Modular naval vessels and the impact on the design and effectiveness

M.L. Stam

Delft University of Technology

Ministerie van Defensie

Modular naval vessels and the impact on the design and effectiveness

by

M.L. Stam

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday January 15, 2025 at 14:00.

Report number:	MT.24/25.026.M	
Student number:	4921003	
Project duration:	January 8, 2024 – January 15,2025	
Thesis committee:	Dr. A.A. Kana,	TU Delft, committee chairman
	Ir. J.L. Gelling,	TU Delft
	Ir. E. Scheffers,	TU Delft
	Ir. J.E. Streng,	Material and IT Command

Abstract

Modularity is often mentioned as a method to make a vessel's design flexible during its lifetime. However, literature often focuses on ways to apply modularity to naval vessels instead of asking if modularity improves the vessel, or the organizational process, at all. This paper aims to build a framework to give the naval architect valuable insights into the possible benefits and the technical impact of modularity application. When a system is deemed a feasible module, a final evaluation is performed to assess if the modular variant of the system actually improves the vessel or the organizational process.

This research presents a framework consisting of a Modular Function Deployment (MFD), Analytical Hierarchy Process (AHP), and Knowledge Based Engineering (KBE) model to assess the suitability and technical feasibility of modular systems. The MFD aims to identify high-potential modular systems based on modularity drivers defined and rated by the naval architect. Next, the AHP aims to map the most important functions of the vessel. Since modularity always comes with increased weight, the naval architect can use the AHP to ask themselves if the system fulfills a function that is important enough to embrace the increased weight. With the KBE model, the technical impact of modular systems can be assessed in terms of weight, estimated draft, and stability. When a system scores high on the MFD, it indicates the system would benefit from modularity. When its accompanying function scores high on the AHP, it indicates the system fulfills an important function. The technical impact of making the system modular can be assessed with the KBE model. If the technical impact is deemed acceptable, the system can be labeled as a 'feasible' module. The final effectiveness assessment will indicate if the feasible module actually improves the vessel's design or the organizational process. This way, a framework will be developed which gives the naval architect valuable insights into the potential benefits and costs of modularity.

A case study will be presented on a landing platform dock and the future air defender (FuAD) of the RNLN. Results show the FuAD has higher-potential systems for modularity, so the KBE model is applied to only the FuAD. In the KBE model, an air surveillance radar and Laser-Directed Energy Weapon (LDEW) are modeled as a non-modular system and then as a modular variant. This way, the impact of making a system modular is assessed. The KBE model results in a technically feasible module for the air surveillance radar and LDEW. The final effectiveness assessment results in a preference for a non-modular air surveillance radar and a modular LDEW. This shows that modularity does not necessarily improve the system and a structural way to approach modularity and compare it to a non-modular variant is required.

The framework can be applied to a wide variety of vessels, including commercial vessels. The framework uses generally applicable methods, and by combining them in a structural way the decision-making on whether to use modularity or not can be improved. For naval vessels, the effectiveness depends on the intentions of the end user. By qualifying the expert opinion using AHP, both by identifying the most important functions and the final evaluation, this intention is integrated into the framework. This also personalizes the outcome: based on the intentions of the end-user, completely different outcomes can be retrieved from this framework. After computing the framework for a specific vessel type, the results can partially be applied to other vessel types, within the same organization due to the end-user intentions mentioned above, as well. If a modular system is preferred over the non-modular variant, this implies the other vessel types will also benefit from this system as a module. Since this system is already defined as an HLP in the KBE model, the system can easily be imported into another design. The hull form can be easily changed as well since this already is an external Rhino file imported into the Python file. These factors make the framework applicable to a wide variety of different vessel types.

Preface

The presented thesis is the final work of my six-and-a-half-year journey as a student in Delft. This thesis would not have been possible without the help of many people, who I want to thank for their support.

First, I would like to thank my daily supervisors Ir. Jurjen Streng and Dr. Austin Kana. Jurjen has provided me with great guidance from COMMIT. He guided me from the start and included me in activities to get to know COMMIT better. The regular meetings lead to useful discussions and new insights in naval vessel design. Austin has been of equally great help and provided guidance from a more academic point of view. Even though he had a busy schedule, he always found time to grant me feedback. Last, I would like to thank both Jurjen and Austin for their flexibility. My work for the Dutch Air Force as a reserve NCO required some flexibility in the planning of this thesis. Whenever I discussed my work and the uncertainty of the planning, they were fine with it as long as I kept updating them. I want to thank you both sincerely for everything during this thesis.

Next, I want to thank my colleagues at COMMIT. I was welcomed like a new colleague and the interest in my project and results felt like a compliment. The many discussions at the beginning of the thesis really helped to get insights into the many different opinions about modularity and how it could be applied to naval vessels. This really helped my own understanding of the topic, and naval vessel design in general, and it showed me how diverse people think about modularity.

Finally, I want to thank my family and friends for their endless support throughout the entire journey. They gave me the, sometimes forced, time to relax.

M.L. Stam
Delft, January 2025

Table of Contents

List of Figures

List of Tables

Glossary

Adaptability	The ability to change boundaries by changing the platform itself (adapted from [77]).
Building block	A collection of physical hardware and/or software components that cannot be related to a certain function [25].
Effectiveness	The degree to which something is successful in producing a desired result or success [84].
Efficiency	Achieving maximum productivity with minimum wasted effort or expense [84].
Expert	Someone whose expertise in a particular area makes his assertions reliable—more likely to be true than false [101]
Flexibility	The ability to adapt to changing missions and technologies without changes to the platform (adapted from [77]).
Modularity	Creating fixed boundaries, defined interfaces, and defined ship services to standard portions of a ship, which are termed modules [77].
Module	A collection of physical hardware and/or software components that build a dedicated function with in the system. To be considered as a module,it has to fulfill a function [25].
Neutralization	The production of an effect that removes the effect of something else [12].
Non-dominated solution	A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists that is better in one objective attribute and at least as good in all others [11].
Pareto front	In a pool of solutions the Pareto front is the solution in which one of the objectives cannot be improved without worsening another objective. It is a set of solutions that are non-dominated by each other but are superior to the rest of the solutions in the search space [107].
Stakeholders	Parties that are (in)directly involved with the vessel or have other interests in its existence [17].

Acronyms

AAW	Anti-Air Warfare
AHP	Analytical hierarchy process
AMS	Maritime Systems Division (Afdeling Maritieme Systemen)
AMW	Amphibious Warfare
AoO	Area of Operations
ASuW	Anti-Surface Warfare
ASW	Anti-Submarine Warfare
ASWF	Anti-Submarine Warfare Frigate
ATS	Amfibisch Transportschip
CBRN	Checmical, Biological, Radiological, Nuclear
COMMIT	Materiel and IT Command
CSS	Combat Support Ship
CONOPS	Concept of Operations
C2	Command and Control
C4I	Command, Control, Communications, Computers and Intelligence
DE	Diesel Engine
DMO	Defensie Materieel Organisatie
DPM	Design Property Matrix
EEDI	Energy Efficiency Design Index
EOD	Explosive Ordinance Disposal
EPM	Electronic Protective Measures
EW	Electronic Warfare
FRISC	Fast Raiding Interception and Special forces Craft
FuAD	Future Air Defender
GB	Gearbox
GEN	Generator
GT	Gas Turbine
HADR	Humanitarian Assistance and Disaster Relief
HLP	High Level Primitive
ICE	Internal Combustion Engine
IM	Interface Matrix
IMO	International Maritime Organization
JOR	Joint Operation Room
JSS	Joint logistic Support Ship
KBE	Knowledge Based Engineering
KPI	Key Performance Indicator
LCF	Luchtverdedigings- en Commandofregat
LCS	Littoral Combat Ship
LDEW	Laser directed energy weapon
LPD	Landing Platform Dock

MARIN	Maritime Research Institute Netherlands
MFD	Modular Function Deployment
M-frigate	Multipurpose Frigate
MIM	Module Indication Matrix
MoD	Ministry of Defence
MOE	Measure of Effectiveness
MOP	Measure of Performance
MSO	Maritime Security Operations
NATO	North Atlantic Treaty Organisation
OMOE	Overall Measure of Effectiveness
OPV	Ocean-going Patrol Vessel
PMM	Product Management Map
QFD	Auality Function Deployment
RAM	Rolling Airframe Missile
RAS	Replenishment at sea
RF	Radio Frequency
RHIB	Rigid Hull Inflatable Boat
RNLN	Royal Netherlands Navy (Commando Zeestrijdkrachten)
ROI	Return on investment
SEWACO	Sensors, Weapons and Communication
SOF	Special Operations Forces
STANFLEX	Standard Flex
TLC	Through-life costs
UAV	Unmanned Aerial Vehicle
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicle
UXV	Unmanned Vehicle
VLS	Vertical Launch System
VOP	Value of Performance

Nomenclature

A	Area	m^2
B	Beam	m
C	Admiralty constant	-
C_b	Block coefficient	-
COB	Center of buoyancy	m
D	Draught	m
GM	Geometric Mean	m
LOA	Lenght overall	m
LWL	Lenght of the waterline	m
P	Power	kW
T	Draft	m
V	Speed	kn
W	Watt	$\mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-3}$
ρ	Density	$\frac{\mathrm{ton}}{\mathrm{m}^3}$
Δ	Displacement	ton

1

Introduction

The Dutch Ministry of Defense (MoD) in-house development of naval vessels is emphasized more than in other countries [39]. However, designing naval vessels comes with its challenges. The first challenge is the unpredictable geopolitical environments in which they need to be able to operate[3]. The MoD's surface combatant's main task is to perform combat operations, while in times of peace, they are used for operations such as humanitarian aid after natural disasters or counter-narcotics operations [65]. Another challenge most navies, including the Royal Netherlands Navy (RNLN), face is a limited budget [3]. Modern vessels are required to carry out missions and be ahead of opposing actors. These opposing actors can differ as well. Where Russia uses large-scale military force against Ukraine, pirates in front of the coast of Somalia would operate in a completely different way. These opposing actors are evolving their gear and weapon systems as well, so the vessel must be able to make adjustments to continue doing its missions during its lifetime. But making a vessel suitable for all predicted future requirements at the same will result in, at least some degree of, overdesign, resulting in inevitable compromises on the vessel's performance [25, 67]. A possible way to mitigate these challenges is to make the vessel adaptable to handle a wider variety of tasks. However, designing and building these modern vessels is extremely expensive and time-consuming. To give an idea: the Dutch MoD has ordered two new Anti Submarine Warfare frigates (ASWFs). The costs for these two vessels are estimated to be €1.9 billion [58], and the first frigate will be delivered in 2029 while the second frigate will be delivered in 2031. This delivery time shows another challenge the MoD faces since they must be able to conduct their missions at all times, otherwise a capability gap would occur. The new vessels must be designed and manufactured before the old vessels are out of service. In short, the Dutch MoD is seeking less time-consuming ways to design future naval vessels that can handle a wide variety of tasks [32, 91, 92].

A method that could mitigate these challenges is modularity. For example, when the vessel can install and exchange modules for each purpose, the modules needed for the designated mission can be installed so the vessel retains -or at least decreases the negative impact on- its mission capability without making significant changes to the platform. This form of modularity is called *mission modularity.* This is often applied by containers on deck [32] that can, for example, operate as surgery rooms, an extra armory, or sleeping accommodation. Another possibility is to create storage rooms that can be rebuilt very easily. For the financial and time-consuming advantages, think about the situation when for example NATO partners would need to buy new vessels at the same time, but each of them requires some modifications to make it suitable for the way each country operates [32]. When the design of parts of the vessel can be combined, time and money could be saved. This can be achieved by modularity as well. This type of modularity would probably look more like buying a car. The basics are the same for everyone, but certain options, like the type of radar or guns used, can be selected by country. This would be a form of *payload modularity* [86]. Another way to reduce design time is by applying *geometrical modularity*, which aims to design generic parts of the vessel, such as hotel facilities, to reduce design time [32, 95]. So, for the MoD modularity might be able to mitigate the challenges that are being addressed.

This literature study will show the lack of a proper cost-benefit analysis for modularity application to naval vessels. Many sources in the literature mention modularity as a way to mitigate the challenges mentioned above, but they do not mention the costs of it relative to a non-modular design. It is mentioned that modularity influences design freedom since modules usually require volume margins and have increased weight [82, 5], sometimes leading to a decrease in performance, and additional training for the crew is required to handle the different modules. There are no clear frameworks found in the literature to check whether modularity would be beneficial for a naval vessel at all. It is important that a framework is developed to couple the naval vessel's effectiveness to modular designing to assess the impact on the vessel's design. Therefore, it is important to shift the focus on modular naval vessels from the detailed design phase to the concept exploration phase and ask ourselves if we should apply modularity in the first place. A framework is required to connect the impact of modularity application on the naval vessel's effectiveness.

1.1 Thesis objective

Modularity can help mitigate several challenges in naval vessel design. However, the literature often assumes using modularity and research methods to apply modularity to naval vessels without investigating if the application of modularity is the best solution for the design problem. Therefore, this thesis will develop a framework for the concept design phase to investigate the impact of modularity with respect to a non-modular solution. The main research question of the thesis will become:

How can the decision-making for modular systems in naval vessel design be performed in a structural way and evaluated on its effectiveness compared to a non-modular solution?

The thesis will consist of two parts. First, a literature review will be performed. The goal of the literature review is formulated in section 1.2. Next, a framework will be developed. The framework aims to give a structured way to assess which systems have a high potential to be modular and evaluate the technical impact on the design of modular systems. When a system is a feasible module, the last step is to assess the impact on the vessel's effectiveness to check if the modular system will actually improve the vessel, or if the non-modular solution is preferred.

1.2 Literature review objective and structure

A systematic review of the literature will be performed. A 'published work analysis' and 'detailed literature review approach' are computed, which can be seen in Appendix A. The literature review has the following research objective:

Investigate the state-of-the-art on naval vessel effectiveness assessment and the application of modularity, and this way identify the research gaps

This is done by answering the following research questions:

RQ-1	*Which type of missions are performed by the RNLN naval vessels?*
RQ-2	*Which design drivers influence the vessel's performance and how can this be evaluated in terms of effectiveness?*
RQ-3	*What is the state-of-the-art in modularity and how would this be applicable to naval vessels?*
RQ-4	*What are the main challenges in naval vessel design for the RNLN and how could modularity mitigate these challenges?*

1.3 Structure

The literature review is structured as follows: chapter 2 will discuss the first two research questions focusing on the operational profile and effectiveness assessment of naval vessels. In chapter 3 research questions three and four about modularity on naval vessels and specific challenges the RNLN faces when designing vessels are discussed. At last, the research gap & methodology are discussed in chapter 4.

Next, the framework is introduced in chapter 5. The framework's MFD, AHP, and KBE will be discussed in more detail in respectively chapter 6, chapter 7, and chapter 8. The final evaluation of the effectiveness of the feasible modular systems, compared to their non-modular variant, is performed in chapter 9. The final conclusion and recommendations are formulated in chapter 10. The thesis will end with a personal reflection in chapter 11.

Part I

Literature review

2

Naval vessel effectiveness

This chapter aims to answer research questions one and two, focussing on the operational profile and naval vessel effectiveness. Expert opinion remains relevant in naval vessel design and effectiveness assessment, which will be discussed in this chapter. The definition of an expert as used in this report is defined as 'someone whose expertise in a particular area makes his assertions reliable—more likely to be true than false' [101]. Research question one is answered in section 2.1 and research question two in section 2.2.

2.1 RQ-1: Which type of missions are performed by the RNLN naval vessels?

This section aims to provide insight in the operations performed by Dutch naval vessels. The operational profile discussed will be a global explanation about the different type of operations naval vessels can perform and which vessel types conduct which type of missions. First, in subsection 2.1.1, the spectrum of conflict is discussed. This spectrum is important to understand the force naval vessels can encounter. Next, general knowledge about maritime operations, the so-called 'fundamentals of maritime operations' are discussed in subsection 2.1.2, after which in subsection 2.1.3 the mission capability of RNLN vessels is discussed. Last, the RQ is answered in subsection 2.1.4.

2.1.1 Spectrum of conflict

In vessel design, a distinction can be made between two types of vessels: transport vessels and service vessels [69, 100]. Transport vessels usually are designed to perform the task of transporting cargo from one point to another, whereas service vessels usually have a wide range of operations to perform. In this sense, most naval vessels are service vessels. Where transportation can be one of the tasks of a naval vessel, they usually have additional missions they must be able to perform as well. The tasks a vessel needs to perform can change during the lifetime of the vessel due to changing politics and geopolitical situations [69]. These missions can range from anti-submarine-, anti-air-, and anti-surface warfare (ASW, AAW, and ASuW respectively), including amphibious operations, humanitarian assistance and disaster relief (HADR), anti-piracy and counter-narcotics operations to simpler tasks like cargo and personnel transportation [69, 65, 47]. This shows the varying operational requirements and the complex operational profile of naval vessels compared to commercial vessels [84].

Another important difference between commercial and naval vessels is the hostile environment in which naval vessels must be able to operate. In these situations, naval vessels must be able to continue the most important parts of their operations after sustaining considerable damage. For this reason, designers usually go to great lengths to improve the vessel's survivability [84]. The amount of force a vessel may encounter is visualized in Figure 2.1. The level of force a vessel will encounter or have to enforce can fluctuate as well. This is visualized in the conceptual conflict cycle in Figure 2.2. This shows the importance of the ability to scale up and down in the use of force with the systems on board naval vessels.

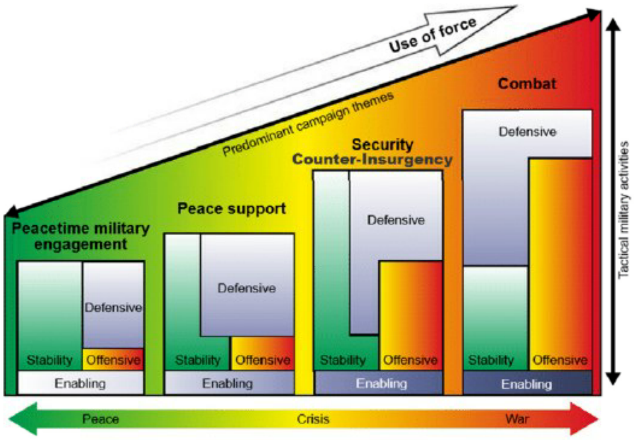


Figure 2.1: The spectrum of conflict indicates the level of force a unit may encounter [18]

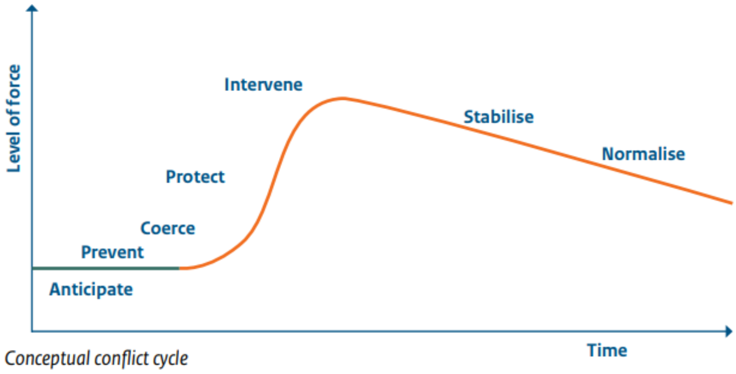


Figure 2.2: Conceptual conflict cycle [65]

2.1.2 Fundamentals of maritime operations

To gain general knowledge about maritime operations, the Dutch MoD has computed the ‘fundamentals of maritime operations’ [65]. The three types of operations, and their most common mission types, are visualized in Figure 2.3. The three types of operations; maritime assistance, maritime security operations, and maritime combat operations, will be discussed in more detail. Furthermore, it is important to understand the difference between missions, tasks, capabilities, and systems. These differences, and the correlation between one another, are visualized in Figure 2.4.

