the supportability together with the maintainability determine the duration of the state of failure. The instant of time the system is in state of functioning is represented by T_R.

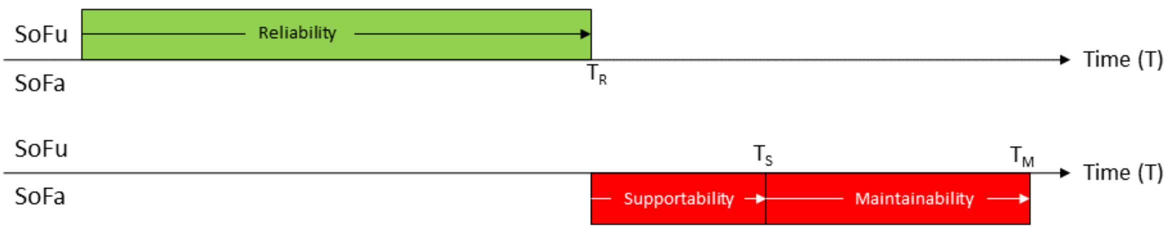

Figure 3-4: Contribution of reliability, maintainability and supportability to the functionability profile. Adapted from [3].

According to the definition of maintainability it can be assumed that it is directly proportional to the required time to finish the required maintenance task to restore the system to the state of functioning. The time needed to finish the required maintenance task is represented by the interval T_M and T_S. But the duration of the state of failure is also influenced by the supportability of the system. The only way a maintenance task can be performed is when there are enough available logistic support factors (resources). Examples of logistic support factors include personnel, technical manuals, spare parts, training, test and support equipment and facilities [15][3]. The additional time needed to finish maintenance tasks because of essential support resources is expressed as the supportability. This additional time needed is represented in 3-4 by T_S. The operational availability is thus a function of the factors reliability, maintainability and supportability.

3-2-1 Mathematical expression for the operational availaiblity

The operational availability is expressed as the total amount of time during which the frigate is capable of performing a mission over a certain time horizon. The operational availability is thus the absolute total duration of the state of functioning [3]:

$$OperationalAvailability = T_{SoFu} \tag{3-1}$$

Where T_{SoFu} is the period of time in state of functioning.
For our problem it is more interesting to express the operational availability as the ratio of the time the system is operationally available to the total time:

$$NetOperationalAvailability = \frac{T_{SoFu}}{T_{SoFu} + T_{SoFa}} \tag{3-2}$$

Equation 3-1 and 3-2 describe the operational availability in terms of the functionability of the system. The operational availability can also be mathematically described in terms of maintenance. Dhillon, Jin et.al. and Andela state that the net operational availability, from now on referred to as operational availability, can be defined by the following equation [17] [18] [19]:

$$Ao = \frac{MTBMA}{MTBMA + MDT} = \frac{MTBMA}{MTBMA + AMT + ADT + MLDT} \tag{3-3}$$

where
MTBMA = mean time between maintenance actions
MDT = mean downtime
AMT = active maintenance time
ADT = administrative delay time
MLDT = mean logistics delay time

The MTBMA in equation 3-3 equals the T_{SoFu} in equation 3-2 or, in other words, the reliability of the system. The AMT in equation 3-3 equals the maintainability in SoFa in equation 3-2 and the ADT and MLDT are equal to the supportability in SoFa in equation 3-2.

The main difference between the term MG, that was discussed in the previous section, and the operational availability can thus be explained as follows: the MG is determined by calculating the availability of the different installations on the ship every three months and the operational availability is calculated by taking the ratio between the time the ship is available and the down time of the ship over a certain time period. For the purpose of this thesis it was chosen to use the term 'operational availability' to calculate the availability of the ships, because this gives a good overview of the amount of time the ship is available over a certain time period.

Chapter 4

Current situation

Chapter 3 showed that the operational availability is a function of the amount of time that maintenance is performed on the ships. Therefore, to determine the operational availability of the ships of the RNLN, the maintenance process should be examined. This chapter will describe the existing maintenance process of the frigates and OPVs of the RNLN. Information for writing this chapter was gathered by performing desk research and conducting interviews with employees from the DMO, the RNLN and the Directie Materiële Instandhouding.
Section 4-1 gives a description of the organisational structure that is built around the ships of the RNLN. Section 4-2 gives some background on the different maintenance strategies found in literature and used by the RNLN. The existing maintenance process for the frigates and OPVs is discussed in Section 4-3. With the information from Section 4-3, the required and actual operational availability for the frigates and OPVs is determined in Section 4-4.

4-1 Organisational structure

Naval ships can also be referred to as weapon systems. To make sure that, during their whole life cycle, the weapon systems are operationally available for deployment at the right time against as low costs as possible but within the operational safety framework, Weapon System Management (WSM) has been introduced into the organisation [20]. The working principle of WSM can be summarized into the so-called 'WSM-Triangle' as shown in Figure 4-1.

At the top of this triangle stands the operational section of the Royal Netherlands Navy which is the 'user' of the weapon system. The RNLN uses the ships to perform the tasks that were described in Section 2-1-2.
The DMO sets the standards for the weapon systems and stands in the lower right corner of the triangle as 'standard setter'. The DMO determines the requirements for a new weapon system during the design process. The DMO is not only involved during the design phase of a weapon system, but also during the in-service phase of a weapon system by determining if certain modifications are needed. Modifications are changes to a system on the ship which are aimed to increase the initial level of performance of the system. They can concern the

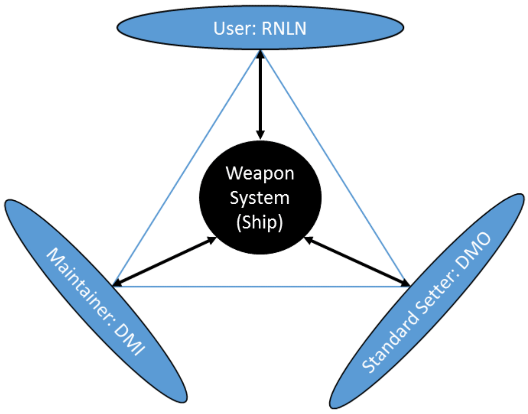

Figure 4-1: WSM Triangle

improvement of the maintainability or the lifespan of a system [2].
The 'maintainer' of the ships of the RNLN is the 'Directie Materiële Instandhouding (DMI). The DMI is responsible for the planning and execution of the maintenance works on the ships. Another task of the DMI is to implement modifications on the weapon systems. During a deployment, the RNLN (user) also performs certain small maintenance tasks, this is explained later. It is important that the 'user', 'standard setter' and 'maintainer' cooperate intensively to ensure that the weapon system is operationally available when needed. For this reason there are three WSM managers for every ship class (user, standard setter and maintainer), who meet frequently.

Besides WSM there is also Technical System Management (TSM). TSM is responsible for the technical installations on the ship. Like for WSM, the working principle of TSM can be summarised in a triangle.

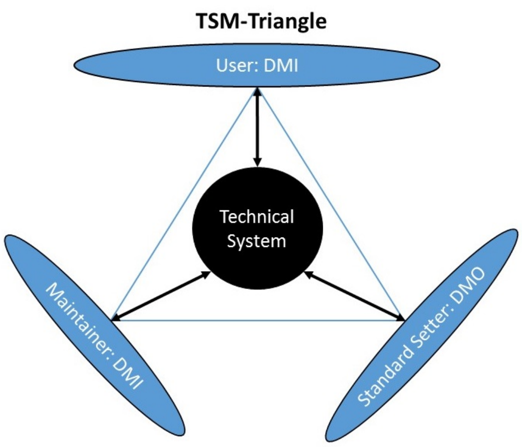

Figure 4-2: TSM Triangle

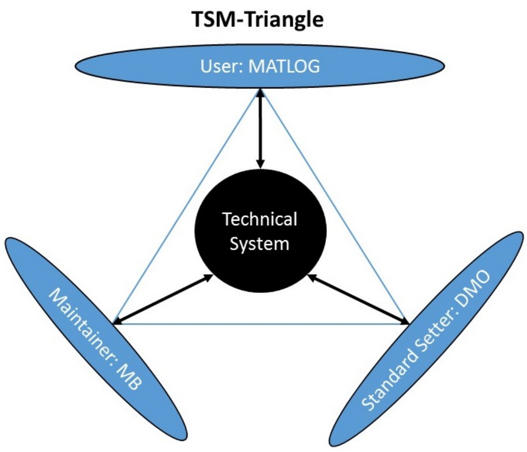

Figure 4-3: Old TSM Triangle

The TSM triangle is shown in Figure 4-2 and looks slightly different then the WSM triangle. The 'standard setter' is again the DMO but now the 'user' and the 'maintainer' are both the DMI. The reason for this is that the DMI was formed by combining the 'Marinebedrijf (MB)' and 'MATLOG' which is shown in Figure 4-3 as the old TSM triangle. The MB was the maintainer in the old situation and MATLOG was the user. However, because the MB and MATLOG were combined to the DMI, now both the user and the maintainer are represented by the DMI: 'DMI user' is the military branch of the DMI and 'DMI maintainer' is the civilian maintainer. The purpose of TSM is to ensure that the installations on the ship are available at the right time, against low costs and within the operational safety framework. When changes on an installation are needed the 'standard setter' (DMO) has a leading role. In case of radical changes, WSM is involved by TSM because TSM is a step lower on the hierarchical ladder than WSM. The WSM managers then decide whether the changes are carried out.

4-2 Maintenance strategies

According to Parida et.al. a paradigm shift in maintenance management occurred over the last century [21]. Prior to the early 1900s up until World War II maintenance was always performed in a reactive way to restore the functional capability of a failed item. The general attitude towards this maintenance strategy was, "it costs what it costs", and it was seen as a 'necessary evil'. After World War II maintenance became more and more important as a support function for production and manufacturing processes. New maintenance strategies like preventive maintenance and condition monitoring resulted in a perception change to: "It can be planned and controlled". This trend was stretched even further and today, maintenance is increasingly considered as an essential part of the business process, which changed the attitude towards maintenance to: "It creates additional value". This paradigm shift in maintenance has led to roughly three different maintenance strategies which can be described as follows [22]:

- **Corrective maintenance**: Is the oldest type of maintenance. This type of maintenance is performed when a fault in a system has already occurred: it is a reactive approach to maintenance. It can therefore also be called run-to-failure maintenance [22][23][18].
- **Preventive maintenance**: The aim of preventive maintenance is to prevent faults or, by all means, reduce the probability or the impact of the occurrence of faults by taking maintenance actions in advance and therefore improving the safety, availability and reliability of the system [22][23][24].
  Planned or time-directed maintenance is the most commonly used form of preventive maintenance. It consists of a fixed maintenance scheduling. A maintenance schedule is drafted by making use of knowledge and experience and/or by using 'Original Equipment Manufacturer' (OEM) instructions. Planned maintenance is done by using a checklist of items that have to be checked at regular time intervals regardless of other information that may be available at that time. For example, when using planned maintenance, it is stated that every 52 weeks the oil of a diesel engine has to be replaced by new oil, even when it is unnecessary at that time. Preventive maintenance actions that are not well planned can lead to more failures, unnecessary replacements and additional costs [22][25].
- **Condition-based maintenance**: This is a form of preventive maintenance. Condition-based maintenance (CBM) takes the real conditions of the system into account by doing

measurements [22]. Condition means the 'state' of the system at a certain time. For example, the condition could be classified as 'good', 'awaiting maintenance' or 'unacceptable' and it depends on the degradation process of the equipment. Only when certain indicators (degradation thresholds) show signs of decreasing performance or upcoming failures of a component in the system, and thus a worsening condition, maintenance should be carried out [22]. By using CBM, maintenance can be scheduled in a way that no system down-time for failures is needed and the downtime for inspections and performing maintenance is minimised [26][25]. The aim of CBM is to detect future equipment failures so maintenance can be scheduled when it is actually needed, not before it is needed. Because the condition of the components has to be known, CBM requires frequent monitoring of the degradation state of the components. Therefore, measurements are done at periodic time intervals or continuously, to determine the true state of the equipment [22]. CBM also improves the reliability, availability and safety of the system in comparison to planned maintenance and corrective maintenance because possible failures are detected and can be corrected before they actually occur and unnecessary replacements are avoided as well.

4-3 Existing maintenance process

This section explains the existing maintenance process for the MFFs, LCFs and OPVs. Section 4-3-1 first explains the different maintenance levels used by the RNLN. Then Section 4-3-2 describes the life cycle of the shipbuilding process. The 'in-service phase' of a ship is discussed in more detail in 4-3-3. Lastly, Sections 4-3-4 and 4-3-5 discuss the different maintenance periods which were stated in Section 4-3-3. Lastly, in Section 4-4 the required and actual operational availability for the MFFs, LCFs and OPVs is calculated.

4-3-1 Maintenance levels

Maintenance facilities for the Netherlands Armed Forces are generally divided over three different levels: Organic Level Maintenance (OLM), Intermediate Level Maintenance (ILM) and Depot Level Maintenance (DLM) [27][28][4]. These different levels of maintenance will now be discussed for the RNLN.

Organic Level Maintenance In the 'Systeemplan' of the MFFs and LCFs it is stated that a ship should be able to survive 30 days at sea without any help from outside. This is 21 days for the OPVs. Therefore, the crew of the ship should be able to perform different maintenance tasks on the different systems on the ship and there should be a minimum stock for 30 days on the MFFs and LCFs and a minimum stock for 21 days on the OPVs. The maintenance that is performed by the crew of the ship (the RNLN) on a day-to-day basis in support of its own operations is called OLM. The objective of OLM is to keep the ship in a mission capable status. The means (tools and spare parts) needed for OLM are available on board of the ship and most of the OLM tasks can be performed at sea, as well as onshore and do not take a large amount of time. On the OPVs, the crew of the ship is supported by a Wal Ondersteuning Patrouilleschip (WOPS) team when necessary. The WOPS team was established because of the reduction in crew on the OPVs. The OLM tasks can be divided into tasks of different maintenance strategies as follows:

- *Corrective maintenance tasks*: Fixing a system that breaks down by, for example, changing parts. Frequently, a failure should first be located before it can be fixed. This locating is also a task of the crew.
- *Preventive maintenance (planned)*: For every system on the ship, there are so-called 'PO-tasks', which should be performed periodically. Every PO-task has a corresponding PO-card, which states what preventive maintenance actions should be taken. For example, it should be checked if the diesel engine is not leaking oil once every day. Then the PO-card states a 'D' from daily and the task 'check the Diesel Engine for leaking oil'. Every system on board has its own corresponding PO-cards. An example of a PO-card is included in Appendix E.
- *Condition-based maintenance*: Some PO-cards include tests to monitor the condition of a system. For example every week a sample of the oil in the diesel engines should be checked on fouling. The oil should be replaced when it does not meet the requirements anymore.

Intermediate Level Maintenance ILM can be performed on a day-to-day basis but most of the time it does not fit within the operational schedule of the ship and is performed during a planned period (Assisted Maintenance period). In some cases ILM can be performed by the crew of the ship (the RNLN) but generally the assistance of the DMI is required. The goal of ILM is to sustain and enhance the operational availability of the ship. Some ILM tasks can be performed at sea but most of the tasks need to be done onshore. The means (tools and spare parts) that are needed for ILM are sometimes on board but equipment from DMI or external parties is often needed. Just like for OLM, the ILM tasks can be divided into tasks of different maintenance strategies, but they are often more complex:

- *Corrective maintenance*: Failed equipment that lead to maintenance tasks that are too complicated for OLM is fixed during ILM.
- *Preventive maintenance*: Planned maintenance tasks are performed for which the assistance of DMI is required.
- *Condition-based maintenance*: CBM tasks can also be performed during ILM.

Depot Level Maintenance DLM is the most intensive level of maintenance. It cannot be performed by the crew of the ship but is performed by DMI and/or external companies. DLM is scheduled by the DMI during an approximately one year period (Benoemd Onderhoud period) and it should be performed onshore. For some tasks the ship needs to be in the dock. DMI owns a lot of tools that are needed for DLM, but it is also possible that tools have to be purchased or hired from external companies. The needed spare parts are in the warehouses of DMI but a lot of parts have to be purchased. There are different kinds of maintenance tasks that need to be performed during DLM:

- *Corrective maintenance*: Excessive structural repairs in order to extend the integrity of the ship should be performed.
- *Preventive maintenance*: Tasks that cannot be done during OLM or ILM, but also PO-tasks that by chance need to be done during the DLM period.
- *Overhaul of repairable articles.*
- *System modifications* that need to be performed on certain systems are executed during DLM.

Figure 4-4 schematically summarises the different maintenance levels on the MFFs and LCFs.

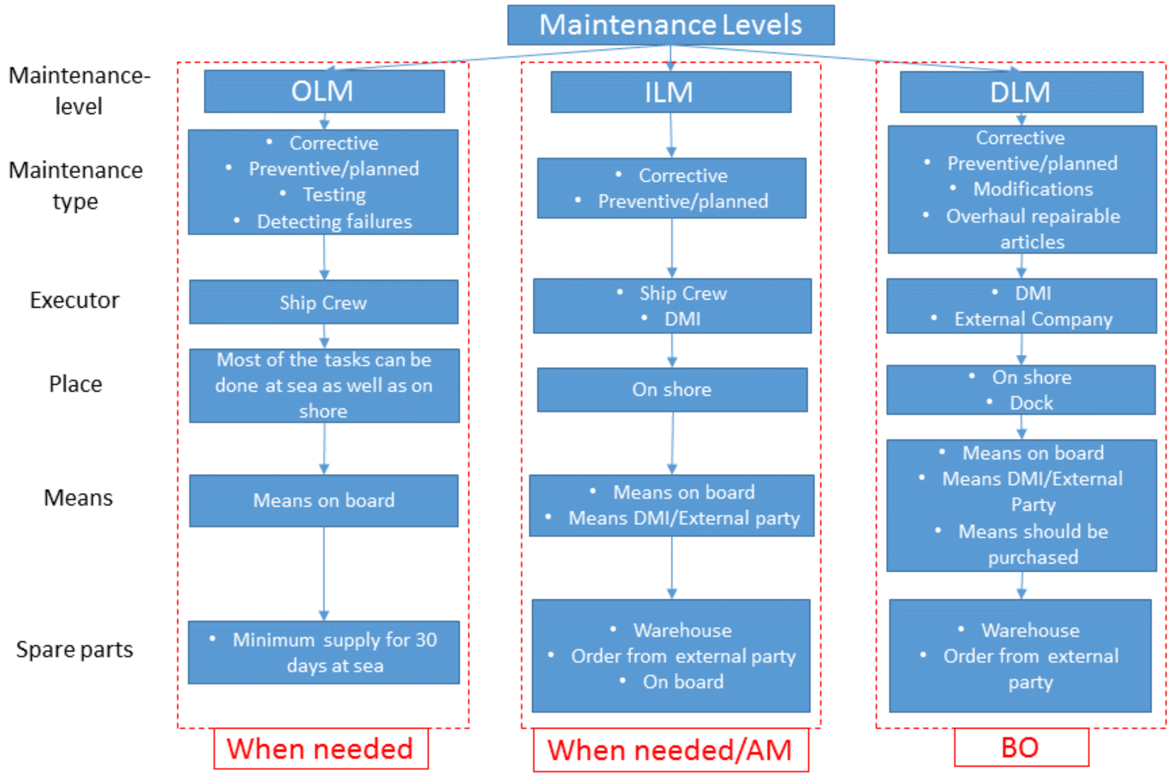

Figure 4-4: Different Maintenance Levels

There is a fourth maintenance level which is called *Contractor Level Maintenance* on the OPVs. This level of maintenance is the same as DLM but it is outsourced to a company outside the defence organisation. This company has the tools, spare parts and people to perform the required maintenance tasks. For the MFFs and LCFs, the outsourced maintenance falls within DLM.

4-3-2 Life cycle of a shipbuilding project

Figure 4-5 shows the different phases of the life cycle of a shipbuilding process. The operational concept, operational requirements and functional capacities for the ship are described in the concept phase. After that the ship is designed during different design phases. When the design is completed, the ship is built during the realisation phase. After completing the manufacturing of the ship, it is commissioned and enters the in-service phase. This is the actual lifespan of the ship in which it can be used for deployments and other tasks. When the ship has reached the end of its life, it is sold or it is discarded. The shipbuilding lifecycle is schematically shown in Figure 4-5. The different DMP phases, that were explained in Section 2-3, are also shown in this figure.

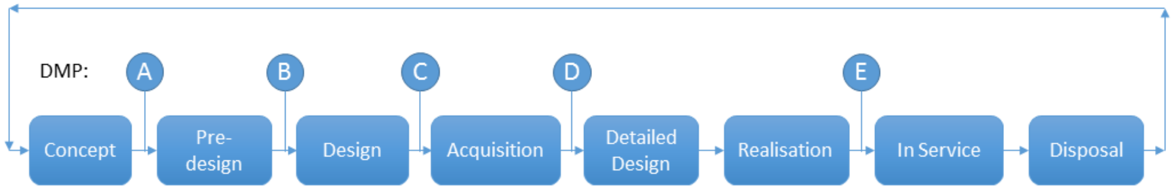

Figure 4-5: Life cycle of a shipbuilding project. Adapted from [4].

As stated in Section 2-3, the concept phase for the future M-Frigates project has already started. To examine the existing maintenance process of the frigates and OPVs, the 'in-service phase' of the existing frigates and OPVs should be further examined.

4-3-3 In-service phase

During the in-service phase (or lifespan) of the ship, the ship is deployed to all kinds of destinations under constantly changing circumstances. To ensure that the systems on the ship function properly, it is important that maintenance is performed when needed.

A ship has a lifespan of around 25 years. This lifespan is divided into 5-year maintenance cycles. In the first four years of this five year cycle there are one or two so-called 'Assisted Maintenance (AM)' periods every year. In an AM-period ILM is performed. There are no requirements for the lead time of the AM periods, however, it is learned from interviews and schedules that the lead time of an AM period is around four weeks. The ship cannot be deployed during an AM period. The operational requirements of the ship are taken into account when scheduling the AM periods to make sure that the ship is not scheduled for an AM period when a deployment is planned.

After the first four years of the five year cycle the ship is subjected to a one year large maintenance period, which is called a Benoemd Onderhoud (BO) period. In a BO period DLM is performed. The ship is not available for deployment during this period. Every five years a 'small' BO period and every ten years a 'large' BO period is scheduled. Again, there are no hard requirements for the lead time of the small and large BO periods, however, it is learned from interviews that the BO periods of the MFFs and LCFs should have a lead time of one year. For the OPVs, the lead time of the BO periods was originally set to 6 months but because of the reorganisation of the DMI this was extended to 8 months.

When the ship reaches approximately half its lifespan, a midlife upgrade (Instandhoudings Programma (IP)) is performed in which (large scale) modifications are implemented to keep the ship up-to-date with the latest technologies and to solve recurring problems with systems. A midlife upgrade is performed directly after a BO period and takes up to one year. As stated before, the IPs of the current MFFs started in 2010 and finished in 2015.

Figure 4-6 graphically displays the lifespan of the MFFs and LCFs. For the OPVs, this figure looks slightly different because of the BO period of 8 months instead of one year.

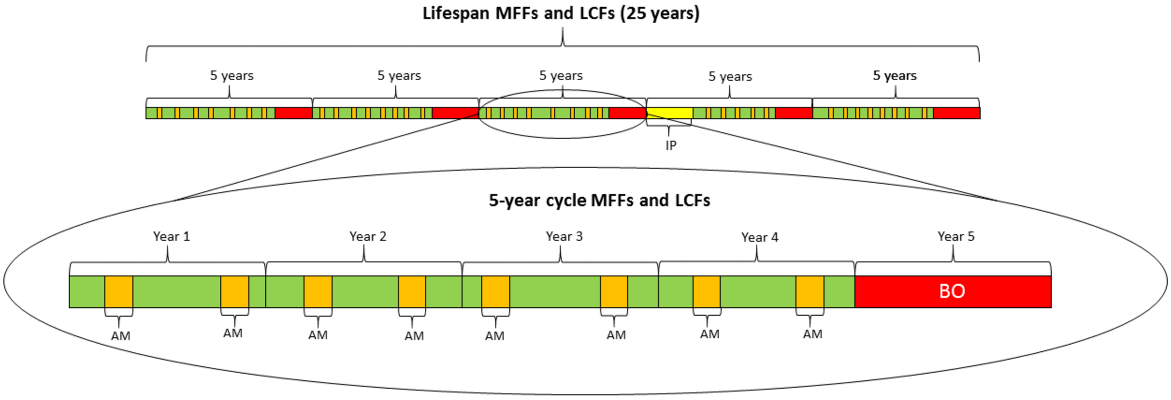

Figure 4-6: In-service phase of the MFFs, LCFs and OPVs

There are four MFFs (2 NL, 2 BE), four LCFs and four OPVs. In principle there should always be three ships of every class available for deployment (except when there is also a ship having an AM period) and sometimes even four ships. In between the AM and BO periods the ship should be available for deployments. During these periods small maintenance tasks (OLM and sometimes ILM) are performed by the crew of the ship.

It can be concluded that OLM is constantly performed on the ship during its whole lifespan and that ILM and DLM are only performed during AM and BO periods. Those periods are all separate projects that have to be planned and managed. However, the first BO projects (BO-1) for all four ships of a ship class are quite similar, the second BO projects (BO-2) for all four ships of a ship class are quite similar, etc.

4-3-4 Benoemd Onderhoud process

The goal of a BO project is to maintain the ship and to implement modifications in such a way that the next four years the ship is operationally available and no large maintenance (except for OLM and ILM) is needed during this period. Every BO period is a different project. The costs for a single BO project are approximately CONFIDENTIAL euros for the OPVs and CONFIDENTIAL euros for the MFFs and LCFs [29][30]. These costs are highly dependent on the amount of man hours and spare parts needed and thus on the amount of maintenance tasks that should be performed. Every BO project goes through a process that is divided into six phases as shown in Figure 4-7.

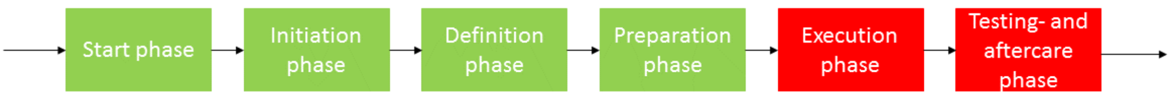

Figure 4-7: Phases of the BO process [5]

The start phase, initiation phase, definition phase and preparation phase are the phases in which the maintenance works are prepared. During these phases the ship is still available

for deployment (green). The execution phase and testing and aftercare phase are the phases during which the ship is not available for deployment (red). In Section 4-3-3 it was mentioned that the lead time of the BO periods should be one year for the MFFs and LCFs and 8 months for the OPVs. This lead time is the time the execution phase and testing- and aftercare phase take. The start, initiation, definition and preparation phase together also take between 1.5 and two years. So the total length of a BO project is actually between 2.5 and three years, but the ship is unavailable for only one year.
A detailed description of the different phases in a BO project can be found in Appendix F.

4-3-5 Assisted Maintenance process

In an AM project ILM is performed on the ship. An AM project is a lot shorter than a BO project, as was discussed in Section 4-3-3. One AM project costs between CONFIDENTIAL euros, depending on the tasks that need to be performed [31]. Every AM project goes through a process that can be divided into four different phases as shown in Figure 4-8.

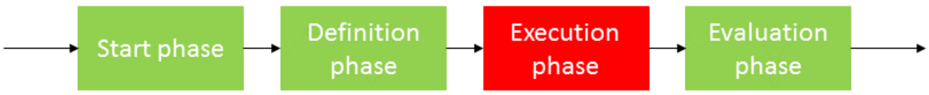

Figure 4-8: Phases of the AM process [6]

In the start phase and definition phase the maintenance activities are prepared. During these phases, the ship is still available for deployment. In the execution phase, the maintenance activities are performed and the ship is not available for deployment. The evaluation phase evaluates the project and in this phase the ship is ready for deployment again. In Section 4-3-3 it was stated that the lead time of an AM period is about four weeks. This lead time is the time the ship is not available for deployment and thus the lead time of the execution phase of the AM project. The time a complete AM project takes (from start phase to evaluation phase) is about 16 weeks. A detailed description of the different phases in a BO project can be found in Appendix G.

4-4 Operational availability of the Royal Netherlands Navy ships

In this section the required operational availability is calculated based on the information discussed in the previous sections. Subsequently, the actual operational availability of the ships of the MFFs, LCFs and OPV is calculated.

4-4-1 Required operational availability

As already mentioned in Section 4-3 the time span of a maintenance cycle is five years. In the first four years the ships have two AM periods per year, with a lead time of approximately four weeks. The last year of this cycle, the ship has a BO period with a lead time of one year for the MFFs and LCFs and eight months for the OPVs. With this information the required operational availability per year can be calculated by using equation 3-3 that was described in

Chapter 3. For the first four years, the MDT is represented by the time of the AM periods (in months) and the MTBMA is represented by the time between these AM periods (in months). Using this in Equation 3-3 gives the required operational availability for the first four years of the five year cycle:

$$Ao_{min} = \frac{12 - 2}{12} = 0.833$$

In the year that the BO takes place the MFFs and LCFs are in maintenance for a whole year, the MDT is thus one year and the MTBMA is zero. Using this in Equation 3-3 gives the required operational availability during a BO year for the MFFs and LCFs:

$$Ao_{min} = \frac{12 - 12}{12} = 0$$

Because the OPVs have a BO period of eight months the required operational availability for the OPVs during a BO year is:

$$Ao_{min} = \frac{12 - 8}{12} = 0.333$$

In the first four years the MFFs, LCFs and OPVs should be available for deployment 83.3% of the time. In the year the BO takes place the MFFs and LCFs are not available for deployment and the OPVs are 33.3% of the time available for deployment.
When the required operational availability is calculated in this way, it is assumed that a BO period always starts at January 1 and ends at December 31 for the MFFs and LCFs and starts and ends somewhere between these dates for the OPVs. The problem with this way of calculating the required operational availability of the ships is that the BO periods are not always from January 1st till December 31st. Therefore, it is more appropriate to calculate the required operational availability over a time period of a maintenance cycle (or multiple cycles), thus over a period of five years (or a multiple of five years). Again, by using Equation 3-3 the required operational availability can be calculated. The MDT in this equation is represented by the AM and BO periods and the MTBMA is represented by the time between AM and BO periods. This gives the following required operational availability for the MFFs/LCFs and OPVs, respectively:

$$Ao_{minMFF/LCF} = \frac{(60 - 4 * 2 - 12)}{60} = 0.667$$

$$Ao_{minOPV} = \frac{(60 - 4 * 2 - 8)}{60} = 0.733$$

This means that the operational availability over a period of five years (or a multiple of five years) should at least be 66.7% for the MFFs and LCFs and 73.3% for the OPVs. The higher the operational availability, the more possibilities for the CDS to deploy a ship when required, so it should always be the objective to have an operational availability as high as possible.

4-4-2 Actual operational availability

In order to calculate the actual operational availability, the actual maintenance time of the ships of the RNLN should be known. The RNLN works with a long term planning and a short term, or detailed, planning for their ships. The long term planning is called the '*Gereedstellingsplan (GSP)*' which is a planning with a time horizon of multiple years (approx. 5-8 years). This is a global planning in which the BO periods and large deployments are included, but for example not the AM periods and leaves. The short term planning is a very detailed planning of a one-year period and is called the '*Operationeel Jaarplan (OJP)*'. The OJP includes everything the ship needs to do during that year including deployments, AM periods, BO periods, leaves, family days etc. An example of a modified version (for confidentiality reasons) of an OJP is included in Appendix H.
The OJPs of the period 2013-2017 were analysed to determine the actual operational availability of the MFFs, LCFs and OPVs. The period of 2013-2017 was chosen because the OPVs are in service since 2013. In the detailed description of the BO phases (Appendix F) it was stated that when Safety And Readiness Check 3 (SARC 3) is finished, the ship can independently go to sea and is thus available for certain tasks if necessary. Therefore, the end of the BO period is set at SARC 3 for the calculation of the operational availability.
Figures 4-9, 4-10 and 4-11 show the operational availability of MFFs, LCFs and OPVs respectively.

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Figure 4-9: Operational Availability MFFs 2013-2017

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Figure 4-10: Operational Availability LCFs 2013-2017

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Figure 4-11: Operational Availability OPVs 2013-2017

Figure 4-9 shows that the actual operational availability of the MFFs lies between CONFIDENTIAL which is significantly lower than the required 66.7%. This means that the MFFs were operationally available for only 2.5 to 3 years out of 5 years. One of the factors that could have influenced the operational availability of the MFFs in this period is the 'Instandhoudingsproject (IP)', during which the ship is not operationally available for another period of time after a BO period, however, Zr. Ms. Van Speijk already had the IP in the period 2010-2012 and this ship still not meets the operational availability requirements.

Figure 4-10 shows that in the period 2013-2017 the actual operational availability of the LCFs does not meet the requirement of 66.7% as well. Only one LCF has an operational availability that is more than CONFIDENTIAL while the others have an operational availability between CONFIDENTIAL. The actual operational availability of the LCFs could be partly explained by the fact that in BO-2 of the LCFs, the diesel generators and shaft had to be replaced. However, Zr. Ms. De Zeven Provinciën already had BO-2 in 2011-2012 and this ship still not meets the operational availability requirements. Figure 4-11 shows that the OPVs do not meet the operational availability requirements as well. The ships all have an operational availability between CONFIDENTIAL but the required 73.3% was never reached.

From this it can be concluded that the actual operational availability of the MFFs, LCFs and OPVs in the period 2013-2017 does not meet the operational availability requirements.

4-4-3 Room for improvement

If we compare the operational availability of the MFFs, LCFs and OPVs with the operational availability of ships from commercial shipping companies, a large difference is found. Information was gathered from three different commercial shipping companies by performing interviews. The information found can be summarised as follows:

- *Company 1*: Uses a five year maintenance cycle. After 2.5 years there is a small maintenance period of seven days and after 5 years there is a large maintenance period of 2 or 3 weeks during which the ship is in the dock. Due to unplanned maintenance actions, the ship is unavailable for service another five days per year. Company 1 uses this five year cycle, because this is imposed by the maritime classification bureaus. This results in an operational availability of approximately 97%.
- *Company 2*: Also uses a five year maintenance cycle. After 2.5 years there is a docking survey period of seven days and after five years there is a special survey with a duration of seven days. Besides that, there is an annual survey of two days but this survey takes place when the ship is in-service. Company 2 uses this five year cycle for the same reason as Company 1. This results in an operational availability of approximately 99%.
- *Company 3*: Company 3 was hesitant with giving information about their maintenance process because this information can be used by their competitors. The only information given was that there is a dry-dock period of two weeks every year. Information about the length of their maintenance cycle was not given but judging from the other companies they should use a five year cycle because this is imposed by the maritime classification bureaus. This would mean that the operational availability of the ships is approximately 96%.

It can be concluded that the operational availability of commercial ships is a lot higher than the operational availability of the RNLN frigates and OPVs. Important to keep in mind here is that warships are a lot more complex compared to commercial ships. There are no weapons and highly advanced military sensor and communication systems on commercial ships. Therefore, the maintenance on warships is much more complex than the maintenance on commercial ships. Furthermore, the commercial companies and the RNLN have different interests. The commercial companies want to make a profit, which is only possible when the ships are operationally available as much as possible. Therefore, they will do anything to make sure that the maintenance on the ships is performed as fast as possible. The RNLN also wants their ships to be operationally available as much as possible. However, the RNLN does not have to make a profit and they have a certain maintenance budget available every year. This, and the complexity of the warships makes it practically impossible to have an operational availability that is as high as the operational availability of the commercial ships. However, there certainly is room for improvement.

Equation 3-3 implies that the operational availability of the ships can be improved by:

1. Increasing the MTBMA
2. Decreasing the MDT

The MTBMA can be increased in different ways, namely: increasing the time of the maintenance cycle while keeping the MDT the same, or by decreasing the MDT. The MDT was divided into the AMT, ADT and the MLDT. So by decreasing one of these three aspects, the MDT will also decrease. Therefore, in order to increase the operational availability the current maintenance process should be analysed.

Chapter 5

Process analysis

Chapter 4 showed that the actual operational availability of the frigates and OPVs does not meet the requirements. To find out the reasons for this an analysis of the current maintenance process of the ships is performed in this chapter. In Section 5-1 the complete maintenance process is analysed with the Delft Systems Approach [1]. Then, the main contributor to the low operational availability will be analysed in Section 5-2.

5-1 Maintenance process analysis

In order to identify the causes for the low operational availability of the frigates and OPVs, the Delft Systems Approach (DSA) described by Veeke et.al. is used to analyse the maintenance process [1].
The process is first represented as a black box, which is defined by in 't Veld as a system or subsystem of which the internal elements and relations are not yet known to the researcher, or that are not studied by the researcher (yet) [32]. In the highest aggregation layer, only the inputs and outputs of the black box are looked at. After that, the black box will be opened to reveal black boxes of one aggregation layer deeper, which results in more information about the working principle of the process. Going an aggregation layer deeper can be repeated as many times as considered necessary to trace relevant issues in the maintenance function of the RNLN.

Figure 5-1 shows the black box for the complete maintenance process for the frigates and OPVs. Inside this black box, the ship in need of maintenance is transformed into a maintained ship.
The *input* stream of the black box consists of the ships that are in need of maintenance. This does not directly mean that the ships are not operationally available, although this is sometimes the case.
The *output* stream consists of the ships that had maintenance and are thus maintained and operationally available.

The *function* 'maintaining the ship' transforms the input to the output according to certain *requirements*. The overall requirement for the maintenance process is the required operational availability. The *performance* of the black box function is the actual operational availability, so the objective of the 'maintaining the ship' function is to maintain the ship in such a way that the required operational availability is achieved.

Figure 5-1: Black box approach to complete maintenance process

As was shown in Section 4-4, the operational availability requirements are not met for the frigates and OPVs. This means that somewhere inside the black box things are not going as planned. Therefore, the 'maintaining the ship' function should be opened. When this is done, different smaller black boxes appear as shown in Figure 5-2.

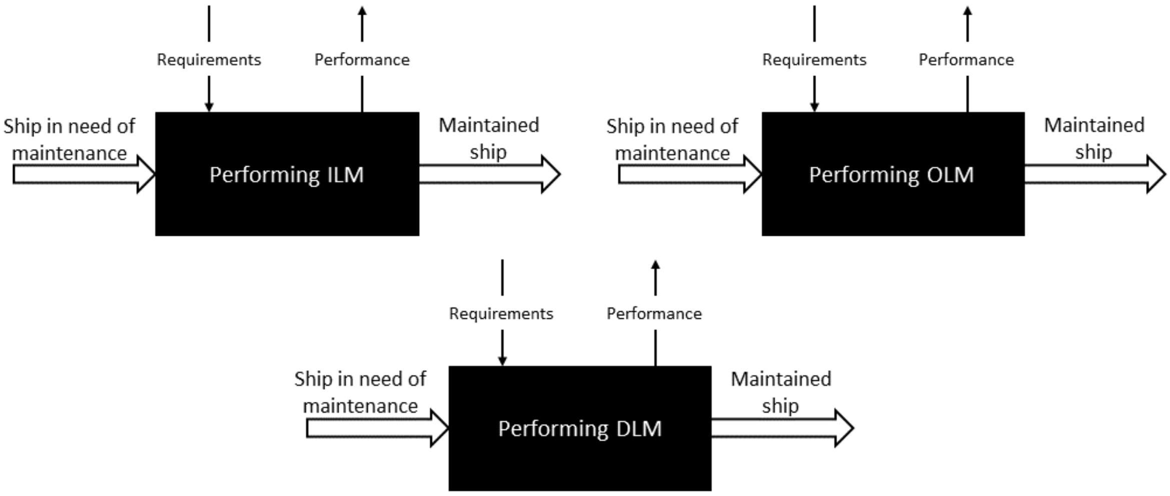

Figure 5-2: Opened 'maintaining the ship' function

The different black boxes found when opening the black box from Figure 5-1 are:

- *Performing OLM*: Section 4-3-1 explained that OLM is performed on board of the ship by its own crew. The objective is to keep the ship in a mission capable status. When the ship enters this black box, it stays operationally available.
- *Performing ILM*: In other words this usually means: 'executing an AM project'. It is also possible that unscheduled corrective ILM has to be performed outside an AM period. The ship is not operationally available when it enters this black box.

- *Performing DLM*: In other words 'executing a BO project'. The ship is not operationally available when it enters this black box. It is also possible that unscheduled DLM has to be performed outside a BO project. Most of the times unscheduled DLM tasks are planned in the BO period, however, it is also possible that unscheduled DLM has to be performed outside a BO project. A recent example of a large unscheduled DLM task is the main electric motor (Hoofd Elektromotor (HEM)) from the Joint Support Ship (JSS) Zr. Ms. Karel Doorman. On March 10th 2016, the starboard HEM got heavily damaged. The motor had to be taken of the ship to go back to the manufacturer (General Electric) in France [10]. It turned out that a modification in the design of the HEM was needed. Consequently, the port HEM had to go to France as well. Because of this unscheduled event Zr. Ms. Karel Doorman is operationally not available up until the summer of 2017.

The MDT in equation 3-3 thus consists of the AM periods, BO periods and possible unplanned maintenance actions. To be able to decrease the MDT and thus increase the operational availability, the lead time of the AM projects and/or the lead time of the BO projects should be reduced and the amount of unscheduled corrective maintenance actions during which the ship is operationally unavailable should be as low as possible.
Data from the OJPs show that the actual lead time of AM periods is normally not much longer than the planned lead time. When certain maintenance tasks are not finished during an AM period they are passed on to the next AM period. This means that the AM period is finished in time, but some maintenance tasks still need to be performed which can lead to a following AM period that is longer, or a BO period with more tasks. This has an influence on the operational availability, although most of the times this influence is minimal.
The OJPs also show that there is no significant influence of unscheduled maintenance tasks on the operational availability of the MFFs, LCFs and OPVs.
On the contrary, the BO periods have a significant influence on the operational availability of the frigates and OPVs. First of all because the lead time of a BO project is one year and also because the actual lead time is often longer than the planned lead time. At the moment, the execution phase and aftercare phase up until SARC 3 (during which the ship is not operationally available) of the BO projects almost always have a longer lead time (months) than the planned lead time. Besides that, the planned lead time is often already longer than the required one year. This has a large influence on the operational availability of the ships. The duration of nine different BO projects is shown in Figure 5-3. This figure illustrates that the lead time for every BO project is significantly longer than planned. The longer lead times for the BO projects for the MFFs can be partly explained by the fact that these were BO+IP projects. The longer lead times for the BO-2 projects of the LCFs can be partly explained by unforseen modifications of the diesel generators and shaft. Especially BO-2 of Zr. Ms. De Zeven Provinciën is affected by this because this was the first BO-2 LCF project. For the other BO-2 LCF projects the same modifications had to be performed and this was already known in advance. Therefore, one could expect a shorter BO-2 lead time for the three other LCFs. Figure 5-3 shows that the lead time of BO-2 Zr. Ms. Tromp indeed is a lot shorter than the lead time of BO-2 De Zeven Provinciën. However, BO-2 Zr. Ms. De Ruyter and Zr. Ms. Evertsen again show a longer lead time than BO-2 Zr. Ms. Tromp, while one would expect a downwards learning curve. This indicates that there should be other problems in the BO process that cause the longer lead times.

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Figure 5-3: Duration BO projects

Because the biggest room for decreasing the MDT lies within the BO process, the BO process will now be further analysed.

5-2 BO process analysis

Figure 5-4 shows the black box for the BO process of the MFFs, LCFs and OPVs. Inside this black box, the ship in need of DLM is transformed into a maintained ship.

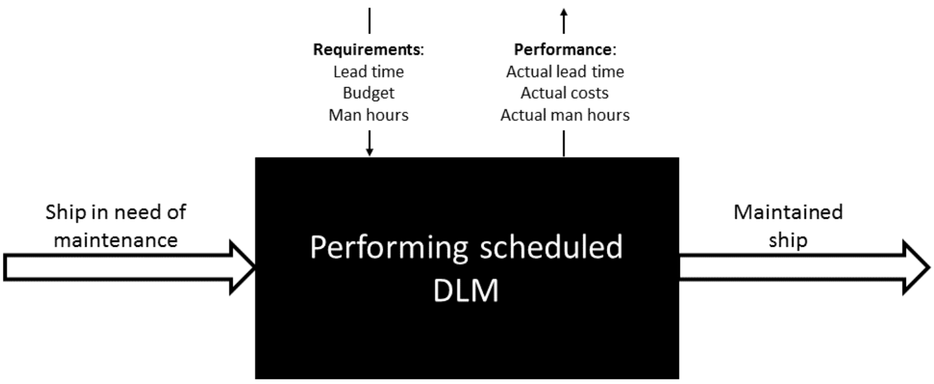

Figure 5-4: Black box approach to BO process

The *input* stream of the black box consists of the ships that are in need of DLM. This does not directly mean that the ships are not operationally available, although this is sometimes the case. Once the ships enter the black box, they get the status 'operationally not available'. The *output* stream consists of the ships that had DLM and are thus maintained and operationally available again.
The *function* 'performing scheduled DLM' transforms the input to the output with certain *requirements*. The requirements for the BO project can be found in the project mandate. This document contains the budget (money and man hours) and the maintenance period for

the project. The *performance* of the black box function is measured by Key Performance Indicators (KPIs). The KPIs are the total money spent, the man hours used and the lead time of the project.
As was shown in Section 3-2, the *operational availability* of the ship is directly related to the lead time of the BO projects.

To analyse the BO process properly, more details are needed. Therefore, the black box is opened to look at one aggregation layer deeper, which has been described as a process performance model (PROPER model). Veeke et.al. introduced this model and stated that it should at least contain the following three aspects [1]:

1. *"The 'product' as a result of a transformation."*
2. *"The flow of orders; without customer orders no products will flow. In this flow, orders are transformed into handled orders."*
3. *"The 'resources' (people and means) required to make the product. To make use of them, they must enter the system and they will leave the system as used resources."*

This model allows the use of different aspects in one model and this connection is of importance to analyse the BO process further. The PROPER model for the BO process is shown in Figure 5-5.

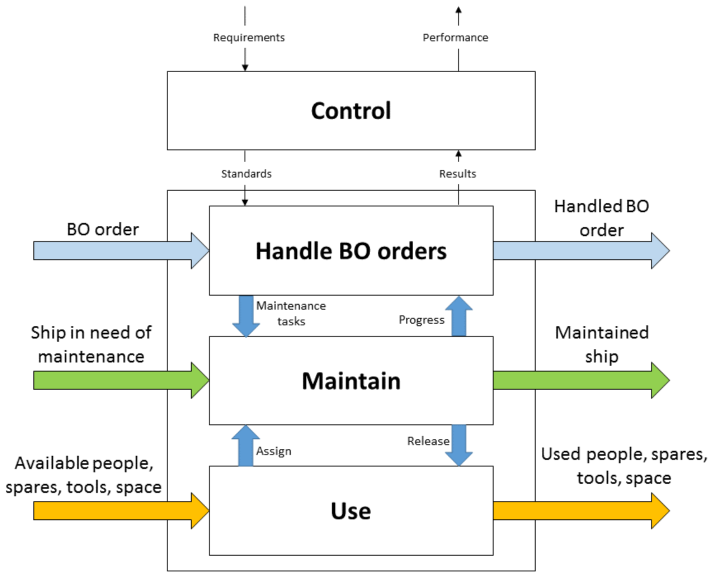

Figure 5-5: PROPER Model BO project

The three aspects for the BO process are orders, ships and resources. The order is the incoming order for the BO project that was approved by the management. The resources needed for the BO project are people, spare parts, tools and space (dock and quay). The orders form the tasks for the 'maintain' function and the people, spare parts, tools and space (dock and quay) are the resources that are used to perform the 'maintain' function. These streams are shown as thick arrows between the functions handle BO orders, maintain and use.

The 'control' function translates the requirements into usable standards for the process and checks the results to determine if the performance meets the set requirements. By looking at the different aspects of the PROPER model and their interaction, the BO process is analysed and the main reason(s) for the long lead time of the BO projects can be determined.

5-2-1 The 'handle BO orders' function

The 'handle BO orders' function is shown in 5-6. The 'incoming order' is the order for the BO project that was approved by the management.

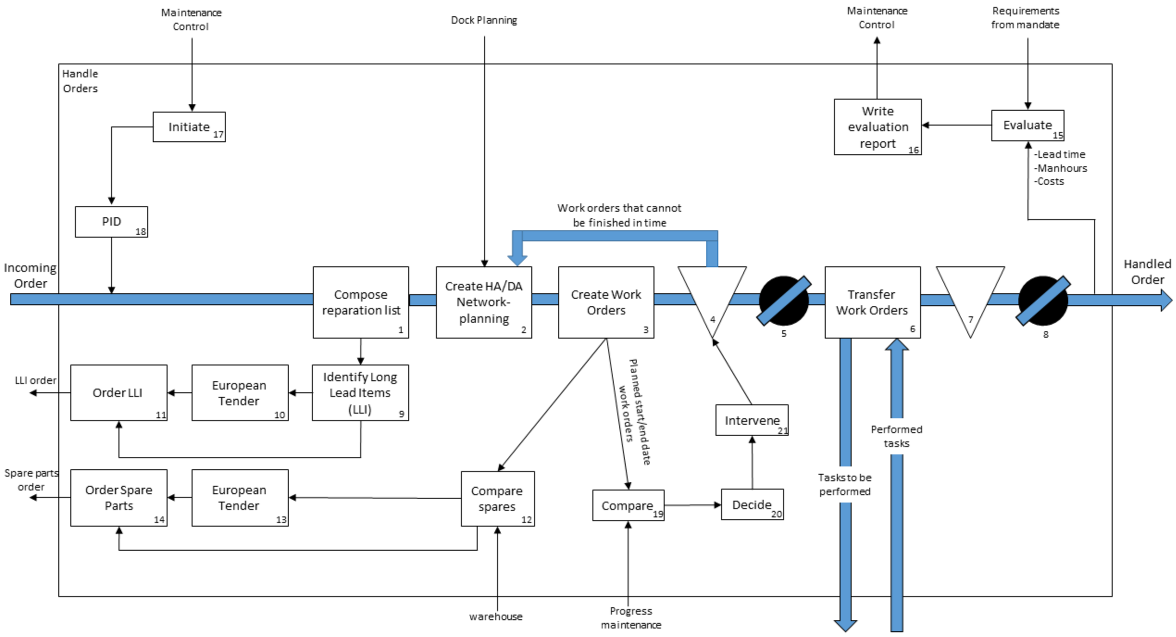

Figure 5-6: Zoomed in on the 'handle BO orders' function

The different functions in the order flow can be described as follows (numbers correspond to the numbers in Figure 5-6):

1. *Compose repair list*: This function composes the repair list that includes all maintenance tasks that need to be performed in this project.

2. *Create HA/DA Networkplanning*: The repair list is the input for this function. The different tasks on the repair list are clustered under 'Hoofdactiviteiten (HA)' and 'Deelactiviteiten (DA)'. The dock planning is also an input for this function because the dock capacity is limited and therefore critical. The maintenance tasks that have to be performed in the dock should be planned in the period that was indicated in the dock planning. *It is normal for the planners to already plan a couple of weeks 'extra time' for every DA of every installation that needs maintenance, so that it is less likely for the maintenance to be delayed. The planning is 'spacious'.* Besides that, the HA/DA planning is constantly adjusted during the process. If certain tasks cannot start in time, this is altered in the planning and the work orders are changed. *The planning is not 'rigid'.*

3. *Create Work Orders*: Work orders are created in SAP by means of the HA/DA Network planning. SAP is the software program used by the Dutch Ministry of Defence that supports the whole material logistical management. Work orders include the task description, start time, finish time and needed resources for the maintenance task.

4. *'Buffer' function*: A 'buffer' function is indicated by a triangle in Figure 5-6. The 'buffer' function (in this case SAP can be seen as a buffer) stores all work orders until their planned start date. If work orders that are still in the buffer cannot be finished in time, they move out of the buffer and are re-planned.

5. *'Tap' function*: The 'tap' function is indicated by a black circle with the rotated blue line. This function will let the orders through when they have to be processed.

6. *Transfer work orders*: This function transfers the work orders for the maintenance tasks from the 'handle BO orders' function to the 'maintain' function. Work orders that are performed by the 'maintain' function are received back.

7. *'Buffer' function*: Following the 'transfer work orders' function, again a 'buffer' function is added. This buffer collects all finished work orders.

8. *'Tap' function*: The 'tap' function only opens when all work orders are finished. The incoming order is now transformed to a handled order.

9. *Identify Long Lead Items (LLI)*: At the moment the repair list is known, the Long Lead Items are identified and it is decided if a 'European Tender' (Europese Aanbesteding) is required.

10. *European Tender*: A 'European Tender' implies that for items that cost more than a certain amount of money an order should be put into the European market. Companies then can react on this order and come up with a price. The best bid gets the order. *This function can take a lot of time.*

11. *Order LLI*: The needed LLI are ordered after a 'European Tender' or directly after the 'identify LLI' function.