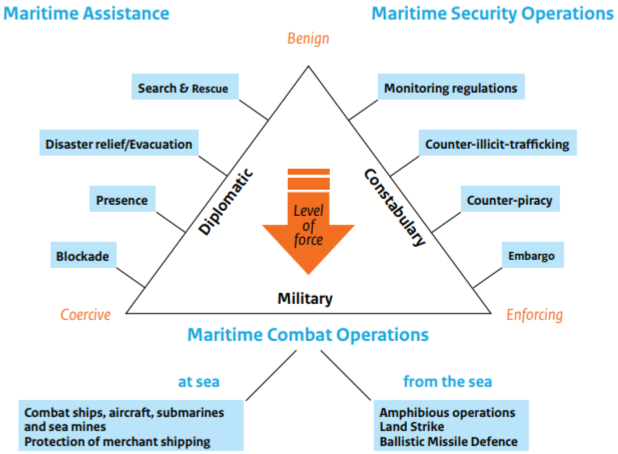


Figure 2.3: Fundamentals of maritime operations [65]

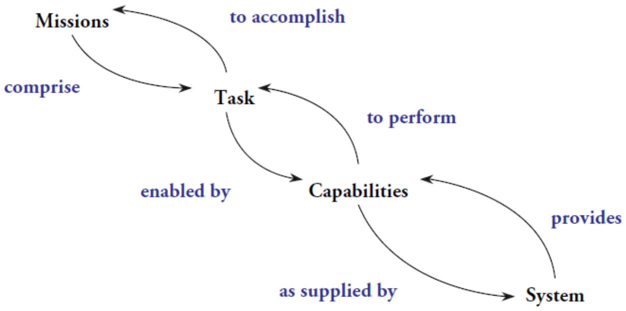


Figure 2.4: Ship Design to Mission Accomplishment Relationships [10]

2.1.2.a Maritime assistance

Maritime assistance operations are using military capacity to support either diplomatic efforts or civil authorities [65]. This can range from benign situations where very little to no force is required, to situations such as blockades where a high level of force is used. An example of maritime assistance to diplomacy is by 'showing the flag', where friendly relations with other nations are underscored, which is often performed by a routine visit by a naval vessel to a foreign port. Another form of diplomacy, called naval diplomacy, involves the use of maritime forces to endorse diplomatic statements [65]. This form of diplomacy aims to prevent harm to national interests of friendly nations. A form often used for this type of diplomacy is the permanent maritime presence, where the presence of naval forces in the area serves to send a warning signal to (potential) adversaries. An example at a small scale would be the presence of a Dutch ocean-going patrol vessel (OPV) in the Caribbean for counter-narcotics operations, and on a large scale NATO's standing maritime groups. Naval diplomacy can also have a more coercive character. In this case, military presence is used to challenge an excessive legal claim of a coastal state by deliberately entering the disputed area [65]. This type of operation is called a freedom of navigation operation.

Maritime capacity building aims to reinforce local maritime security services so the friendly nation will be able to cope with security problems independently by supporting, advising, and training maritime security services such as the navy, coastguard, and (harbor) police [65]. The need for maritime capacity building usually arises when local security services are unavailable or unable to perform their task properly. Maritime assistance can also focus on assistance to civil authorities (usually of the same nation as the particular navy). This generally takes place if civil capacities are non-existent or inadequate, for example in humanitarian assistance, disaster relief, or search and rescue or when specific military capabilities are required, for example for explosive ordinance disposal (EOD), diving activities, or hydrographic surveys.

2.1.2.b Maritime security operations

Maritime security operations (MSO) are designed to protect interests in the maritime domain against breaches of the international rule of law [65]. MSO targets civil actors who violate agreements regarding the use of the sea, such as international treaties. A typical activity in most forms of MSO is boarding, in which a team of military personnel boards another vessel to search it and, in case illegal activity is spotted, detain the vessel, cargo, crew, or passengers. MSO does not only counter direct security threats in the maritime domain, such as maritime terrorism and violent forms of crime such as piracy but also threats that are a threat on land as soon as they get there, such as the trafficking of goods and people. MSO can vary from the escortation of vessels at the low end of the spectrum to the ending of hijacks and hostage situations, involving special operation forces (SOF), at the high end of the spectrum.

2.1.2.c Maritime combat operations

Maritime combat operations are the essence of the military organization: the threat and use of lethal force to safeguard interests and realize specific objectives [65]. Maritime combat operations can be divided into two forms:

- **At sea,** friendly naval and air forces engage with and defend themselves and others against hostile naval and air forces.
- **From the sea,** maritime forces deliver striking power to create effects on and above land to support the battle at sea, in the air, or on land.

Maritime combat operations at sea aim to destroy or neutralize the enemy's warfighting assets underwater, on the surface, or over sea. This can be achieved by physical striking power, such as armed forces, and by information activities, such as deception and electronic warfare. Combat operations underwater, on the surface, and over sea can be divided into the following maritime warfares:

- antisubmarine warfare (ASW)
- antisurface warfare (ASuW)
- anti-air warfare (AAW)
- naval mine warfare (NMW)

ASW, ASuW, and AAW are often performed by frigates, cruisers, and destroyers (although the RNLN itself only has frigates) [84] while submarines can be used for ASuW and the gathering of intelligence [65]. Frigates are more often specialized in one of these categories since they are restricted by their size. For the RNLN this results in M-frigates, LCFs, and the (yet-to-be-built, but already ordered) ASW-frigates (ASWF). The need for specialization of frigates can be seen in the replacement of the Dutch M-frigates, which are replaced by ASWFs. Instead of working with one type of frigate which can do all (ASW, ASuW, and AAW) the choice has been made to work with two types of frigates, the LCF (ASuW and AAW) and ASWF (ASW and ASuW).

Naval mine warfare can be split into defensive and offensive mine warfare, of which the RNLN only participates in defensive NMW. Within the RNLN, the frigates are designed for these types of combat operations [84]. For coastal waters, smaller vessels (so-called 'minehunters') are in service specialized in finding mines and conducting EOD operations, without the need to defend themselves like frigates do. However, in the replacement of the minehunters, it can be seen the RNLN is prepared to operate at the higher end of the spectrum. Where the current minehunters only have 3 M2-heavy machine guns [64], the new minehunters will be equipped with a 40mm canon, 2 remotely operated heavy machine guns, and 4 large-caliber machine guns [52].

Maritime combat operations launched from the sea are generally offensive in nature [65]. This can range from amphibious operations, in which troops are either introduced to -or extracted from- hostile territory ashore, to maritime strike operations. Maritime strike operations can be performed with the use of aircraft from carriers, (cruise) missiles launched from vessels or submarines, or with naval guns. These capabilities are used in offensive situations and as such are not a focus of the RNLN [84]. A change can be seen in the RNLN's intention to start working with the long-range tomahawk cruise missile, which can destroy hostile targets in a range up to 1600 kilometers from the vessel [40].

Maritime special operations are usually small-scale clandestine operations [65]. Large surface vessels can be used to support these operations by transporting the special forces to a certain location from where they can start the operation using helicopters, FRISCS, or RHIBS. Submarines can be used directly for special operations, either as support (in the case of transporting special forces to the mission area) or as part of the mission itself (mostly used for gathering intelligence).

2.1.2.d Maritime sustainability

Another type of operation worth mentioning is maritime sustainability, which ensures the available military power during the other operations is sustained or even increased if necessary [65]. When operating far from friendly ports, this needs to be done at sea. This can be done on different scales, from supporting a single vessel to a task group (and sometimes ground forces) with logistical and organizational capabilities. The most important missions are:

- Replenishment at sea
- Strategic transport
- Sea basing
- Command & control

These missions either support forces in the execution of their mission or in the case of strategic transport and sometimes sea basing, the logistic capabilities required by (ground) forces. When looking at the RNLN, replenishment at sea (RAS) can be performed by the JSS and the yet-to-be-delivered CSS. The remaining missions can be performed by the JSS and LPDs. Command & control can be fulfilled by the LCF as well since these vessels have command facilities on board.

2.1.3 Vessel capability

To give a general overview of the types of vessels that are used for specific mission subjects, eight different vessel types are defined, based on the RNLN. These types are: Submarine, Landing Platform Dock (LPD), Luchtverdedigings- en Commandofregat (LCF), Anti-Submarine Warfare Fregat (ASWF), Multi-purpose frigate (M-Frigate), Ocean-going Patrol vessel (OPV), Joint logistic Support Ship (JSS), and Combat Support Ship (CSS). The distribution of capabilities across these vessels is shown in Table 2.1. It should be noted that this is a very basic approximation of the required (combat) capabilities of these vessels. Besides these operations, the JSS and LPDs can perform disaster relief, while the OPVs support counter-narcotic operations. This indicates the table can be expanded by describing the missions in more detail, as shown in Figure 2.3. Since this report will not focus on certain vessels conducting specific operations, it is chosen to show the basic combat operations the vessels are designed for. Besides, it is important to notice these capabilities are what these vessels were originally designed for, but they are not limited to it. The LPDs for example, are designed to conduct landing operations. However, these vessels can be used for the transportation of goods and personnel as well (supply capability). It is important to understand that these capability requirements result in demands for technical systems onboard these vessels to achieve these capabilities.

Table 2.1: Vessel type capability matrix [85]

	Landing	AAW	ASuW	ASW	Supply
Submarine			X		
LPD	X				
LCF		X	X		
ASWF			X	X	
M-Frigate		X	X	X	
OPV			X		
JSS					X
CSS					X

2.1.4 Conclusion RQ-1

This section has highlighted the spectrum of conflict, the fundamentals of maritime operations, and the RNLN vessel's capabilities. From the spectrum of conflict, it became visible that the environment in which a naval vessel must be able to operate can differ from little to no force on the low end, to lethal force on the high end of the spectrum. The naval vessels must be able to survive on the high end of the spectrum, while they would most likely operate on the lower end of the spectrum most of the time. The fundamentals of maritime operations show the diverse types of operations a naval vessel can counter, such as maritime assistance (low end of the spectrum), maritime security operations (low to middle end of the spectrum), and maritime combat operations (high end of the spectrum). Maritime assistance operations use military capacity to support either diplomatic efforts or civil authorities. Maritime security operations are designed to protect interests in the maritime domain against breaches of the international rule of law, and maritime combat operations aim, by the threat and use of lethal force, to safeguard interests and realize specific objectives. Last, the RNLN vessel capability is analyzed. It can be concluded a naval vessel's operational profile has high uncertainty since the operations that need to be performed in the future are unknown. While naval vessels would often operate in the low to medium range of the spectrum, they must be prepared for combat operations in the high end of the spectrum. This uncertainty makes it hard to determine a detailed representative operational profile of a naval vessel during the design process. Therefore, this report will focus on the main capabilities the Dutch naval vessels are designed for at the high end of the spectrum.

2.2 RQ-2: Which design drivers influence the vessel's performance and how can this be evaluated in terms of effectiveness?

Now that the vessel's operational profiles are discussed, it is time to focus on the vessel itself. First, in subsection 2.2.1, the need for adaptability for naval vessels is discussed. Next, automation is highlighted in subsection 2.2.2. The vessel's characteristics and design drivers are discussed in more detail in subsection 2.2.3. The importance of these requirements during different missions is discussed in subsection 2.2.4. Next, possible ways to assess a (naval) vessel's effectiveness are discussed in subsection 2.2.5. At last, subsection 2.2.6 shows the conclusion.

2.2.1 Adaptability

In recent decades, the building of naval vessels has slowed down across many countries [82]. According to Smith [82], navies previously had several designs underway that would follow closely behind each other, while nowadays the designing of new naval vessels is more disconnected. The lifetime of naval vessels has expanded, which means the mid-life update is becoming more important since new technology is required to make sure the vessel remains performing as it should. However, these updates are expensive and the existing platform architecture has its limitations, such as the available volume and maximum additional weight [82]. This shows the importance of designing adaptability into naval vessels. In this report, adaptability is defined as 'The ability to change boundaries by changing the platform' and flexibility as 'The ability to adapt to changing missions and technologies without changes to the platform', both adapted from Schank et al. [77]. The need for adaptability shows itself in the trend across several navies towards more flexible, multi-role platforms that can perform a wider spectrum of missions. A recent example is the OPV Zr.Ms. Holland which would originally head towards the Caribbean for counter-narcotic operations but was last-minute rerouted to be standby for a possible non-combatant evacuation operation in Israel [60]. Due to this need for flexibility across the naval fleet, adaptability has been an objective of naval ship acquisition since the end of the Cold War [5].

Two prime reasons why naval vessels should have adaptability as their primary capability driver are stated by Andrews [3]:

1. The highly unpredictable geopolitical environment in which future naval operations will take place. This became visible especially after the Cold War since the vessels designed during that period were designed to operate in a specific area and to conduct specific missions. Afterward, a wider spectrum of missions were required to be performed. This redirection was spelled out in the Strategic Defence Review of the United Kingdom (U.K.) Royal Navy in 1998, which would emphasize the need to operate worldwide and across a broad range of defense missions. These range from full power block confrontation through UN and NATO peacekeeping to Defence Diplomacy and constabulary tasks, such as countering piracy and anti-narcotics operations. As a result, requirements for new naval vessels has an increased focus on flexibility in operations and ability of the platform to change capabilities during its lifetime.

2. Most navies have to deal with limited budgets. In major defense procurement, there has been a reluctance to pay any more than the absolute minimum for new military products. Until very recently this meant minimizing the initial procurement cost and this often resulted in increased running costs, which includes the lack of the ability to upgrade the product during its operational life. This can be seen at an extreme for naval vessels, which as the largest of complex individual military units, have highly politically visible procurement costs. Since less highly tuned naval vessels were necessary, a reduction of the costs of naval vessels was required. This has occurred despite the recognition that the life cycle costs, rather than just initial procurement costs, are most likely higher. As a result, naval vessel designers had to refocus on the challenging issue of 'Design for Adaptability'.

Most of the weapon systems currently used already have some degree of modularity or adaptability through being designed to interface with vessel elements, such as silos used for launching missiles [5]. The need for adaptability will most likely increase when the use of unmanned air vehicles (UAVs) increases since they are likely to be updated more often than manned aircraft [5]. As a result, the equipment needed on board vessels would likely have to be updated regularly too. It is important to keep in mind that updating certain equipment might not only require additional volume and weight but can also result in more personnel on board, like additional maintenance crew for newly added systems.

To design an adaptable naval vessel, certain margins should be included in the design process. The concept of margins in naval vessel design is quite sophisticated as there are three distinct types of margins [5]. These margins will be described below, from a COMMIT point of view [85]. The first margin, primarily concerned with adaptability, is the future growth margin. This margin is determined by the naval staff rather than the designers and it aims to address the added weight of future upgrades during the vessel's lifetime without causing issues in for example stability and propulsion [26, 87]. The next margin is the concept design margin, which is required due to the lack of knowledge early in the design phase [87]. This knowledge can range from the number of pumps to install to the required crew size, and the accompanying accommodations and storage rooms. The concept design margin aims to prevent every change in these parameters will require redesigning the entire vessel [87]. The last margin is the contractual design and build margin. These margins allow uncertainties, for a certain percentage, during the design and building process of the vessel [26]. These margins are necessary since the manufacturing of the vessel itself and its equipment can differ by a small percentage. By implementing this uncertainty in the design process, the vessel does not need to be re-engineered later on in the process. These include margins in the vessel's weight, volume, and location of systems.

Without incorporating the margins described above in the design, the vessel will only meet its stability, structural strength, powering standards, and requirements right after being built, or even only on paper before the building process has even started [5]. Therefore, to design an adaptable naval vessel, these margins should be implemented in the design phase. These margins are determined by the naval architects in charge of designing the vessel.

2.2.2 Automation

Another important aspect in the design process is the increased automation on board of vessels. Especially for manpower intensive tasks that are dirty, dull, deep, and dangerous, vessel design should focus on automation [82]. These include functions such as fire suppression and flood control. Besides, automation is already applied in many systems used on board naval vessels, such as the use of unmanned vehicles (UXVs). An example would be the use of unmanned underwater vehicles (UUVs) to provide mine countermeasure capabilities so navy divers would not need to perform the deep and dangerous work. As a downside, these forms of automation lead to constraints in the vessel's design in volume, weight, power, launch & recovery systems, and communications & control systems [82]. Smith [82] also mentions the use of UXVs can lead to an increase of required manpower, since UXVs will lead to a larger number of maintenance, operators, and support staff on board the vessel.

However, it remains important to critically review the literature. Smith [82] mentions the through-life costs (TLC) will reduce when applying automation, while this does not necessarily needs to be true. For example, Smith [82] reasons that the automation of fire suppression will lead to a reduction of required manpower. While on board naval vessels, this is a side activity for appointed personnel. For this reason, automation of fire suppression systems may lead to a faster suppression of the fire, it will not lead to a reduction in manpower. Besides, it is questionable if a naval vessel is willing to rely on automated systems without a (manned) back-up alternative. Otherwise, in the case of considerable damage, it is possible the automated system is damaged and the vessel will burn down.

Another aspect to keep in mind in the case automation would lead to a higher efficiency, is the Jevons' Paradox. William Stanley Jevons described that an increase in technological efficiency -in his case specifically the more efficient use of coal in mechanical engines- actually increased the overall coal consumption [1]. He uses the argument that when efficiency is increased, the employment of -in his case- coal becomes more profitable, and thus the present demand for coal is increased. This indicates that increasing efficiency does not lead to a lower fuel consumption, since people will not perform the same tasks with less fuel but rather increase the required performance for the same fuel. It is important to understand Jevons used an economic point of view for his paradox. However, this theory can apply to naval vessels as well. When sailing becomes more efficient and the deployment rate stays the same, the navy will decrease its fuel consumption. However, it is also possible to deploy more vessels since the fuel consumption per mile sailed is decreased. Therefore, it is important to notice an increased efficiency does not necessarily lead to a lower overall fuel consumption (which saves volume and weight of the naval vessel), but can also lead to increased performance requirements.

2.2.3 Vessel Characteristics

A naval vessel can use different systems to accomplish its missions. Usually, many alternative lists of systems are computed during the concept exploration phase to investigate the most suitable outcome [84]. These systems will influence the effectiveness in multiple ways. Since a naval vessel needs to perform well in multiple categories, a vessel performing optimal in every single category cannot be designed. This leads to multiple non-dominated solutions in which the designers need to choose the vessel they think is most suitable for the mission requirements. The definition of a non-dominated solution is mentioned by Brown and Salcedo [11]: "A non-dominated solution, for a given problem and constraints, is a feasible solution for which no other feasible solution exists that is better in one objective attribute and at least as good in all others". These non-dominated solutions result in a Pareto front, which consists of the non-dominated solutions in which one of the objectives cannot be improved without worsening another objective [107]. The Pareto front is often presented in a multidimensional plot showing the correlation between the design's effectiveness, cost, and risk [10]. A typical representation in a 2D plot can be seen in Figure 2.5. In this figure, the non-dominated solutions are circled. When these solutions are connected, a Pareto front can be created. An example is shown in Figure 2.6. The infeasible region is bounded by the definition of a non-dominated solution and the boundary of feasible designs, for example a vessel with an effectiveness over 1 or a costless vessel. From a design point of view, the goal is to achieve maximum effectiveness for minimal costs. The Pareto front shows the multiple possible 'best' designs, depending on whether the focus is on costs or overall measure of effectiveness (OMOE).

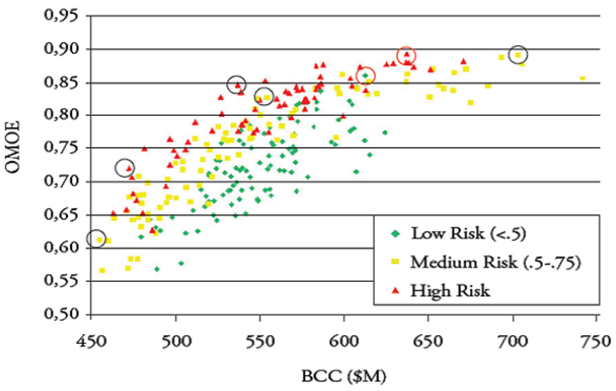


Figure 2.5: Non-Dominated Frontier [10]

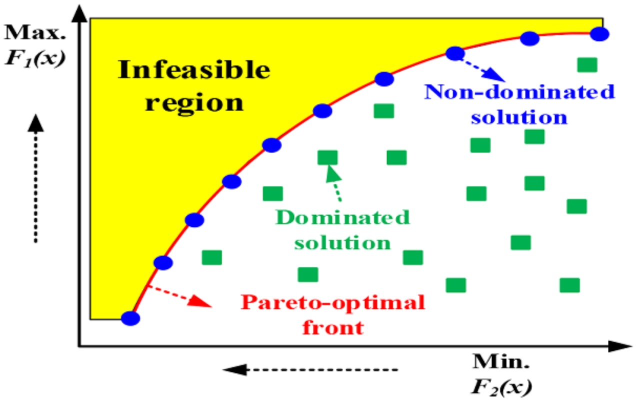


Figure 2.6: Pareto front [45]

With these feasible designs, decision-makers are offered an insight into the trade-offs that need to be made, and specific concept designs can be chosen for a more detailed analysis. Another challenge, specifically for naval vessels, is the unknown required mission profile in the future. An assessment of the current mission profile only is not sufficient, as it is unknown how long this remains an accurate representation. The possible changing mission profile should be considered as well when making design decisions. It is important to gain as much knowledge as possible during early-stage design since approximately 80% of the ultimate acquisition costs are already locked in during concept design [11]. In addition, the costs of design changes grow by a factor of ten for each step in the design and construction process [36], which is shown in Figure 2.7. More details about the effectiveness assessment of naval vessels are given in subsection 2.2.5.