12. *Compare spares*: When the work orders are created in SAP, it is determined which spare parts need to be ordered. This function compares the spare parts that are in stock with the needed spare parts.

13. *European Tender*: It can again be necessary to do a 'European Tender' before the spare parts can be ordered.

14. *Order Spares*: The needed spare parts are ordered after a 'European Tender' or directly after the 'compare spares' function.

15. *Evaluate*: This function evaluates the lead time, man hours and costs of the project and compares them with the requirements from the project mandate.

16. *Write evaluation report*: The evaluation report contains the differences in required lead time, man hours and costs.

17. *Initiate*: This function initiates the project with the requirements from the project mandate.
18. *PID*: The PID contains the more detailed requirements for the project.

Looking at the lead times of the different HAs, it is shown that the actual lead time of these HAs is often longer than the planned lead time. For the BO-2 project of Zr. Ms. Evertsen, Figure 5-7 shows that all the activities above the red line have an actual lead time that is longer than the planned lead time. In percentages, this means that CONFIDENTIAL of the HAs has a longer lead time than the planned lead time. Furthermore, CONFIDENTIAL of the HAs is finished later than expected. The difference in these percentages is caused by the fact that a lot of activities also start later than the planned start date. Therefore, activities that are performed in the planned lead time can still finish too late. CONFIDENTIAL of all activities started too late. Those percentages are representative for almost all BO projects. To be able to identify the reasons for the longer lead times, not finishing activities on time and starting activities too late, the 'maintain' function in Figure 5-5 should be further analysed.

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Figure 5-7: Planned vs actual duration HA BO-2 Evertsen

5-2-2 The 'maintain' function

The 'maintain' function that was shown in Figure 5-5 transforms the incoming ship that is in need of maintenance into a maintained ship that is able to go safely and independently to sea. Figure 5-8 shows the 'maintain' function one aggregation layer deeper. This figure will now be explained in detail.
To be able to process the incoming ships further, an encoding function is added (the box with the letter 'c' and number 1). This function splits the ship into different installations with their own BSMI number (not physically). The processable parts (BSMIs) then enter a buffer (2) in which the installations are stored (not physically) until the first maintenance tasks need to be performed on the installation. When an order for a certain installation/BSMI comes in, the tap (3) lets this BSMI through and the 'perform maintenance' function (4) transforms this installation into a maintained installation. The maintained installations then again enter a buffer (5) which stores the different installations until all installations are maintained. When the maintenance tasks on all installationss are finished and the installations are stored in the

buffer, the tap (6) lets them through to the 'testing' function (square with diagonal lines and a pie with a piece missing (7)). The 'testing' function tests the installations (quality check) and if necessary adds the missing. When all tests are passed, the installations enter the 'decoding' function (the box with 'dc' (8)) which puts the installations back together (not physically) so they become a complete ship again. After the 'decoding' function, the ship is ready and leaves the process as a 'maintained ship'. To be able to identify the problems that cause the long lead time of the BO process the 'performing maintenance' function and the 'testing' function from Figure 5-8 are now opened.

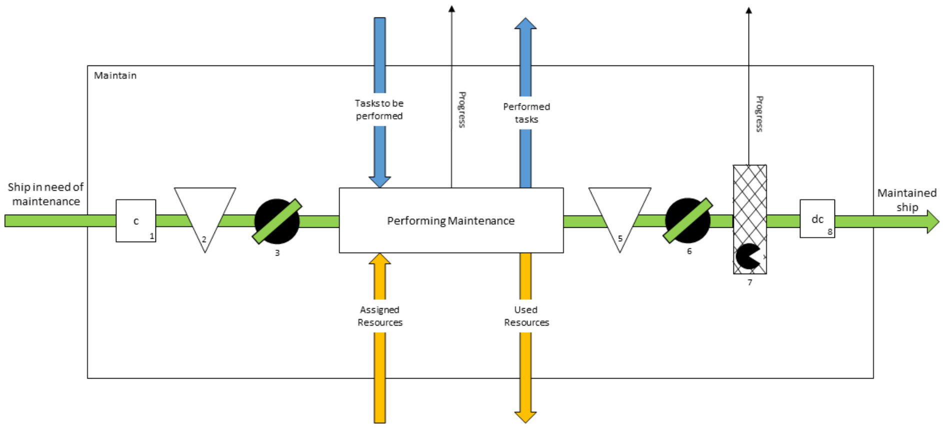

Figure 5-8: Zoomed in on the 'maintain' function

Zoomed in on the 'perform maintenance' function

The 'performing maintenance' function is the key function of the BO process. In this function the actual maintenance activities are performed. This function could be the most interesting in order to understand why the execution phase of the BO process does not perform according the requirements. Figure 5-9 shows the 'perform maintenance' function in detail.
The streams between the 'handle BO orders' function and the 'performing maintenance' function are included to show that the tasks that have to be performed in the 'performing maintenance' function are assigned by the 'handle BO orders' function. The streams of the 'use' function are also included to show the different resources that are needed for the 'performing maintenance' function.

The different functions in the 'performing maintenance' function can be described as follows (numbers correspond to the numbers in 5-6):

1. *Demounting*: The installations that enter the 'performing maintenance' function first enter the 'dismounting' function. In this function the installations of the ship are dismounted and then sent to the 'perform maintenance before dry-dock' function. During the dismounting, parts are dismounted from the installations. Some of these parts are discarded but a lot of the dismounted parts are send to the workshop for overhaul. It is also possible that a complete installation is dismounted from the ship and then send to the workshop for overhaul.

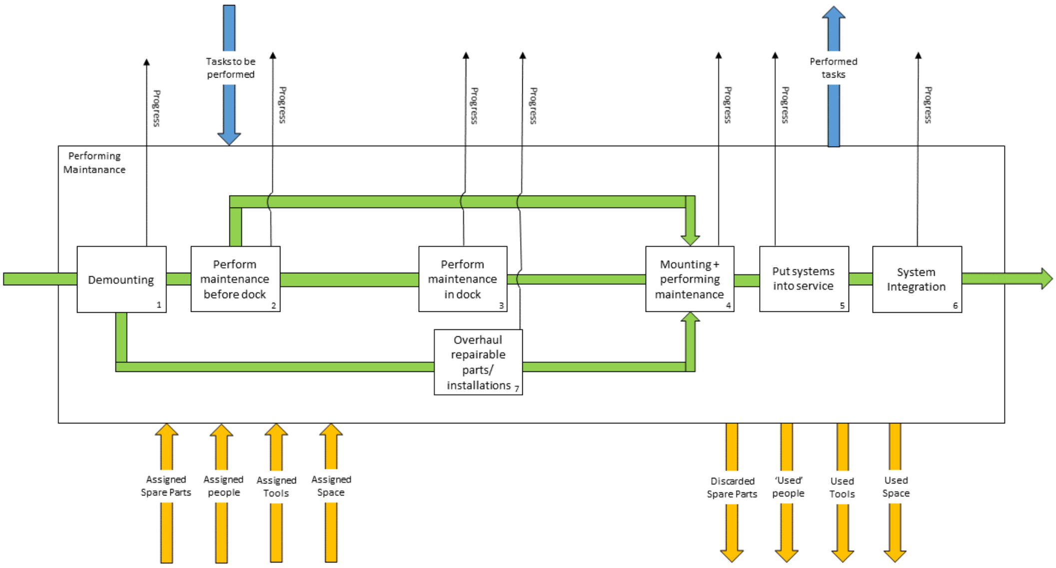

Figure 5-9: Zoomed in on the 'performing maintenance' function

2. *Perform maintenance before dock*: The maintenance tasks that can be performed without the ship being in dry-dock are performed in this function. If maintenance activities on an installation are needed when the ship is in dry-dock, the installation follows its way to the 'perform maintenance in dock' function, else, it proceeds to the 'mounting + performing maintenance (after dock)' function.

3. *Perform maintenance in dock*: In this function the maintenance activities are performed that have to be executed when the ship is in dry-dock.

4. *Mounting + performing maintenance*: The maintenance activities that have to be performed after the ship has been in dry-dock are performed in this function. After the dry-dock, the mounting of the overhauled repairable parts/installations (if they are ready) and spare parts (if they are available) can take place.

5. *Put systems into service*: When all maintenance activities are performed on an installation the installation can be put into service.

6. *System integration*: After the installationss are put into service they can be integrated.

7. *Overhaul repairable parts/installations*: In this function the repairable parts/installations that were dismounted in the 'dismounting' function are overhauled.

Figure 5-9 illustrates that *when the 'overhaul repairable parts/installations' function does not perform according the requirements the process can stagnate.* Looking at, for example, the BO-2 planning of Zr. Ms. Evertsen it shows that the overhaul of repairable parts/installations is frequently delayed (Figure 5-10). CONFIDENTIAL of all the overhaul works has a longer lead time than originally planned. Also CONFIDENTIAL of all overhaul activities is not finished on the planned end date. This case is representative for all BO projects.

Every function in 5-9 receives tasks from the 'handle BO orders' function and uses resources from the 'use' function. Figure 5-11 shows this for the function 'perform maintenance before

Figure 5-10: Planned vs actual duration overhaul

dock'. This figure illustrates that if there is a stagnation in the resource flow, the process cannot continue and there will be a delay. Evaluation reports and supply chain data of different BO projects include the performance of the spare parts flow. Analysis of these data shows that the percentage of spare parts not delivered in time is about CONFIDENTIAL [30][33]. This could be a reason for the long lead times of the BO projects. Therefore, the 'use' function of Figure 5-5 should be analysed further. But before this is done, the 'testing' function in the 'maintain' function will be analysed.

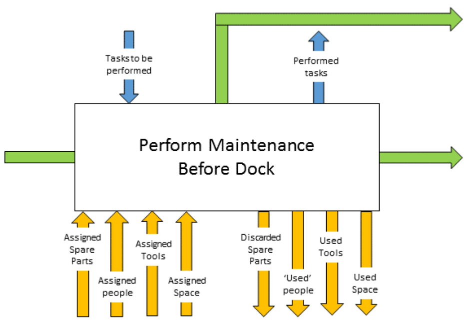

Figure 5-11: Zoomed in on the 'Perform maintenance before dock' function

Zoomed in on the 'testing' function (quality check)

The systems that were maintained in the 'performing maintenance' function are tested/checked in the 'testing' function. Therefore, this function can also be seen as a quality check for the performed maintenance tasks. Figure 5-12 zooms in on the 'testing' function that was shown in Figure 5-8.

The different functions in the 'performing maintenance' function can be described as follows (numbers correspond to the numbers in 5-6) [34]:

1. *SARC 1*: The first function that is encountered when entering the 'testing' function is the 'SARC 1' function in which it is checked if the ship is safe to enter. SARC 1 is a procedure that is practically the same for every BO project.

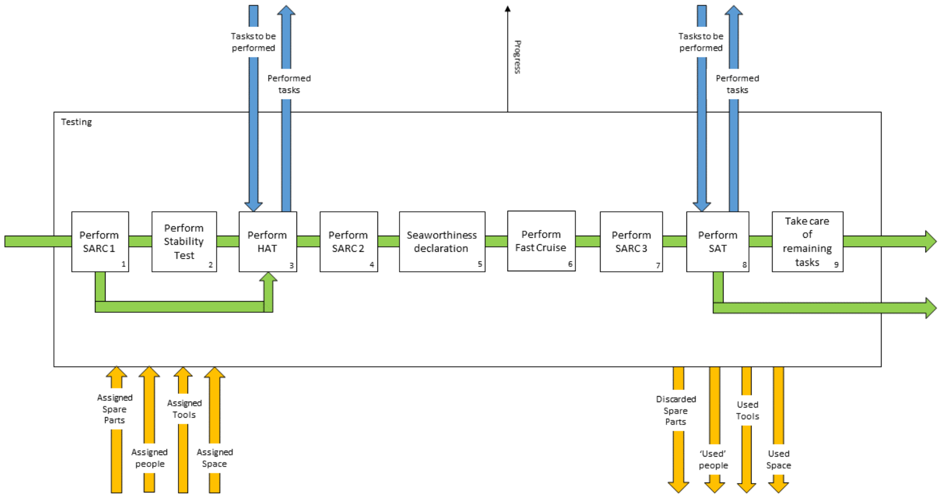

Figure 5-12: Zoomed in on the 'testing' function

2. *Stability Test*: When the 'SARC 1' function is passed the ship can go to the 'stability test' function. If for example a modification on a certain system has resulted in a lot more weight for that system on the ship, it should be checked if the ship is still stable. This is done during a 'stability test'.

3. *HAT*: Directly following SARC 1, or after passing the stability test, the ship enters the 'HAT' function. In the 'HAT' function all systems on the ship are tested when the ship is still moored. The tasks that need to be performed in the 'HAT' function depend on the maintenance that is performed on the different systems on the ship. These tasks are assigned by the 'order' function.

4. *SARC 2*: After the 'HAT' function the ship enters the 'SARC 2' function. In the 'SARC 2' function it is tested if the management (bedrijfsvoering) and the condition of the unit are fitted and complete so the unit can go safe to sea. Like SARC 1, SARC 2 is a procedure that is practically the same for every BO project.

5. *Seaworthiness Declaration*: When SARC 2 is finished a meeting is held to declare the ship seaworthy (able to go to sea safely). This is done in the 'Seaworthiness declaration' function.

6. *Fast Cruise*: When the function 'Seaworthiness declaration' is passed the ship enters the 'Fast Cruise' function. In this function a day at sea is simulated when the ship is still moored. The whole crew is on board and all systems are tested (even the radar and sonar system).

7. *SARC 3*: Following the 'Fast Cruise' function, the ship enters the 'SARC 3' function. In the 'SARC 3' function the focus lies on training and testing the safety organisation. It has to be executed before the unit is allowed to go to sea independently.

8. *SAT*: After SARC 3 the ship goes to the 'SAT' function. The SATs are performed at sea. The purpose of the 'SAT' function is to functionally check the working of the systems which had maintenance. The tasks that need to be performed in the SAT function

are assigned by the 'handle BO orders' function. At the end of the 'SAT' function a remaining tasks list is constructed which shows the maintenance tasks that still have to be performed. If there are no remaining tasks found, the ship leaves the 'testing' function when the 'SAT' function is finished.

9. *Take care of remaining tasks*: The 'take care of remainting tasks' function takes care of the rest tasks that follow from the 'SAT' function. When all remaining tasks are finished the ship leaves the 'testing' function.

A lot of the functions inside the 'testing' function (SARC 1, SARC 2, Seaworthiness Declaration, Fast Cruise, SARC 3) have a fixed lead time. In most of the BO projects the 'testing' function has a lead time between two and three months and it is not common that this is exceeded.

5-2-3 The 'use' function

It is important that there are enough resources available at the right time, in order to perform all the maintenance activities within the planned lead time. Figure 5-13 zooms in on the 'use' function of Figure 5-5. The different resource flows will now be discussed in detail.

Spare parts flow Spare parts that enter the system and are not directly needed are stored in a buffer (warehouse Den Helder). Spare parts that are directly needed also have to pass the buffer before they can enter the 'maintain' function. *In the previous section it was stated that approximately CONFIDENTIAL of the spare parts are not delivered in time to the 'maintain' function.* One of the reasons for this could be retraced to the 'handle BO orders' function. Figure 5-6 showed that LLI are ordered after the repair list is composed and normal spare parts are ordered when the work orders are defined in SAP.
Spare parts are categorised into different groups with a mean purchase time (Gemiddelde verwervingstijd (GVT)):

- Category A: GVT $\leq$ 60 days
- Category B: 60 days $<$ GVT $\leq$ 240 days
- Category C: 240 days $<$ GVT $\leq$ 540 days
- Category D: GVT $>$ 540 days

Most parts fall into category B and thus have a GVT that lies between two and eight months. Spare parts can only be purchased after tender of the BO project. Normally the LLI are ordered 6-12 months before the first maintenance works start. If these items have a GVT that is longer than these 6-12 months, it is impossible that they are delivered in time. The normal spare parts should be ordered at least 8 weeks before the execution phase of the BO project starts. This again means that it is plausible that parts are not delivered in time.
Another problem is the time it takes between the arrival of a spare part and the delivery to the 'maintain' function. Parts that enter the system all have to go through the 'buffer' function. This 'buffer' function can take about four weeks. *Consequently, even if a spare part*

is delivered in time by the manufacturer, it can be the case that it will not be delivered in time to the 'maintain' function.
The spare part problem is recognised within the DMI and at the moment different people are working on it.

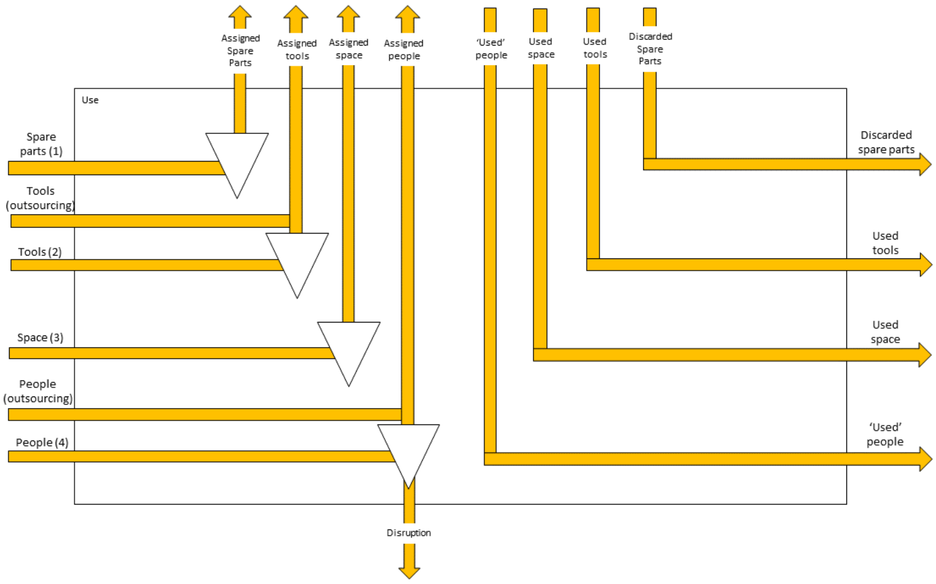

Figure 5-13: Zoomed in on the 'use' function

Tools flow Tools are essential to perform the different maintenance activities. The DMI owns a lot of different tools but sometimes tools have to be hired from external companies (outsourcing). There are no significant problems found in the tools flow.

Space flow Space is needed to perform the different maintenance activities. One of the spaces that is critical in the BO process is the dry-dock. The dry-dock has a very tight schedule which means that the ship has to go into the dry-dock when planned and delays cannot be afforded. When the ship is not in dry-dock, it stays at a quay that is assigned to the ship. The DMI owns different workplaces to perform the overhaul of the repairable parts. No significant problems are found in the 'space' flow.

People flow The mechanics that work at the DMI are 'stored' in a buffer and enter the 'maintain' function if needed. Some mechanics are specialists for a certain installation. Because of the reorganisation of the DMI, some of these specialists have become scarce. *If a problem occurs at a system on an operational ship, the specialist is pulled out of the warehouse (disruption) or out of te mainenance process and he first has to fix the problem on the operational ship. This is a major disruption in the BO process, because the maintenance activities assigned to the specialist cannot be performed, which causes delays.*
There are also different maintenance activities that are outsourced to external companies which provide the people and tools for the maintenance activities. Maintenance activities that are performed by external companies are finished within the planned lead time most of the times.

5-2-4 Influence of ship design on BO process

The design of the ship has a large influence on the maintenance of the ships in their in-service phase. Different unstructured interviews implied that during the design phase of the ships they did not, or barely, keep the maintenance process in mind. This is caused by the budget-driven culture. This can be illustrated with the following examples:

- There are too few transportation routes incorporated into the ships. During a BO project different transportation routes have to be established (stairs have to be removed, holes have to be made) before certain parts/installations can be transported to the workplace. This especially is a problem for systems that are situated deep inside the ship like diesel engines.
- Cables and pipes are placed in such a way that they can form an obstruction when certain maintenance works have to be performed. For example, in the case a hole has to be cut into the hull of the ship to remove an installation, first all the cables and pipes have to be removed because they are mounted on the skin of the ship.
- Another important problem that causes delays in the BO projects are so called 'herverdelingen'. This are reallocations of installations from one ship to another ship of the same ship class. This is caused by a phenomenon that is called obsolescence. During the design of a ship, installations that are available on the market at that moment are chosen to be built on the ship. The design of the ship takes place a couple of years before the actual manufacturing of the ship. This means that the installations chosen for the ship are already 'old' when they are placed on the ship. This is especially the case for Commercially of the Shelf (COTS) installations that have a high development rate. At a certain moment the manufacturer of the installation decides to stop producing the 'older' installations. This is the point where the problems start. The spare parts for the 'older' installations that are built on the ship are no longer produced, which leads to a moment that they are no longer available. When this happens, the installation on the ship is called 'obsolete'. An example of an obsolete system are the Rolls-Royce 'Spey' gas turbines on the MFFs and LCFs. For these gas turbines the problem is solved with a Memorandum Of Understanding (MOU) with the British Royal Navy. Because of this MOU, there is a pool of gas turbines from which the RNLN can 'take' a gas turbine when needed. Therefore, no 'herverdelingen' are needed yet. Thus, for the gas turbines the problem is partly solved up until the pool of gas turbines gets empty. For other installations, especially on the LCFs, there are no spares left and there are no possibilities for an MOU. This causes a large problem, because when an LCF is in a BO project, the project can only finish when an obsolete installation is pulled from another LCF and mounted on the LCF in the BO project. This means that the other LCF (from which the obsolete system is taken) is not operationally available while it should be. Zr. Ms. De Zeven Provinciën stays at the quay in Den Helder at the moment, because different installations had to go to Zr. Ms. Evertsen to finish the BO-2 project. *Thus, 'Herverdelingen' are another serious problem for the RNLN.* It is important that during the design of a new ship the obsolescence of installations is taken into account to avoid the the same problems as on the current ships.

- Standardisation (familievorming) of components/installations is barely or not applied on the ships. For example, on every ship a lot of pumps and compressors are used in different installations on the ship. For almost every installation, pumps and compressors from different manufacturers are used. This is not beneficial for the maintenance process. If a lot of different pumps and compressors are used, spare parts are needed for all these different pumps and compressors, which makes the logistics more complex than in the case pumps and compressors from the same manufacturer are used. Another example are the diesel engines and the diesel generators on a ship. If these are from the same manufacturer, the same spares can be used. However, most of the times this is not the case. It can be concluded that in the design of the ship *standardisation is not taken into account.*

- Systems are not designed for 'plug-and-play'. *The interfacing of the systems on the ships is very specific* and therefore, it is often difficult to implement modifications.

- Little condition based maintenance is used on the ships. For the MFFs and LCFs this can be explained by the fact that they were designed in the 1980s and begin 1990s when CBM was not yet a proven technology. For the OPVs this is interesting because CBM is already widely used in other industries. The use of more condition monitoring data could decrease the amount of preventive maintenance works.

From the above mentioned points it can be concluded that maintainability, described by Nowlan & Heap as "the ease with which scheduled or corrective maintenance can be performed on an item" [16], does not have a high priority during the design of a new ship. This is caused by the budget-driven culture. This has a significant influence on the lead time of the BO projects, but also on the lead time of other maintenance activities.

5-3 Summary

This section gives a short summary of this chapter. In this chapter the Delft Systems Approach was used to determine the problems that cause the low operational availability of the frigates and OPVs. It was shown that the MDT can be decreased by decreasing the lead time of the BO and AM projects and by decreasing the amount of unscheduled corrective maintenance actions. The BO projects have the biggest influence on the MDT because of the long lead times (Figure 5-3).
Therefore, the BO process was further analysed using the PROPER model. The PROPER model of the process was shown in Figure 5-5 and showed that the three aspects for the BO process are: orders, ships and resources. The different functions of the PROPER model were further analysed to determine the problems that cause the long lead time of the BO projects. This analysis showed the following problems (bottlenecks) in the process:

- *A very spacious planning*: There is a lot of space in the BO project plannings. It is normal for the planners to plan a couple of weeks 'extra time' for every task so that it is less likely for the tasks to be delayed.

- *No 'rigid' planning*: The HA/DA-planning is not 'rigid'. During the process the planning is altered different times. There are no consequences (penalties) involved for this.

- *Overhaul of repairable parts/installations*: Repairable parts/installations are overhauled during the BO process. If the overhaul is not finished in time, the mounting of the installations cannot proceed, which causes delays. It was shown for BO-2 of Zr. Ms. Evertsen that CONFIDENTIAL of the overhauls had a longer lead time than originally planned and CONFIDENTIAL of the overhauls was delayed. This problem causes a longer AMT and therefore, a longer MDT.

- *Spare parts flow*: The spare parts flow is a major problem in the BO process. Approximately CONFIDENTIAL of the spare parts needed for the BO process are not delivered in time. The reason for this was found in the 'handle BO orders' function, where the spare parts needed for the project are ordered. The spare parts can only be ordered when there is a tender for the project. This is often too late for the spare parts to be in time. Another problem that was found is that spare parts, which are directly needed in the BO process, first have to be processed by the warehouse in Den Helder. This can take up to four weeks. The spare part problem is recognised within the DMI. This problem causes a longer MLDT and therfore, a longer MDT.

- *People flow*: Some installations can only be maintained by a certain specialist. Because of the reorganisation of the DMI, the amount of specialists has decreased rapidly. If a specialist is needed for an operational ship, this ship gets the priority. The specialist is then taken from the BO process and the maintenance activities are delayed. This problem causes a longer MLDT and therefore, a longer MDT.

It is also shown that the design of the ship has a large influence on the BO process. During the design of the current ships they did not, or barely, take the maintenance into account on the following points:

- Transportation routes
- Placement of cables and pipes
- 'Herverdelingen'
- Standardisation
- Plug-and-play design
- Condition-based maintenance

Chapter 6

Research goal

6-1 Initial research goal

Section 2-3 described the original research setting for this thesis in the following way:

> "A problem with the current frigates and OPVs is that the operational availability is too low. It is important that the ships are as much available as possible, because when the need is there, the CDS should be able to deploy a ship immediately. At the DMO, there is a substantial feeling that the low availability of the ships has something to do with the current maintenance concept of the ships. Until now, the way of maintenance of the ships and corresponding logistics are an underexposed subject during the design of the ship. The budget-driven design leads to less clever choices in these areas, which results in longer maintenance periods and higher exploitation costs. At the DMO, they all have the feeling that it could be done a lot 'better', but the question is how."

This resulted in the following initial research goal:

Determine the current availability of the ships of the Royal Netherlands Navy, identify the reasons for not meeting the availability requirements and find solutions for the found problems so at least the required operational availability can be achieved for the new multipurpose frigates.

This research goal especially concerns the new multipurpose frigates.

6-2 Final research goal

Chapter 4 showed that the operational availability of the frigates and OPVs does not meet the requirements. By looking at equation 3-3 it was found that the operational availability can be increased by decreasing the MDT of the ship. The MDT is directly related to the total maintenance time. By decreasing the total maintenance time, the operational availability increases. The analysis performed in Chapter 5 showed that the BO process is the main contributor to the MDT. The BO process has a planned lead time of one year and an actual lead time that is even longer. Therefore, the BO process was further analysed and a significant amount of problems were found that contribute to the long lead time. To decrease the lead time of the BO process, these problems have to be eliminated from the BO process. It is impossible to solve all the found problems in the amount of time available for this thesis. However, the information found in this thesis has a significant value. Therefore, it is very important that the information found in this thesis is secured inside the organisation in order to eventually solve the different problems found. Instead of finding an optimal solution for all the problems at once, the problems should be solved problem by problem. Therefore, a continuous process improvement plan should be implemented into the organisation to eventually achieve a desired operational availability for the frigates and OPVs in an iterative way. Together with experts at the DMO, a desired operational availability was determined by looking at the operational availaiblity of ships of the commercial shipping companies and thereby considering the differences between the navy and the commercial shipping that were explained in Section 4-4-3. This has resulted in a desired value (target) for the operational availability of 80% or higher.
The found problems should not only be solved in order to achieve the desired operational availability for the new ships that the RNLN is developing, but also in order to improve the operational availability of the existing ships to a value of at least 80%. This leads to the following final research goal:

Design a continuous process improvement dashboard that can be used by the Royal Netherlands Navy to achieve an operational availability of 80% or higher, both for the existing ships and in the design process of new ships.

This final research goal, in contrast with the initial research goal, also concerns the current ships of the RNLN.

Chapter 7

Improvement plan

In this chapter, the working principle of continuous process improvement will be discussed in Section 7-1. Subsequently, in Section 7-2, a commonly used method for continuous process improvement will be explained. This method will be used in 7-3 to develop a continuous process improvement dashboard for the RNLN.

7-1 Continuous process improvement

The Institute of Quality Assurance defined continuous improvement as *"a gradual never-ending change which is: focussed on increasing the effectiveness and/or efficiency of an organisation to fulfil its policy and objectives. It is not limited to quality initiatives. Improvement in business strategy, business results, customer, employee and supplier relationships can be subject to continuous improvement. Put simply, it means 'getting better all the time'* [35]*"*. Summarising this, the term continuous process improvement (CPI) can be defined as *"an ongoing effort to improve products, services or processes* [36]*"*.
In this thesis, the continuous process improvement can be defined as the ongoing effort to improve the operational availability of the ships of the RNLN to at least 80%. When this target is achieved, there are two options: adjust the target to a higher value or improve a new process, but the continuous process improvement never stops.

7-2 Continuous process improvement method

A widely used continuous improvement method in the business world is the Plan-Do-Check-Act cycle (PDCA cycle). Walter A. Shewhart was the first to describe this cycle in his book, Statistical Method From the Viewpoint of Quality Control (1939) [37]. A student of Shewhart, named W. Edwards Deming, further developed the work of Shewhart. He was the person that brought the PDCA cycle to the attention of the wider public. For this reason, the PDCA cycle is sometimes also referred to as the Shewhart cycle or Deming cycle [38]. The fundamental principle of the PDCA cycle is iteration. The PDCA cycle can be used in all kinds of business processes, from product development to product lifecycle and supply chain management. The four steps in the PDCA cycle can be explained as follows [38]:

- *Plan*: In this step you plan what you are doing. The first thing that should be done is identifying the problem: what is the problem you are looking at? After the problem identification, the target should be defined: what do you want to achieve and what is/are the goal(s)? With the goal(s) in mind the situation should be analysed (what is the existing baseline/standard?) and causes for the problem should be identified.
- *Do*: In this step, solutions are developed to solve the problem(s) found in 'plan'. Subsequently, the best solution(s) should be selected.
- *Check*: The results from 'do' should be studied in this step. Questions that should be asked in this step are: Do the found solutions improve the existing situation? Is the desired goal achieved?
- *Act*: In this step it is decided what comes next. This depends entirely on the outcome of 'check'. If 'check' shows that the found solution(s) is/are an improvement to the existing baseline/standard, the solution(s) should be implemented. If there is an improvement, it is extremely important to secure the found solution(s) in the organisation to prevent that the process falls back to where it started: the solutions should be standardised. If 'check' shows that the found solution(s) is/are not an improvement, then the existing baseline/standard is not changed.

This PDCA cycle should be repeated as many times as needed to achieve the desired goal. Even when the initial goal is realised, it is important to keep improving the process, the PDCA cycle is never-ending. Figure 7-1 graphically shows the PDCA cycle.

Figure 7-1: PDCA cycle. Adapted from [7].

7-3 Applying the PDCA cycle

In this section, the PDCA method will be used to develop a continuous process improvement dashboard for the RNLN to improve the operational availability of their ships. This dashboard should also be a usable tool in the design process of new ships to help the designers make the right decisions that result in a satisfying operational availability.

7-3-1 Plan

Problem identification and target

The first step in 'plan' is *identifying the problem.* The problem was already extensively discussed in Section 4-4 and can be summarised as follows: the operational availability of the frigates and OPVs of the RNLN does not meet the set requirements $Ao_{minMFF/LCF} = 66.7\%$ and $Ao_{minOPV} = 73.3\%$. If nothing changes, it is very likely that the new frigates are not going to meet the operational availability requirements as well. Just look at the OPVs: the operational availability of the OPVs, which are only in service since 2013, already have an operational availability that does not meet the requirements.
When the problem is identified, the *target should be defined*: what does the RNLN want to achieve? The target operational availability was already determined in Section 6-2. The target of this continuous improvement process is to achieve an operational availability of 80% for the ships of the RNLN. This target is also used for the new ships that are going to be build.

Problem analysis

The last step in 'plan' is *analysing the existing situation* and thereby identifying the causes for the problem found. Different methods can be used to analyse the problem. Because of the magnitude of the problem in this thesis and the unknown relationships in the processes, the Delft Systems Approach by Veeke et.al. is particularly useful to analyse this problem [1]. In the Delft Systems Approach the process is first represented as a black box. The relations of the internal elements of the black box are not known to the researcher yet. In the highest aggregation layer (the first black box) only the inputs, outputs, requirements and performance are studied (Figure 7-2).

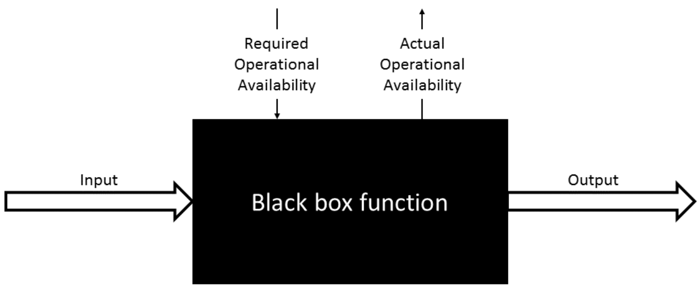

Figure 7-2: Black box

This black box approach enables the researcher to look at the problem in a helicopter view, which ensures everything is taken into account. When the first black box is known, it can be opened to reveal new black boxes one aggregation layer deeper. This results in more information about the working principles of the process. Going an aggregation layer deeper can be repeated as many times as needed until all relevant issues are traced. The black box approach only shows one aspect of the process at a time. For the analysis of industrial systems the following aspects and their interrelations, should always be considered: the order flow, the material flow and the resource flow. In order to see the connections of these different aspects in the process, the PROPER model should be used. The PROPER model for this dashboard is shown in Figure 7-3.

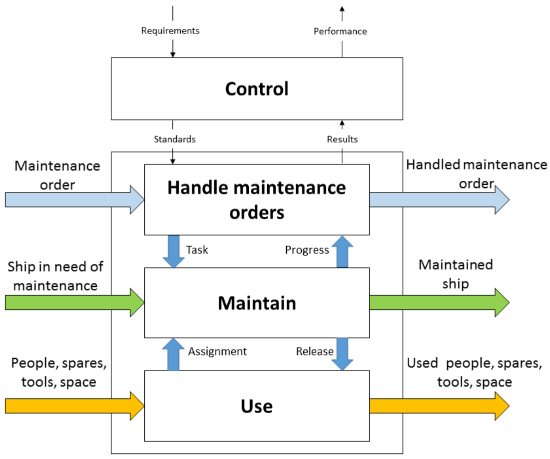

Figure 7-3: PROPER model

When the PROPER model is constructed one can zoom into the different functions to analyse every function in more detail. This makes it possible to find the problems in the process that cause the main problem that was identified in the previous step.

As explained in 7-2, it is not the intention to solve all the found problems that cause the main problem at once. A choice should be made which problem(s) need to be tackled in this iteration of the PDCA cycle. The choice could be based on the size of the problem, but also on the ease with which the problem can be solved. The problem that has the most potential for a large improvement could be tackled first. However, the problem that is easiest to solve could also be chosen. The choice depends on the researchers preference. But, it might be a good choice to start with the problem that is/are the easiest to solve, because the solutions for these problems are probably the easiest to implement in the organisation. This problem selection is important, because when all problems are tackled at once, it might be very hard to find a suitable solution. Even if a suitable solution is found, it probably is too complicated to integrate this solution inside the organisation.

Figure 7-4 graphically shows 'plan' as a dashboard. This dashboard can be used every time 'plan' has to be passed in the cycle.

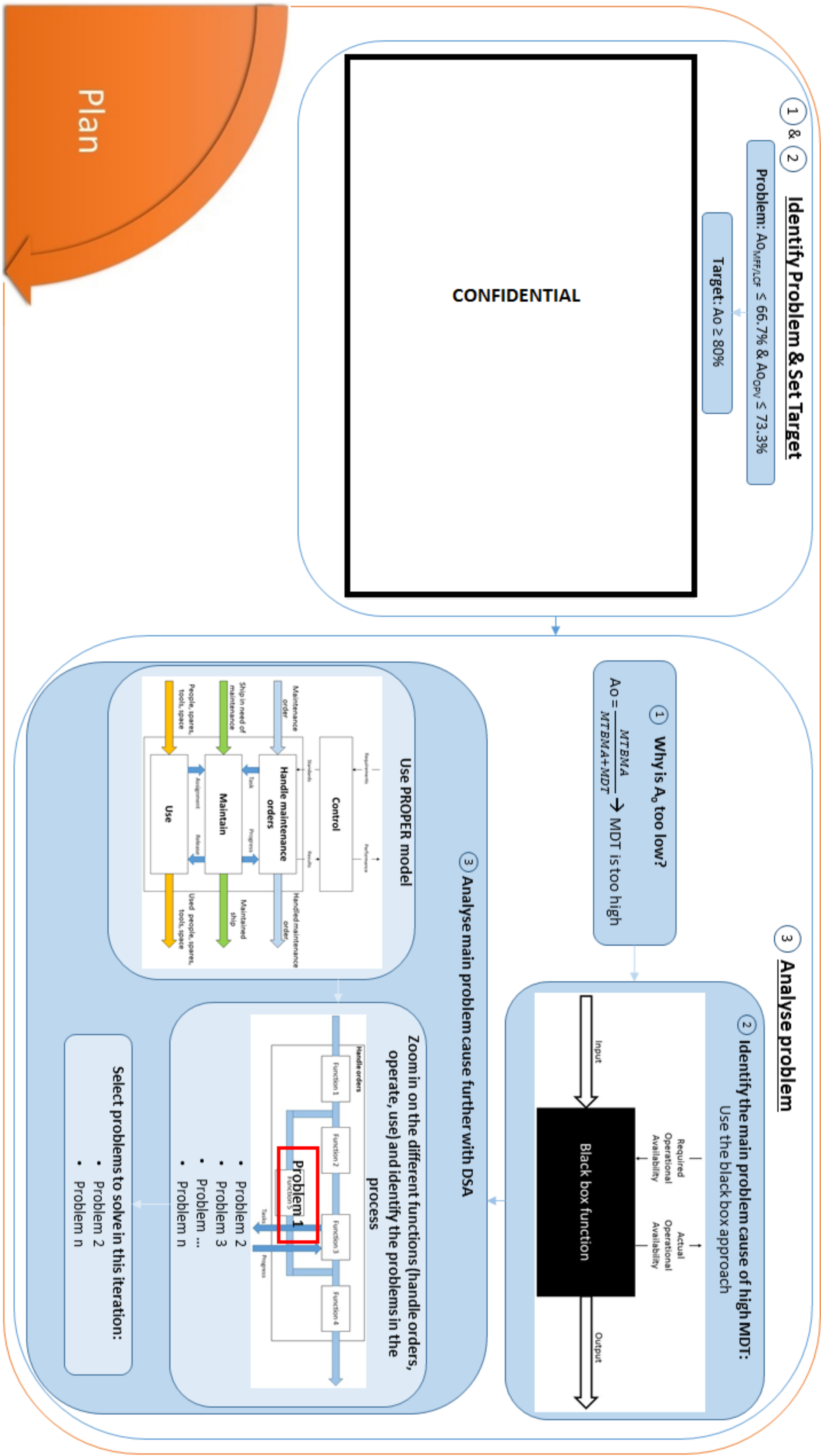

Figure 7-4: Plan-Do-Check-Act

7-3-2 Do

Developing solutions

The first thing that needs to be done in 'do' is *developing solutions* to solve the problem(s) that were found and selected in 'plan'. Solutions for the problems can be found in the following ways:

- *In literature*: Explore literature that deals with the same kind of problems and see what solutions the literature puts forward.
- *Looking at other navies*: Other navies probably have to deal with the same kind of problems. It is possible they already found solutions for these problems.
- *Looking at other industries*: Other industries probably also deal with the same kind of problems. Maybe they already found solutions that might be applicable in our situation.
- *Talk to experts*: Experts in the field often already have ideas how the found problems can be solved.

Morphological overview The different solutions found should now be combined to generate solution concepts. A tool that can be used for this purpose is a so-called 'morphological overview'. An example of a morphological overview is shown in Figure 7-5. In this overview, the found solutions for the different problems are stated. By combining solutions for the different problems, the solution concepts are generated.

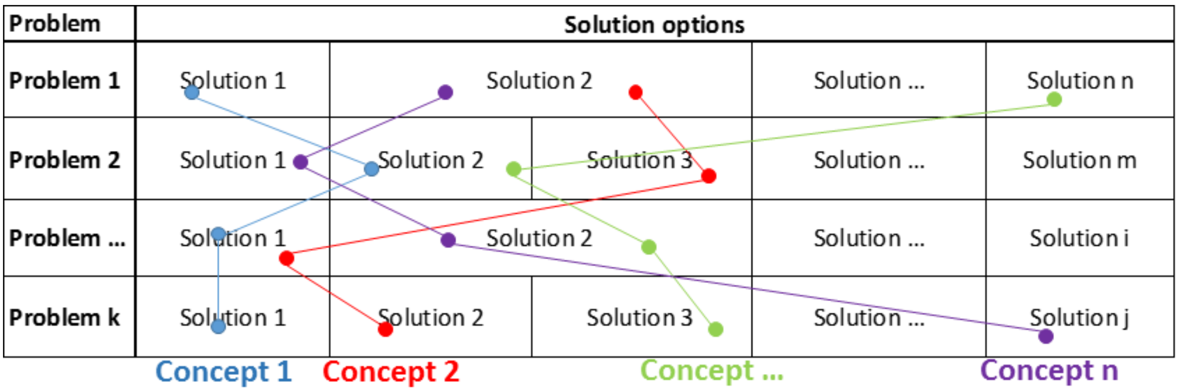

Figure 7-5: Morphological overview

Concept selection

The next step in 'do' is deciding which concept(s) is/are the best to be implemented. The selection of a concept can be subjective and difficult. Therefore, Thomas L. Saaty developed a method to make the selection process more objective, the Analytic Hierarchy Process (AHP) [39][8]. The general structure of the AHP can be described as follows [39][8][40]:

- Determine the alternatives/concepts
- Determine relevant criteria: criteria are the dimensions from which the alternatives can be viewed.
- Weigh the criteria: the relative importance of the criteria should be determined by attaching numerical values to them.
- Rank the alternatives/concepts on the selection criteria by attaching numerical values to them.
- Determine a ranking of the alternatives/concepts by processing the numerical values.

Determine the alternatives/concepts This was already completed in the previous step by using the morphological overview.

Determine relevant criteria There is no generic approach available to determine the relevant criteria. One of the most important things to keep in mind when determining the criteria are the requirements of the process. Examples of requirements are: low operational costs, at least the current service level and the solution should be implementable. The criteria result from the requirements of the process. Often, different selection criteria are conflicting, for example, costs and lead time.

Assigning criteria weight factors The key element of the AHP is the use of pair-wise comparisons of the criteria. The criteria are compared in pairs to determine which one is more important. The scale of the comparisons is between 1-9 and an explanation of this scale is shown in Figure 7-6. For example, if criterion A is found much more important than criterion B, the relative weight is $w_A/w_B = 9$ [8][39].

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Figure 7-6: Explanation of the comparison scale. Adapted from [8]

When the pair-wise comparison is finished, the results are collected in a reciprocal comparison matrix $\mathbf{M}$:

$$\mathbf{M} = \begin{bmatrix} 1 & \frac{w_A}{w_B} & \cdots & \frac{w_A}{w_n} \\ \frac{w_B}{w_A} & 1 & \cdots & \frac{w_B}{w_n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{w_n}{w_A} & \frac{w_n}{w_b} & \cdots & 1 \end{bmatrix}$$

By calculating the eigenvalues of the comparison matrix, the weight factors for the criteria can now be determined. The normalised eigenvector related to the largest eigenvalue, contains the criterion weight factors.
Normalising a vector usually means that the vector is divided by its length to create a unit vector of length 1, but this is not the goal of the AHP. The goal of the AHP is to create a vector of which the sum of elements is 1 [39][8]. When this definition is used for normalisation, the vector is divided by the sum of the n vector elements instead of by its norm:

$$\vec{\lambda}_{normalised} = \frac{\vec{\lambda}}{\sum_{i=1}^{n} \lambda_i}$$

The consistency of the comparison matrix should be checked before the weight factors can be used. It is almost impossible for a decision maker to answer the pair-wise comparisons in a perfectly consistent manner. Perfectly consistent would mean the following:

$$\frac{w_A}{w_C} = \frac{w_A}{w_B} \cdot \frac{w_B}{w_C} = 8 \cdot \frac{1}{4} = 2$$

So when criterion A is 8 times more important than criterion B, and criterion C is 4 times more important than criterion B, the decision maker also finds criterion A 2 times more important than criterion C.

If each row in the comparison matrix is a constant multiple of the first row, the decision maker filled in the pair-wise comparison perfectly consistent. In this case, there is only one non-zero eigenvalue. As stated before, pair-wise comparisons will not be perfectly consistent in practice. However, in case of small inconsistencies, the method described in this section can be used to determine the normalised eigenvector with the criteria weight factors. The degree of inconsistency of the comparison matrix is indicated by the consistency ratio (CR). A CR of zero would mean a perfectly consistent pair-wise comparison. The higher the CR becomes, the lower the consistency of the comparison matrix. The consistency ratio is calculated by using the consistency index (CI) and the random consistency index (RCI). CI is calculated as follows:

$$CI = \frac{(\lambda_{max} - n)}{n - 1}$$

where λ_{max} is the largest eigenvalue. Then the CR is derived by dividing the CI by the RCI. The random consistency index is obtained from Table 7-1. If CR ≤ 0.10, the inconsistencies are acceptable and the resulting weight factors can be used. However, if CR > 0.10, the comparison matrix should be checked for inconsistencies and the inconsistent pair-wise comparisons should be revised with the decision maker.

Table 7-1: RCI for comparison matrices of n x n [8]

n	1	2	3	4	5	6	7	8	9
RCI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Multi-criteria analysis The weighted criteria that follow from the normalised eigenvector are required to perform a ranking of the concepts: a multi-criteria analysis (MCA). In an MCA the different concepts are ranked on the selection criteria. It is often difficult to make a quantitative ranking of the concepts because different criteria cannot be expressed in quantitative data and data for the criteria that could be ranked quantitatively are lacking. Therefore, one can choose to use a scale from 1 to 10 with 1 being the lowest score and 10 being the highest score. The scores per criteria per concept result in a matrix. This matrix is then multiplied by the criteria weight factors. If, for example, there are three concepts and four criteria, the MCA looks like this:

$$\begin{array}{c} \\ Concept1 \\ Concept2 \\ Concept3 \end{array} \begin{array}{c} \begin{array}{cccc} Crit1 & Crit2 & Crit3 & Crit4 \end{array} \\ \begin{bmatrix} a_1 & a_2 & a_3 & a_4 \\ b_1 & b_2 & b_3 & b_4 \\ c_1 & c_2 & c_3 & c_4 \end{bmatrix} \end{array} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} a_1 * w_1 + a_2 * w_2 + a_3 * w_3 + a_4 * w_4 \\ b_1 * w_1 + b_2 * w_2 + b_3 * w_3 + b_4 * w_4 \\ c_1 * w_1 + c_2 * w_2 + c_3 * w_3 + c_4 * w_4 \end{bmatrix}$$

The outcome of the MCA is a vector with the scores per concept. The concepts can now be ranked from the best concept (highest score) to the worst concept (lowest score).

Figure 7-7 graphically shows 'do' as a dashboard. This dashboard can be used every time 'do' has to be passed in the cycle.

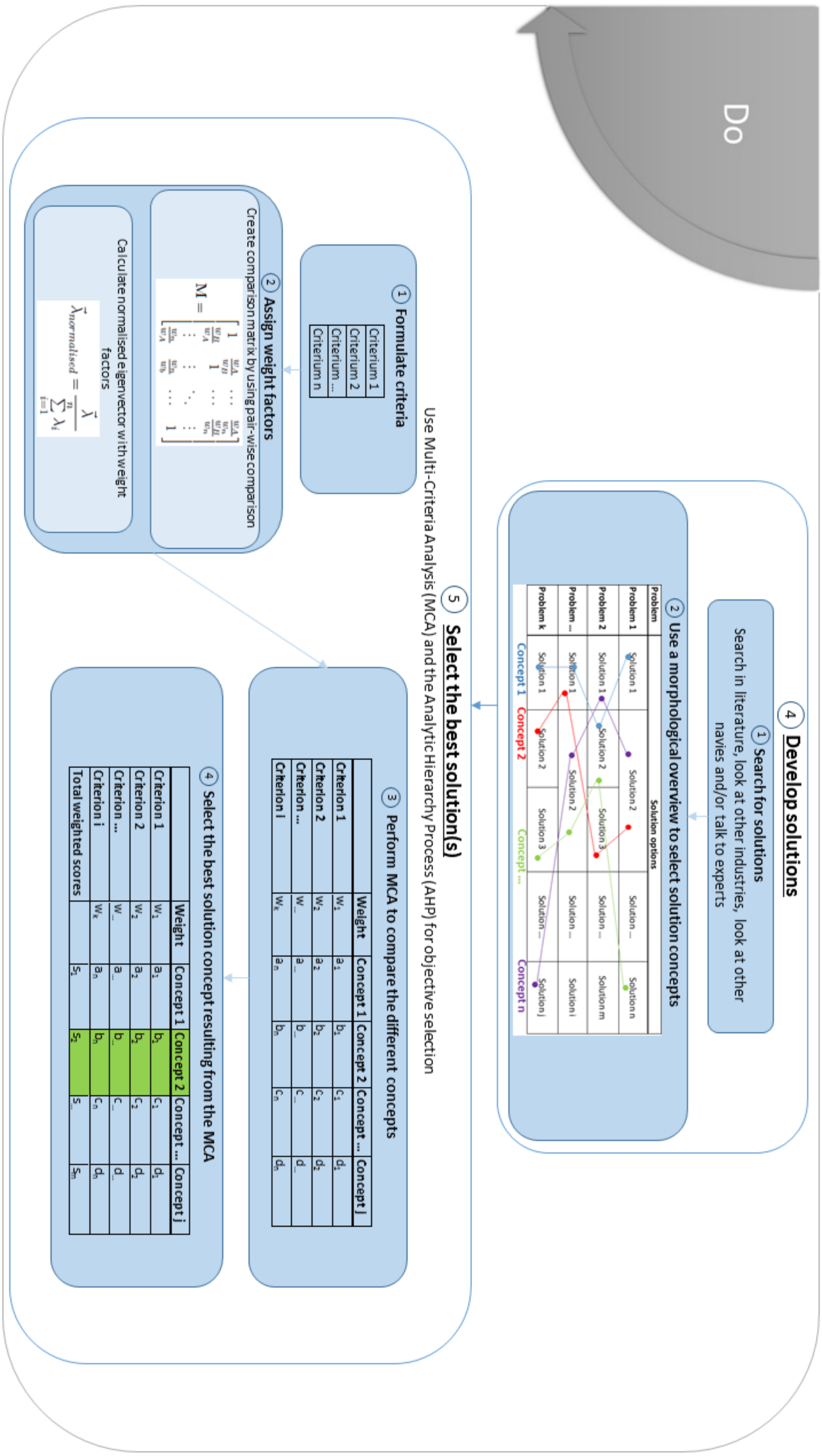

Figure 7-7: Plan-**Do**-Check-Act

7-3-3 Check

Trends

The first thing that needs to be done in 'check' is study the solution(s) that were found in 'do'. Are there any trends visible in the found solutions?

Improvement

In 'check' it should be checked whether the found solutions improve the current situation and if the target was achieved. The new operational availability should be calculated for the case that the solution(s) found in 'do' are implemented. There are three possible outcomes of this step:

- Positive: The solutions found in 'do' increase the operational availability of the ships. A fictive example of a positive outcome is shown in 7-8.
- Negative: The solutions found in 'do' decrease the operational availability of the ships. A fictive example of a negative outcome is shown in Figure 7-9.
- No differences: The solutions found have no influence on the operational availability of the ships.

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Figure 7-8: Fictive example of a positive outcome

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Figure 7-9: Fictive example of a negative outcome

A simulation study could be performed to investigate the effect of the found solution(s) on the operational availability. There are a lot of different simulation tools available to perform such a simulation. When the simulation study shows promising results, it might be interesting to implement the solution(s) on a small scale to study the actual improvement before the solution(s) are implemented on a larger scale.

Figure 7-7 graphically shows 'check' as a dashboard. This dashboard can be used every time 'check' has to be passed in the cycle.