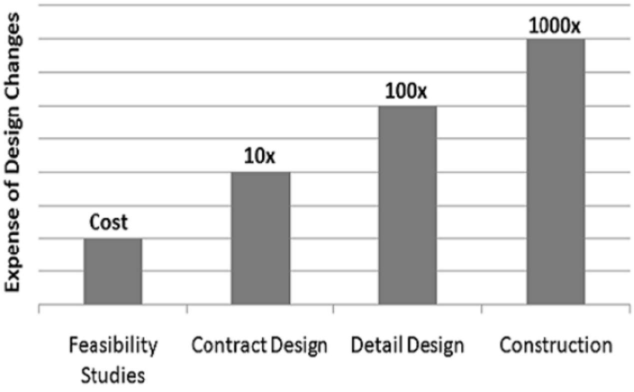


Figure 2.7: Estimates of change costs during different stages of design for naval vessels [44]

To gain more insights into the trade-offs in a naval vessel's design, different categories can be defined. Each design change will influence at least one of these categories. The list of categories computed by Streng [84] is shown below. This list is checked for its relevance by analyzing the required vessel capabilities mentioned by the maritime doctrine by the Dutch Ministry of Defence [65]. After this analysis, the list below is deemed relevant.

- Offensive capabilities
- Survivability
  - Susceptibility
  - Vulnerability
  - Recoverability
- Mobility
  - Top speed
  - Acceleration and deceleration
  - Manoeuvrability
- Range
- Endurance

2.2.3.a Offensive capabilities

The required offensive capabilities are continuously changing. At the beginning of the 20th century, naval vessels had batteries of large guns all over the deck. On modern warships, this has drastically changed, since extensive sensor technology is used which can host several (sometimes guided) weapon systems like anti-ship, anti-air, anti-ground missiles, or torpedoes [84]. This shows the shifting from 'as much firepower as possible' to 'as most effective firepower as possible'. It is important to keep these (future) developments in mind when designing a naval vessel since they might need upgrades to keep the vessel as effective as possible. This can be seen in the expectation for ever stronger radars, adoption of direct energy weapons, and increased automation on board naval vessels [78]. The sensor, weapon, and communication (SEWACO) systems can be integrated into command and control (C2) systems. This way information can be shared with other vessels, helicopters, and maritime patrol aircraft [84] to improve overall operations. A range of smaller (self-defense) weapon systems are also installed on naval vessels. An example would be the .50 machine guns, which can be used in case the vessel is attacked by small boats.

2.2.3.b Survivability

Survivability plays a significant role in vessels designed to operate in the high end of the spectrum of conflict [84]. It is important for vessels operating at the high end of the spectrum to maintain the ability to accomplish their missions while avoiding or, in the case it is hit, withstanding weapon effects [29]. This is necessary to keep the vessel in operation and to save the crew. Survivability can be divided into several distinct areas, influenced by both the operation of the vessel and its design. These areas can be seen in Figure 2.8 where, from the top to the bottom, the focus is shifting from avoiding being hit by a weapon to recovering from the impact after being hit. These areas can roughly be divided into three main categories: susceptibility, vulnerability, and recoverability [29]. Depending on the required capabilities of the vessel, one category can be more important than others. A submarine operates with the focus on remaining undetected, while a frigate requires more heavily defensive capabilities to survive [29].

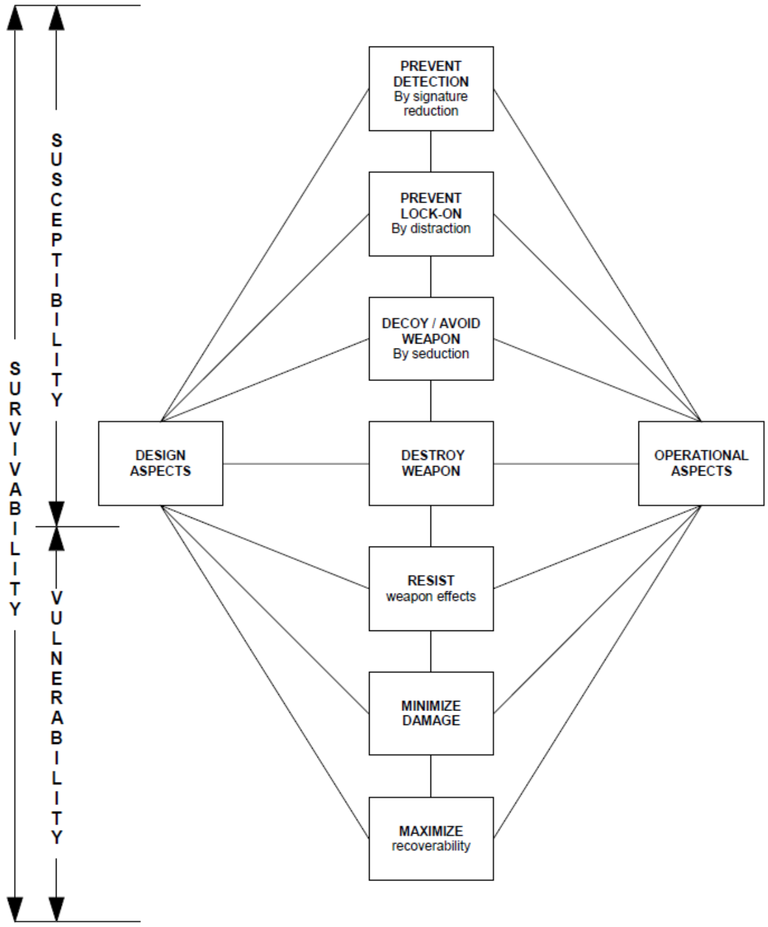


Figure 2.8: Subjects within survivability [73]

The susceptibility of a naval vessel involves the ease with which the vessel can prevent being detected and hit [73]. This also includes the use of countermeasures, such as jamming equipment or signature changes, in the case the vessel is detected. When focusing on the platform itself, thus leaving SEWACO out, the most important subject is to prevent detection. The vessel's vulnerability concerns the sensitivity to impact and the resulting damage. When damage is done, this can be categorized as primary and secondary damage [29, 73]. If a system is sensitive to primary damage, the impact itself can easily take the vessel out of operation [84]. Secondary damage is the possible propagation of damage after a system is hit. Think about high flammable fuels and gasses which might cause explosions and exacerbate any damage already done. Flooding is also considered a form of secondary damage. Recoverability refers to the degree and time in which any lost capabilities can be recovered [73]. This can either be achieved by maintenance or in the case of redundancy, by switching to the backup system [84]. Recoverability analysis is still a challenging field since damage propagation and human response are hard to model correctly.

2.2.3.c Mobility

High mobility can help the vessel avoid being hit by projectiles or torpedoes by either outmaneuvering the projectile or by moving beyond the weapon range [84]. Other aspects of mobility are the ability to remain close to the fleet or the ability to perform dynamic positioning (DP) operations. A high available brake power will result in an easier acceleration or deceleration of the vessel, giving it more options to outmaneuver incoming projectiles [84]. From this point of view, mobility could be seen as a factor of survivability. However, with modern weapon systems like guided torpedoes, the possibility of outmaneuvering attacks is decreasing, since these weapons will adjust their course to hit the vessel. Other factors why mobility is important can be seen in missions where speed and mobility are essential for the success of the mission. This can be seen with anti-piracy and counter-narcotics missions, where targets need to be intercepted after they are spotted (usually by UAVs or patrol aircraft). A vessel's maneuverability (and possibly DP capability) is important for vessels that conduct amphibian operations or deliver other support from a stationary location [84].

2.2.3.d Range and endurance

Range and endurance (sometimes referred to as autonomy) have a different influence on the vessel's effectiveness. While the other factors mostly affect how well the vessel can perform its mission, range and endurance address how long a vessel can do so. Range and endurance have a direct influence on the vessel's area of operations (AoO). The better they are, the longer the vessel can stay in the AoO, and a vessel simply can't perform a mission if it's not in the AoO. The vessel's range is mainly determined by two factors, the cruising speed (and the resulting fuel consumption) and the fuel capacity, and is often expressed in nautical miles (nm) [84]. The endurance is a way to measure the time a vessel can spend in the AoO independently. The vessel's endurance is influenced by all the different consumables required to continue operations and the reliability of the systems onboard [84]. For this reason, range and endurance are often hard requirements that have to be fulfilled completely [99].

2.2.3.e Constraining factors

Besides the requirements mentioned above, designing a naval vessel also comes with constraining factors. The most important constraining factors considered here are displacement & volume and organizational constraints. Depending on the type of vessel the displacement, volume, and/or deck area are often limiting factors [84]. It is already challenging to design a naval vessel with these constraints since SEWACO systems, auxiliary systems, medical treatment requirements, accommodation, freshwater makers, storage space for food, spares, ammunition, and other consumables all require volume and increased displacement. But without them, the vessel is (at least) less capable since these subjects are essential for the naval vessel's effectiveness and endurance. To make a naval vessel's design even more complex, the location of a system (or component) is of strong influence on the ease of operation and the vessel's effectiveness [49, 100]. Furthermore, requirements for speed and maneuverability can limit the hull to (very) slender designs, limiting the available volume and displacement even more.

2.2.3.f Maintainability

Maintainability does not directly influence the naval vessel's effectiveness during a mission like the subjects mentioned above, it does influence the vessel's effectiveness during its lifetime. A vessel is 0% effective when it is moored for maintenance, so the shorter the maintenance period, the sooner the vessel can operate again. This affects both small and large maintenance. In the case of the RNLN, vessels get a mid-life update (MLU) to modernize the vessel to make sure the vessel can stay in operation for the rest of its lifetime.

This is a time-consuming update that usually takes the vessel out of service for more than a year. To increase the vessel's overall maintainability during the design phase, the placement and construction of equipment and machinery should be considered. When these are placed in a way they can be removed with minimal destructive alterations of the vessel's hull or superstructure, maintenance and updates can be performed in an easier, less costly, and less time-consuming manner. This will lead to a higher readiness of the fleet.

2.2.3.g Non-technical factors

Besides the technical factors mentioned above, some non-technical factors play an important role as well. An important role is taken by the military's doctrine and the country's (local) politics. In the military doctrine, the way in which personnel and materials are used is described, ranging from small-scale tactics to large-scale strategy. Even though technical feasibilities can influence the military doctrine, technical superiority is never superior to a good doctrine [84]. National politics play an important role in the design of naval vessels as well since they assign the budgets to navies. It is important to understand the existence of these factors, but they will play a minor role in the rest of the report since the focus will be on the technical impact on the design.

2.2.4 Mission requirements

This section will examine the required capabilities for certain missions. When looking at more detail to the design of a vessel, more properties will influence the effectiveness of the vessel. In the level of the design this research is focusing on, such a level of detail is not yet reached so the properties assessed here are assumed to be sufficient. The list of technical capabilities and design drivers of which the importance will be evaluated is the same in subsection 2.2.3. In the following subsubsections, the mission capabilities are discussed, resulting in a mission-capability matrix.

2.2.4.a Maritime assistance operations

For missions focusing on the support of civil authorities, modest capability requirements are in place [85]. Although basic navigation and communication systems are always necessary, there is no need for advanced SEWACO systems (if they were needed it wouldn't be assistance anymore but security or combat operations). As for all naval vessels, vulnerability plays an important role, since these vessels need to withstand (small) hostile confrontations. When looking at disaster relief & evacuation, transport capability is the most important, since people and/or relief supplies need to be transported through a non-hostile environment. This requires high reserve displacement and volume.

2.2.4.b Maritime security operations

For security operations, survivability is of increased importance [84]. The main categories to increase survivability are vulnerability and recoverability. These operations take place in a hostile environment. However, it should be noted the hostiles (like pirates or illegal traffickers) often only have small arms. The tracking and interception of these hostiles put higher requirements on the sensors, maneuverability, and top speed of the vessel [85]. Most of the time, these vessels sail to a relatively close distance to the to-be-intercepted vessel, after which FRISCs or helicopters deployed from the naval vessel perform the actual interception.

2.2.4.c Maritime combat operations

Since maritime combat operations take place at the high end of the spectrum of conflict in very hostile environments, the capability requirements are the highest [85]. Technological advanced SEWACO systems are necessary to be able to detect and neutralize enemy threats. Therefore, the survivability of the vessel is of great importance. The vessel needs to be able to prevent being hit in the first place, and if they get hit it is important to stay in operation and minimize damage. Mobility plays a moderate role since it might be useful to evade an enemy submarine or large surface vessel, but aircraft can't be evaded and torpedoes can maneuver through the water by modern technology, so the chance of evading a (well-functioning) torpedo is very small [84].

2.2.4.d Maritime sustainability operations

Operations to achieve maritime sustainability often involve the transportation of goods [65]. This would require reserve payload volume and displacement. The goods to be transported determine where the focus should be since some goods require more reserve displacement and others require more reserve volume. A distinction should be made for vessels that operate in hostile environments (like during command & control operations). Besides the capability to transport goods, increased SEWACO systems and survivability are required.

2.2.4.e Mission-capability matrix

After analyzing the capabilities required by different types of operations, a mission-capability matrix can be computed. In this matrix, an assessment of the importance of the categories mentioned above will be made by ranking the category between 1 and 9 (1,3,5,7, or 9). Similar to other subjective ranking systems it appears that this scale is standard for subjective prioritization [84]. Using this index, instead of an index showing the percentage of importance per mission (so the total of a mission is always 100%), the relation between different missions and the required capabilities can be seen. As mentioned before, these categories will not be discussed in great detail. Therefore, offensive capabilities will be mentioned as SEWACO. However, survivability and mobility will be split into the smaller categories mentioned above since there can be large differences in importance during certain missions. For example, when looking at mobility, during counter-terrorism it is extremely important to reach the AoO as fast as possible (= top speed), while maneuverability is less important. Other categories worth mentioning are range and endurance. These categories can be seen as a separate, hard requirement for the vessel itself, independent of the vessel's mission profile. For example, the endurance of practically all RNLN large surface vessels is 30 days [84]. An example of a mission-capability matrix for the RNLN, made by Streng [84], can be seen in Table 2.2.

Table 2.2: Mission-capability matrix [84]

	Mar. Assistance		Mar. Security			Mar. Combat				Mar. Sustainability			
	Assist. to civil authorities	Disaster relief & Evacuation	Monitoring Regulations	Maritime interdiction operation	Counter-terrorism	ASW	ASuW	AAW	Amphibious operations	Replenishment at sea	Strategic transport	Sea basing	Command & control
SEWACO	1	1	1	3	3	9	9	9	3	1	1	3	7
Susceptibility	1	1	1	1	1	9	5	3	1	3	3	3	3
Vulnerability	3	1	3	3	3	3	7	9	7	3	3	3	3
Recoverability	1	1	1	3	3	7	7	7	5	3	3	3	3
Range	3	5	3	3	3	5	5	5	5	5	5	5	5
Endurance	3	5	3	3	3	5	5	5	5	5	5	5	5
Top speed	3	3	3	5	5	7	9	5	5	5	3	3	5
Acceleration	3	1	3	3	3	7	3	3	3	1	1	1	1
Manoeverability	3	3	3	1	1	7	3	3	7	3	1	3	3
Payload volume	1	7	1	3	3	1	1	1	7	5	7	7	5
Payload weight	1	7	1	3	3	1	1	1	7	9	5	7	3
Total	23	35	23	31	31	61	55	51	55	43	37	43	43

2.2.5 Vessel effectiveness assessment

Measuring the effectiveness of a naval vessel is not a straightforward procedure because of the spectrum of different missions a single vessel must be able to perform at different times [84]. The different types of vessels also perform different types of missions, so it is important to set up a procedure to take into account the different mission requirements for each vessel. It can be difficult to determine a naval vessel's requirements during the design stage [10, 11, 100]. As a result, the effectiveness assessment of a vessel is difficult as well [84]. Another important difference between commercial and naval vessels is the motivation to make certain design choices. When, for example, looking at reasons to reduce fuel consumption a different motivation can be seen between commercial and naval vessels. For commercial vessels, the companies are either looking from a cost perspective or compliance with international emission regulations. For naval vessels, the motivation is the need to continue operations in times when it's hard to maintain supply lines. This indicates a different method is needed to assess naval vessel effectiveness.

Naval vessels are often tailored to the highly specific requirements of the operators. In the case of the RNLN, in-house development is accentuated more than it is in other countries to obtain a similar product against lower costs [39]. This in-house development results in even smaller series, ranging from 1 vessel (the JSS), 4 (the LCF), or at most 8 (M-frigate) for the larger vessels and up to 10 smaller vessels. The high production value means it is not feasible to develop prototypes for additional insights into the technical performance (early on) in the design process [4]. This shows the importance of the need to systematically analyze the impact design decisions have on a vessel in order to assess the optimal solution. One way to assess a naval vessel's effectiveness is by developing key performance indicators (KPIs).

2.2.5.a Commercial vessel effectiveness assessment

For transport vessels, a KPI can be found relatively easily to indicate the level of a vessel's effectiveness. In this case, this also is an indication of the vessel's efficiency. The difference between the two, as explained by Streng [84], is the following: effectiveness is "the degree to which something is successful in producing a desired result of success" while efficiency is "achieving maximum productivity with minimum wasted effort or expense". For transport vessels, the effectiveness is a combination of the amount of load it can carry, the power it requires, and how long it takes the vessel to get to its destination. However, it is important to keep the operating expenses (OPEX) in mind. A faster vessel might seem more effective for being twice as fast, but if that means the vessel's OPEX is 10 times more a company will not use the vessel. Other constraints, for example for a vessel's beam, could be the maximum beam allowed to use certain passages. For this reason, the KPI for commercial vessels is often based on efficiency [84]. In general, the most efficient commercial vessel is the one that makes the most profit.

2.2.5.b Naval vessel effectiveness assessment

Describing a naval vessel's effectiveness is more complex, for the same challenges a naval vessel is facing during its design. These vessels must be able to handle and complete different tasks than just 'making money' like commercial vessels. When looking at a naval vessel's effectiveness, Brown and Salcedo [11] describe the following seven inputs to be of importance:

- Defense policy and goals
- Threat
- Existing force structure
- Mission needs
- Mission scenarios
- Modeling and simulation results
- Expert opinion

When developing an approach to assess a naval vessel's effectiveness, the following terminology is important [68]:

- **Overall Measure of Effectiveness (OMOE)** — Index (scale 0-1.0) describing the vessel's effectiveness for all assigned (and expected future) mission types.
- **Measures of Effectiveness (MOE)** — Index for specific missions or performance categories (such as offensive capabilities, mobility, survivability).
- **Measures of Performance (MOP)** — Specific vessel or system performance metric independent of the mission (such as speed, range, seakeeping, vulnerability, reliability).
- **Value of Performance (VOP)** — Index (scale 0-1.0) specifying the value of a specific MOP to a specific mission category for the specified mission type.

To give an example of how these terms relate to each other, a structured breakdown tree considering OMOEs, MOEs, and MOPs is shown in Figure 2.9. The importance of using well-structured breakdown trees in the design phase has been highlighted by Brown [10], Brown and Salcedo [11].

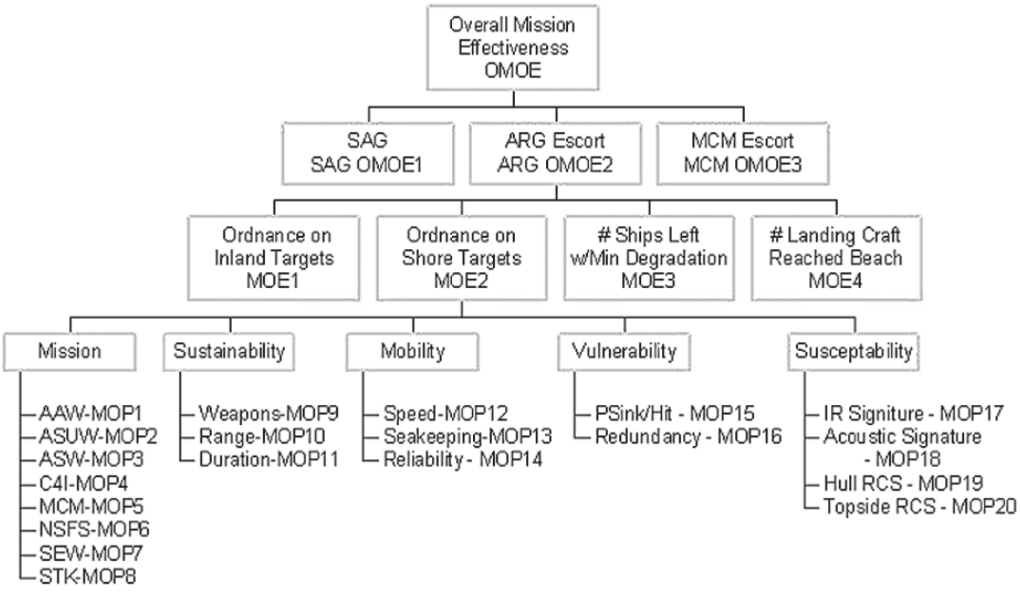


Figure 2.9: MOP breakdown tree [11]

It is important to include the multi-mission profile of a naval vessel [68, 84]. An example why this is important would be counter-narcotics operations, where the drug traffickers could get away if the OPV cannot reach them in time. This could mean a (small) reduction of energy consumption would not just lead to a small reduction in effectiveness but to a complete failure of the mission. Therefore, it is important to include the vessel's Concept of Operations (CONOPS) in the effectiveness assessment [68]. One way of including the vessel's mission profile is by implementing it in a capability breakdown as a OMOE (as shown in Figure 2.9). The next step is to assign a weight to the components. Since a naval vessel should perform well during combat operations, but usually don't encounter these operations much, applying weights based on the importance of the naval vessel's mission is preferred [84]. Even though combat operations are performed a small percentage of the time, the weight should be high. This shows the importance of balancing the percentage of time a certain mission is (expected to be) performed and the necessity of the ability to perform a mission when determining the weight. Another important factor is the type of vessel itself. Significant differences can be expected when designing a submarine instead of a surface vessel. Therefore, it is important to compute a general method to assess a naval vessel's effectiveness which can then be modified for the specific vessel under investigation.