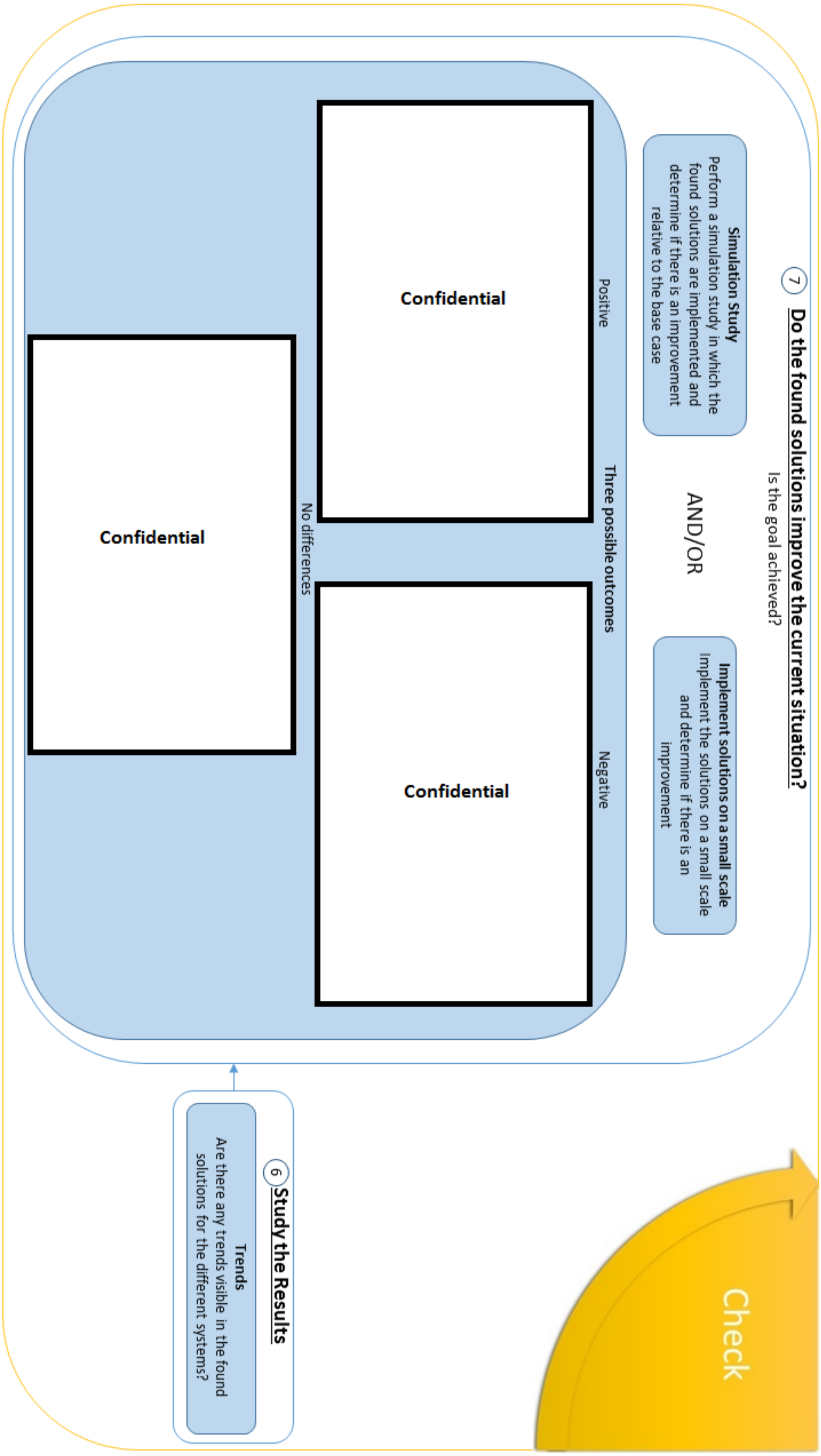

Figure 7-10: Plan-Do-**Check**-Act

7-3-4 Act

Solution implementation

In 'act', it is decided what comes next. This depends entirely on the outcome of 'check'. If the found solution(s) do not increase, or even decrease, the operational availability, the solution(s) should not be implemented. If 'check' shows that the implemented solution(s) increase the operational availability of the ships, then the solution(s) should be implemented. The solution(s) should be implemented according to the following steps:

Make the organisation ready The first step in the implementation of the found solutions is making the organisation ready for the implementation. The defence organisation is a large and rigid organisation in which things are a bit crusted sometimes. Therefore, it is important to prepare the organisation for the implementation of the found solution(s). The following things might be needed to make the organisation ready for the implementation of the solutions:

- Adjust the corporate culture: Try to adjust the corporate culture to the desired culture gradually, by involving employees of all organisational levels in the solution implementation process.
- Adjust the budget structure: The rigid budget structure can obstruct solutions from being implemented. For example: the budget for a new ship cannot be changed. Even when it is proven that when the initial costs of the ship are slightly higher than the budget, the exploitation costs will be a lot lower and the operational availability will be higher. It would be a waste if solutions, which, in the end, decrease the costs and increase the operational availability, cannot be implemented because of the rigid budget structure.
- Give trainings: Setup training programs for the employees when new technical and/or social skills are required.

Standardise the solution(s) When the organisation is ready, the solution(s) should be implemented and secured inside the organisation. The new solution(s) should become the new standard. To secure the found solution(s) in the organisation, everything should be properly documented.

Maintain new standard When the solutions are implemented, it is important that it is regularly checked whether the new standard is maintained. If this is forgotten, it is very likely that the organisation gradually slips back to the old (worse) standard.

Start a new PDCA cycle

When the solutions are implemented in the organisation as the new standard, a new PDCA cycle can start. In case the operational availability improved but the target of 80% was not achieved, a new PDCA cycle should start. In this new cycle, an analysis should be performed again to find the problems that still cause the low operational availability. Ideally, the problem(s) tackled in the first iteration of the cycle should not show up again in the analysis of the second iteration because they were solved in the first iteration.

If it was proven in 'check' that the found solutions lead to an operational availability of 80% or higher, the target was reached. If the target was reached in one iteration of the cycle, this can indicate that the target was set too low. A new iteration of the cycle with a new target can be started to try to improve the operational availability even more. It can also be decided to tackle a completely new problem in a new cycle.

Figure 7-7 graphically shows 'act' as a dashboard. This dashboard can be used every time 'act' has to be passed in the cycle.

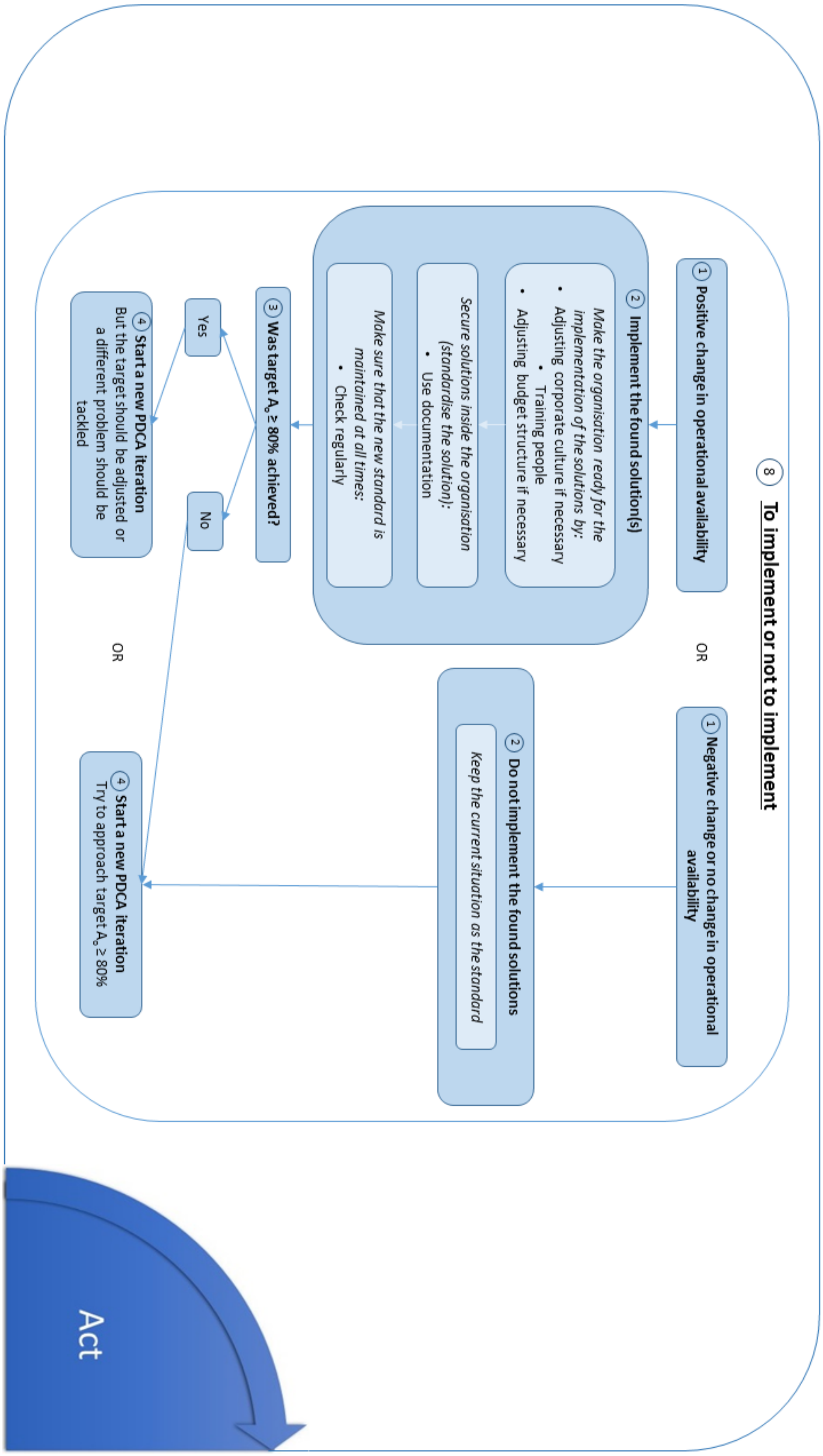

Figure 7-11: Plan-Do-Check-**Act**

7-3-5 The complete dashboard

The Plan, Do, Check and Act dashboards can now be combined to a cycle which is shown in 7-13 as a complete dashboard. This dashboard gives guidance in the continuous process improvement for the RNLN. Every iteration of the dashboard contains the following eight general steps:

1. Identify problem
2. Set target
3. Analyse problem
4. Develop solutions
5. Select the best solution(s)
6. Study the results
7. Do the found solutions improve the current situation?
8. To implement or not to implement

Figure 7-13 shows the complete continuous process improvement dashboard. As already mentioned, the PDCA cycle is never-ending. The intention of the PDCA cycle is to get one step closer to the target with every iteration. Figure 7-12 graphically represents the continuous process improvement as a slope. The first iteration of the PDCA cycle is started at the foot of the slope and every time an iteration gives an improvement, the solution(s) are standardised. In this way, the operational availability increases over a certain period of time to the target of 80% in small steps. The figure might suggest that the process is improved in a linear way. However, in practice this will never be the case. When the target is achieved, the target can be adjusted to a higher value or a new process can be improved, but the continuous process improvement never stops.

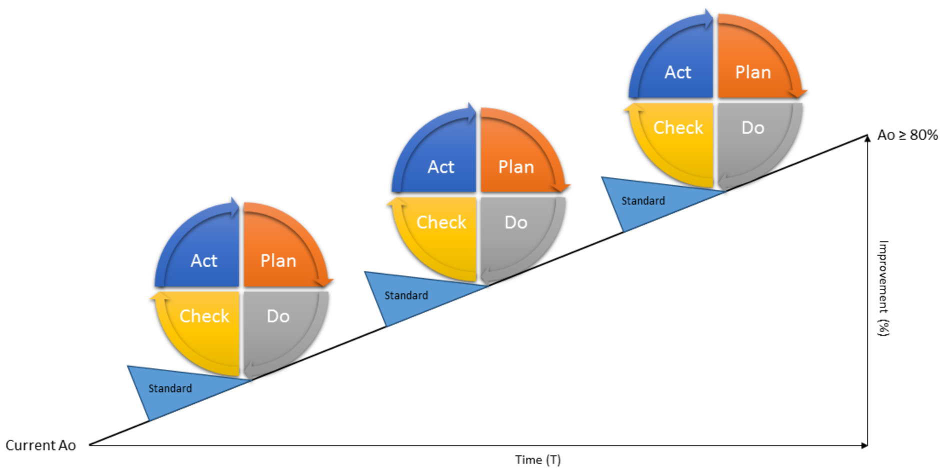

Figure 7-12: PDCA method

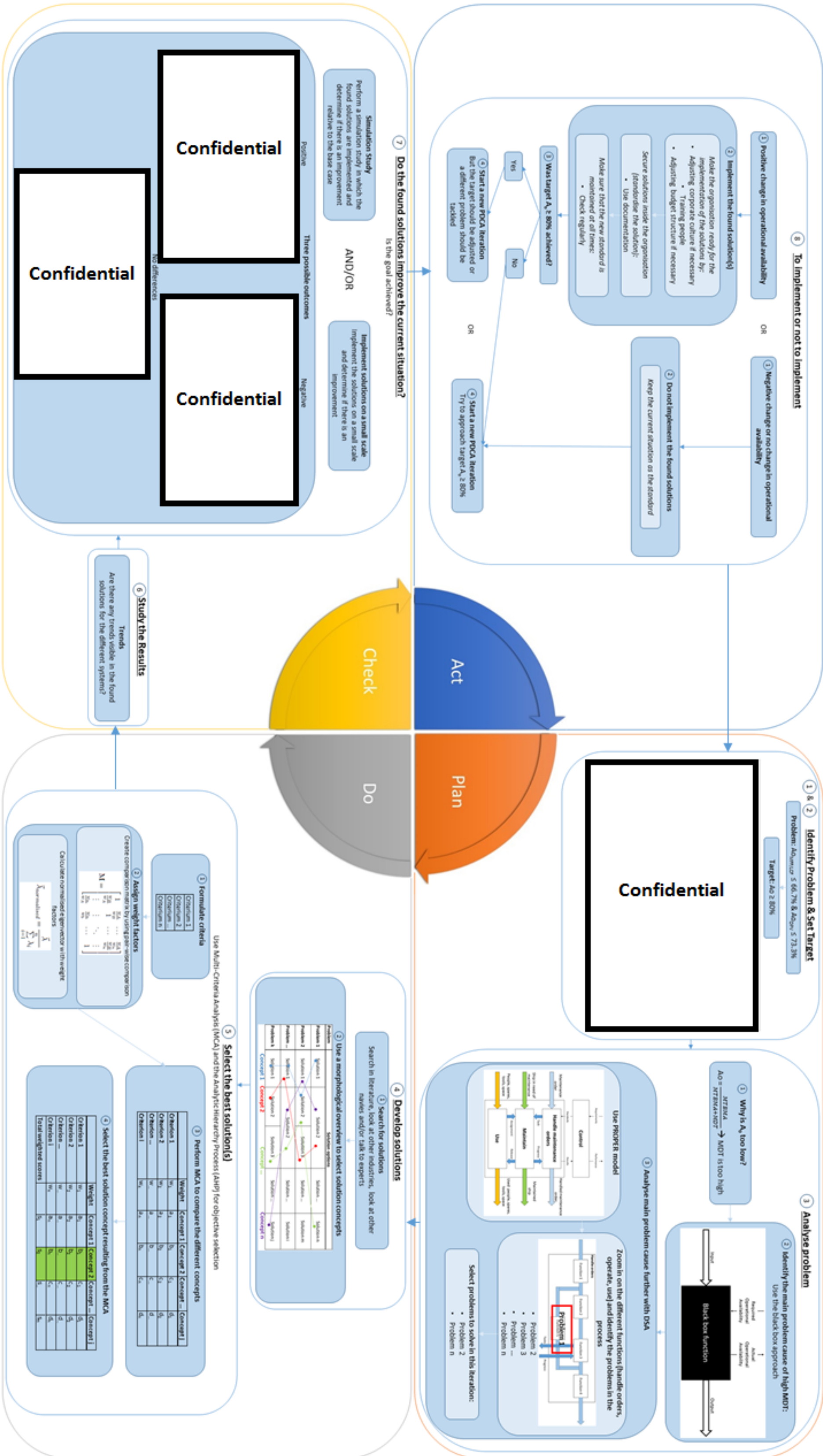

Figure 7-13: PDCA Cycle Applied

Difference existing ships and new ships

The developed dashboard is usable for the RNLN to achieve an operational availability of 80% or higher, both for the existing ships and in the design process of new ships. However, there are some differences between these two cases.
For existing ships, the analysis in 'plan' is more straightforward because measurement data are available for the existing ships. It is difficult to analyse something in advance, which is the case for the new ships. However, in case nothing changes in the processes for the existing ships, the process for the new ships will probably be the same. Therefore, measurement data from the existing ships can also be used in the analysis of the new ships.
For the existing ships, it can be more difficult to implement the found solutions (the 'act' step) than on a new ship. First of all, because it is possible that modifications on the ship are needed, but also because everyone is used to the existing situation. On a new ship it is easier to implement the found solutions because the 'new standard' directly is the standard when the ship enters its in-service phase.
The last important difference is the timeframe of the continuous process improvement. For the new ships, the time the continuous process improvement can take is the time until the final design is ready. For the existing ships it should be clearly established in advance how long an iteration can take. This determines the amount of people that have to work on the continuous process improvement.

Chapter 8

Case study

To verify the working of the dashboard developed in Chapter 7, a case study of one iteration is performed in this chapter. This case study will show that the dashboard can be used to improve the operational availability of the existing ships of the RNLN and that it is also usable in the design process of new ships.

8-1 Plan

This section discusses the steps of 'plan' that were described in the dashboard in the following way:

- Identify problem in Section 8-1-1
- Set target in Section 8-1-1
- Analyse problem in Section 8-1-2

8-1-1 Problem identification and target

The first two steps in 'plan' were already discussed in Section 7-3-1 in Chapter 7. The found *problem* can be summarised as follows: the operational availability of the frigates and OPVs of the RNLN does not meet the set requirements $Ao_{minMFF/LCF} = 66.7\%$ and $Ao_{minOPV} = 73.3\%$ (see Figures 4-9, 4-10 and 4-11).
Different experts from the DMO were consulted to determine a target operational availability. This has led to a *target* operational availability of 80% or more.

8-1-2 Problem analysis

The analysis of the problem was already extensively discussed in Section 5-1. It was shown that the operational availability of the ships of the RNLN does not meet the requirements because the MDT of the ships is too high. The MDT is a result of the maintenance that is performed on the ships. The Delft Systems Approach by Veeke et.al. was used to analyse the complete maintenance process [1]. The complete maintenance process was represented as a black box. This black box was opened and this showed the main contributor to the low operational availability: the BO process. The planned lead time of the BO process is already too long and the actual lead time is even longer. Again by using the Delft Systems Approach, the following factors that have the most influence on the BO process lead time were identified:

- The way of planning the BO projects
- Overhaul of repairable parts/installations within the process
- Spare parts flow
- People flow
- Design of the ship (maintainability)

A choice should be made which problem(s) should be tackled in this iteration of the improvement cycle. It was decided not to look at the 'the way of planning the BO projects' problem in this iteration of the improvement cycle, because this is an organisational problem and very complex to solve. The 'spare parts flow' problem will not be solved in this iteration of the cycle as well, because it is already acknowledged inside the organisation. Different people are already looking at solutions for this problem. It certainly is an option to tackle the spare parts problem and the planning problem by using the developed dashboard, but this is out of the scope of this research because of time limitations.
The 'overhaul of repairable parts/installations within the process (and to a certain extend the design of the ship)' problem and 'people flow' problem are tackled in this iteration of the cycle. This choice was made because these problems can be tackled relatively easy with respect to the other problems.

However, the size of the problem is still quite big because the BO process includes every installation on the ship. To make the problem more manageable, it was chosen not to focus on every installation in need of maintenance during a BO project, but only on a couple of installations that are 'critical' for the BO lead time. In this case, 'critical' means that these installations have a longer lead time than the required one year. To determine the installations that are 'critical' in the BO process, different BO plannings were extensively examined. These plannings showed a significant amount of installations that have a lead time longer than one year and therefore are called 'critical'. Seven of the 'critical' installations were chosen to examine in this improvement cycle:

- Diesel engines
- Goalkeeper

- Cannon
- Diesel generators
- Mirador
- APAR
- Gas turbines

Unfortunately it was not possible to determine if these installations are also on the critical path of the BO project, because the critical path of the BO projects is not known.
If the lead time of the chosen 'critical' installations can be decreased and these installations happen to be on the critical path of the BO process, the BO lead time will also decrease. This will then lead to an increase in operational availability.

8-2 Do

The two steps in 'do' that were described in the dashboard are discussed in this section as follows:

- Develop solutions in Section 8-2-1
- Select the best solution(s) in Section 8-2-2

8-2-1 Developing solutions

Solutions have to be found for the problems that were chosen in 'plan'. Different solutions for these problems were found by studying literature, looking at other industries and other navies and by conducting interviews with experts from the DMO and the DMI. First, the solutions for the 'overhaul of repairable parts/installations' problem are given and then the solutions for the 'people flow' problem are described.

Overhaul of repairable parts/systems

As was described in Chapter 5, the current situation for the overhaul of repairable parts and installations is as follows:

- *Repairable parts*: The repairable parts are dismounted from the installation and send to the workshop to be overhauled. When the overhaul is finished, they are mounted back on the installation. The overhaul process is coupled with the BO process.
- *Repairable installations*: The repairable installations are overhauled on the ship or dismounted from the ship, overhauled in the workplace and mounted back on the ship again. The overhaul process is coupled with the BO process.

- *'Herverdelen'*: For some types of installations, there are not enough installations or parts available to have them on all ships of a ship class. During a BO project of a ship, such an installation or part is located on an operational ship. Before a BO project can finish, the installation or part should be pulled from an operational ship and mounted on the ship that is having the BO period. This action should be performed as late as possible in the BO process, because then the other ship can stay operationally available as long as possible. However, most of the times an operational ship 'gives' all the installations and parts that need to be 'herverdeeld' to the ship in BO. This results in a ship that is not operationally available while not in maintenance. For example, the 'herverdeel' installations and parts needed for finishing BO-2 of Zr. Ms. Evertsen were pulled from the operational ship Zr. Ms. De Zeven Provinciën. Because of this, Zr. Ms. De Zeven Provinciën became operationally unavailable and lies ashore for at least half a year before the BO period of this ship starts. This decreases the operational availability of the ships enormously.

Solutions Different solutions were found that could solve the 'overhaul of repairable parts/installations' problem:

1. *Decoupling the complete installation overhaul from the BO process by using line-replaceable units (wisselsets).* The US Department of Defence defines a line-replaceable unit (LRU) as follows [41]:

   "An LRU is an essential support item which is removed and replaced at field level to restore the end item to an operationally ready condition."

   In our case, the 'essential support item' is the installation and the 'end item' is the ship. If the complete maintenance of an installation is decoupled from the BO process by using LRUs, this means that the maintenance on the installation is performed in the workplace and meanwhile another installation is available on the ship. The use of LRUs is already a proven concept in the aviation industry. An aircraft is composed of all kinds of installations that can be exchanged very easy (LRUs). If an LRU is defect, it is removed from the aircraft and an overhauled LRU is then placed back on the aircraft. The actual overhaul of the LRUs is separated from the maintenance of the aircraft. This results in an AMT on the aircraft that is very short because it only consists of removing and placing back the LRU. An example of an LRU in the aircraft industry is the jet engine. A jet engine can be completely removed from the aircraft and another jet engine is placed back on the aircraft directly, so it can return to operate again.
   If LRUs are used, it is necessary to have a number of LRUs in stock which can be exchanged with the LRUs that are in need of maintenance. The needed stock of LRUs depends on the amount of installations in-service. This results in extra initial investment costs and extra storage costs. On the contrary, the maintenance costs will decrease with the use of LRUs, because the process is simplified. The actual maintenance on the LRUs is decoupled from the BO process which leads to a decreased AMT on the ship.
   When it is chosen to use LRUs, it is important that during the design of the ship the interfacing of the LRUs is kept in mind. The LRUs need to be installed on the ship in such a way that they can be easily removed and placed back again. It is common

for LRUs to have standardised connections for quick removal, cooling air, power and grounding.
The use of LRUs or 'modules' is an upcoming trend in naval ship design. This is called modular design. Examples of ships that have a modular design are the Iver Huitfeldt class ships and the Absalon class ships of the Danish Royal Navy and the Littoral Combat Ships of the US Navy. For the Iver Huitfeldt class and Absalon class the Danish Royal Navy makes use of different easily exchangeable modules. It is possible to exchange a module in a couple of hours. In this way, the maintenance of these modules can be performed in a workplace while the ship is operationally available. Another advantage of the modules is that they are designed in such a way that different modules fit in the same mounting. In this way, the ship is very flexible and can be adapted to the planned mission [42][43][44][45][46].

2. *Decoupling the overhaul process of repairable parts from the BO process by using exchangeable repairable parts (shop-replaceable units)*: Shop-replaceable units (SRUs) are similar in nature to LRUs but instead of being complete functional units they represent component functions. With the use of SRUs, the overhaul of repairable parts can be decoupled from the BO process. This decoupling will result in a shorter lead time of the maintenance processes. As for LRUs, it is necessary to have a number of SRUs in stock, depending on the amount of SRUs in-service. This will again lead to extra initial and storage costs. It is also improtant that SRUs can be dismounted and mounted quickly. But why SRUs and not always LRUs? If a complete system is very large and heavy and it is situated on a place where it is impossible to lift the complete system from the ship, it might be more interesting to use SRUs instead of an LRU. Also, when large maintenance tasks only have to be performed once in the lifetime of a ship on an installation, the use of LRUs could not be the best choice.

3. *Decoupling the complete installation overhaul from the BO process by using a complete new installation and discarding the old one*: Every time DLM maintenance needs to be performed on the installation, the installation is removed from the ship and a completely new installation is placed on the ship. The 'old' installation is then discarded. This might be an option for systems that are not too expensive, however, for expensive installations the costs of this solution will quickly soar. Another disadvantage is that there are a lot more storage costs involved with this solution. The advantage of this option is that the overhaul of the system does not have to be carried out, which decreases man hour costs and spare parts costs. For expensive installations, this will never outweigh the costs of the new installations needed every time DLM needs to be performed.

4. *Decoupling the overhaul process of repairable parts from the BO process by using new parts and discarding the old ones*: This could be an interesting option for some repairable parts that are not too expensive. However, again more initial and storage costs are involved with this solution. The Kraljic matrix can be used to determine the logistics of the articles. This matrix provides insight in the risk that certain articles bring with them [47]. The Kraljic matrix is shown in Figure 8-1.