The weight of the mission profile applied to the RNLN fleet, computed by Streng [84], can be seen in Table 2.3. Diplomatic missions are left out since an estimation of the time these missions are performed cannot be assigned to a single vessel. Showing the flag can be done by any naval vessel, and other diplomatic missions depend on the kind of assistance a friendly nation requests. However, these missions will fall under another category of maritime operations, which is represented in the table. Therefore, diplomatic missions can be left out. Maritime strike operations and naval mine warfare are left out since the RNLN large surface vessels have no significant role in these types of operations. It is also important to notice the mission profile in the table is not necessarily a representation of the mission a vessel actually does during its lifetime. In addition, the mission profile may look different in war times than in times of peace.

Table 2.3: Mission profile RNLN [84]

	Mar. Assistance		Mar. Security			Mar. Combat				Mar. Sustainability			
	Assist. to civil authorities	Disaster relief & Evacuation	Monitoring Regulations	Maritime interdiction operation	Counter-terrorism	ASW	ASuW	AAW	Amphibious operations	Replenishment at sea	Strategic transport	Sea basing	Command & control
LCF	0	0	0	0	0	0.15	0.15	0.5	0	0	0	0	0.2
M-Frigate	0	0	0	0	0	0.6	0.2	0.2	0	0	0	0	0
OPV	0.2	0.1	0.1	0.2	0.2	0	0.2	0	0	0	0	0	0
LPD	0	0.1	0	0.05	0.05	0	0	0	0.3	0	0.15	0.15	0.2
JSS	0	0.15	0	0.05	0.05	0	0	0	0.15	0.4	0	0.1	0.1
CSS	0	0	0	0	0	0	0	0	0	0.7	0.3	0	0

One method to gain a numerical value for a MOP is to use a wargaming model. The model predicts the MOEs of vessel performance inputs for a series of probabilistic scenarios [11] after which a regression analysis could be performed on these results to define a mathematical relationship between input MOPs and output MOEs. However, exact methods and equations are not described in the literature since they are (commercially) confidential. Another method is to directly use expert opinion to integrate diverse inputs and assess the value of the vessel's MOPs in an OMOE function [11]. According to Brown and Salcedo [11], the analytical hierarchy process (AHP) is a common method to imply expert opinion in a numerical method. After consulting colleagues, a similar method is used to assess effectiveness at COMMIT [86]. Therefore, the AHP method is chosen to study in more detail.

The AHP is a tool for solving multi-attribute decision problems originally developed by Saaty [75]. A hierarchy is a simplified abstraction of the structure of a system (such as the MOP breakdown tree in Figure 2.9) that can be used to study the functional interactions of its attributes and their impact on the performance of the system [11]. Brown and Salcedo [11] also describe that in a hierarchy, it is assumed that important system entities can be grouped into sets, with one group's entities or level influencing another group's entities or level.
The first step in building an AHP model is identifying critical attributes affecting the decision or system behavior [11]. The next step is to organize these attributes. An example is the MOP breakdown tree in Figure 2.9, which shows the hierarchy between OMOEs, OMEs, and MOPs. In this breakdown, system MOPs comprise the bottom hierarchy level.

Successful application of AHP requires a very structured process as described by Brown and Salcedo [11]:

1. **Identify, define, and bound decision attributes.** Identify critical mission scenarios. Identify MOEs for each mission scenario and establish goals and thresholds for all MOEs. Identify the vessel's MOPs critical to mission scenario MOE assessment and set goals and thresholds for these MOPs.
2. **Build OMOE/MOP hierarchy.** Organize MOEs and MOPs into a hierarchy with specific vessel MOPs at the lowest level.
3. **Determine MOP value and hierarchy weighting factors.** Use expert opinion and pair-wise comparison to determine MOP value and the quantitative relationship between the OMOE and MOPs.

These MOP values and hierarchy weighting factors can be determined in multiple ways. The method must include pairwise comparison since this is fundamental in using the AHP [75]. The first method is by using wargaming to gain insights in the vessel's performance. By changing one variable at a time, an effectiveness assessment can be made as described above. An example of pairwise comparison resulting from wargaming models can be seen in Figure 2.10, where the weapons capacity is a discrete MOP and the vessel's speed a continuous MOP. The weapons capacity metric is the number of vertical launch cells, with a threshold of 32 cells and a goal of 128 cells. Thresholds represent the absolute minimum number that needs to be installed to achieve an acceptable performance.

Goals are usually represented by a point of diminishing marginal value or a technology limitation [11]. A downside of applying wargaming to determine the MOPs values is the high number of simulations that need to be done and assessed before values for all MOPs can be retrieved since the same simulation already needs to be done multiple times with only one parameter changing every time. This cycle must be iterated multiple times for different situations to gain accurate insights into the (estimated) vessel's operational profile.

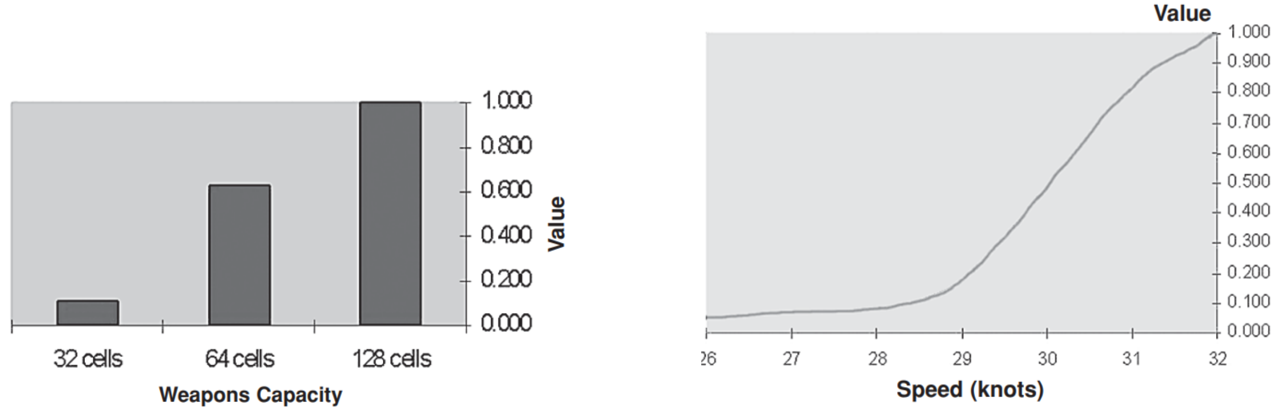


Figure 2.10: Discrete (left) and Continuous (right) MOP value function [11]

Another method is the use of pairwise comparison matrices, which uses expert opinion to judge the relative importance of pairs of categories, as described by Saaty [75]. The number of judgments required to create a particular matrix of order n (the number of compared elements) is $n(n\text{-}1)/2$ because the matrix will be reciprocal and the diagonal elements have value 1 (relation to itself). This means $a_{ij}=1/a_{ji}$. The numerical value of a judgment is described in Table 2.4 [75]. Next, ratio scales can be derived in the form of principal eigenvectors [75]. This is done by retrieving the principal eigenvector of the comparison matrix and normalizing the result. A numerical example of this method is worked out in Appendix B. A big advantage of this method is that it is less time-consuming since the expert opinion can be directly used in matrices (and no scenarios need to be built and modeled), after which a numerical value can be calculated. This way, the expert opinion can be used qualitatively.

Table 2.4: The fundamental scale [75]

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 moderately 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 judgements	When compromise is needed
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

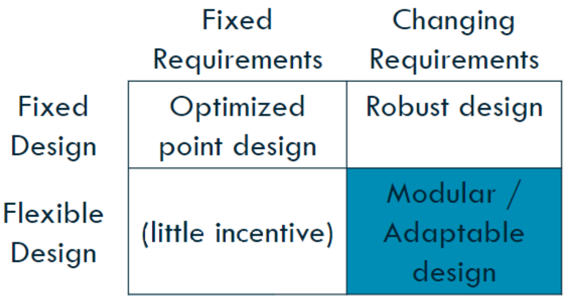
2.2.6 Conclusion RQ-2

Designing a naval vessel is not a straightforward process. They need to be adaptable since the future area of operation is unknown and technology is advancing rapidly. Important naval vessel design drivers are the offensive capabilities, survivability, mobility, range, and endurance. These design drivers influence each other, which makes it impossible to design an optimal vessel for every single design driver at once. To gain insights in a vessel's performance, an effectiveness assessment must be made. This is not a straightforward process since expert opinion will remain highly important. Therefore, the development of a method to qualify this opinion is required. A promising method is the application of the analytical hierarchy process (AHP). By creating a hierarchical overview, the level of influence can be distinguished. This results in the overall measure of effectiveness (OMOE) at the top level, measure of effectiveness (MOE) at the middle level, and measure of performance (MOP) at the bottom level. Numerical values on performance can be retrieved by wargaming, which is extremely time-consuming, or by applying pairwise comparison matrices. With the use of expert opinion, the reciprocal importance of elements can be rated. By using the principal eigenvector and normalizing the result, a numerical value of relative importance can be retrieved. This method can help the designer gain critical insights into the reciprocal importance of different functions of naval vessels.

3

Modularity for naval vessels

The main differences between naval and commercial vessel designing are the uncertainty and time varying dependencies naval vessel design has to deal with [36]. When vessels are designed for fixed requirements and no required changes to the platform during its lifetime, it can be optimized for these requirements [21]. When the design is fixed but the requirements are changing during the vessel's lifetime, a robust, over-designed vessel is required [21]. Another possibility to handle changing requirements is to create a flexible design, in which the platform can be changed depending on the changing requirements. These different combinations are visualized in Figure 3.1, which suggests using a modular/adaptable design for the combination of changing requirements and a flexible design. For naval vessels, the changing requirements are caused by the uncertain geopolitical environment in which naval vessels operate [3]. The design needs to stay adaptable due to technology that keeps evolving during the lifetime of the vessel [91] and it needs to stay flexible for the possibility of quickly changing operations [60]. For these reasons, it is interesting to research the possibilities of modular designing for naval vessels. In short, modularity aims to decouple systems in order to make either the design and building phase faster or to make the vessel more adaptable. Research question three concerning modularity on vessels is discussed in more detail in section 3.1. Research question four concerning the main challenges the RNLN faces while designing vessels, and how modularity could mitigate these challenges, is discussed in section 3.2.



	Fixed Requirements	Changing Requirements
Fixed Design	Optimized point design	Robust design
Flexible Design	(little incentive)	Modular / Adaptable design

Figure 3.1: When to use modularity [21]

3.1 RQ-3: What is the state-of-the-art in modularity and how would this be applicable to naval vessels?

This section will discuss different aspects of modularity. First, subsection 3.1.1 will discuss different applications and types of modularity. Next, different methods to integrate modularity in the design process are discussed in subsection 3.1.2. The section is finalized with a conclusion in subsection 3.1.3

3.1.1 Modularity

Modularity aims to decouple systems to create independent elements with clear interfaces [77, 25]. In literature, the definition of modularity is inconsistent. This report uses the following definition, formulated by research organization RAND [77], for modularity: "Creating fixed boundaries, defined interfaces, and defined ship services (such as power and cooling) to standard portions of a ship, which are termed modules". A module is defined by Fuchs and Golenhofen [25] as "A collection of physical hardware and/or software components that build a dedicated function with in the system. To be considered as a module,it has to fulfill a function". If the collection does not fulfill a function yet, it is considered a 'building block' [25]. Modularity can be applied in multiple ways. In Figure 3.2, the correlation between different types of modularity and its adaptability, both given in complexity and time, is shown. The 'build adaptability' shows the difference between designing parts of the hull and detailed systems on board, whereas 'operational adaptability' distinguishes itself in troops and equipment, such as the FRISCs and helicopters, and complex systems on board the vessels, like drones.

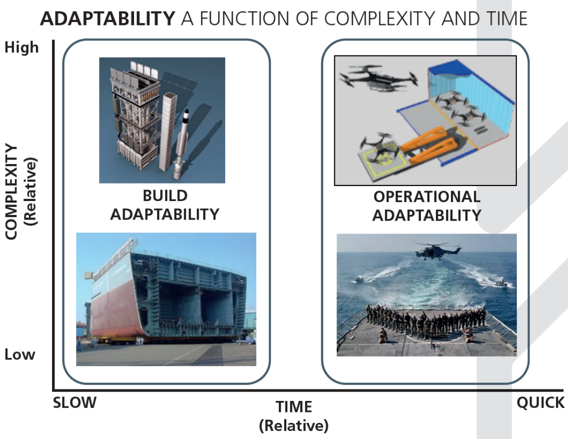


Figure 3.2: Adaptability as a function of complexity and time [95]

To gain insights into high-potential modular parts of platforms it is important to focus on the common core of these platforms. When this common core can be made modular, it can easily be placed on multiple platforms, which saves time in the design and production process.

It is important to understand that modularity is most effectively realized when implemented in the early-stage design phase [81]. This can be seen when analyzing the ARAPAHO project by NATO, which aimed to modularise the requirements to operate and sustain 4 SeaKing ASW helicopters in standard 40ft containers [5]. The idea was to use container vessels as platforms for these helicopters so they could provide emergency convoy defense. Since these vessels are not designed to take helicopters, the full capability needed to be provided. This consists of a flight deck, hangar, accommodation, weapons, C3, servicing, on-board logistics and additional power, which required 73 specially outfitted 40ft containers and 92 modules (needed for the hangar and flight deck structure since the vessel was not designed for it). The project demonstrated that modularizing a vessel, especially when not designed for it, can be extremely space-inefficient compared to integrated combat systems into naval vessels.

After analyzing literature a distinction can be made in different types of modularity. In the literature, inconsistent terminology is used for these types. Therefore, the types of modularity mentioned below are named according to the RNLN's definitions [86]. The projects mentioned as an example will be discussed in subsection 3.2.3.

- Geometrical modularity: This type aims to design standardized parts of the vessel, for example the hotel facilities, in order to reduce the design time of a vessel and make parallel production possible, which reduces the production time [32, 95]. An example of this type of modularity is the Damen Naval SIGMA (Ship Integrated Geometrical Modularity Approach) project [95].

- Payload modularity: This type aims to make it relatively easy to (re)place systems on board of vessels. This is achieved by designing a platform that can handle multiple systems. An example of small scale payload modularity is the multi purpose floating floor on board of the dutch LCFs [86]. By designing it in such a way the springs in the floor can be changed in location, it becomes possible to re-arrange the room without having the demolish and install an entire new floating floor. On large scale, the German MEKO and Danish STANFLEX projects are good examples, which focused on replacing large equipment on board like the canon's [95].

- Mission modularity: This type aims to bring mission-related equipment onto the vessel [86]. The difference with payload modularity is that mission modularity has very little impact on the platform itself. Mission modularity can be a wide aspect which includes, but is not limited to, additional medical equipment for HADR, containerized cells during counter-piracy operations, additional RHIBs or FRISCs, and additional crew accommodation. Most of the times, this can be done by standardized TEU container spots with standard electrical connections on board [32]. An example is the Danish Cube-system from SH Defence.

- Software modularity: This type aims to make it possible for different systems to run on the same software [86]. This way, a kind of 'plug and play' is developed which makes it easier to switch the systems that are used on board of vessels. This is extra important in combination with payload modularity, where the software on board are subjected to changing systems. An example of this type of modularity is the GAUDI (Gemeenschappelijke Architectuur Defensie) project by the dutch MoD.

An example of a single system which consists of multiple types of modularity is the MK41 Vertical Launch System (VLS). The MK41 VLS is a launchin system that is capable to simultaneously communicate with weapon control systems and missiles for different area's: AAW, ASW, ASuW, ballistic missile defence and land attack [95]. The VLS consists of basic building blocks of eight cells, and each cell can accept any missile. The desired number of cells can be installed on each vessel to meet the specific mission and hull requirements. When analyzing this system, it can be seen the VLS module is a form of payload modularity, while the capability to launch different types of missiles is a form of mission modularity.

The next step is to look into the architectural platform approach, which defines how a platform is structured during the design phase [67]. Three types of architectural platform approaches can be distinguished [25]:

- Modular approach - Product family members are derived by substituting and/or removing modules. They can be complemented with individually designed product portions.
- Integral approach - A platform is computed which is a single, monolithic part of the product. Individually designed portions can be added to the platform to create a finished product.
- Scalable or parametric approach - A platform is provided that has a number of scaling variables that can be used to ”stretch” or ”shrink” the platform in one or more dimensions.

The difference between modular and integral architectures is the way how product features relate to each other. This difference is visualized in Figure 3.3, and the differences are worked out in more detail in Figure 3.4. This shows the importance of focusing on the use of commonality between different components of vessels. When singular products on board of certain vessels are made modular, it will result in compromises on performance while scale advantages won't be reached.

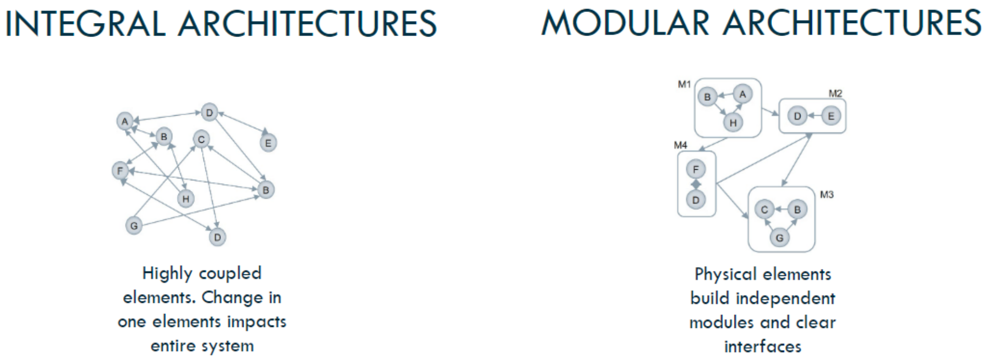
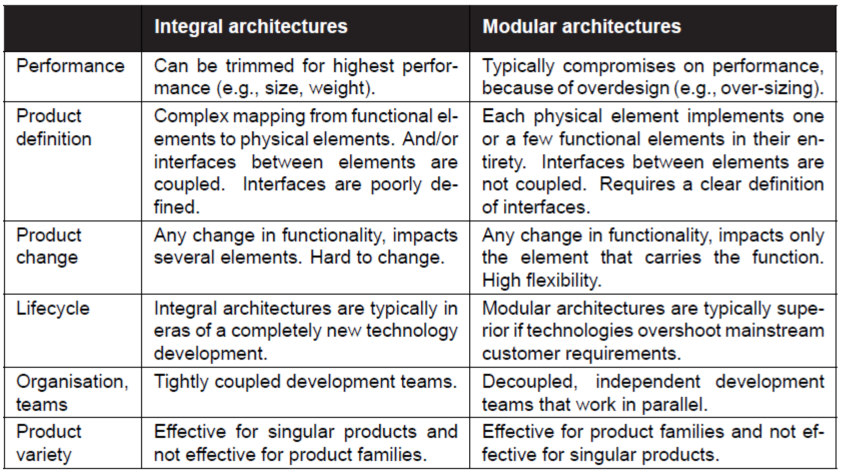


Figure 3.3: integral vs modular architectures [25]



	Integral architectures	Modular architectures
Performance	Can be trimmed for highest performance (e.g., size, weight).	Typically compromises on performance, because of overdesign (e.g., over-sizing).
Product definition	Complex mapping from functional elements to physical elements. And/or interfaces between elements are coupled. Interfaces are poorly defined.	Each physical element implements one or a few functional elements in their entirety. Interfaces between elements are not coupled. Requires a clear definition of interfaces.
Product change	Any change in functionality, impacts several elements. Hard to change.	Any change in functionality, impacts only the element that carries the function. High flexibility.
Lifecycle	Integral architectures are typically in eras of a completely new technology development.	Modular architectures are typically superior if technologies overshoot mainstream customer requirements.
Organisation, teams	Tightly coupled development teams.	Decoupled, independent development teams that work in parallel.
Product variety	Effective for singular products and not effective for product families.	Effective for product families and not effective for singular products.

Figure 3.4: Key Differences between Integral and Modular Architectures [25]

The modular platform approach is deemed the most relevant for a potential modular naval vessel. As Fuchs and Golenhofen [25] mentions, a modular architecture is typically superior if technologies overshoot mainstream customer requirements. Another important difference compared to an integral architecture is the decoupled, independent development teams that can work in parallel. This way, design time can be decreased. Another advantage of the decoupled systems is the high flexibility this brings along [25]. When an element is changed in the future, this only impacts the element that carries the function. This can make future upgrades more easy to install. This flexibility is necessary for a naval vessel since it must be flexible in the type of operations it performs and be able to operate at high performance at all times since you do not know when a situation will escalate, but it is unnecessary to operate at maximum performance at all times [86].

3.1.2 Modularity methods

Before looking at different modularity methods, it is important to define the requirements for applying these methods. First, naval vessels are often designed with fixed functional requirements and design parameters [86]. Therefore, a modularity method would need to change or indicate modules on board rather than changing the vessel's design itself. Another aspect is the modularity drivers. As discussed in chapter 2, commercial vessels aim to save as much money as possible, while naval vessels have different motives that will be highlighted in more detail in section 3.2. Modularity drivers play an important role and can be defined as 'expected benefits' [2], such as the possibility for international cooperation or decreasing the design and building time. The goal is to find a method that gives an indication of potential modular systems for different modularity drivers. Since the expert opinion is of high importance in the design process of naval vessels [11, 85], it is important the tool will not define modules but rather return an indication, which leaves the actual decisions to the designers. The final important note is that this report focuses on the technical impact of modularity on a naval vessel's effectiveness, and leaves the economic side out of consideration. This decision has been made since cost-saving is not considered a primary driver for the RNLN to apply modularity [32].

There are various methods to support modular designing, as described by Stjepandić et al. [83] and Fuchs and Golenhofen [25] as:

- Axiomatic design (AD) - A systems design method that uses matrices to systematically analyze customer requirements and transform these into functional requirements, design parameters, and process variables.
- Function modeling or heuristic approach - This method places product functions as a central idea for structuring the product into modules.
- Design Structure Matrix (DSM) - This method can be used to define modules within a single product's architecture. A matrix that maps components and/or functions against each other is used. Once these functions and/or components interactions are mapped a clustering algorithm can be applied to group the functions and/or components to maximize interactions within a cluster and minimize interaction with other clusters. The created clusters indicate potential modules.
- Modular Function Deployment (MFD) - By using different matrices including a vessel's requirements, functions, systems, and modularity drivers, the interaction between them can be mapped. This method gives the designer an insight into high-potential modules.
- Variant Mode and Effects Analysis - This method helps to depict the impact of product variants in all units of the enterprise from the definition of the product program to distribution. This method includes an evaluation of costs and indicates cost-saving potential by eliminating product variety that is not customer-perceived.
- Five-step algorithm - A five-step algorithm is used to group functions and create a dendrogram to find potential modules across products. The algorithm calculates the distance between two modules or groups of modules to create a hierarchical dendrogram to help decide what function groups share enough commonality to be replaced by a common module.

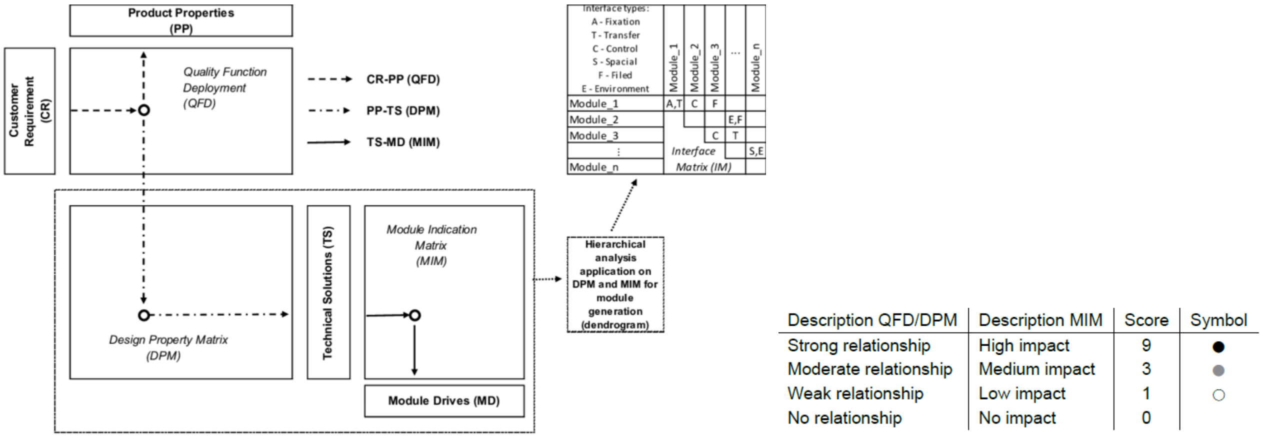
AD gives functional requirements and design parameters, while for naval vessels these parameters are often fixed [86]. DSM and the five-step algorithm method looks at the commonality within functions to determine whether it could be a module, while for naval vessels the modularity drivers will determine whether this is what the designers want to achieve or if other goals are pursued. Variant Mode and Effects Analysis focuses more on the cost-saving potential of modularization, while this report will focus on the effect on the naval vessel's effectiveness. MFD will indicate high-potential modules for each corresponding modularity driver while leaving the final decisions to the designer. Therefore, MFD has a high potential to be applied to complex naval vessels and will be discussed in more detail below.

3.1.2.a Modular Function Deployment (MFD)

MFD is a method to map information that can link interactions between requirements, functions, systems, and modularity drivers into different matrices. This can be computed into a collection of matrices known as the Product Management Map (PMM) [80]. A PMM consists of a Quality Function Deployment (QFD, interaction between requirements and functions), a Design Property Matrix (DPM, interactions between functions and systems), and a Module Indication Matrix (MIM, impact of functions/systems on modularity drivers). Optionally, the Interface Matrix (IM) is introduced. This matrix will show the module interfaces used to connect modules (multiple interfaces per module are possible). The following categorization is used:

- Attachment interface (A in matrix)- A physical connection between the modules is used.
- Transfer interface (T in matrix) - Provides a conduit for transferring power or media from one module to another.
- Command & control interface (C in matrix)- Other components control the state of a component.
- Spatial interface (S in matrix)- Determines the boundary between modules. It is the spatial location and volume a component can occupy.

An example of a PMM and IM is shown in Figure 3.5a. The accompanying rating scale of these interactions (QFD, DPM) and impact (MIM)is shown in Figure 3.5b.



Description QFD/DPM	Description MIM	Score	Symbol
Strong relationship	High impact	9	●
Moderate relationship	Medium impact	3	●
Weak relationship	Low impact	1	○
No relationship	No impact	0	

(a) Product Management Map and Interface Matrix [24]

(b) Rating scale [81]

Figure 3.5: Product Management Map and accompanying rating scale

During the vessel's life cycle, MFD considers different stakeholders. Depending on the life cycle phase, MFD compromises points of view from different perspectives, each with its own experience and responsibilities. Smit [81] mentions the stakeholders as the 'Voice of Customer', 'Voice of Engineer', and 'Voice of Business'. Definitions of these concepts refer to one of the three key conceptual attributes of Simpson et al. [80] mentioned below. Figure 3.6 illustrates how these aspects relate to the QFD, DPM, MIM, and interface matrix.

- The module containment - Responding to the Voice of Customer perspective to ensure the module will fulfill a function bearing a technical solution identified by quality and cost. Typically represented by the marketing function.
- The physical limits of the module - Representing the Voice of Engineer in its need to manufacture modules that properly fit together and deliver the required technical solutions. Combines input from engineering, manufacturing, quality, supply chain, and the after-market.
- Modularity driver - Reflecting on the Voice of Business in configuring a product variant using a module. Shareholders, corporate officers, or others involved in corporate governance who determine which value discipline is crucial to the success of not only the product but the business as a whole. For naval vessels, this would be the focus of the vessel's effectiveness and possible international design projects.

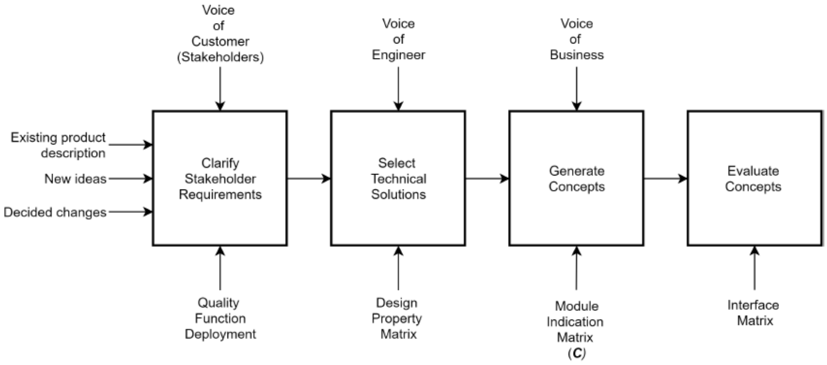


Figure 3.6: MFD Roadmap [81]

However, Simpson et al. [80] worked out these 'Voices' in more detail. These voices, and where they play a part in the vessel's lifecycle, are visualized in Figure 3.7. A division can be made, as described by Smit [81], in the following voices and their accompanying modularity drivers:

- **Voice of Customer** - Reflects the need for variance for a product platform. Two module drivers are available to describe this voice:
    - *Different/Technology specification*; Imparts the strategic need for a market-specific technical solution in the product platform [25, 80].
    - *Styling*; Imparts the strategic need for brand-driven appearance variance in the product platform as it is influenced by fashion and trends [25, 80].
- **Voice of Engineering** - Addresses the need to manage modules of the architecture that will have or will not have a planned design change during the platform's lifetime. Three modularity drivers address the engineering perspectives:
    - *Carry over*; Imparts strategies of technology re-use across generations for the product platform [25, 80].
    - *Technology push or technology evolution*; Imparts the development of technology during the lifecycle, driven by external forces outside the company [25, 80].
    - *Product planning or planned design change*; Imparts the company's internal strategies to launch new products, meet changing customer requirements, or decrease product costs [25, 80].
- **Voice of Manufacturing** - Strives to maintain a consistent, effective, and efficient manufacturing process. Two modularity drivers that strengthen this approach are:
    - *Common units*; Imparts the strategy that a required function must have the same physical form in principally every product variant [25, 80].
    - *Process and/or organization*; Imparts the strategy that there is a suitable collection of technology-driven work content, for a manufacturing cell or workgroup [25, 80].
- **Voice of Quality** - Seeks to improve the manufactured quality of a product. The following modularity driver is applied to address this:
    - *Separate testing*; Imparts strategies where functions can be tested independently of the product [25, 80].
- **Voice of Supply Chain** - Provides manufacturing with the material and component it needs to build the product a customer desires. The modularity driver that addresses this is called:
    - *Purchase, supplier availability or black box engineering*; Imparts strategies to outsource 'black box' technology in a module. In other words, a specialist/vendor can deliver the technical solution as a complete standard module instead of individual parts [25, 80].
- **Voice of After Market** - The addition of non-factory accessories, parts, services, or upgrades. The following three modularity drivers support this voice:
    - *Service and maintenance*; Imparts strategies where service on a product is an important customer value [25, 80].
    - *Upgrading*; Imparts strategies that extend the product lifetime or improve the product performance [25, 80].
    - *Recycling*; Imparts strategies that enable codes regarding the disposal of hazardous as well as homogeneous materials [25, 80].

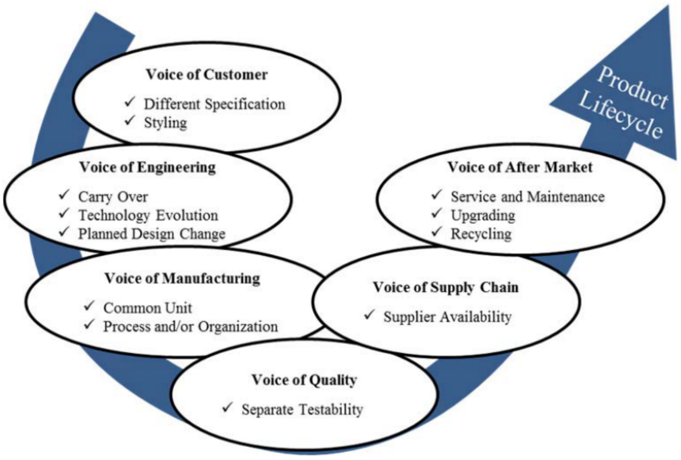


Figure 3.7: Modularity Drivers Positioned along a Product Lifecycle Stream [80]

3.1.3 Conclusion RQ-3

Different types of modularity can be applied to naval vessels. The following types come back in the literature under different names, so this report uses the definitions used by COMMIT. The first type of modularity is geometrical modularity, which aims to design standardized parts of the vessel, such as hotel facilities, to reduce the design time and enable parallel production [32, 95]. The next type is payload modularity, which aims to make it relatively easy to (re)place systems on board of vessels [91]. The challenge with this modularity type is the required ability of the platform to handle multiple systems. A modularity type not involving the platform is mission modularity, which aims to bring mission-related equipment onto the vessel [86]. This is often achieved by standardized TEU container spots with electrical connections for cooling on board [32]. The last type is software modularity, which aims to create the possibility of running different systems on the same software [86]. This way, a plug-and-play principle is created. Modular systems have the advantage of being decoupled systems. This way, changes in functionality only impact the element that carries the function and the modules can be developed by independent research teams that work in parallel [25]. As a result, future updates can be designed more easily and the design process can be accelerated. However, modularity will not be a solution for every challenge in all cases. Applying a modular architecture will typically result in compromises on performance since overdesign will be inevitable [25, 67]. Therefore, it is important to clearly understand the challenge that needs to be mitigated, and then determine if modularity is a suitable method to do so.

When looking at different methods for modularity application, it is important to first define the required output. For naval vessels, the functional requirements and design parameters are often fixed [86] meaning the modularity method should not apply changes to the vessel's design itself. Modularity drivers play an important role and can be defined as 'expected benefits' [2], such as the possibility for international cooperation or decreasing the design and building time. The goal is to find a method that gives an indication of potential modular systems for different modularity drivers. Since the expert opinion is of high importance in the design process of naval vessels [11, 85], it is important the tool will not define modules but rather return an indication, which leaves the actual decision to the designers. Modular Function Deployment (MFD) will indicate high-potential modules for each corresponding modularity driver while leaving the final decisions to the designer. Therefore, MFD has a high potential to be applied to complex naval vessels.

3.2 RQ-4: What are the main challenges in naval vessel design for the RNLN and how could modularity mitigate these challenges?

As addressed in section 3.1, applying modularity without a proper understanding of the challenges trying to be mitigated can fail the project, while modularity itself might have been a suitable solution. Therefore, it is important to understand the main challenges the RNLN faces during the designing of their naval vessels. First, subsection 3.2.1 will discuss the main challenges the RNLN faces while designing new naval vessels. Next, subsection 3.2.2 will discuss how modularity could mitigate these challenges. Previous and running projects involving modular (naval) vessels are analyzed for potential benefits and threats when working with modularity in subsection 3.2.3. The section is finalized with a conclusion in subsection 3.2.4.

3.2.1 Challenges

[7] Designing naval vessels comes with specific challenges, besides the challenges already mentioned in section 2.2. After analyzing literature and consulting experts in naval vessel design from COMMIT, the following (main) challenges for the RNLN are computed [91, 32, 92]:

- Complexity: Some details, for instance interfaces, are already needed in early-stage design, while the design knowledge is still low. This makes it time-consuming to select the most suitable systems and possibly results in a less suitable system when evaluating the final design.
- Maintenance & Upgrades: The time a vessel is in port/dock for maintenance, it can't be deployed on operations. Every vessel needs upgrades to handle the changing threats over its lifetime (think about MLU), which usually takes the vessel out of operation for a long period.
- Short-term adaptability: Vessels are required to be adaptable to perform various missions and the mission profile itself can change during the lifetime of a vessel as well. Therefore, the equipment on board may vary during the vessel's lifetime, but it can also be mission-dependent. When, for example, a vessel needs to assist during disaster relief, it needs to be equipped quickly with medical aid and/or search and rescue equipment.
- High design and production time for small series: When every part of the vessel needs to be engineered from the beginning, a lot of time is consumed. For small production series, this is relatively time-consuming since these engineered equipment (specified for one type of vessel) can't easily be reused on other designs. The production time goes up since almost no equipment and structures can be built before the vessel is completely designed.
- High economic costs for small series: As mentioned before, small series result in high design and production times. The high design time will result in more costs since engineers will require more hours to design a functioning vessel. During production, the advantages of mass production, such as reduced prices when buying large amounts of goods, don't apply to small series. As mentioned before, this thesis will not include the economic costs or benefits from modularity.

3.2.2 Modularity as a possible mitigation

Applying modularity has three main functions: making complexity manageable, enabling parallel work, and accommodating future uncertainty [7, 83]. The last function shows how modularity could be used as a design style solution to the issue of adaptability, which has been an objective to the fore of naval ship acquisition since the end of the Cold War [5]. Modularity could mitigate the challenges mentioned in the section above in the following ways [32, 91, 92]:

- Complexity: Modularity can help to make complexity manageable [7, 83]. For example by making standardized interfaces that can handle various systems. This way, the selection of detailed systems is postponed so the proper system can be selected at the end of the design phase and the production can start earlier since the standardized interface can be used.
- Maintenance & Upgrades: By using modules it can become easier to conduct maintenance and install upgrades [9, 94]. When modules can (relatively) easily be replaced, it is possible to change to broken module in port to a new one so the vessel is quickly back in operation again. The required maintenance can then be done in port, so the maintenance time of the actual module won't affect the vessel's operational readiness. This will only be useful when the maintenance time is more than the time required to change the module to a new one. Similarly, when modules can relatively easily be replaced, the required upgrades will take less time to install. This way the vessel will have a lower down-time, improving its overall effectiveness.
- Short-term adaptability: By using exchangeable modules on board, it is possible to change the equipment needed to conduct certain missions quickly [94]. For example, quickly exchangeable rooms which can supply extra medical rooms in the case of disaster relief. Most mission modules are focused on the lower end of the spectrum of conflict up to maritime security operations [86].
- High design and production time for small series: When basic modules are applicable for different vessel types, future designs require less design time since already existing modules can be used in the models and parallel production becomes a possibility [7, 9, 94]. When it is known a certain module will be used early on in the design phase it can be ordered before the building of the vessel itself starts since it already has been designed, reducing the production time.

- High economic costs for small series: As mentioned before, time can be saved which could save money. This does not necessarily need to be true, because it can take more time to design a module since it needs to be suitable for multiple platforms. Another way the economic costs might be reduced is more modules can be ordered at once compared to single parts for a specific design, which makes it possible to gain scale advantages [67]. Another possibility is when a single vessel type can perform multiple missions that are nowadays conducted by different vessel types. This could lead to larger series, resulting in production scale benefits.

Using modules on board naval vessels will result in 'knowledge blocks' since the modules are already designed before application on the vessel. By reusing available information, multiple design possibilities can be generated and evaluated, after which the best-performing design can be chosen. This way a more suitable starting point (first design) can be generated, which would reduce the required iterations for the final design, thus reducing design time. As mentioned before, the design time reduction is an important factor for modern navies, thus looking at methods for reusing information is relevant. One of these methods to study in more detail is Knowledge Based Engineering (KBE), which is chosen because it is an already proven advantageous methodology in other sectors (aerospace, automotive, and architecture) [13]. KBE is described by Charisi [13] as 'the approach of the compilation of knowledge required in a product development process and aims to the identification, record, and re-use of engineering knowledge by combining Artificial Intelligence (AI) techniques, IT tools and Object-Oriented methodologies'.

KBE is a method developed in the artificial intelligence (AI) sector designed to solve multidisciplinary problems by a rule-based reasoning process that gives an output in computer-aided design (CAD) software [13]. KBE can be used in a parametric design. When using the parametric design procedure, (sub)systems will be automatically coupled to an algorithm calculating various parameters chosen by the designer [37]. The KBE model consists of parametric building blocks, called 'High Level Primitives' (HLPs) [13]. These HLPs can incorporate and reuse relevant knowledge, such as the calculations for the vessel's stability and center of gravity. This way, KBE can be used to investigate changes in these parameters when changing non-modular systems into modular variants. A KBE model for modular offshore service vessels (OSVs) has been computed by Kao [38]. By using knowledge about OSV designs and implementing this in CAD software, automated designs are made and the most suitable design is delivered as output. Kao did a case study on a vessel to test his model, and the resulting design was already close to the values of the actual, optimized design. This shows the potential of using KBE to reduce the required iterations for designers to reach the final design.