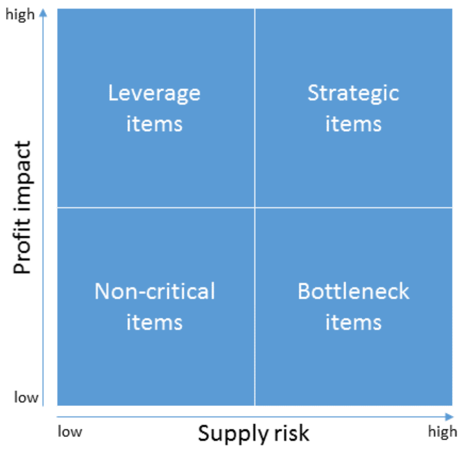

Figure 8-1: Kraljic matrix

The supply risk and financial risk are shown on the two axes. With these two dimensions, four types of items can be distinguished [47]: strategical items (high profit impact, high supply risk), bottleneck items (low profit impact, high supply risk), leverage items (high profit impact, low supply risk) and non-critical items (low profit impact, low supply risk). For strategic items, a contract with the supplier is favourable. Bottleneck items are the items that have to be in stock at all times. For the leverage items, there should be a certain amount of items in stock. The non-critical items can be purchased when needed.
The advantage of this solution would be that the overhaul of the repairable parts does not have to be carried out, which decreases man hour costs.

People flow

The current situation for the people flow is not optimal. The BO process does not get the priority and there are not enough specialists for some installations which leads to delays.

Solutions Solutions that could solve the 'people flow' problem are:

1. *Contracting more people*: The most obvious solution for the 'people flow' problem is contracting more people at the DMI. However, because of the reorganisation of the DMI, this is not a feasible solution. During the reorganisation, a lot of people had to leave the DMI and it is not possible to contract more people.

2. *Outsourcing*: Another solution is outsourcing the maintenance of the installation. The complete maintenance works are outsourced and an external company is thus responsible for the manpower, spare parts and logistics. This option is probably faster than the current situation, but it is probably also more costly. The following example shows that this solution can have a large influence on the lead time of the maintenance works: A diesel engine of an LCF was in need of maintenance, the cylinder heads had to be overhauled. The RNLN asked the DMI how long this would take. The DMI could

perform the maintenance in ten weeks. The RNLN then went to Wärtsilä, the supplier of the diesel engines, they could do the same work in ten days. The RNLN again went to the DMI and suddenly they could do the work in four weeks. However, Wärtsilä could still do it a lot faster. One of the reasons for this, is that the DMI dismounts the cylinderheads, overhauls them and then places them back, while Wärtsilä uses spare cylinder heads and overhauls them at another moment.
This example shows that outsourcing the complete maintenance, including spare parts and logistics, can save a lot of time, but the downside of outsourcing is that the maintenance could become more costly. However, in case of the mentioned example, the total costs were the same in both situations.

Morphological overview

The different solutions found for the 'overhaul of repairable parts/installations' problem and the 'people flow' problem are now combined in a morphological overview to select solution concepts (Figure 8-2).

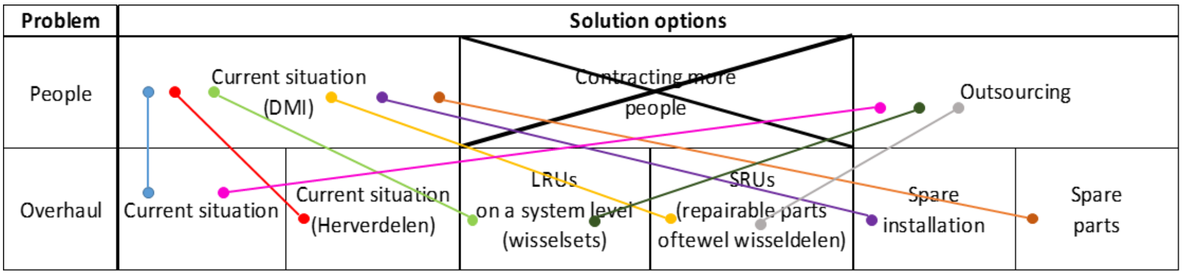

Figure 8-2: Morphological overview

As shown in Figure 8-2, the solution 'contracting more people' is not used because of the already given explanation. A total of 12 concepts could be selected. However, when the maintenance works are outsourced, the situation 'herverdelen' will not exist. This also holds for the situation outsourcing and spare installation because a spare installation is very expensive and the manufacturer that maintains the installation will never use this option. The option outsourcing and spare repairable parts is also not included because when parts are repairable, the manufacturer will always overhaul them instead of discarding them. So eventually, the following *concepts are selected*:

1. **Concept 1**: The maintenance is performed by manpower of the DMI. Furthermore, the installations are maintained on board of the ship or they are removed from the ship, maintained in the workshop and placed back on the ship afterwards. Repairable parts are dismounted and overhauled in the workshop and then mounted back on the installation. This is the most common current concept for the maintenance of the installations on the ships.

2. **Concept 2**: The maintenance is performed by the manpower of the DMI and the installation is 'herverdeeld'. This concept is a current concept used by the DMI, which is caused by the obsolescence problem already explained in 5-2-4 .

3. Concept 3: The maintenance is performed by the manpower of the DMI and an LRU (wisselset) is used for the installation. The overhaul of the installation is thus decoupled from the BO process. This concept is already used sometimes. To make this concept work, it is important that during the design of the ship, the installations are designed in such a way that the installation can be quickly removed and placed back on the ship and that there are good transportation routes available on the ship.

4. Concept 4: The maintenance is performed by the manpower of the DMI and SRUs (wisseldelen) are used for repairable parts. The overhaul of the repairable parts is performed in the workplace and is decoupled from the BO process in this concept.

5. Concept 5: The maintenance is performed by the manpower of the DMI and the installation that needs to be overhauled is replaced by a new installation. The installation that is removed is then discarded.

6. Concept 6: The maintenance is performed by the manpower of the DMI and the repairable parts that need to be overhauled are replaced by new parts. The repairable parts that are dismounted are then discarded.

7. Concept 7: The maintenance is outsourced and the installations are maintained on board of the ship or they are removed from the ship, maintained in the workshop and mounted back on the ship again. Repairable parts are dismounted, overhauled in the workshop and mounted back on the ship again.

8. Concept 8: The maintenance is outsourced and an LRU (wisselset) is used for the installation. The overhaul of the installation is thus decoupled from the BO process. To make this concept work, it is important that during the design of the ship, the installations are designed in such a way that the installation can be quickly removed and placed back on the ship again.

9. Concept 9: The maintenance is outsourced and SRUs (wisseldelen) are used for repairable parts. The overhaul of repairable parts is thus decoupled from the BO process in this concept.

8-2-2 Select the best solution(s)

As was described in the dashboard, the AHP developed by Thomas L. Saaty will be used to select the best solution concept objectively [39][8]. First of all, in order to be able to compare the different concepts, criteria have to be described. Then, weight factors are assigned to the criteria by using pair-wise comparisons. The different concepts are then evaluated on all the selection criteria in an MCA which will result in a selected concept that performs the best.

Criteria

As was already mentioned before, there is no generic way to determine the relevant criteria. In cooperation with different employees from the DMO, the following criteria were determined:

1. *Lead time*: The lead time of the maintenance is directly related to the operational availability of the ship. When the lead time of all critical installations decreases, the lead time of the BO process will decrease and the operational availability will increase.

2. *Initial costs*: The initial costs are the money that has to be spent to buy the extra installations/parts if the solution is LRU, SRU, spare installation or spare parts are chosen. For example, when an LRU (wisselset) is chosen as the solution, extra installations should be bought when the ship is built to ensure the ship can be maintained later.

3. *Maintenance costs*: The maintenance costs are the costs necessary to maintain the ship. This includes the man hour costs, material costs and the costs of the tools needed.

4. *Maintainability*: Is the solution maintainer friendly? Is it difficult or easy to perform the maintenance on the installation when a certain solution is chosen? For example, if the installation is maintained in the workplace, this is easier than on the ship where there is a limited amount of space available.

5. *Implementability*: Is the solution implementable? This is a go/no go criterion. If the solution concept is not implementable, the concept should not be considered.

6. *Design effort*: Is there an extra design effort needed before the found solution can be implemented? For a new ship it might be easier to implement certain solutions than for an existing ship.

7. *Flexibility*: Is the maintenance flexible? Can the maintenance be performed when there are workers available or should the maintenance be performed in a certain planned period? For example: if an LRU (wisselset) is used for a certain installation, the maintenance on that installation can be performed in the period between placing the installation in the workplace until the installation is needed again for another ship. If no LRU is used, the installation should be maintained on the ship in the planned period. A wisselset is therefore more flexible than maintaining the installation on the ship.

8. *Logistics*: What are the logistical consequences of the solution? Logistics includes storage and transportation. Is there extra storage place needed? What are the consequences for the transportation? For example, an LRU (wisselset) has to be stored somewhere and transported from the ship to the workplace and back.

Assigning criteria weight factors

Now that the criteria are known, weight factors can be assigned to them according to the method described in 7-3-2. The pair-wise comparison was conducted from the perspective of the 'user', 'maintainer' and 'standard setter' and filled in by three employees from the DMO, who all have experience with these three perspectives. The criterion 'implementability' is not considered in the pair-wise comparison because it is a go/no go criterion. This criterion is always more important than the other criteria. The results of the pair-wise comparisons are 9 comparison matrices which can be found in Appendix I. The consistency ratio of these matrices was not directly satisfying but after reviewing the pair-wise comparisons together with the employees, the consistency was improved to an acceptable value. The weights of the criteria were calculated by using the method described in 7-3-2 and a summary of the weights assigned by the three employees from the DMO can be found in Table 8-1. This table shows that there is a variation in the assigned weights for the different perspectives. The 'user' and 'maintainer' value other criteria more than the 'standard setter'.

Table 8-1: Assigned Weights

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The average weights for the 'user', 'maintainer' and 'standard setter' and the average overall weights are shown in 8-2.

Table 8-2: Average weights

	Average user	Average Maintainer	Average Standard Setter	Average Overall
Lead time	0,14	0,12	0,06	0,10
Initial costs	0,04	0,05	0,32	0,14
Maintenance costs	0,06	0,18	0,14	0,13
Maintainability	0,43	0,28	0,11	0,27
Design effort	0,05	0,04	0,23	0,11
Flexibility	0,20	0,23	0,07	0,17
Logistics	0,08	0,10	0,07	0,08

Multi-criteria analysis

The concepts can now be evaluated on the different selection criteria. It is difficult to make a quantitative ranking of the concepts because different criteria cannot be expressed in quantitative data and data for the criteria that could be ranked quantitatively cannot be obtained in the limited time available. Therefore, it was choosen to use a scale from 1 to 10 with 1 being the lowest score and 10 being the highest. For example, if the concepts are evaluated

on the criterion 'lead time', 1 means a very long lead time and 10 means a very short lead time and if the concepts are evaluated on the criterion 'initial costs', 1 means very high initial costs and 10 means very low initial costs.
The ranking of the concepts was performed for the different critical installations that were chosen in 'plan'. The resulting scores were then multiplied by the corresponding weight factors. To determine the different preferences for the 'user', 'maintainer' and 'standard setter' the scores were multiplied by the different corresponding weight factors (Table 8-2).
To show that the continuous process improvement dashboard is applicable for the existing ships but also in the design process of new ships, two MCAs are performed for every installation:

1. MCA 1: Rank the solution concepts for the existing ships: what is the best solution to implement on the existing ships?
2. MCA 2: Rank the solution concepts for a new ship: what is the best solution to implement on a new ship that has not been built yet?

The details of the ranking of the concepts per criteria can be found in Appendix J.
The results of the MCAs will now be further discussed per installation, starting with the diesel engines.

Diesel engines The results of MCA 1 and MCA 2 for the diesel engines are shown in Table 8-3. The current situation, or base case, for the diesel engines is concept 1. The maintenance is carried out by the DMI and the repairable parts are dismounted, transported to the workplace, overhauled, transported back to the ship and mounted back on the diesel engines again. The results of MCA 1 show that concept 3, 5 and 8 are 'no go concepts' for the existing ships. On the existing ships, it is impossible to implement the concept of an LRU (wisselset) for the diesel engines because it is impossible to make a transportation route for the complete diesel engines in an existing ship. The solution prefered by the user, maintainer and standard setter in MCA 1 is concept 9 (Outsourcing+SRUs). This means that the maintenance should be outsourced and the overhaul of repairable parts is decoupled from the BO process by using SRUs (wisseldelen). Concept 9 is followed by concept 4 (DMI+SRUs) in which SRUs are used as well, but the maintenance is performed by the DMI.
The results of MCA 2 are different. Concepts 3, 5 and 8 are no 'no go' concepts in this case, because it is possible to design a new ship in such a way that an LRU (wisselset) can be used. However, this will take a significant design effort. There are two concepts that are prefered overall in MCA 2: concept 8 and concept 9. For the user and maintainer, the prefered concept has switched from concept 9 to concept 8, which means that an LRU is prefered over an SRU. The standard setter still prefers concept 9 over concept 8.
MCA 1 and MCA 2 both show that the base case concept is not the best choice.

Table 8-3: Results MCA Diesel Engines

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	2,0	2,2	5,8	3,4	2,0	2,2	5,8	3,4
Concept 3	NO GO	NO GO	NO GO	NO GO	8,0	7,8	6,7	7,5
Concept 4	7,5	7,4	7,0	7,3	7,6	7,5	7,5	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	6,3	3,8	5,8
Concept 6	7,0	6,2	4,7	5,9	7,1	6,3	5,1	6,1
Concept 7	3,2	3,3	6,3	4,3	3,2	3,3	6,3	4,3
Concept 8	NO GO	NO GO	NO GO	NO GO	8,5	8,2	6,9	7,8
Concept 9	8,0	7,7	7,2	7,6	8,1	7,8	7,6	7,8

Goalkeeper Table 8-4 shows the results of MCA 1 and MCA 2 for the goalkeeper. The current situation, or base case, for the goalkeeper is concept 3. However, sometimes an LRU is not available and then concept 1 is used.
MCA 1 and MCA 2 both show the same results. The prefered solution for the user, maintainer and standard setter is concept 8 (Outsourcing+LRU) and the second best solution is concept 3 (DMI+LRU). The overhaul of the complete goalkeeper is decoupled from the BO process in both concepts by making use of an LRU (wisselset).
Both MCAs show that the base case concept is the second best concept from the perspective of the user, maintainer and standard setter (they prefer outsourcing even more).

Table 8-4: Results MCA Goalkeeper

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	2,0	2,2	5,8	3,4	2,0	2,2	5,8	3,4
Concept 3 (base case)	8,5	8,4	7,4	8,1	8,5	8,4	7,4	8,1
Concept 4	6,6	6,8	7,1	6,8	6,6	6,8	7,1	6,8
Concept 5	7,8	6,7	4,9	6,5	7,8	6,7	4,9	6,5
Concept 6	6,2	5,9	5,2	5,7	6,2	5,9	5,2	5,7
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,1	9,0	7,7	8,6	9,1	9,0	7,7	8,6
Concept 9	7,1	7,1	7,3	7,1	7,1	7,1	7,3	7,1

Cannon The results of MCA 1 and MCA 2 for the cannon are shown in Table 8-5. The current situation, or base case, for the cannon is concept 1. The cannon is removed from the ship, transported to the workplace, overhauled, transported back to the ship and placed back on the ship again.
MCA 1 shows that the prefered solution for the user and maintainer is concept 8 followed by concept 3. In both concepts an LRU (wisselset) is used for the cannon. The prefered solution for the standard setter is also concept 8 followed by concept 9, however, the differences are minimal.
The results of MCA 2 show no differences in prefered solutions when compared to the prefered solutions resulting from MCA 1. Furthermore, both MCAs show that the base case concept is not the best solution concept.

Table 8-5: Results MCA Cannon

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,4	8,3	6,7	7,8	8,4	8,3	6,9	7,9
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,9	7,0
Concept 5	7,7	6,6	4,4	6,2	7,8	6,7	4,7	6,3
Concept 6	6,5	5,9	5,0	5,8	6,5	6,0	5,2	5,9
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,0	8,8	6,9	8,2	9,0	8,9	7,2	8,3
Concept 9	7,4	7,3	6,8	7,2	7,5	7,4	7,0	7,3

Diesel generators The results of MCA 1 and MCA 2 for the diesel generators are shown in Table 8-6. The current situation, or base case, for the diesel generators is concept 1.
The results of MCA 1 show that concepts 3, 5 and 8 are 'no go' concepts because they are not implementable for the existing ships. It is impossible to make a proper transportation route to transport an LRU (wisselset) diesel generator through the ship. The best concept for the user, maintainer and standard setter in MCA 1 is concept 9 (outsourcing + SRUs) followed by concept 4 (DMI + SRUs). In both concepts SRUs (wisseldelen) are used to decouple the overhaul from the BO process.
MCA 2 shows different results. In MCA 2, concepts 3, 5 and 8 are no 'no go' concepts, because in a new ship design, transportation routes can be included to transport an LRU. Now the best concept for the user and maintainer is concept 8 (outsourcing + LRU) followed by concept 3 (DMI + LRU). For the standard setter, concept 9 stays the best concept followed by concepts 4 and 8.
Both MCA 1 and MCA 2 show that the base case concept is not the best choice.

Table 8-6: Result MCA Diesel Generators

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,1	6,3	4,1
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	NO GO	NO GO	NO GO	NO GO	8,2	8,1	7,3	7,8
Concept 4	6,9	6,9	6,6	6,8	7,1	7,1	7,6	7,3
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,4	4,2	6,0
Concept 6	6,5	5,9	5,0	5,8	6,5	6,0	5,2	5,9
Concept 7	3,3	3,6	6,4	4,4	3,4	3,8	6,5	4,6
Concept 8	NO GO	NO GO	NO GO	NO GO	8,9	8,7	7,6	8,4
Concept 9	7,5	7,4	6,9	7,3	7,5	7,5	7,7	7,6

Mirador The results for MCA 1 and MCA 2 for the mirador are shown in Table 8-7. The current situation, or base case, for the mirador is again concept 1.
The results of MCA 1 show that the user, maintainer and standard setter all prefer concept 8 (outsourcing + LRU) followed by concept 3 (DMI + LRU).
The results for MCA 2 match the results for MCA 1. Both MCAs show that the base case concept is not the best solution.

Table 8-7: Results MCA Mirador

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,5	8,5	7,4	8,1	8,6	8,5	7,6	8,2
Concept 4	7,0	7,0	7,0	7,0	7,1	7,0	7,2	7,1
Concept 5	7,7	6,6	4,4	6,2	7,8	6,7	4,7	6,3
Concept 6	6,4	5,7	4,5	5,5	6,4	5,7	4,7	5,6
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,1	8,9	7,6	8,5	9,1	9,0	7,8	8,6
Concept 9	7,4	7,4	7,1	7,3	7,5	7,4	7,4	7,4

APAR The results of MCA 1 and MCA 2 for the APAR are shown in Table 8-8. For the APAR, the current situation, or base case, is concept 1.
The results of MCA 1 show that concept 3, 5 and 8 are 'no go concepts' for the existing ship, because the APAR is a large installation and it is difficult to change the interfacing (plug and play) in such a way that an LRU can be used. The user, maintainer and standard setter all prefer the same concept: concept 9 (outsourcing + SRUs), followed by concept 4 (DMI + SRUs).
In MCA 2, a different concept is prefered by the user and the maintainer. Concept 8 (outsourcing + LRU) is prefered the most, followed by concept 3 (DMI + LRU). The standard setter prefers concepts 8 and 9 followed by concepts 3 and 4.
The MCAs show that the base case concept is not the best choice.

Table 8-8: Results MCA APAR

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1 (base case)	3,0	3,1	6,2	4,1	3,0	3,1	6,2	4,1
Concept 2	2,6	2,5	5,8	3,7	2,6	2,5	5,8	3,7
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	8,0	7,1	7,7
Concept 4	6,9	6,9	6,9	6,9	6,8	6,8	7,1	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,3	4,5	6,1
Concept 6	6,5	6,1	5,1	5,9	6,5	6,1	5,3	6,0
Concept 7	3,4	3,4	6,3	4,4	3,5	3,5	6,3	4,5
Concept 8	NO GO	NO GO	NO GO	NO GO	8,7	8,6	7,4	8,2
Concept 9	7,4	7,4	7,1	7,3	7,5	7,4	7,4	7,4

Gas turbines The results of MCA 1 and MCA 2 for the gas turbines are shown in Table 8-9. As already explained in Chapter 5, the gas turbines of the frigates of the RNLN are overhauled by the British Royal Navy. When a gas turbine needs to be overhauled, it is removed from the ship and a new turbine is mounted on the ship. The removed gas turbine is then overhauled in Britain. Therefore, the current situation, or base case, is concept 8 because an LRU (wisselset) is used and the maintenance is outsourced (to Britain).
MCA 1 shows that the user, maintainer and standard setter all prefer concept 8 (outsourcing + LRU) followed by concept 3 (DMI + LRU). The same results are found in MCA 2.
Both MCAs show that the base case concept is also the best concept.

Table 8-9: Results MCA Gas Turbines

	Existing ship (MCA 1)				New ship (MCA 2)			
	User	*Maintainer*	*Standard Setter*	*Overall*	*User*	*Maintainer*	*Standard Setter*	*Overall*
Concept 1	2,9	3,4	6,4	4,3	2,9	3,4	6,4	4,3
Concept 2	2,1	2,3	5,8	3,5	2,1	2,3	5,8	3,5
Concept 3	8,7	8,6	8,2	8,5	8,7	8,6	8,2	8,5
Concept 4	6,8	6,9	7,5	7,1	6,8	6,9	7,5	7,1
Concept 5	7,9	6,9	5,4	6,7	7,9	6,9	5,4	6,7
Concept 6	6,3	5,7	5,4	5,8	6,3	5,7	5,4	5,8
Concept 7	3,2	3,5	6,3	4,4	3,2	3,5	6,3	4,4
Concept 8 (base case)	9,2	9,1	8,4	8,9	9,2	9,1	8,4	8,9
Concept 9	7,3	7,3	7,6	7,4	7,3	7,3	7,6	7,4

Sensitivity analysis

A sensitivity analysis was performed to check the sensitivity of the results. The assigned weights were varied to find out the influence of the weight factors on the ranking of the concepts. In Appendix K, the detailed results of this analysis are shown. The sensitivity analysis showed that the prefered concept did not change by varying the weights for the 'user' and 'maintainer'. The solution prefered by the 'standard setter' often had a little difference with the concept that was prefered second. The sensitivity analysis shows that the prefered concept by the 'standard setter' sometimes changes when different weights are used. Therefore, in case of the 'standard setter', the MCA is sensitive for little changes.
This can be avoided by letting more people fill in the pair-wise compairison of the criteria. Then the outliers can be eliminated and the weights become more reliable.

8-3 Check

The two steps in 'check' that were described in the dashboard are discussed in this section as follows:

- Study the results in Section 8-3-1
- Improvement of the existing situation (operational availability) in Section 8-3-2

8-3-1 Study the results

The first thing that needs to be done in 'check' is study the solution(s) that were found in 'do'. Looking at the best solution concepts found for the examined installations in 'do', the following things are noticed:

- The current situation, or base case, is not the best solution for six out of seven installations. Only for the gas turbines the base case concept is the best solution. For the goalkeeper, the base case is the second best solution.
- For different installations, the best solution concept for the 'user' and 'maintainer' is different than the best solution concept for the 'standard setter'. This can be explained

by the fact that the 'standard setter' has a preference towards the solutions with low initial costs and little design effort. This can be traced back in the weight factor assignment. At the DMO, they know that this is not right but because of the budget-driven culture it is reality. On the other hand, the 'user' and 'maintainer', prefer the solutions that have the best maintainability and flexibility. In the ideal situation, the 'user', 'maintainer' and 'standard setter' would prefer the same solutions.

- For the diesel engines and diesel generators, the best solution for the 'user' and 'maintainer' differs in MCA 1 and MCA 2. For an existing ship, it is impossible to implement a solution concept with an LRU while for a new ship, solution concepts with an LRU are possible and also prefered by the user and maintainer.
- For almost every installation, the concepts in which the maintenance is outsourced scores better than the concepts in which the maintenance is performed by the DMI.

8-3-2 Improvement of the existing situation

In this section, it should be checked whether the best solution concepts found improve the operational availability of the ships. Old plannings of different BO projects are used to check if the lead time of the maintenance on the examined installations is decreased. It is difficult to estimate the lead time reduction for the diesel engines, diesel generators and gas turbines, because every BO project, different maintenance tasks need to be performed. The maintenance tasks are dependent on the amount of hours the installation was used. Sometimes small maintenance tasks are performed and sometimes large maintenance tasks are performed. Therefore, it is difficult to find out the exact difference in lead time when the found solution is applied. On the other hand, the SEWACO installations (cannon, goalkeeper, APAR and mirador) mostly need the same kind of maintenance every BO project. This makes it easier to estimate the decrease in lead time when the found solutions are implemented.

Figure 8-3 shows a planning scheme for the maintenance of the goalkeeper when LRUs are not used. This information was obtained from the installation manager of the goalkeeper at the DMI. Figure 8-3 shows that when the solution prefered by the user, maintainer and standard setter (LRU) is used for the goalkeeper, the 'workshop overhaul' is removed from the BO process. Therefore, the lead time of the maintenance decreases from CONFIDENTIAL weeks. This is a lead time reduction of more than 70%. In the prefered solution, the maintenance works are outsourced which probably will also lead to another lead time reduction. However, it is very difficult to estimate this reduction because no data are available.

For the APAR, mirador and cannon, such a clear overview of the lead time of the installation was not available. Therefore, old plannings of BO projects were used to estimate the planning schemes of these installations.
Figure 8-4 shows the estimated planning scheme of the cannon. In the current situation, the cannon is removed from the ship, overhauled in the workplace and then placed back on the ship again. This scheme shows that if the solution that was prefered by the user, maintainer and standard setter in both MCAs (LRU) was implemented, the 'workshop overhaul' is removed from the process. Therefore, the lead time will reduce from CONFIDENTIAL. This is a lead time reduction of 50%.

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Figure 8-3: Lead time goalkeeper

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Figure 8-4: Lead time cannon

The estimated planning scheme for the mirador is shown in Figure 8-5. In the current situation, the mirador is removed from the ship, overhauled in the workplace and then placed back on the ship again. When the found solution for the mirador, that was prefered by the user, maintainer and standard setter (LRU), is implemented, this will remove the workshop overhaul from the BO process. This leads to a lead time reduction of CONFIDENTIAL or 75%.