3.2.3 Analysis of previous and running projects

This subsection will analyze naval projects involving modularity to gain insight into the potential benefits, tradeoffs, and lessons learned.

MEKO (Merhzwecks Kombination or Multi Role Combination) & Damen SIGMA
In the 1970s Blohm and Voss designed a naval vessel that used a common hull but had specific locations designated for operational modules, with a primary focus on weapon systems [95]. The idea behind these modules was to make them interchangeable by using a standard interface between the module and the hull (bus modularity). This resulted in reduced building time through the parallel development of cheap and simple designs of both the modules and vessels [95]. As a downside, changing modules took a significant refit period, which meant quickly changing the vessel's layout was impossible. The modules were bolted into place and sealed with resin to structurally integrate the modules into the vessel. The concept of the MEKO project has been adopted and implemented by Damen Group which resulted in the currently used SIGMA Class [8]. The reason most modern navies do not use these vessels is the relatively basic technology used when designing these vessels, which does not fit the requirements made by navies focused on modern technology application [86].

STANFLEX (Standard Flex)
STANFLEX used a standard vessel as well, including standard propulsion and bays for containerized equipment. The aim for the project was to gain increased mission flexibility by the ability to change modules in port. For STANFLEX, this could be done in a couple of hours without performing significant refits, which gained huge advantages compared to the MEKO project. By standardization of the vessel, the vessel's building time and cost were reduced [95]. Another advantage by separating the modules from the vessel is the ability to develop both of them independently from each other. When the Absalon Class replaced the initial vessel, no new modules were required [95] since they were refitted into the Absalon Class. The other way is also possible, meaning upgraded modules can easily be placed while using the same vessel.

As a downside, to keep the required flexibility more module types are needed than there are fits at vessels. If, for example, the frigates should remain flexible, both ASW and AAW modules should be available for every vessel. These modules are already expensive, while they might not be used at all, which makes it a large investment to create adaptability on board vessels[32]. Another disadvantage is the requirement for increased crew training since they need to be trained to operate each module individually [95].

LCS (Littoral Combat Ship)
Another project aiming for quickly adaptable reconfigurations is the Littoral Combat Ship (LCS), which was designed with twenty mission module stations [95]. The idea was to design a combat vessel for littoral waters capable of performing all kinds of combat operations. Different, easily changeable modules would compute the vessel's configuration. The designed adaptability focused on three mission module types: ASuW, NMW, and ASW [70].

This project failed for multiple reasons. To start with, the acceptance and testing of the different mission modules were too slow [95]. As a result, the vessel was built before some of the modules were ready for operational use. After testing, some of the modules were unable to deliver useful functionality [70]. Other challenges were the lack of firepower, bad (structural) engineering, and unforeseen complexity of systems [95, 70]. The lack of firepower was a result of the chosen modules. An example would be the use of hellfire missiles, which can reach targets just over 10 miles when the weather conditions are favorable [70]. Since these vessels should have been able to conduct combat operations on land targets, different missiles had to be installed during the vessel's lifetime. Bad (structural) engineering became clearly visible when the first LCSs went into service. Multiple hulls started cracking shortly after vessels had been deployed, and combination gear (coupling the diesel engines and gas turbines output) broke down, which resulted in the LCS needing to be towed back to port [70]. Another important mistake was the lack of redundancy: one hit could take out the whole propulsion, combat capability, or damage control ability [70]. This is one of the risks when designing a combat vessel as small as possible, without paying attention to the ability to continue operations after taking sustainable damage. Lastly, the vessel resulted in maintenance issues. The systems onboard, such as the waterjets, became so complex the crew could not compute the maintenance themselves and had to rely on contractors [70].

The LCS project shows the importance of a proper (process) assessment before making important design choices. It is important to note that the project's failure was not by the focus on using modularity, but rather on bad design choices and planning [95, 70]. According to Kana et al. [36], these choices were a result from "difficulties in decision-making, and the inability for designers to fully comprehend their impacts on the design realizations through time". An important lesson from this project is to not blindly focus on modularity but keep asking yourself what problem you are trying to solve, and if modularity is the best solution. Another lesson is to pay close attention to the chosen modules and their implication on a naval vessel. The choice for a waterjet seemed reasonable when looking at the desired mobility and top speed, but its complexity resulted in maintenance issues that the vessel's crew could not solve. Another challenge was raised by the choice of weapon systems on board. They were made modular, but the chosen modules were only suitable for close-range defense. As a result, the LCS was unable to conduct its combat operations as intended.

3.2.4 Conclusion RQ-4

Designing naval vessels comes with specific challenges, besides the difficulty of assessing their effectiveness as discussed before. For the RNLN, designers face challenges in the vessel's complexity, maintenance & upgrades, short-term adaptability, high design and production time for small series, and high economic costs for small series. For vessels that require a flexible design and face changing requirements, modular design can be used as a method to mitigate these challenges. It can decrease a vessel's complexity by using standardized interfaces that can handle various systems, and the application of modules can ease the maintenance and upgrade costs and time. When modules are relatively exchangeable, short-term adaptability is increased since the vessel's configuration can be changed without the need for major refits. For the last two challenges, modularity enables the ability to use modules on more vessel types, which increases the number of vessels to which it can be applied. A larger application will decrease the relative costs since it is already designed but can be used for more purposes. This will also reduce the design and production time since parts of the future vessel (the already existing modules) are already designed.

Another advantage of reusing modules among multiple vessels is the possibility of using Knowledge Based Engineering (KBE). The KBE model consists of parametric building blocks, called 'High Level Primitives' (HLPs) [13]. These HLPs can incorporate and reuse relevant knowledge. This way, KBE can be used to investigate changes in these parameters when changing non-modular systems into modular variants.

4

Research gap & Methodology

This chapter aims to define the research gap and set up the methodology for the framework development. First, the research gap is discussed and the main research question for the thesis is formulated in section 4.1 Next, the methodology is discussed in section 4.2.

4.1 Research Gap

As mentioned in chapter 3, modularity can help mitigate several challenges in naval vessel design. However, the literature often assumes using modularity and research methods to apply modularity to naval vessels without investigating if the application of modularity is the best solution for the design problem. Therefore, this thesis will develop a framework for the concept design phase to investigate the impact of modularity with respect to a non-modular solution. The main research question of the thesis will become:

How can the decision-making for modular systems in naval vessel design be performed in a structural way and evaluated on its effectiveness compared to a non-modular solution?

The framework aims to give a structured way to assess which systems have a high potential to be modular and evaluate the technical impact on the design of modular systems. If a system is a feasible module, the last step is to assess the impact on the vessel's effectiveness to check if the modular system will actually improve the vessel, or if the non-modular solution is preferred.

4.2 Methodology

The framework will combine the application of MFD, AHP, and KBE. It will focus on the application of payload modularity. This choice has been made since it is deemed most suitable to show the impact of modularity on the platform, whereas geometrical modularity would focus on designing standardized generic systems without changing the systems on board, mission modularity adds containers to the platform rather than changing the platform itself, and software modularity focuses more on the IT side of the problem.

In short, MFD will indicate high-potential modular systems, AHP will asses the reciprocal importance of the vessel's functions, and KBE will assess the technical feasibility and changes of several parameters of the design. The final evaluation of the effectiveness will be done with the AHP method again. The framework will be applied to a case study for an RNLN surface combatant. Each method will be explained in more detail in subsection 4.2.1, subsection 4.2.2, and subsection 4.2.3 respectively.

4.2.1 Modular Function Deployment

The first method applied in the framework will be MFD. The goal of applying MFD is to identify high-potential modular systems for different modularity drivers chosen by the designer. Therefore, it is important to identify the challenges that need to be mitigated and then check if modularity is a possible solution, instead of using modularity and coming up with challenges that are solved. To achieve this, the vessel's requirements, functions, systems, and modularity drivers need to be defined. It is important to notice that during this method, the assumption is made modularity will be used and the MFD will indicate if a system could benefit from modularity.

4.2.2 Analytic Hierarchy Process

The AHP will be applied as described in subsection 2.2.5. When applying AHP, it is important to make a well-structured MOP breakdown tree as shown in Figure 2.9. The next step is to make pairwise comparison matrices and assess the reciprocal importance of the vessel's OMOEs, MOEs, and MOPs. It is important to use real experts for grading the reciprocal importance of different systems. The definition of an expert used in this report is defined as 'someone whose expertise in a particular area makes his assertions reliable—more likely to be true than false' [101]. At COMMIT, naval architects who design the vessels for the RNLN are deemed experts in naval vessel design. Therefore, the case study will use the expert opinion of multiple naval architects at COMMIT to compare their opinions. The final ranking of the AHP will give insights in the most important functions of the vessel. These functions can be coupled to their accompanying systems, which gives an indication of the most important systems.

4.2.3 Knowledge Based Engineering

For building the KBE model, the method as performed by Charisi [13] is used and adjusted:

1. **Identification of the design requirements**
   The first step is to determine the design requirements, which are dependent on the vessel type and the specific design problem. The design requirements correspond to the input variables, which lead to the tuning of the model to fit different design problems. The design requirements are already defined during the MFD phase.

2. **Main drivers analysis**
   The main drivers are analyzed to identify the way the vessel should be parameterized. These main drivers are already identified by the AHP method.

3. **Determine the HLPs**
   This step consists of the determination of the HLPs of the specific vessel. The developed HLPs form the toolkit from which different parts can be combined to form the different vessel alternatives.

4. **Qualitative description of the HLPs**
   The qualitative description will be the guideline for the mathematical representation. In the context of developing the geometric model of the vessel, space reservation should be ensured.

5. **Mathematical representation of the HLPs**
   The mathematical description of the HLPs is defined based on their qualitative description. Hence, their interrelations are also defined, and thus, the vessel's architecture can be created.

6. **Define the HLPs for each 'total ship' architecture**
   The selected HLPs from the vessel's toolkit are combined to form the 'total ship' architecture according to the design decisions of the naval architect. The total of the different design decision combinations leads to the different solutions in the design space.

7. **Tuning the HLPs to fit the design problem**
   The selected HLPs are being tuned to fit a specific design problem. The design requirements are being used as the guidelines to form a feasible and suitable design solution for the design problem.

8. **Extract and evaluate the geometric model**
   The output of the described framework is the geometric model of the vessel for the naval architect to visualize his ideas and use the model as an input for analysis. This design can be evaluated by using parametric design software.

For the parametric design software, this thesis will use a Python file integrated into Rhinoceros 6 retrieved from the course 'Design of Complex Specials' given during the master Marine Technology at Delft University of Technology. Basic frigate hulls can be retrieved and adjusted with this file, and the systems onboard can be drawn as building blocks. This way, a naval vessel can be designed in Rhinoceros with HLPs, and the Python file will return important design parameters. When creating designs during the case study, it is important to start with a non-modular design. This way, the changes in parameters of a modular design can be compared to the non-modular version. During the design, naval architects at COMMIT will be asked for advice to retrieve realistic values for the systems onboard. The non-modular design can be taken as a starting point, after which systems can be adjusted to a modular variant.

Part II

Framework development

5

Framework introduction

This chapter introduces the framework that will be developed. A global description of the framework is given in section 5.1. The case study selection is described in section 5.2.

5.1 Framework description

The framework developed in this thesis aims to give valuable insights for the naval architect to asses whether modularity could improve their design. It will consist of an MFD, AHP, KBE model, and a final evaluation of the effectiveness using AHP again. During the MFD model, the vessel's requirements, functions, systems, and modularity drivers are mapped by matrices. These must be formulated well since they are required during the AHP and KBE models. With the AHP model, the reciprocal importance of the vessel's functions is determined using expert opinion. The technical impact of modular systems on the design will be modeled in the KBE model. Different configurations of systems will be used, so the non-modular systems will be compared to their modular variants. This way, the technical feasibility of modular systems is assessed. So, the KBE model translates from operational performance to technical performance. When the modular systems, resulting from the MFD and AHP, are deemed feasible by the KBE, a final evaluation of the vessel's effectiveness is done to assess if the vessel would benefit from a modular variant of the system. A flowchart of the framework can be seen in Figure 5.1.

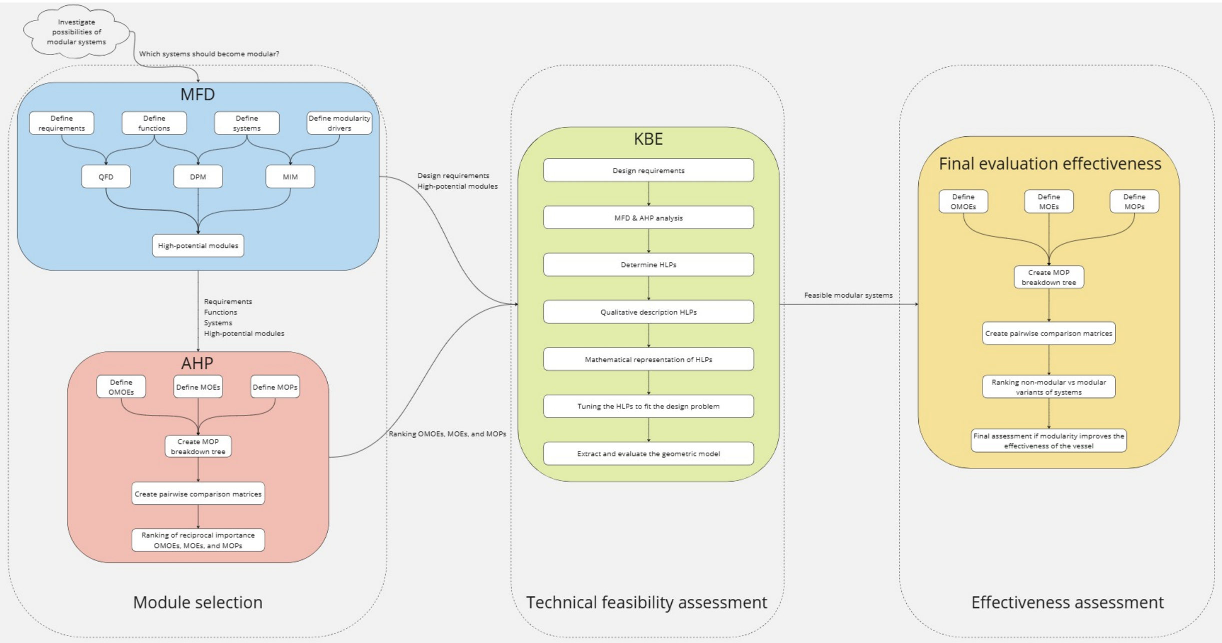


Figure 5.1: Flowchart framework

5.2 Case study

When choosing a case study, it is important to choose a vessel that would be a realistic design for current operations but is expected to benefit from modularity. Another important aspect is the vessel should not be originally designed for modularity application. This way, the impact of modularity on a non-modular design can be investigated. The four major running projects within COMMIT and the LPD-2, a landing platform and the first European advanced commando platform, are investigated to see which vessel is deemed most suitable for a case study.

These projects are Mican, Future Air Defender (FuAD), ASWF (Anti-Submarine Warfare Frigate), and Amfibisch Transportschip (ATS, an amphibious transportation vessel), while the LPD-2 has already proven itself as a multi-functional vessel [88]. These projects are discussed in subsection 5.2.1, after which the choice for the case study will be formulated in subsection 5.2.2.

5.2.1 Project suitability

The projects Mican, FuAD, ASWF, ATS, and LPD-2 will be discussed here and it will be mentioned whether they are deemed suitable for a case study. The selection for a case study will be done in the next subsection.

Mican
During the Mican project, low-manned surface vehicles are designed that can operate attached to a mothership (LCF, OPV, or other) [41]. The aim is to use a commercially available off-shore tender to launch missiles from containers placed on deck on command of the mothership [41]. Besides, these vessels should be able to survey threats in the North Sea, such as Russian spy- and research vessels [42]. Since this project already focuses on the application of mission modularity, it cannot be compared to a non-modular solution. Therefore, this project is deemed unsuitable for a case study.

FuAD & ASWF
FuAD and ASWF are projects focused on designing frigates specialized in AAW and ASW respectively. In these projects, payload modularity could help ease future upgrades and maintenance of the systems on board. Another possible advantage is the common use of modules on different vessels, which could decrease the design time of other projects or make it easier to cooperate in vessel design internationally. A downside of these projects is the uncertainty future upgrades would bring along, such as the unknown weight and volume increase. Different configurations could be made to test the influence of different margins in the design to create insights for the designer into the trade-offs. As a result, a case study would mainly focus on the application of payload modularity. Since these vessels were originally designed as a non-modular solution and modularity could improve the design, both vessels are deemed suitable for a case study.

ATS
The ATS is a unique project combining the replacement of the LPD and OPV in a single vessel; the ATS. As a result, a single vessel needs to be able to conduct landing and Coast Guard operations, such as the counter-narcotics operations currently done by OPVs in the Caribbean [61]. The ATS is already designed for adaptability by applying additional volume and weight [61] which can be used for future upgrades or additional SEWACO systems. Modularity could not only be applied in the same ways as the FuAD and ASWF projects but also as a way to use the vessel's space more efficiently when switching operation types. When performing landing operations, additional space is required for the troops and their equipment conducting the landing. By applying modularity, it could be possible to use this space differently when conducting Coast Guard operations, for example as storage space for confiscated goods or prison cells. Since this vessel is originally a non-modular solution and could benefit from modularity, this project is deemed suitable for a case study.

LPD-2
The last project is a vessel already built and operating for over 15 years; the LPD-2 named 'Zr. Ms. Johan de Witt'. An advantage of using an operating vessel is the design and usage of the vessel are known, while the other projects can still change during the design phase. The LPD-2 has been chosen since it is designed for two principal tasks: amphibious operations and functioning as a command vessel for up to 50.000 troops [56]. Besides, it can be used for disaster relief, counter-piracy, and a sailing hospital [56]. This multi-mission profile makes it interesting to look at the application of mission modularity and payload modularity as described above. Since this vessel is originally a non-modular solution and could benefit from modularity, this project is deemed suitable for a case study.

5.2.2 Case study selection

The case study selection will consist of two parts, already making use of the framework. The first part, during the MFD and AHP modelling, two types of vessels will be used. This will be a frigate and an amphibious transport vessel. By applying the model on both vessels, the most suitable vessel for the KBE phase can be selected based on the outcomes of the MFD- and AHP-models instead of choosing a vessels now with still little knowledge about the possible modular advantages. For both vessels, it is important the particular vessel could potentially benefit from at least two types of modularity. This is required to show the framework can be used for the application of different types of modularity.

The choice for the frigate is the Future Air Defender (FuAD), which is highlighted in subsubsection 5.2.2.a. The choice for the amphibious transport vessel is the LPD-2, which is highlighted in subsubsection 5.2.2.b.

5.2.2.a FuAD

For the case of the frigate, the FuAD is deemed most suitable. This choice is made because this frigate type will replace the LCF, whereas the ASWF is a new vessel type replacing the M-frigates. As a result, more public information can be found on the LCF which can be used to make assumptions for the FuAD because it will be a larger, but mission-wise comparable, vessel than the LCF.

The Future Air Defender will be a larger vessel than the LCF. Therefore, the vessel will be compared to the LCF, and its dimensions are compared to the similar German project the F127, having a displacement of 10,000 tonnes, a length of 160 meters, and a beam of 21 meters [71]. The cruise and maximum speed will be taken over from the LCF, since the tasks, such as escorting allied vessels with speeds up to 30 kn, will not change. When the systems under 'Reference FuAD' are described more general than the reference LCF, it means the exact system is not yet known. Other data, such as the crew size, is not yet known and is therefore left empty. The mission profile for the LCF, retrieved from Table 2.3, can be seen in Table 5.2.

Table 5.1: Specifications reference vessel LCF [54, 63, 71, 98]

Category	**Reference LCF [54, 63, 98]**	**Reference FuAD [71]**
Name	De Zeven Provinciën	-
Number	F802	-
In service	2002	-
Dimensions [LxBxT]	144 x 18.8 x 5.1 [m]	160 x 21 x 5.5 [m]
Displacement	6.050 [tonnes]	10.000 [tonnes]
Maximum speed	30 [kn]	30 [kn]
Cruise speed	18 [kn]	18 [kn]
Crew	174	150
Additional personnel	28	70
Propulsion **Power generation**	10.8 MW; 2 Wärtsilä 16 V26 dieselengines 39 MW; 2 Rolls Royce Spey SM 1A gasturbines	-
Weapons	Oto Breda-kanon 127mm-canon Mark 41-vertical launching system Harpoon anti-ship missile Goalkeeper 30mm Mark 46-torpedoes	Oto Breda-kanon 127mm-canon Vertical launching system Naval strike missiles Rolling Airframe Missile (RAM) Torpedoes Tomahawk cruise missiles
Sensors	SMART-L Active Phased Array (APAR) Atlas Elektronik DSQS-24C sonar	SMART-L APAR Block 2-radar Sonar
Aircraft capability	NH90 helicopter	NH90 helicopter

Table 5.2: Mission profile LCF [84]

Mission type	**Distribution**
ASW	15%
ASuW	15%
AAW	50%
Command & Control	20%

5.2.2.b LPD-2

For the case of the amphibious transport vessel, the LPD-2 is deemed most suitable. The vessel's design and operations are known in real-life conditions rather than the expected performance of the yet-to-be-built ATS. Besides, this vessel is suitable to look at both payload modularity for SEWACO systems and mission modularity for the different missions, such as hosting the staff to command up to 50.000 soldiers on land and conducting amphibious operations [56], which are never performed at the same time [90]. Right now, the vessel has a dedicated staff deck consisting of offices, sleeping facilities, and a joint operation room [56]. This space is not used when the vessel conducts amphibious operations, while there is empty space on the vessel when conducting command operations since it requires less volume than amphibious operations. If mission modularity could remove the staff deck by combining volume for amphibious and command operations, volume and weight could be saved and the vessel could become more efficient. The reason the LPD-2 is preferred over the ATS is that the physical design for the ATS, for example, if it is going to have a helicopter deck or if it becomes a flat-top carrier, is still unknown [43].