Figure 8-6 shows the estimated planning scheme for the APAR. In the current situation, repairable parts are dismounted from the APAR installation, overhauled in the workplace and then placed back on the installation. When the solution prefered in MCA 1 (SRUs) is implemented, the overhaul of repairable parts is removed from the BO process. This leads to a lead time reduction of CONFIDENTIAL, which is more than 50%. When the solution prefered by the user, maintainer and standard setter in MCA 2 is implemented, the maintenance on board is also removed from the BO process. This leads to a lead time reduction of CONFIDENTIAL or 60%.

Figure 8-5: Lead time mirador

Figure 8-6: Lead time APAR

On the basis of the statements above, it can be concluded that the lead time of the SEWACO installations can be decreased by approximately more than 50% by making use of LRUs. In case the maintenance is also outsourced, this will probably give a lead time reduction as well, but it is hard to estimate this because data is lacking.
As explained before, it is a lot harder to estimate the change in lead time when the found solutions are implemented for the platform installations (diesel engines, diesel generators and gas turbines). However, with some common sense, it would be very likely that the lead time of the maintenance on these installations will also decrease. For example, when the overhaul of repairable parts from the diesel engine is removed from the BO process, this will lead to a lead time reduction.

Now the question remains: what is the impact of the found solutions on the operational availability of the ships? It is not possible to determine the change in operational availability for the following reason: the critical path of the BO process is unknown. In case the examined installations are on the critical path, the lead time of the BO process will decrease and the operational availability will increase. However, this is not known, so the change in operational availability cannot be determined. In order to determine the exact increase in operational availability, an MCA for every installation on the ship should be performed and the critical path should be known. With the results of these MCAs, a critical path simulation study can be performed to find out the exact decrease in the total BO lead time. It might not be profitable to implement an LRU for every installation. A balance should be found between the desired improvement and the costs involved. For example, if a certain solution results in a small decrease in lead time but is a large expenditure, this solution should better not be implemented.

8-4 Act

In 'check', it was shown that the lead time of the maintenance on the examined installations decreases. This is a positive outcome because this can lead to an increase in operational availability. Therefore, the found solutions should be implemented in the organisation.

8-4-1 Solution implementation

The different steps described in the dashboard to implement the solutions should be followed. These steps will now be explained for the implementation of the found solutions for the existing ships and for the new ships.

Existing ship

Make the organisation ready The MCAs showed that, for different installations, the user and maintainer prefer a different solution than the standard setter. Therefore, before the solutions can be implemented the user, maintainer and standard setter should discuss the results of the MCAs together. Together, they should decide which solution should actually be implemented. This is a *change in the corporate culture* because normally only the standard setter decides which solutions are implemented while the user and maintainer have a minimal influence. This is wrong because the user and maintainer are the ones that have to work with the installations on the ship. Therefore, they should be included in the decision making process.
The implementation of the solutions involves quite large initial expenditures, especially in the case of an existing ship and LRUs. So an important step in the implementation is *freeing up budget* that is needed to implement the found solutions. It could be decided to first implement the found solutions for one or two of the installations, preferably the installations that have the longest lead time at the moment, if budget is not available for all installations at once. If the implementation of these solutions is succesful, it can be decided to free more budget to implement the solutions for the other installations.
The found solutions involve some changes in the way maintenance should be performed. If it is decided to outsource the maintenance works, this should be communicated to the employees of the DMI. It should be explicitely mentioned that this is not a bad change. The work pressure on the employees of the DMI will decrease when the solutions are implemented and

there will be plenty of work left. If it is decided to keep the maintenance works at the DMI, the employees should be trained in the new way of performing maintenance.

Secure solution inside the organisation It should be made sure that the found solutions are preserved in the organisation. The solution should become the new standard. It should be properly documented what the new solution is and how it should be preserved. For an LRU it should be very well documented that an LRU cannot be used as a 'source of spare parts'. This is very important because otherwise the whole idea of an LRU is gone. It should also be properly documented that the LRU should be overhauled as soon as possible when it enters the workplace, but at least x days before it is needed again.

Make sure the new standard is maintained There should be frequent checks to make sure the new standard is maintained. For an LRU it should be frequently checked that it is untouched and that the overhaul is completed at least x days before it is needed. In case of deviations from the standard this should be corrected as soon as possible.

New ship

Make the organisation ready In case of a new ship the MCAs also show different prefered solutions for the user and maintainer and standard setter. Generally, the user and the maintainer do not have a large influence on the design of the ship. Because of this, less clever choices are made in the field of maintenance in the design of the ship. Therefore, it is very important that the user and maintainer are not forgotten in the design process of a new ship. The MCAs showed that the current maintenance situation for the different installations is not optimal. For a new ship the user, maintainer and standard setter should discuss the results from the MCAs so they can come to a solution that is acceptable for all parties.
The implementation of the different solutions involves extra design costs and initial costs. However, if the solutions are implemented, the maintenance costs will probably decrease more than the initial costs. Therefore, a change in the budget structure is required. The initial budget should be increased, for example, by shifting part of the maintenance budget to the initial budget.
The employees of the DMI should already be trained for the solutions that are going to be implemented on the new ships so the maintenance can directly start smoothly.

Secure solution inside the organisation It is extremely important that the found solutions are secured inside the organisation as the standard for the new ships. Therefore, everything should be documented properly to avoid discussions when the ship enters its utilisation phase.

Make sure the new standard is maintained A checking mechanism should already be described in the design process of a new ship. This checking mechanism should ensure that when the ship enters its operation phase the new standard is preserved at all times.

8-4-2 What next?

When the solutions are implemented a new PDCA cycle should start. In the new cycle it can be checked how much the implementation of the solutions has changed the operational availability. In case the target operational availability of 80% or higher was achieved, the target should be altered in the next cycle. Otherwise, a new analysis should start to indicate the problems that still cause the low operational availability.

8-5 Case study conclusion

The case study showed that by using the dashboard that was developed in Chapter 7, the lead time of the examined installations can be decreased drastically. It was also shown that the dashboard can be used for the existing ships, but also as a tool in the design process of a new ship class. It was shown that different solutions were found for the problems for the existing ships and for a new ship. This makes this a very usefull tool, because it shows that by making changes in the design of the ship, the maintenance lead time can decrease.
The case study also revealed that the user, maintainer and standard setter have different interests. These interests can lead to different prefered solutions. Therefore, it is very important that the user, maintainer and standard setter seek the conversation in order to find a solution that is acceptable for everyone.
It was not possible to determine the change in operational availability of the ships in this case study, because the critical path of the BO process is not known.

Chapter 9

Conclusions & Recommendations

9-1 Conclusions

The objective of this thesis was to design a continuous process improvement dashboard that can be used by the Royal Netherlands Navy to achieve an operational availability of 80% or higher, both for the existing ships and in the design process of new ships.

To succeed in this endeavor, first a mathematical definition for the operational availability was found:

$$Ao = \frac{MTBMA}{MTBMA + MDT} = \frac{MTBMA}{MTBMA + AMT + ADT + MLDT}$$

With this equation, the required and actual operational availability for the ships of the RNLN were calculated. This calculation showed that the operational availability requirements are not met (see Figures 4-9, 4-10 and 4-11 in Chapter 4).

To find out which factors have a negative influence on the operational availability, the maintenance process was analysed by using the Delft Systems Approach [1]. The analysis showed that the lead time of the BO process has the largest negative influence on the operational availability of the ships. After zooming in on the BO process, the following problems that cause the long lead time of the BO projects were identified:

- A very spacious planning
- The planning is not 'rigid'
- Overhaul of repairable parts and installations is coupled to the BO process
- Spare parts flow

- People flow
- Maintenance is barely taken into account during the design of a new ship.

The analysis showed that there is a lot of room to improve the operational availability of the ships of the RNLN. However, it is impossible to solve all the found problems at once. Therefore, a continuous process improvement dashboard, based on the Plan-Do-Check-Act cycle, was developed in this thesis. This dashboard can be used by the RNLN to improve the operational availability of the ships of the RNLN to a target value by solving the found problems in an iterative way. This dashboard is also useful in the design process of a new ship class to ensure the new ships achieve the target operational availability.

The working principle of the dashboard was verified by conducting a case study of one iteration. The case study examined solutions for two problems found in the BO process: the 'overhaul of repairable parts/installations' problem and the 'people flow' problem. To make the case study more manageable, it was decided to look at seven 'critical' installations with a long lead time. The case study showed different things:

- The results of the MCAs showed that the current situation is the best solution concept only one time.
- In different cases, the user and maintainer prefer a different solution concept than the standard setter. This is a result of the budget-driven culture at the defence organisation. In a project for a new ship, the focus of the standard setter is on the initial budget, the initial budget is leading.
- For two installations, the prefered solutions were 'no go' solution concepts for the current ships. For existing ships it is impossible to implement an LRU for the diesel engines and diesel generators. This shows that it is very important to already consider the maintenance in the design process of a ship.
- The maintenance lead time of the examined installations will decrease drastically when the prefered solution concepts are implemented.
- The prefered solution concepts often imply larger initial costs but lower maintenance costs.

In case the examined installations are on the critical path, the lead time of the BO process will decrease and the operational availability will increase. However, this is not known. Therefore, it was not possible to determine the change in operational availability.
The case study has shown that the continuous process improvement dashboard is a useful tool that, for a given critical path, can be used to increase the operational availability of the ships of the RNLN. Besides that, the case study showed that different solutions are found in case the dashboard is used in the design process of a new ship instead of for an existing ship. Therefore, the dashboard is also a useful tool in the design of a new ship. The dashboard can also be used for other issues that desire a continuous process improvement approach.

Concluding all this, the developed dashboard is a valuable tool that should be used by the RNLN to ensure that they are able to protect what is close to our hearts at all times.

9-2 Recommendations

In the case study it was not possible to determine the change in operational availability when the found solutions would be implemented. In order to determine the change in operational availability, the critical path of the BO process should be determined. When the critical path is known, the dashboard can be used to decrease the lead time of the installations on the critical path.

The solutions found in the case study should be implemented on the existing ships to determine the exact decrease in maintenance lead time of the installations. Furthermore, the dashboard should be used by the RNLN to increase the operational availability of the existing ships to a value of 80% or higher. The dashboard should also be used in the design process of a new ship class in order to achieve an operational availability of 80% or higher.

This thesis showed different solutions that could improve the operational availability of the ships. However, the financial consequences of these solutions should still be investigated. It might be possible that the found solutions cannot be implemented because of financial reasons.

The possibilities of modularity should be studied by the RNLN. The concept of modularity is already used by the Danish Royal Navy in their Absalon class and Iver Huidtfeld class. They make use of Stanflex modules that can be shared across both ship classes. This makes it possible to fit the equipment of the ships for different deployment types. The RNLN should consider the use of modules in the design of the new multipurpose frigates. It might be an option to design modules that can also be used for the ships that are going to replace the LCFs.

The possibilities to make the designer of the ships responsible for the maintenance of the ships should be investigated. If the designer is made responsible for an operational availability of 80% or higher, they will design the ship in a different way. They probably will, for example, make better transportation routes and use standardised articles. This will very likely have a positive influence on the maintainability of the ships.

The five year maintenance cycle that is used by the Royal Netherlands Navy for their ships is based on 'it has always been this way and it works quite well'. Nobody could tell why this is not four years or six years or based on the age of the ship (less maintenance in the first x years of the ships life). A reason for the five year cycle could be because this is imposed by the maritime classification bureaus (Lloyd's Register (LR) and Det Norske Veritas (DNV)). In principle the navies are excluded from the rules of LR and DNV but the RNLN decided to try to stick to the rules as much as possible. Another reason given was the 'paint system' of the ship. The ships have to be painted every five years but nobody could tell if this could also be six or seven years. Furthermore, all systems on the ship have a different maintenance cycle. The Goalkeeper, for example, has an ideal maintenance cycle of six years. This gives rise to the following question: is the five year cycle the most optimal maintenance interval? If the maintenance cycle is changed to, for example a six year cycle or a cycle that is based on the age of the ship, the MTBMA is longer and the operational availability will increase. Therefore, the optimal maintenance cycle should be determined.

One of the trends in the maintenance world is remote diagnostics. For remote diagnostics, the conditon of the equipment should be closely monitored. By using failure trends, it can be predicted (from a distance) when and where maintenance is needed. Remote diagnostics is already used in all kinds of industries but the shipping industry is lagging behind in this area. Nevertheless, remote diagnostics has a great potential in the shipping industry. How nice would it be that when the ship enters the harbour, the maintenance crew is ready to perform the necessary maintenance tasks. However, there are a couple of issues for the RNLN when it comes to remote diagnostics. One of the issues of the use of remote diagnostics on naval ships is that the condition monitoring data have to be send to the shore. This involves security issues. Another issue with remote diagnostics is that when a ship is on a deployment it can be at sea for a long time. It should be made sure that the ship does not need maintenance in this period of time. Therefore, it should be investigated what the possibilities are to overcome these issues.

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Appendix A

Scientific research paper

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Appendix B

Ships Royal Netherlands Navy

B-1 Sub surface vessels

This category contains the submarines of the Royal Netherlands Navy. The submarines are of the Walrusclass and belong to the most modern conventional, non-nuclear submarines of the world. Because of their relatively small dimensions they can collect intel or perform explorations even in shallow waters. Table B-1 lists the submarines of the Walrusclass.

Table B-1: Submarines (Walrusclass) [2][10]

Name	**Commissioned**
Zr. Ms. Zeeleeuw	1990
Zr. Ms. Walrus	1992
Zr. Ms. Dolfijn	1993
Zr. Ms. Bruinvis	1994

B-2 Small surface vessels

This category of ships consists of a lot of different ships. Every ship has its own specific tasks. Table B-2 lists the ship type, the amount of ships of this type, the class of the ship and the tasks of the ships [2][10].

Table B-2: Klein Bovenwater Eenheden [2][10]

Type of vessel	Amount	Class/Type	Tasks
Minehunter	6	Alkmaar	Keeping the sea, coast waters and harbor entrances mine free. They also can protect Navy-units during missions in which mines form a threat.
LCU-Landing craft	5	Mark II	Used for transportation of materials from Landing Platform Docks to the shore and back.
LCVP-Landing craft	12	MKV(c)	Smaller than the LCU and designed to transport personnel.
Hydrographic Recording Vessel	2	Snellius	Mapping the seas to provide information for nautical charts.
Supporting Vessel	1	Pelikaan	Supports Defense in the Carribean Area.
Torpedo Work Ship	1	Mercuur	Supports submarines during exercises. Functions, for example, as a floating maintenance hall for torpedoes.
Diving Support Vessel	5	Cerberus	Serve as a platform during diving works.
Tugboats	6	Noordzee Linge Breezand	Assist during mooring and unmooring.
FRISC-motorboat	19	Boarding Craft Raiding Craft Support Craft	FRISC (Fast Raiding Interception and Special Forces Craft) are very fast interception and special forces motorboats. They can for example be used for counter drug and terrorism operations.
RHIB-motorboat	24	700 2000 2000D	RHIB (Rigid Hull Inflatable Boat) are used for a lot of tasks. They serve as additional ship for big above surface vessels and are used for counter drug operations, boarding operations and river operations.
Sailing Educational Ship	1	Urania	Navy officers in training are trained with this ship.
Marine Educational Ship	1	Van Kinsbergen	Used for nautical training.

B-2-1 Logistic support ships

The different ships in this category are shown in Table B-3.

Table B-3: Ships of category Groot Grijs

Type	Name	Class	Commisioned
Joint Support Ship	Zr. Ms. Karel Doorman	Karel Doorman	2015
Landing Platform Dock	Zr. Ms. Rotterdam	Rotterdam	1998
Landing Platform Dock	Zr. Ms. Johan de Wit	Johan de Wit	2007

The only Joint Support Ship of the Royal Netherlands Navy, Zr. Ms. Karel Doorman of the Karel Doorman Class, is their newest and biggest ship (Figure B-1). It is a logistic support ship that was commisioned in 2015. This ship can transport a lot of big (military) equipment, it can supply other naval ships and it can function as a base at sea for land operations.
The Royal Netherlands Navy owns two Landing Platform Docks, Zr. Ms. Rotterdam (1998) (Figure B-2) and Zr. Ms. Johan de Wit (2007). The most important task of these ships is the support of amphibian operations on the boundary of land and water by bringing personel and supplies ashore, even when there is no harbor available. Like the JSS the LPD's can also function as a base at sea to control large scale amphibian and maritime operations. Both the JSS and LPD's are not equiped for combat, so the armament available is only for self-defense [2][10].

Figure B-1: Zr. Ms. Karel Doorman [2]

Figure B-2: Zr. Ms. Rotterdam[2]

Appendix C

Basis Standaard Materieel Indeling (BSMI)

Because of the large pool of installations on their ships, the RNLN uses a certain installation that categorises the installations. This installation works with so called 'Basis Standaard Materieel Indeling (BSMI)' indexes which are numbers with four digits (sometimes five). CONFIDENTIAL CONFIDENTIAL CONFIDENTIAL...

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Figure C-1: BSMI indices

Appendix D

Required systems for departure to sea

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Figure D-1: Required systems for departure to sea [9]

Appendix E

PO-card

Figure E-1: Example PO-card

Appendix F

Phases BO project

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Figure F-1: Snapshot HA/DA planning

Appendix G

Phases AM project

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Appendix H

Operationeel jaarplan (OJP)

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Figure H-1: Snapshot of an OJP

Figure H-1 shows a snapshot of a modified Operationeel Jaarplan (OJP). This planning shows when the ship is in maintenance. The letters shown in the OJP can be explained as follows:

- T = the ship is in a BO-period
- AM = the ship is in an AM-period
- HAT = Harbour Acceptance Tests

- SARC 1 = SARC 1 is performed
- SARC 2 = SARC 2 is performed
- SARC 3 = SARC 3 is performed
- Fast Cruise = Fast Cruise is performed
- M = The ship can have maintenance
- SAT = Sea Acceptance Tests

Appendix I

Pair-wise comparisons

Table I-1: Pair-Wise comparison 1

Table I-2: Pair-Wise comparison 2

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Table I-3: Pair-Wise comparison 3

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Appendix J

Ranking the concepts

Table J-1: Ranking the concepts for the diesel engines

MCA 1 diesel engines							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	2	1	9	2	8
Concept 2	1	9	2	1	9	1	4
Concept 3	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 4	7	6	6	7	5	7	6
Concept 5	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 6	7	3	3	7	5	8	3
Concept 7	4	9	1	1	9	3	8
Concept 8	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 9	8	6	5	7	5	8	9
MCA 2 diesel engines							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	2	1	9	2	8
Concept 2	1	9	2	1	9	1	4
Concept 3	8	3	8	8	1	8	4
Concept 4	7	7	7	7	6	7	6
Concept 5	8	1	3	8	1	8	1
Concept 6	7	3	2	7	6	8	3
Concept 7	4	9	1	1	9	3	8
Concept 8	8	3	6	8	1	8	9
Concept 9	8	7	5	7	6	8	9

Table J-2: Ranking the concepts for the goalkeeper

MCA 1 goalkeeper							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	8
Concept 2	1	9	2	1	9	1	4
Concept 3	9	2	8	9	4	8	5
Concept 4	8	5	7	7	6	7	7
Concept 5	9	1	1	9	4	9	2
Concept 6	8	3	4	7	6	8	3
Concept 7	4	9	2	1	9	4	8
Concept 8	10	2	6	9	4	9	9
Concept 9	9	5	5	7	6	8	9
MCA 2 goalkeeper							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	8
Concept 2	1	9	2	1	9	1	4
Concept 3	9	2	8	9	6	8	5
Concept 4	8	5	7	7	8	7	7
Concept 5	9	1	1	9	6	9	2
Concept 6	8	3	4	7	8	8	3
Concept 7	4	9	2	1	9	4	8
Concept 8	10	2	6	9	6	9	9
Concept 9	9	5	5	7	8	8	9

Table J-3: Ranking the concepts for the cannon

MCA 1 cannon							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	8	3	1	8	2	8
Concept 2	1	8	2	1	8	1	3
Concept 3	9	2	8	9	4	8	5
Concept 4	7	5	7	7	6	7	6
Concept 5	9	1	1	9	4	9	3
Concept 6	7	3	3	7	6	8	4
Concept 7	4	8	2	1	8	4	8
Concept 8	10	2	6	9	4	9	9
Concept 9	8	5	5	7	6	8	9
MCA 2 cannon							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	8	2	8
Concept 2	1	9	2	1	8	1	3
Concept 3	9	2	8	9	6	8	5
Concept 4	7	5	7	7	8	7	6
Concept 5	9	1	1	9	6	9	3
Concept 6	7	3	3	7	8	8	4
Concept 7	4	9	2	1	8	4	8
Concept 8	10	2	6	9	6	9	9
Concept 9	8	5	5	7	8	8	9

Table J-4: Ranking the concepts for the diesel generators

MCA 1 diesel generators							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	7
Concept 2	1	9	2	1	9	1	3
Concept 3	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 4	6	6	7	7	4	6	6
Concept 5	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 6	6	3	3	7	4	8	3
Concept 7	4	9	2	1	9	4	7
Concept 8	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 9	7	6	5	7	4	7	9
MCA 2 diesel generators							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	7
Concept 2	1	9	2	1	9	1	3
Concept 3	8	3	8	9	3	8	4
Concept 4	6	6	7	7	7	6	6
Concept 5	8	1	2	9	3	9	1
Concept 6	6	3	3	7	7	8	3
Concept 7	4	9	2	1	9	4	7
Concept 8	9	3	7	9	3	9	9
Concept 9	7	6	5	7	7	7	9

Table J-5: Ranking the concepts for the mirador

MCA 1 mirador							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	8
Concept 2	1	9	3	1	9	1	3
Concept 3	8	3	8	9	4	8	6
Concept 4	6	6	7	7	6	6	7
Concept 5	8	1	1	9	4	9	3
Concept 6	6	2	2	7	6	7	5
Concept 7	4	9	2	1	9	4	8
Concept 8	9	3	6	9	4	9	9
Concept 9	7	6	5	7	6	7	9
MCA 2 mirador							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	2	8
Concept 2	1	9	3	1	9	1	3
Concept 3	8	3	8	9	6	8	6
Concept 4	6	6	7	7	8	6	7
Concept 5	8	1	1	9	6	9	3
Concept 6	6	2	2	7	8	7	5
Concept 7	4	9	2	1	9	4	8
Concept 8	9	3	6	9	6	9	9
Concept 9	7	6	5	7	8	7	9

Table J-6: Ranking the concepts for the APAR

MCA 1 APAR							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	1	9	2	2	9	2	8
Concept 2	1	9	1	2	9	2	4
Concept 3	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 4	5	5	6	6	6	7	7
Concept 5	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 6	5	3	4	6	6	8	4
Concept 7	3	9	1	2	9	3	8
Concept 8	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO	NO GO
Concept 9	7	5	4	6	6	8	9
MCA 2 APAR							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	1	9	2	2	9	2	8
Concept 2	1	9	1	2	9	2	4
Concept 3	8	2	7	8	4	8	4
Concept 4	5	5	6	6	8	7	7
Concept 5	8	1	1	8	4	9	2
Concept 6	5	3	4	6	8	8	4
Concept 7	3	9	1	2	9	3	8
Concept 8	9	2	5	8	4	9	9
Concept 9	7	5	4	6	8	8	9

Table J-7: Ranking the concepts for the gas turbines

MCA 1 gas turbines							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	3	8
Concept 2	1	9	2	1	9	2	3
Concept 3	9	4	8	9	9	8	5
Concept 4	6	6	7	7	9	6	7
Concept 5	9	2	2	9	9	9	2
Concept 6	6	4	3	7	9	7	4
Concept 7	3	9	1	1	9	4	8
Concept 8	10	4	7	9	9	9	9
Concept 9	7	6	6	7	9	7	9
MCA 2 gas turbines							
	Lead time	Initial costs	Maintenance costs	Maintainability	Design effort	Flexibility	Logistics
Concept 1	2	9	3	1	9	3	8
Concept 2	1	9	2	1	9	2	3
Concept 3	9	4	8	9	9	8	5
Concept 4	6	6	7	7	9	6	7
Concept 5	9	2	2	9	9	9	2
Concept 6	6	4	3	7	9	7	4
Concept 7	3	9	1	1	9	4	8
Concept 8	10	4	7	9	9	9	9
Concept 9	7	6	6	7	9	7	9

Appendix K

Sensitivity analysis

A sensitivity analysis was performed to check the sensitivity of the results. The assigned weights are varied to find out the influence of the weight factors on the ranking of the concepts. Table K-1 shows the five different variations in weight factors that were used to perform the sensitivity analysis.

Table K-1: Variaton of weight factors

1				2				3			
User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
0,14	0,12	0,06	0,10	0,1	0,12	0,08	0,10	0,14	0,12	0,06	0,11
0,04	0,05	0,32	0,14	0,04	0,05	0,30	0,13	0,04	0,05	0,32	0,14
0,06	0,18	0,14	0,13	0,06	0,18	0,14	0,13	0,06	0,18	0,19	0,14
0,43	0,28	0,11	0,27	0,43	0,24	0,11	0,26	0,47	0,32	0,06	0,28
0,05	0,04	0,23	0,11	0,05	0,04	0,23	0,11	0,05	0,04	0,23	0,11
0,20	0,23	0,07	0,17	0,24	0,27	0,07	0,19	0,16	0,2	0,07	0,14
0,08	0,10	0,07	0,08	0,08	0,1	0,07	0,08	0,08	0,09	0,07	0,08

4				5			
User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
0,17	0,1	0,06	0,11	0,17	0,12	0,06	0,12
0,04	0,05	0,32	0,14	0,03	0,05	0,32	0,13
0,06	0,2	0,14	0,13	0,06	0,18	0,14	0,13
0,37	0,24	0,18	0,26	0,46	0,28	0,11	0,28
0,05	0,04	0,16	0,08	0,05	0,07	0,19	0,10
0,23	0,23	0,07	0,18	0,2	0,23	0,07	0,17
0,08	0,14	0,07	0,10	0,03	0,07	0,11	0,07

The concepts are ranked for every installation with the different weight factors that were shown in Table K-1. The results are shown in Tables K-2, K-3, K-4, K-5, K-6, K-7, K-8. These tables show that for the goalkeeper, cannon, mirador and gas turbines the results of the ranking stay the same in the five cases. For the diesel engines, diesel generators and gas turbines, the results for the 'user' and 'maintainer' stay the same in the five cases. However, the results for the 'standard setter' change in some cases. The tables show that some concepts are very close to each other in case of the 'standard setter'. In order to reduce the sensitivity, more people should fill in the pair-wise comparison of the criteria. The outliers can then be eliminated and the weights become more reliable. This also holds for the multi-criteria analysis.