To get personnel and goods on land without using a port, the LPD-2 can lower its stern up to 4 meters [62]. By doing so, water can flow into its internal dock and the landing craft can sail out. For the HADR operations, the vessel has operation rooms, intensive care units, treatment rooms, and an emergency hospital capacity for 100 patients at its disposal [62]. The main parameters and equipment of the LPD-2 are listed in Table 5.3. The mission profile for the LPD-2, retrieved from Table 2.3, can be seen in Table 5.4.

Table 5.3: Specifications reference vessel LPD-2 [56, 62]

Name	Johan de Witt
Number	L801
In service	2007
Dimensions [LxBxT]	176 x 29 x 6 [m]
Displacement	15.500 [tonnes]
Maximum speed	19 [kn]
Cruise speed	15 [kn]
Crew	146
Additional personnel	555
Propulsion **Power generation**	19.800 hp; 4 x Stork Wärtsilä Podded Propulsers
Weapons	2x Goalkeeper 30mm 10 heavy 12,7mm-machineguns
Sensors	Thales NS100 air- and surface surveillance radar Scout Mk3 navigation radar Thales GATEKEEPER Thales Vigile-D ESM Chaff Torpedo deception system
Aircraft capability	6 NH90, Cougar, or Chinook helicopters
Landing craft	6 Landing craft; 2 LCU's & 4 LCVP's
Vehicles	32 Leopard 2-tanks and Patriot air defense systems

Table 5.4: Mission profile LPD [84]

Mission type	**Distribution**
Disaster relief & Evacuation	10%
Maritime interdiction operations	5%
Counter-terrorism	5%
Amphibious operations	30%
Strategic transport	15%
Sea basing	15%
Command & Control	20%

6

Framework MFD

This chapter will work out the MFD model discussed in subsubsection 3.1.2.a. To keep the MFD coherent, the results for the FuAD are shown in this chapter, while the results of the LPD-2 are shown in Appendix C. However, the MIM contains the results of both vessels since this is needed to discuss the final results of the MFD. The properties of the MFD, including the requirements, functions, and systems used are formulated in section 6.1. Next, the QFD, DPM, and MIM are formulated in respectfully section 6.2, section 6.3, and section 6.4. The results are analyzed in section 6.5. The chapters ends with a conclusion and discussion in subsection 6.6.2.

6.1 Define properties MFD

First, it is important to get insights into the expected mission profile of a vessel and the stakeholders involved during the vessel's life cycle. This will lead to specific requirements and functions for the future vessel, which in turn will lead to required systems. The mission profile of the RNLN fleet can be seen in Table 2.3.
It is important to understand which parties influence this mission profile. These parties are called stakeholders and are either directly or indirectly involved with the vessel or have other interests in its existence [17]. An obvious stakeholder is the operator of each vessel. In the case of the RNLN, this would be the tactical use of the vessel and its crew by the RNLN themselves. Other stakeholders, as mentioned by Van den Berg [97], could be:

- *Vessel owners* - The owner could be an individual, a company, or an institution equipping and exploiting the vessel's cargo or performing a specific mission. In the case of the RNLN, they are the owners themselves.
- *Vessel financiers* - Financiers have to make an investment analysis for their financing activities regarding ships. Changing economic and technical environments could have consequences on the vessel's value. Therefore they need to evaluate the risks and opportunities involved in the investment. For naval vessels, there is no return on investment (ROI) from an economic point of view. In the case of the RNLN, they are the financiers themselves.
- *Regulators* - Regulating parties such as governments and the IMO can be involved by, for example, emission regulations. In the case of the RNLN, they are the regulators themselves.
- *Port authorities* - The port authorities' involvement includes the facilitation of fuel bunkering and port access for vessels. In the case of the RNLN, they are the port authorities in the Netherlands themselves. In foreign countries, it will be other military or civil port authorities.
- *Other stakeholders* - Other parties that could also be involved in the vessel's life cycle, such as pilots and third-party logistic companies. In the case of the RNLN, they often fulfill all tasks in the Netherlands themselves. In foreign countries, it could be other military or civil parties.

The operator as a stakeholder involves the operations and mission-specific requirements of the vessel. Since this thesis focuses on naval operations, the focus will be on the operator as the primary stakeholder.

When formulating the requirements, functions, and systems for the case study, the focus will be on naval operations since these make a naval vessel unique. The requirements, functions, and systems are computed by discussions with naval architects from COMMIT to ensure all important aspects are included, without going into too much detail to keep the lists coherent. Therefore, actions such as mooring/unmooring in port are left. The requirements, functions, and systems of the FuAD will be formulated in respectively subsection 6.1.1, subsection 6.1.2, and subsection 6.1.3.

With this focus in mind, the QFD, DPM, and MIM matrix are computed. Simplifications have been made to keep the matrices coherent. When talking about weapon systems such as torpedoes, missiles, and the canon, accompanying requirements such as munition storage and launching facilities are inherently coupled to the weapon system. For the same reason, fuel tanks are included in the power generation architecture.

6.1.1 Requirements FuAD

The first step in the MFD is to define the vessel's requirements. It is important to notice that anti-surface warfare (ASuW), anti-submarine warfare (ASW), and anti-air warfare (AAW) can be approached as different mission types, while they are often coupled to each other in combat situations. An example would be a hostile naval surface vessel (ASuW), which can fire a torpedo (ASW) or missile (AAW) towards allied vessels. This way, battling a single hostile surface vessel can require ASuW, ASW, and AAW operation capability. The FuAD needs to be able to protect itself and the fleet it is sailing in against ASuW and AAW threats, and should be able to protect itself against ASW threats. The resulting requirements are listed in Table 6.1.

Table 6.1: Requirements FuAD

I	Requirement
Vessel	
i_1	The vessel operates at a cruising speed of 18 kn.
i_2	The vessel needs to reach a maximum speed of 30 kn.
i_3	The vessel needs to be able to operate independently for 30 days.
i_4	The vessel will have a range of 5.000 nm at cruising speed.
i_5	The vessel needs to be inherently stable.
i_6	The vessel's seakeeping needs to be sufficient for typical operations.
Hotel	
i_7	The operators shall be able to drink/eat.
i_8	The operators shall be able to sleep/rest.
i_9	The operators shall be able to control air properties.
i_{10}	The operators shall be able to do laundry.
i_{11}	The operators shall be able to do sanitary needs.
Safety	
i_{12}	The operators shall be able to detect emergency situations.
i_{13}	The operators shall be able to extinguish a fire.
i_{14}	The operators shall be able to abandon the vessel.
i_{15}	The operators shall be able to rescue a person fallen in the water.
Operations	
i_{16}	The operators shall be able to navigate safely and securely, at all times.
i_{17}	The operators shall be able to operate systems remotely.
i_{18}	The operators shall be able to maintain the vessel's systems.
i_{19}	The operators shall be able to maneuver with the vessel.
i_{20}	The operators shall be able to do station keeping.
i_{21}	The operators shall be able to (un)load and store cargo/supplies.
Additional Mission related requirements	
ASW	
i_{22}	The vessel shall be able to protect itself against threats under the surface.
ASuW	
i_{23}	The vessel shall be able to protect itself and the fleet against threats on the surface.
AAW	
i_{24}	The vessel shall be able to protect itself and the fleet against threats through the air.
Command & Control	
i_{25}	The vessel shall be able to communicate with the fleet and land-based command.
i_{26}	The vessel shall be able to host the staff of a fleet of up to 28 pax.
Others	
i_{27}	The vessel shall be able to protect itself against CBRN threats.
i_{28}	The vessel shall be able to support helicopter operations.
i_{29}	The vessel shall be able to conduct electronic warfare.

6.1.2 Functions FuAD

The requirements are mapped into functions. For instance, the requirement to protect itself against threats under the surface (i_{22}), which is translated into three functions; detection of the threat (j_{29}), neutralizing incoming threats under the surface (j_{30}), and neutralizing the source of the threat under the surface when in range of the weapon systems (j_{31}). Both destroying an object and jamming it in such a way the object is not a threat anymore, is classified as neutralization[1]. The functions of the FuAD are formulated in Table 6.2.

---

[1] Neutralization is defined by the Cambridge Dictionary [12] as 'the production of an effect that removes the effect of something else'.

Table 6.2: Functions FUAD

$\boldsymbol{J}$	Function
Vessel	
j_1	To provide mechanical/electrical power.
j_2	To transfer energy generated by the prime mover to the propulsor.
j_3	To generate electric power for the electric consumers.
j_4	To distribute the electrical power.
j_5	To secure stability.
j_6	To secure sufficient seakeeping for typical operations.
Hotel	
j_7	To treat grey and black water.
j_8	To control the air properties.
j_9	To provide fresh water.
j_{10}	To provide sleeping facilities.
j_{11}	To provide facilities for leisure possibilities.
j_{12}	To provide restaurant facilities.
j_{13}	To provide laundry possibilities.
Safety	
j_{14}	To inform the crew of an emergency/critical situation.
j_{15}	To support rescue operations at sea.
j_{16}	To provide multiple alternatives for abandoning the vessel.
j_{17}	To support crew for extinguishing and detecting a fire.
Operations	
j_{18}	To provide the crew with navigational data.
j_{19}	To provide the crew control over systems remotely.
j_{20}	To back-up the electric power system during a black out.
j_{21}	To provide the crew systems information.
j_{22}	To provide the crew space and tools for doing maintenance/repair work.
j_{23}	To alter course if commanded to.
j_{24}	To create a force in transversely direction for movement.
j_{25}	To forestall drifting away due to wind or current.
j_{26}	To provide draught data.
j_{27}	To (un)load cargo/supplies.
j_{28}	To store and secure cargo/supplies.
Additional Mission related functions	
ASW	
j_{29}	To detect threats under the surface.
j_{30}	To neutralize incoming threats under the surface.
j_{31}	To neutralize the source of the threat under the surface when in range of weapon systems.
ASuW	
j_{32}	To detect threats on the surface.
j_{33}	To neutralize the source of surface threat when in range of weapon systems.
AAW	
j_{34}	To detect threats through the air.
j_{35}	To neutralize close-range threats through the air.
j_{36}	To neutralize long-range threats through the air.
j_{37}	To neutralize the source of air threat when in range of weapon systems.
Command & Control	
j_{38}	To communicate with the fleet and land-based command.
j_{39}	To provide workspace for 28 pax.
j_{40}	To provide a staff command information centre.
j_{41}	To provide sleeping facility for 28 pax.
Others	
j_{42}	To provide protection against CBRN threats.
j_{43}	To provide facilities to support helicopter operations.
j_{44}	To detect RF emissions.
j_{45}	To intercept communication.
j_{46}	To jam.

6.1.3 Systems FuAD

The functions a vessel needs to fulfill are mapped into the required systems. In addition to the existing systems of the LCF, a laser that can be used as an AAW weapon system is included as a likely future upgrade. The systems of the FuAD are formulated in Table 6.3.

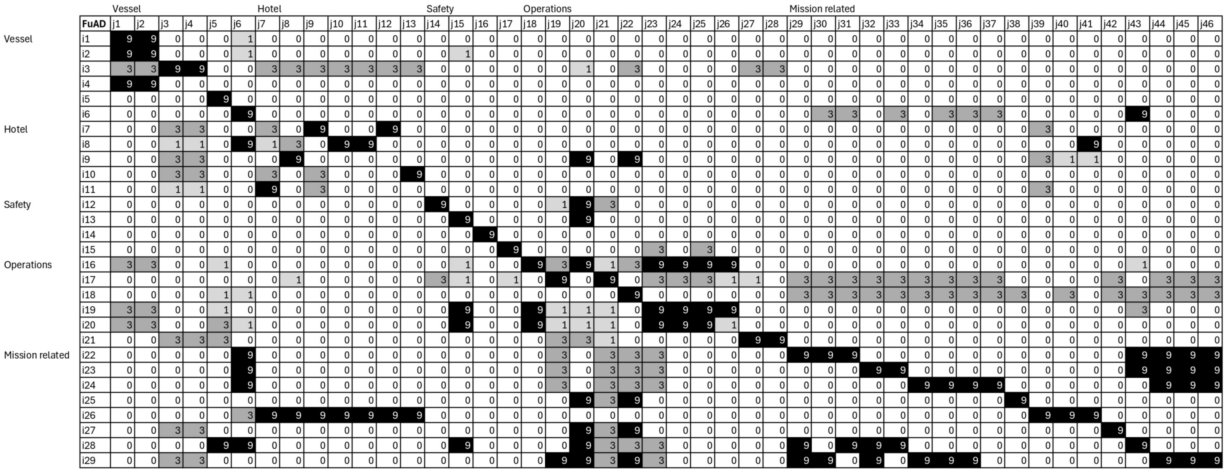
Table 6.3: Systems FuAD

$\boldsymbol{K}$	System
Vessel	
k_1	Hull structure
k_2	Mechanical power generation architecture
k_3	Electrical power generation architecture
k_4	Ballast system
k_5	Active stabilisation system
Hotel	
k_6	Fresh water system
k_7	Cabin
k_8	Climate control system
k_9	Plumbing drainage system
k_{10}	Day room
k_{11}	Galley
k_{12}	Laundry facilities
Safety	
k_{13}	Rescue boat & life raft
k_{14}	Fire fighting system
k_{15}	Emergency alarm system
Operations	
k_{16}	Emergency electrical power generation system
k_{17}	Navigation systems
k_{18}	Engineering control system
k_{19}	Command information centre
k_{20}	Workshop facilities
k_{21}	Propulsor
k_{22}	Transmission system
k_{23}	Ship control system
k_{24}	Bow thruster
k_{25}	Switchboard
k_{26}	Cargo handling system
k_{27}	Hold/deck
k_{28}	Cargo securement
Additional Mission related functions	
ASW	
k_{29}	Sonar
k_{30}	Torpedoes
ASuW	
k_{31}	Horizon surveillance radar
k_{32}	Tracking radar
k_{33}	Fire control radar
k_{34}	Vertical launching system
k_{35}	Surface-to-surface missile
k_{36}	Heavy machineguns
AAW	
k_{37}	Air surveillance radar
k_{38}	Decoys
k_{39}	Canon
k_{40}	Surface-to-air missile
k_{41}	Laser
Command & Control	
k_{42}	Communication system
k_{43}	Office rooms
k_{44}	Staff command information centre
Others	
k_{45}	CBRN Citadel
k_{46}	Pre-wetting system
k_{47}	Helicopter deck
k_{48}	Hanger
k_{49}	Electronic Support Measures
k_{50}	Electronic Counter Measures

6.2 QFD

With the QFD, the relationship between requirements and functions is rated as described in Figure 3.5b. The results can be analyzed to see which functions are related to certain requirements. Another advantage is the ability to check if every requirement has an accompanying function, and if every function fulfills a requirement. This way, it can be avoided that a requirement is not fulfilled or an unnecessary function is implemented. The QFD for the FuAD can be seen in Figure 6.1.

Most of the strong relationships are approximately on the diagonal. This is caused by translating requirements into functions, where the accompanying functions are approximately at the same place in the list as the requirement they fulfill. By the visualization in Figure 6.1, some groups of high values stand out in different positions. An example is the high relation of requirement i_{26}, the hosting of an external staff, with the functions accompanying hotel facilities. This is caused by the need for additional hotel facilities for this added staff. Another group that stands out consists of requirements i_{22} till i_{24} and the accompanying functions j_{44} till j_{46}. This shows the usage of electronic warfare to detect and neutralize ASW, ASuW, and AAW threats.



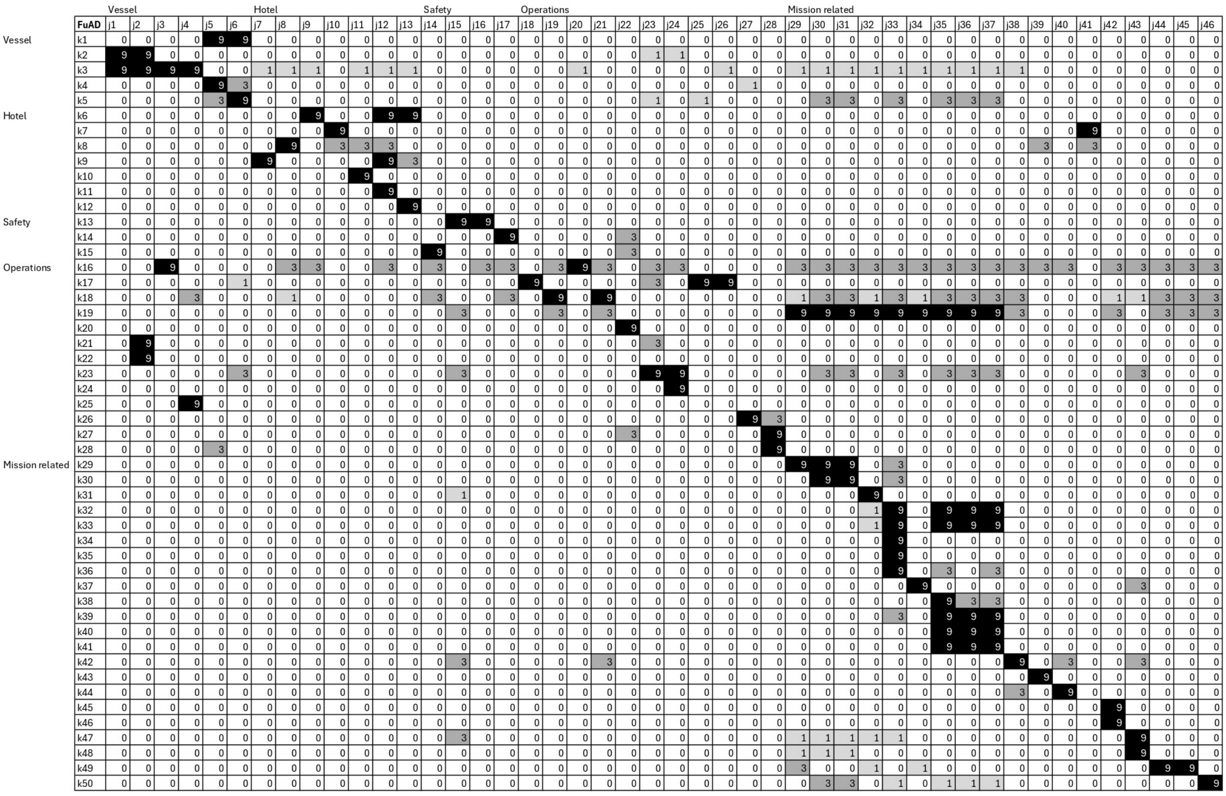
		Vessel						Hotel							Safety				Operations											Mission related																	
	FuAD	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16	j17	j18	j19	j20	j21	j22	j23	j24	j25	j26	j27	j28	j29	j30	j31	j32	j33	j34	j35	j36	j37	j38	j39	j40	j41	j42	j43	j44	j45	j46
Vessel	i1	9	9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i2	9	9	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i3	3	3	9	9	0	0	3	3	3	3	3	3	3	0	0	0	0	0	0	1	0	3	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i4	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i5	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i6	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	3	0	3	3	3	0	0	0	0	0	9	0	0	0
Hotel	i7	0	0	3	3	0	0	3	0	9	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
	i8	0	0	1	1	0	9	1	3	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0
	i9	0	0	3	3	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	9	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	0	0	0	0	0
	i10	0	0	3	3	0	0	3	0	3	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i11	0	0	1	1	0	0	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0
Safety	i12	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	1	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Operations	i16	3	3	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	9	3	9	1	3	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
	i17	0	0	0	0	0	0	0	1	0	0	0	0	0	3	1	0	1	0	9	0	9	0	3	3	3	1	1	0	3	3	3	3	3	3	3	3	3	0	0	0	0	3	0	3	3	3
	i18	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	0	3	0	3	3	3	3	3
	i19	3	3	0	0	1	0	0	0	0	0	0	0	0	0	9	0	0	9	1	1	1	0	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
	i20	3	3	0	0	3	1	0	0	0	0	0	0	0	0	9	0	0	9	1	1	1	0	9	9	9	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i21	0	0	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission related	i22	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	3	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9
	i23	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	3	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	9	9	9	9
	i24	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	3	0	0	0	0	0	0	0	0	0	0	9	9	9	9	0	0	0	0	0	0	9	9	9
	i25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0
	i26	0	0	0	0	0	3	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0
	i27	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	i28	0	0	0	0	9	9	0	0	0	0	0	0	0	0	9	0	0	0	0	9	3	3	3	0	0	0	0	0	9	0	9	9	9	0	0	0	0	0	0	0	0	0	9	0	0	0
	i29	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	3	9	3	0	0	0	0	0	9	9	0	9	0	9	9	9	0	0	0	0	0	0	0	9	9	9

Figure 6.1: QFD FuAD

6.3 DPM

By using the DPM, it can be analyzed which systems are related to which functions. Another advantage is the ability to check if every function has an accompanying system, and if every system has a function. This way, it can be avoided that a function cannot be fulfilled or an unnecessary system is implemented. The DPM for the FuAD can be seen in Figure 6.2.