Table K-2: Ranking concepts diesel engines with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	2,0	2,2	5,8	3,4	2,0	2,2	5,8	3,4
Concept 3	NO GO	NO GO	NO GO	NO GO	8,0	7,8	6,7	7,5
Concept 4	7,5	7,4	7,0	7,3	7,6	7,5	7,5	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	6,3	3,8	5,8
Concept 6	7,0	6,2	4,7	5,9	7,1	6,3	5,1	6,1
Concept 7	3,2	3,3	6,3	4,3	3,2	3,3	6,3	4,3
Concept 8	NO GO	NO GO	NO GO	NO GO	8,5	8,2	6,9	7,8
Concept 9	8,0	7,7	7,2	7,6	8,1	7,8	7,6	7,8
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,0	3,9	2,7	3,0	6,0	3,9
Concept 2	2,0	2,2	5,6	3,3	2,0	2,2	5,6	3,3
Concept 3	NO GO	NO GO	NO GO	NO GO	8,0	7,8	6,7	7,5
Concept 4	7,5	7,3	7,0	7,3	7,6	7,4	7,5	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	6,3	3,9	5,9
Concept 6	7,0	6,2	4,8	6,0	7,1	6,3	5,2	6,2
Concept 7	3,1	3,4	6,2	4,2	3,1	3,4	6,2	4,2
Concept 8	NO GO	NO GO	NO GO	NO GO	8,4	8,2	7,0	7,9
Concept 9	7,9	7,7	7,2	7,6	8,0	7,8	7,6	7,8
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	2,9	6,2	3,9	2,6	2,9	6,2	3,9
Concept 2	2,0	2,2	5,8	3,3	2,0	2,2	5,8	3,3
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	7,9	6,6	7,5
Concept 4	7,6	7,4	7,0	7,3	7,7	7,5	7,4	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	6,4	3,4	5,7
Concept 6	7,0	6,3	4,4	5,9	7,1	6,4	4,9	6,1
Concept 7	3,1	3,2	6,3	4,2	3,1	3,2	6,3	4,2
Concept 8	NO GO	NO GO	NO GO	NO GO	8,5	8,3	6,8	7,9
Concept 9	8,0	7,7	7,1	7,6	8,1	7,8	7,5	7,8
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,2	5,6	3,9	2,7	3,2	5,6	3,9
Concept 2	2,0	2,3	5,2	3,2	2,0	2,3	5,2	3,2
Concept 3	NO GO	NO GO	NO GO	NO GO	8,0	7,6	7,0	7,5
Concept 4	7,5	7,3	7,2	7,3	7,6	7,4	7,6	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	5,9	4,1	5,8
Concept 6	7,0	5,9	4,9	5,9	7,1	6,0	5,2	6,1
Concept 7	3,3	3,6	5,7	4,2	3,3	3,6	5,7	4,2
Concept 8	NO GO	NO GO	NO GO	NO GO	8,5	8,2	7,3	8,0
Concept 9	8,0	7,7	7,4	7,7	8,1	7,8	7,7	7,9
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,3	3,0	6,1	3,8	2,3	3,0	6,1	3,8
Concept 2	1,8	2,4	5,6	3,2	1,8	2,4	5,6	3,2
Concept 3	NO GO	NO GO	NO GO	NO GO	8,3	7,8	6,7	7,6
Concept 4	7,6	7,3	7,1	7,3	7,7	7,5	7,5	7,5
Concept 5	NO GO	NO GO	NO GO	NO GO	7,9	6,4	3,6	6,0
Concept 6	7,3	6,3	4,6	6,0	7,4	6,4	5,0	6,2
Concept 7	2,8	3,3	6,3	4,1	2,8	3,3	6,3	4,1
Concept 8	NO GO	NO GO	NO GO	NO GO	8,5	8,1	7,1	7,9
Concept 9	7,9	7,6	7,3	7,6	8,0	7,8	7,7	7,8

Table K-3: Ranking concepts goalkeeper with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	2,0	2,2	5,8	3,4	2,0	2,2	5,8	3,4
Concept 3	8,5	8,4	7,4	8,1	8,5	8,4	7,4	8,1
Concept 4	6,6	6,8	7,1	6,8	6,6	6,8	7,1	6,8
Concept 5	7,8	6,7	4,9	6,5	7,8	6,7	4,9	6,5
Concept 6	6,2	5,9	5,2	5,7	6,2	5,9	5,2	5,7
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,1	9,0	7,7	8,6	9,1	9,0	7,7	8,6
Concept 9	7,1	7,1	7,3	7,1	7,1	7,1	7,3	7,1
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,0	3,9	2,7	3,0	6,0	3,9
Concept 2	2,0	2,2	5,6	3,3	2,0	2,2	5,6	3,3
Concept 3	8,5	8,4	7,5	8,1	8,5	8,4	7,5	8,1
Concept 4	6,6	6,8	7,1	6,8	6,6	6,8	7,1	6,8
Concept 5	7,9	6,7	5,1	6,6	7,9	6,7	5,1	6,6
Concept 6	6,2	5,9	5,3	5,8	6,2	5,9	5,3	5,8
Concept 7	3,4	3,9	6,4	4,6	3,4	3,9	6,4	4,6
Concept 8	9,1	9,0	7,8	8,6	9,1	9,0	7,8	8,6
Concept 9	7,1	7,2	7,3	7,2	7,1	7,2	7,3	7,2
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	2,9	6,2	3,9	2,6	2,9	6,2	3,9
Concept 2	2,0	2,2	5,8	3,3	2,0	2,2	5,8	3,3
Concept 3	8,5	8,4	7,4	8,1	8,5	8,4	7,4	8,1
Concept 4	6,6	6,7	7,2	6,8	6,6	6,7	7,2	6,8
Concept 5	7,8	6,7	4,5	6,3	7,8	6,7	4,5	6,3
Concept 6	6,1	5,8	5,1	5,7	6,1	5,8	5,1	5,7
Concept 7	3,3	3,6	6,5	4,5	3,3	3,6	6,5	4,5
Concept 8	9,1	8,9	7,7	8,6	9,1	8,9	7,7	8,6
Concept 9	7,0	7,0	7,3	7,1	7,0	7,0	7,3	7,1
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,2	5,6	3,9	2,7	3,2	5,6	3,9
Concept 2	2,0	2,3	5,2	3,2	2,0	2,3	5,2	3,2
Concept 3	8,5	8,2	7,4	8,1	8,5	8,2	7,4	8,1
Concept 4	6,7	6,8	7,0	6,8	6,7	6,8	7,0	6,8
Concept 5	7,9	6,3	4,9	6,3	7,9	6,3	4,9	6,3
Concept 6	6,3	5,7	5,1	5,7	6,3	5,7	5,1	5,7
Concept 7	3,6	4,0	5,9	4,5	3,6	4,0	5,9	4,5
Concept 8	9,2	8,9	7,7	8,6	9,2	8,9	7,7	8,6
Concept 9	7,2	7,2	7,1	7,2	7,2	7,2	7,1	7,2
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,3	3,0	6,1	3,8	2,3	3,0	6,1	3,8
Concept 2	1,8	2,4	5,6	3,2	1,8	2,4	5,6	3,2
Concept 3	8,8	8,5	7,3	8,2	8,8	8,5	7,3	8,2
Concept 4	6,6	6,8	7,1	6,8	6,6	6,8	7,1	6,8
Concept 5	8,3	6,9	4,6	6,6	8,3	6,9	4,6	6,6
Concept 6	6,4	6,0	5,0	5,8	6,4	6,0	5,0	5,8
Concept 7	3,1	3,8	6,5	4,4	3,1	3,8	6,5	4,4
Concept 8	9,2	9,0	7,7	8,6	9,2	9,0	7,7	8,6
Concept 9	7,0	7,1	7,3	7,1	7,0	7,1	7,3	7,1

Table K-4: Ranking concepts cannon with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,4	8,3	6,7	7,8	8,4	8,3	6,9	7,9
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,9	7,0
Concept 5	7,7	6,6	4,4	6,2	7,8	6,7	4,7	6,3
Concept 6	6,5	5,9	5,0	5,8	6,5	6,0	5,2	5,9
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,0	8,8	6,9	8,2	9,0	8,9	7,2	8,3
Concept 9	7,4	7,3	6,8	7,2	7,5	7,4	7,0	7,3
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,0	3,9	2,7	3,0	6,0	3,9
Concept 2	1,9	2,1	5,5	3,2	1,9	2,1	5,5	3,2
Concept 3	8,4	8,3	6,8	7,8	8,4	8,3	7,0	7,9
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,9	7,0
Concept 5	7,8	6,7	4,6	6,3	7,8	6,7	4,8	6,5
Concept 6	6,5	6,0	5,0	5,8	6,6	6,0	5,3	5,9
Concept 7	3,4	3,9	6,4	4,6	3,4	3,9	6,4	4,6
Concept 8	9,0	8,9	7,1	8,3	9,0	8,9	7,3	8,4
Concept 9	7,4	7,4	6,9	7,2	7,5	7,4	7,1	7,3
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	2,9	6,2	3,9	2,6	2,9	6,2	3,9
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,4	8,3	6,7	7,8	8,4	8,4	6,9	7,9
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,9	7,0
Concept 5	7,7	6,7	4,0	6,1	7,8	6,7	4,3	6,2
Concept 6	6,4	5,9	4,8	5,7	6,5	6,0	5,0	5,8
Concept 7	3,3	3,6	6,5	4,5	3,3	3,6	6,5	4,5
Concept 8	8,9	8,8	6,9	8,2	9,0	8,9	7,1	8,3
Concept 9	7,4	7,3	6,8	7,1	7,4	7,3	7,0	7,2
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,2	5,6	3,9	2,7	3,2	5,6	3,9
Concept 2	1,9	2,2	5,1	3,1	1,9	2,2	5,1	3,1
Concept 3	8,4	8,1	6,8	7,8	8,4	8,2	7,0	7,8
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,8	6,9
Concept 5	7,8	6,2	4,6	6,2	7,8	6,2	4,7	6,3
Concept 6	6,5	5,7	5,0	5,7	6,6	5,7	5,1	5,8
Concept 7	3,6	4,0	5,9	4,5	3,6	4,0	5,9	4,5
Concept 8	9,0	8,8	7,1	8,3	9,1	8,8	7,2	8,4
Concept 9	7,5	7,4	6,8	7,2	7,5	7,4	7,0	7,3
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,3	3,0	6,1	3,8	2,3	3,0	6,1	3,8
Concept 2	1,8	2,3	5,4	3,2	1,8	2,3	5,4	3,2
Concept 3	8,6	8,3	6,6	7,8	8,7	8,4	6,8	8,0
Concept 4	7,0	7,0	6,7	6,9	7,0	7,0	6,9	7,0
Concept 5	8,2	6,8	4,2	6,4	8,2	6,8	4,4	6,5
Concept 6	6,7	6,0	4,8	5,8	6,8	6,1	5,0	6,0
Concept 7	3,1	3,8	6,5	4,4	3,1	3,8	6,5	4,4
Concept 8	9,1	8,8	7,0	8,3	9,1	8,9	7,2	8,4
Concept 9	7,3	7,3	6,9	7,2	7,4	7,3	7,1	7,3

Table K-5: Ranking concepts diesel generators with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,1	6,3	4,1
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	NO GO	NO GO	NO GO	NO GO	8,2	8,1	7,3	7,8
Concept 4	6,9	6,9	6,6	6,8	7,1	7,1	7,6	7,3
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,4	4,2	6,0
Concept 6	6,5	5,9	5,0	5,8	6,5	6,0	5,2	5,9
Concept 7	3,3	3,6	6,4	4,4	3,4	3,8	6,5	4,6
Concept 8	NO GO	NO GO	NO GO	NO GO	8,9	8,7	7,6	8,4
Concept 9	7,5	7,4	6,9	7,3	7,5	7,5	7,7	7,6
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,1	6,1	3,9	2,7	3,2	6,2	4,0
Concept 2	1,9	2,1	5,5	3,2	1,9	2,1	5,5	3,2
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	8,0	7,3	7,8
Concept 4	6,9	6,9	6,6	6,8	7,1	7,1	7,5	7,2
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,4	4,4	6,1
Concept 6	6,5	6,0	5,0	5,8	6,6	6,0	5,3	5,9
Concept 7	3,3	3,7	6,3	4,4	3,4	3,9	6,4	4,6
Concept 8	NO GO	NO GO	NO GO	NO GO	8,8	8,7	7,7	8,4
Concept 9	7,5	7,5	6,9	7,3	7,5	7,5	7,7	7,6
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	2,9	6,3	4,0	2,7	3,0	6,4	4,0
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	NO GO	NO GO	NO GO	NO GO	8,2	8,1	7,3	7,9
Concept 4	6,9	6,9	6,6	6,8	7,1	7,1	7,6	7,2
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,5	3,9	5,9
Concept 6	6,4	5,9	4,8	5,7	6,5	6,0	5,0	5,8
Concept 7	3,2	3,4	6,4	4,3	3,3	3,6	6,5	4,5
Concept 8	NO GO	NO GO	NO GO	NO GO	8,9	8,7	7,5	8,4
Concept 9	7,5	7,4	6,8	7,2	7,5	7,4	7,6	7,5
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,3	5,7	3,9	2,8	3,4	5,7	4,0
Concept 2	1,9	2,2	5,1	3,1	1,9	2,2	5,1	3,1
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	7,9	7,5	7,8
Concept 4	6,9	6,8	6,6	6,8	7,1	7,1	7,5	7,2
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,0	4,4	6,0
Concept 6	6,5	5,7	5,0	5,7	6,6	5,7	5,1	5,8
Concept 7	3,5	3,8	5,8	4,3	3,6	4,0	5,9	4,5
Concept 8	NO GO	NO GO	NO GO	NO GO	8,9	8,7	7,8	8,5
Concept 9	7,6	7,5	6,9	7,3	7,6	7,5	7,6	7,6
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,3	3,1	6,2	3,9	2,3	3,2	6,3	3,9
Concept 2	1,8	2,3	5,4	3,2	1,8	2,3	5,4	3,2
Concept 3	NO GO	NO GO	NO GO	NO GO	8,4	8,1	7,2	7,9
Concept 4	6,9	6,9	6,6	6,8	7,1	7,1	7,5	7,2
Concept 5	NO GO	NO GO	NO GO	NO GO	8,0	6,6	4,0	6,2
Concept 6	6,7	6,0	4,8	5,8	6,8	6,1	5,0	6,0
Concept 7	3,0	3,6	6,3	4,3	3,1	3,8	6,5	4,4
Concept 8	NO GO	NO GO	NO GO	NO GO	8,9	8,6	7,7	8,4
Concept 9	7,5	7,4	7,0	7,3	7,5	7,4	7,7	7,5

Table K-6: Ranking concepts mirador with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,2	4,0	2,7	3,0	6,2	4,0
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,5	8,5	7,4	8,1	8,6	8,5	7,6	8,2
Concept 4	7,0	7,0	7,0	7,0	7,1	7,0	7,2	7,1
Concept 5	7,7	6,6	4,4	6,2	7,8	6,7	4,7	6,3
Concept 6	6,4	5,7	4,5	5,5	6,4	5,7	4,7	5,6
Concept 7	3,4	3,8	6,5	4,6	3,4	3,8	6,5	4,6
Concept 8	9,1	8,9	7,6	8,5	9,1	9,0	7,8	8,6
Concept 9	7,4	7,4	7,1	7,3	7,5	7,4	7,4	7,4
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,0	6,0	3,9	2,7	3,0	6,0	3,9
Concept 2	1,9	2,1	5,5	3,2	1,9	2,1	5,5	3,2
Concept 3	8,5	8,5	7,4	8,1	8,6	8,5	7,7	8,3
Concept 4	7,0	7,0	7,0	7,0	7,1	7,0	7,2	7,1
Concept 5	7,8	6,7	4,6	6,3	7,8	6,7	4,8	6,5
Concept 6	6,4	5,7	4,6	5,6	6,5	5,8	4,8	5,7
Concept 7	3,4	3,9	6,4	4,6	3,4	3,9	6,4	4,6
Concept 8	9,1	9,0	7,7	8,6	9,1	9,0	7,9	8,7
Concept 9	7,4	7,4	7,2	7,3	7,5	7,5	7,4	7,4
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	2,9	6,2	3,9	2,6	2,9	6,2	3,9
Concept 2	1,9	2,1	5,7	3,3	1,9	2,1	5,7	3,3
Concept 3	8,5	8,5	7,4	8,1	8,6	8,5	7,6	8,2
Concept 4	7,0	7,0	7,0	7,0	7,1	7,0	7,2	7,1
Concept 5	7,7	6,7	4,0	6,1	7,8	6,7	4,3	6,2
Concept 6	6,3	5,7	4,2	5,4	6,4	5,7	4,5	5,5
Concept 7	3,3	3,6	6,5	4,5	3,3	3,6	6,5	4,5
Concept 8	9,0	8,9	7,5	8,5	9,1	9,0	7,8	8,6
Concept 9	7,4	7,3	7,1	7,3	7,5	7,4	7,3	7,4
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,7	3,2	5,6	3,9	2,7	3,2	5,6	3,9
Concept 2	1,9	2,2	5,1	3,1	1,9	2,2	5,1	3,1
Concept 3	8,5	8,4	7,5	8,1	8,6	8,4	7,7	8,2
Concept 4	7,0	7,0	7,0	7,0	7,1	7,0	7,2	7,1
Concept 5	7,8	6,2	4,6	6,2	7,8	6,2	4,7	6,3
Concept 6	6,4	5,4	4,5	5,4	6,5	5,5	4,7	5,5
Concept 7	3,6	4,0	5,9	4,5	3,6	4,0	5,9	4,5
Concept 8	9,1	8,9	7,7	8,6	9,2	8,9	7,9	8,7
Concept 9	7,5	7,4	7,1	7,3	7,6	7,5	7,3	7,4
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,3	3,0	6,1	3,8	2,3	3,0	6,1	3,8
Concept 2	1,8	2,3	5,4	3,2	1,8	2,3	5,4	3,2
Concept 3	8,7	8,5	7,3	8,2	8,8	8,6	7,5	8,3
Concept 4	7,0	7,0	7,0	7,0	7,1	7,1	7,2	7,1
Concept 5	8,2	6,8	4,2	6,4	8,2	6,8	4,4	6,5
Concept 6	6,6	5,8	4,3	5,6	6,7	5,9	4,5	5,7
Concept 7	3,1	3,8	6,5	4,4	3,1	3,8	6,5	4,4
Concept 8	9,1	8,9	7,7	8,6	9,2	9,0	7,8	8,7
Concept 9	7,4	7,3	7,2	7,3	7,4	7,4	7,4	7,4

Table K-7: Ranking concepts APAR with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	3,0	3,1	6,2	4,1	3,0	3,1	6,2	4,1
Concept 2	2,6	2,5	5,8	3,7	2,6	2,5	5,8	3,7
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	8,0	7,1	7,7
Concept 4	6,9	6,9	6,9	6,9	6,8	6,8	7,1	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,3	4,5	6,1
Concept 6	6,5	6,1	5,1	5,9	6,5	6,1	5,3	6,0
Concept 7	3,4	3,4	6,3	4,4	3,5	3,5	6,3	4,5
Concept 8	NO GO	NO GO	NO GO	NO GO	8,7	8,6	7,4	8,2
Concept 9	7,4	7,4	7,1	7,3	7,5	7,4	7,4	7,4
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	3,0	3,1	6,1	4,1	3,0	3,1	6,1	4,1
Concept 2	2,6	2,5	5,6	3,6	2,6	2,5	5,6	3,6
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	8,0	7,1	7,7
Concept 4	6,9	6,9	6,9	6,9	6,9	6,8	7,1	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,3	4,7	6,2
Concept 6	6,6	6,1	5,2	5,9	6,6	6,2	5,4	6,1
Concept 7	3,4	3,4	6,1	4,3	3,5	3,5	6,2	4,4
Concept 8	NO GO	NO GO	NO GO	NO GO	8,7	8,6	7,4	8,2
Concept 9	7,4	7,4	7,2	7,3	7,5	7,5	7,4	7,4
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	3,0	3,1	6,2	4,1	3,0	3,1	6,2	4,1
Concept 2	2,6	2,5	5,7	3,6	2,6	2,5	5,7	3,6
Concept 3	NO GO	NO GO	NO GO	NO GO	8,2	8,1	7,1	7,8
Concept 4	6,9	6,9	6,9	6,9	6,8	6,8	7,1	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,5	6,4	4,1	6,0
Concept 6	6,4	6,1	5,0	5,8	6,5	6,1	5,2	5,9
Concept 7	3,4	3,3	6,2	4,3	3,4	3,4	6,3	4,4
Concept 8	NO GO	NO GO	NO GO	NO GO	8,7	8,6	7,3	8,2
Concept 9	7,4	7,3	7,1	7,3	7,5	7,4	7,3	7,4
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,9	3,4	5,7	4,0	2,9	3,4	5,7	4,0
Concept 2	2,6	2,6	5,3	3,5	2,6	2,6	5,3	3,5
Concept 3	NO GO	NO GO	NO GO	NO GO	8,1	7,9	7,2	7,7
Concept 4	6,8	6,9	6,9	6,9	6,8	6,8	7,0	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,4	5,9	4,6	6,0
Concept 6	6,5	5,9	5,1	5,8	6,5	6,0	5,3	5,9
Concept 7	3,5	3,6	5,8	4,3	3,5	3,7	5,8	4,4
Concept 8	NO GO	NO GO	NO GO	NO GO	8,7	8,6	7,4	8,2
Concept 9	7,5	7,4	7,1	7,3	7,6	7,5	7,3	7,4
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,6	3,1	6,2	4,0	2,6	3,1	6,2	4,0
Concept 2	2,4	2,7	5,6	3,6	2,4	2,7	5,6	3,6
Concept 3	NO GO	NO GO	NO GO	NO GO	8,3	8,1	7,0	7,8
Concept 4	6,8	6,9	6,9	6,9	6,9	6,9	7,0	6,9
Concept 5	NO GO	NO GO	NO GO	NO GO	7,9	6,5	4,3	6,2
Concept 6	6,6	6,2	5,0	5,9	6,7	6,2	5,2	6,0
Concept 7	3,1	3,4	6,2	4,2	3,1	3,5	6,3	4,3
Concept 8	NO GO	NO GO	NO GO	NO GO	8,8	8,6	7,4	8,2
Concept 9	7,4	7,3	7,2	7,3	7,4	7,4	7,4	7,4

Table K-8: Ranking concepts gas turbines with different weight factors

1								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,9	3,4	6,4	4,3	2,9	3,4	6,4	4,3
Concept 2	2,1	2,3	5,8	3,5	2,1	2,3	5,8	3,5
Concept 3	8,7	8,6	8,2	8,5	8,7	8,6	8,2	8,5
Concept 4	6,8	6,9	7,5	7,1	6,8	6,9	7,5	7,1
Concept 5	7,9	6,9	5,4	6,7	7,9	6,9	5,4	6,7
Concept 6	6,3	5,7	5,4	5,8	6,3	5,7	5,4	5,8
Concept 7	3,2	3,5	6,3	4,4	3,2	3,5	6,3	4,4
Concept 8	9,2	9,1	8,4	8,9	9,2	9,1	8,4	8,9
Concept 9	7,3	7,3	7,6	7,4	7,3	7,3	7,6	7,4
2								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	3,0	3,4	6,2	4,2	3,0	3,4	6,2	4,2
Concept 2	2,2	2,4	5,6	3,4	2,2	2,4	5,6	3,4
Concept 3	8,7	8,6	8,2	8,5	8,7	8,6	8,2	8,5
Concept 4	6,8	6,9	7,5	7,0	6,8	6,9	7,5	7,0
Concept 5	8,0	7,0	5,5	6,8	8,0	7,0	5,5	6,8
Concept 6	6,4	5,7	5,4	5,8	6,4	5,7	5,4	5,8
Concept 7	3,3	3,6	6,2	4,3	3,3	3,6	6,2	4,3
Concept 8	9,2	9,1	8,4	8,9	9,2	9,1	8,4	8,9
Concept 9	7,3	7,3	7,6	7,4	7,3	7,3	7,6	7,4
3								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,9	3,2	6,5	4,2	2,9	3,2	6,5	4,2
Concept 2	2,1	2,3	5,8	3,4	2,1	2,3	5,8	3,4
Concept 3	8,7	8,6	8,2	8,5	8,7	8,6	8,2	8,5
Concept 4	6,9	6,9	7,5	7,1	6,9	6,9	7,5	7,1
Concept 5	7,9	7,0	5,0	6,6	7,9	7,0	5,0	6,6
Concept 6	6,3	5,8	5,2	5,7	6,3	5,8	5,2	5,7
Concept 7	3,1	3,3	6,3	4,2	3,1	3,3	6,3	4,2
Concept 8	9,2	9,0	8,3	8,8	9,2	9,0	8,3	8,8
Concept 9	7,3	7,3	7,6	7,4	7,3	7,3	7,6	7,4
4								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	3,0	3,7	5,8	4,2	3,0	3,7	5,8	4,2
Concept 2	2,2	2,4	5,2	3,3	2,2	2,4	5,2	3,3
Concept 3	8,7	8,5	8,2	8,4	8,7	8,5	8,2	8,4
Concept 4	6,8	7,0	7,3	7,0	6,8	7,0	7,3	7,0
Concept 5	8,0	6,5	5,4	6,6	8,0	6,5	5,4	6,6
Concept 6	6,3	5,6	5,2	5,7	6,3	5,6	5,2	5,7
Concept 7	3,4	3,7	5,7	4,3	3,4	3,7	5,7	4,3
Concept 8	9,3	9,0	8,4	8,9	9,3	9,0	8,4	8,9
Concept 9	7,3	7,4	7,5	7,4	7,3	7,4	7,5	7,4
5								
	Existing ship (MCA 1)				New ship (MCA 2)			
	User	Maintainer	Standard Setter	Overall	User	Maintainer	Standard Setter	Overall
Concept 1 (base case)	2,5	3,4	6,3	4,1	2,5	3,4	6,3	4,1
Concept 2	2,0	2,5	5,5	3,3	2,0	2,5	5,5	3,3
Concept 3	8,9	8,7	8,0	8,5	8,9	8,7	8,0	8,5
Concept 4	6,8	7,0	7,4	7,1	6,8	7,0	7,4	7,1
Concept 5	8,4	7,1	5,1	6,9	8,4	7,1	5,1	6,9
Concept 6	6,5	5,9	5,2	5,8	6,5	5,9	5,2	5,8
Concept 7	2,8	3,5	6,3	4,2	2,8	3,5	6,3	4,2
Concept 8	9,3	9,1	8,4	8,9	9,3	9,1	8,4	8,9
Concept 9	7,2	7,3	7,6	7,3	7,2	7,3	7,6	7,3