Most of the strong relationships are approximately on the diagonal. This is caused by translating functions into systems, where the accompanying systems are approximately at the same place in the list as the functions they fulfill. What stands out is the high coupling of system k_{19}, the command information centre, with functions j_{29} till j_{37}, the detection and neutralization of ASW, ASuW, and AAW threats. This relationship is caused by the indispensable function of the command information centre where all incoming information from sensors and radars are processed and the weapon systems are controlled.



		Vessel						Hotel							Safety				Operations											Mission related																	
	FuAD	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16	j17	j18	j19	j20	j21	j22	j23	j24	j25	j26	j27	j28	j29	j30	j31	j32	j33	j34	j35	j36	j37	j38	j39	j40	j41	j42	j43	j44	j45	j46
Vessel	k1	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k2	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k3	9	9	9	9	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
	k4	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k5	0	0	0	0	3	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	3	3	0	3	0	3	3	3	0	0	0	0	0	0	0	0	0
Hotel	k6	0	0	0	0	0	0	0	0	9	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k7	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0
	k8	0	0	0	0	0	0	0	9	0	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0
	k9	0	0	0	0	0	0	9	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k10	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k11	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k12	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safety	k13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k15	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Operations	k16	0	0	9	0	0	0	0	3	3	0	0	3	0	3	0	3	3	0	3	9	3	0	3	3	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	3	0	3	3	3	3	3
	k17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k18	0	0	0	3	0	0	0	1	0	0	0	0	0	3	0	0	3	0	9	0	9	0	0	0	0	0	0	0	1	3	3	1	3	1	3	3	3	3	0	0	0	1	1	3	3	3
	k19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	0	3	0	0	0	0	0	0	0	9	9	9	9	9	9	9	9	9	3	0	0	0	3	0	3	3	3
	k20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k21	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k22	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k23	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	9	9	0	0	0	0	0	3	3	0	3	0	3	3	3	0	0	0	0	0	3	0	0	0
	k24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k25	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k28	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission related	k29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
	k30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
	k31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	0	9	9	9	0	0	0	0	0	0	0	0	0
	k33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	9	0	9	9	9	0	0	0	0	0	0	0	0	0
	k34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
	k35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
	k36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	3	0	3	0	0	0	0	0	0	0	0	0
	k37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	3	0	0	0
	k38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	3	0	0	0	0	0	0	0	0	0
	k39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	9	9	9	0	0	0	0	0	0	0	0	0
	k40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0
	k41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0
	k42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	3	0	0	3	0	0	0
	k43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0
	k44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	9	0	0	0	0	0	0
	k45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	k46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	k47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	9	0	0	0
	k48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0
	k49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	1	0	0	0	0	0	0	0	0	0	9	9	0
	k50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	1	0	1	1	1	0	0	0	0	0	0	0	0	9

Figure 6.2: DPM FuAD

6.4 MIM

The next step is to rate the systems for their potential modular advantages. The questions, as computed by Fuchs and Golenhofen [25], are formulated below in italics. The interpretation of these modularity drivers is described below the questions, after which the computed MIM for both the FuAD and LPD-2 can be seen in respectfully Figure 6.3 and Figure 6.4.

l_1 *Different specification - Is this part <strongly, fairly, to some extent, not> influenced by specific requirements?*
This modularity driver aims to identify the way in which a specific system is required for a specific vessel type. An example is the air surveillance radar, which will needs to be the state-of-the-art on an air defender to protect the fleet, while a transportation vessel just needs to identify threats for itself. So both vessel types need an air surveillance radar, but the requirements of the system are different, indicating the radar is strongly influenced by specific requirements.

l_2 *Styling - Is this part <strongly, fairly, to some extent, not> influenced by trends and fashion in such a way that form and/or color has to be altered or should it be tied to a trademark?*
This modularity driver aims to identify the way in which systems are influenced by trends and fashion. For naval vessels, the design needs to be functional rather than trendy. Therefore, only some minor systems, such as the cabins and dayroom, are very limited influenced by styling.

l_3 *Carry over - Are there <strong, medium, any, no> reasons that this technical solution should be a separate module because the new design can be carried over to future product generations?*
This modularity driver aims to identify the level in which systems can be carried over to future designs. An important factor is the economic value of the system. If an old system could be carried over, but is relatively cheap and demolishing the system takes a lot of time, such as the interior of a cabin, a new system could be preferred. An example of an expensive system which would be preferred to be carried over would be the state-of-the-art radar systems on the vessels, which are updated when deemed necessary throughout the vessel's lifecycle. This can be seen with the SMART-L and APAR radars, which are currently installed on the LCFs but will be carried over to the FuAD [98].

l_4 *Technology push - Is there <great, medium, some, no> risk that this part will go through a technology shift during the product lifecycle?*
This modularity driver aims to identify the likelyhood a system needs to be updated throughout the vessel's lifecycle by technical developments outside the navy itself. An example would be the RAM system, which could be replaced if an effective laser-weapon becomes available on the market [61].

l_5 *Product planning - Are there <strong, medium, some, no> reasons why this part should be a separate module since it is the carrier of attributes that will be changed according to a product plan?*
This modularity driver aims to identify the likelyhood a system needs to be updated throughout the vessel's lifecycle by technical developments performed by the navy itself. This modularity driver is closely related to l_4 since navies often work together with the industry to develop new technologies.

l_6 *Common unit - Can this function have the same physical form in <all, most, some, none> of the product variants?*
This modularity driver aims to identify commonality between different product variants. For the RNLN, a comparison can be made between the commonality between different vessel types.

l_7 *Process and/or organisation - Are there <strong, medium, some, no> reasons why this part should be a separate module because (a) A specific or specialized process is needed? (b) It has suitable work content for a group? (c) The lead time will differ extraordinarily?*
This modularity driver aims to identify if systems have a suitable collection of technology driven work content for a manufacturing cell or work group, which could result in a shorter delivery time. Since navies often design small series, it could be beneficial to look into work groups that could cooperate between different vessel types. Because of this, in the case of the RNLN, this modularity driver is closely related to l_6 to focus on commonality between vessel types. Another possibility is to look for decoupled systems so the work groups can work independently.

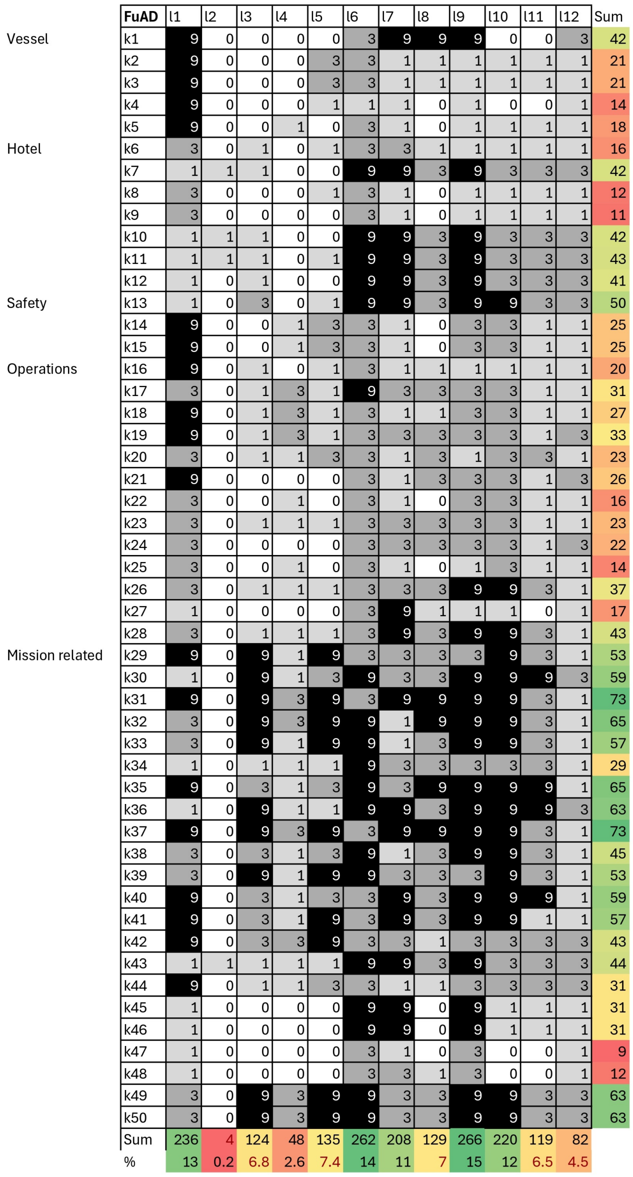
l_8 *Separate testing - Are there <strong, medium, some, no> reasons why this part should be a separate module because its function can be tested separately?*
This modularity driver aims to identify in which level a system could be independently tested. In other words, this modularity driver indicates how independently a system can operate from to the vessel.

l_9 *Purchase - Are there <strong, medium, some, no> reasons that this part should be a separate module because (a) There are specialists that can deliver the technical solution as a black box? (b) The logistics cost can be reduced? (c) The manufacturing and development capacity can be balanced?*
This modularity driver aims to identify possible purchase advantages for the system. If a system could be purchased as a black box, engineering costs and time could be saved. Another possible purchase advantage for small series is to look at the commonality between different vessel types (l_6) to increase scale advantages and decrease development time if a common module could be designed.

l_{10} *Service and maintenance - Is it possible that <all, most, some, none> of the service repairs will be easier if this part is easily detachable?*
This modularity driver aims to identify the level at which making a system easily detachable could ease service and maintenance. This can be done by reducing the required service and maintenance time, for instance by making it more accessible by detaching it, or by detaching a system and maintaining it at port, while a new module is installed so the vessel is ready for operations quickly again.

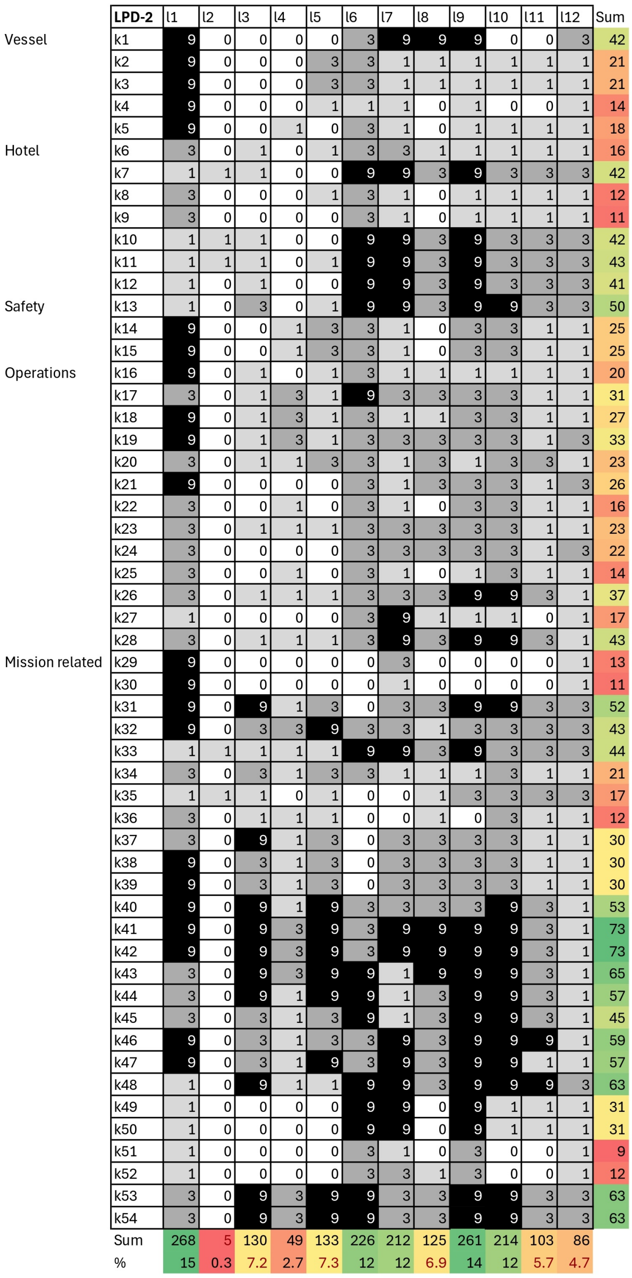
l_{11} *Upgrading - Can <all, most, some, none> of the future upgrading be simplified if this part is easy to change?*
This modularity driver aims to identify how easily a system could be upgraded when it is easy to change. An important difference compared to l_{11} is that an upgrade could require significant changes in the vessel itself, rather than just replacing the current system with a new one. An example is the replacement of the old 127 mm-canon for an upgraded version. Instead of just replacing the canon, a major refit of the systems on board, such as the munition-transportation system, was required, resulting in a 3-deck deep project [59]. Therefore, a system that is easy to change does not necessarily simplify future upgrading.

l_{12} *Recycling - Is it possible to keep <all, most, some, none> of the highly polluting material or easy recyclable material in this part (material purity)?*
This modularity driver aims to identify in which level a system is recyclable. In the case of the RNLN, the naval vessels are not designed to be recyclable [90]. Therefore, most systems are only limited recyclable.



	FuAD	l1	l2	l3	l4	l5	l6	l7	l8	l9	l10	l11	l12	Sum
Vessel	k1	9	0	0	0	0	3	9	9	9	0	0	3	42
	k2	9	0	0	0	3	3	1	1	1	1	1	1	21
	k3	9	0	0	0	3	3	1	1	1	1	1	1	21
	k4	9	0	0	0	1	1	1	0	1	0	0	1	14
	k5	9	0	0	1	0	3	1	0	1	1	1	1	18
Hotel	k6	3	0	1	0	1	3	3	1	1	1	1	1	16
	k7	1	1	1	0	0	9	9	3	9	3	3	3	42
	k8	3	0	0	0	1	3	1	0	1	1	1	1	12
	k9	3	0	0	0	0	3	1	0	1	1	1	1	11
	k10	1	1	1	0	0	9	9	3	9	3	3	3	42
	k11	1	1	1	0	1	9	9	3	9	3	3	3	43
	k12	1	0	1	0	0	9	9	3	9	3	3	3	41
Safety	k13	1	0	3	0	1	9	9	3	9	9	3	3	50
	k14	9	0	0	1	3	3	1	0	3	3	1	1	25
	k15	9	0	0	1	3	3	1	0	3	3	1	1	25
Operations	k16	9	0	1	0	1	3	1	1	1	1	1	1	20
	k17	3	0	1	3	1	9	3	3	3	3	1	1	31
	k18	9	0	1	3	1	3	1	1	3	3	1	1	27
	k19	9	0	1	3	1	3	3	3	3	3	1	3	33
	k20	3	0	1	1	3	3	1	3	1	3	3	1	23
	k21	9	0	0	0	0	3	1	3	3	3	1	3	26
	k22	3	0	0	1	0	3	1	0	3	3	1	1	16
	k23	3	0	1	1	1	3	3	3	3	3	1	1	23
	k24	3	0	0	0	0	3	3	3	3	3	1	3	22
	k25	3	0	0	1	0	3	1	0	1	3	1	1	14
	k26	3	0	1	1	1	3	3	3	9	9	3	1	37
	k27	1	0	0	0	0	3	9	1	1	1	0	1	17
	k28	3	0	1	1	1	3	9	3	9	9	3	1	43
Mission related	k29	9	0	9	1	9	3	3	3	3	9	3	1	53
	k30	1	0	9	1	3	9	3	3	9	9	9	3	59
	k31	9	0	9	3	9	3	9	9	9	9	3	1	73
	k32	3	0	9	3	9	9	1	9	9	9	3	1	65
	k33	3	0	9	1	9	9	1	3	9	9	3	1	57
	k34	1	0	1	1	1	9	3	3	3	3	3	1	29
	k35	9	0	3	1	3	9	3	9	9	9	9	1	65
	k36	1	0	9	1	1	9	9	3	9	9	9	3	63
	k37	9	0	9	3	9	3	9	9	9	9	3	1	73
	k38	3	0	3	1	3	9	1	3	9	9	3	1	45
	k39	3	0	9	1	9	9	3	3	3	9	3	1	53
	k40	9	0	3	1	3	3	9	3	9	9	9	1	59
	k41	9	0	3	1	9	3	9	3	9	9	1	1	57
	k42	9	0	3	3	9	3	3	1	3	3	3	3	43
	k43	1	1	1	1	1	9	9	3	9	3	3	3	44
	k44	9	0	1	1	3	3	1	1	3	3	3	3	31
	k45	1	0	0	0	0	9	9	0	9	1	1	1	31
	k46	1	0	0	0	0	9	9	0	9	1	1	1	31
	k47	1	0	0	0	0	3	1	0	3	0	0	1	9
	k48	1	0	0	0	0	3	3	1	3	0	0	1	12
	k49	3	0	9	3	9	9	3	3	9	9	3	3	63
	k50	3	0	9	3	9	9	3	3	9	9	3	3	63
	Sum	236	4	124	48	135	262	208	129	266	220	119	82	
	%	13	0.2	6.8	2.6	7.4	14	11	7	15	12	6.5	4.5	

Figure 6.3: FuAD MIM



	LPD-2	l1	l2	l3	l4	l5	l6	l7	l8	l9	l10	l11	l12	Sum
Vessel	k1	9	0	0	0	0	3	9	9	9	0	0	3	42
	k2	9	0	0	0	3	3	1	1	1	1	1	1	21
	k3	9	0	0	0	3	3	1	1	1	1	1	1	21
	k4	9	0	0	0	1	1	1	0	1	0	0	1	14
	k5	9	0	0	1	0	3	1	0	1	1	1	1	18
Hotel	k6	3	0	1	0	1	3	3	1	1	1	1	1	16
	k7	1	1	1	0	0	9	9	3	9	3	3	3	42
	k8	3	0	0	0	1	3	1	0	1	1	1	1	12
	k9	3	0	0	0	0	3	1	0	1	1	1	1	11
	k10	1	1	1	0	0	9	9	3	9	3	3	3	42
	k11	1	1	1	0	1	9	9	3	9	3	3	3	43
	k12	1	0	1	0	0	9	9	3	9	3	3	3	41
Safety	k13	1	0	3	0	1	9	9	3	9	9	3	3	50
	k14	9	0	0	1	3	3	1	0	3	3	1	1	25
	k15	9	0	0	1	3	3	1	0	3	3	1	1	25
Operations	k16	9	0	1	0	1	3	1	1	1	1	1	1	20
	k17	3	0	1	3	1	9	3	3	3	3	1	1	31
	k18	9	0	1	3	1	3	1	1	3	3	1	1	27
	k19	9	0	1	3	1	3	3	3	3	3	1	3	33
	k20	3	0	1	1	3	3	1	3	1	3	3	1	23
	k21	9	0	0	0	0	3	1	3	3	3	1	3	26
	k22	3	0	0	1	0	3	1	0	3	3	1	1	16
	k23	3	0	1	1	1	3	3	3	3	3	1	1	23
	k24	3	0	0	0	0	3	3	3	3	3	1	3	22
	k25	3	0	0	1	0	3	1	0	1	3	1	1	14
	k26	3	0	1	1	1	3	3	3	9	9	3	1	37
	k27	1	0	0	0	0	3	9	1	1	1	0	1	17
	k28	3	0	1	1	1	3	9	3	9	9	3	1	43
Mission related	k29	9	0	0	0	0	0	3	0	0	0	0	1	13
	k30	9	0	0	0	0	0	1	0	0	0	0	1	11
	k31	9	0	9	1	3	0	3	3	9	9	3	3	52
	k32	9	0	3	3	9	3	3	1	3	3	3	3	43
	k33	1	1	1	1	1	9	9	3	9	3	3	3	44
	k34	3	0	3	1	3	3	1	1	1	3	1	1	21
	k35	1	1	1	0	1	0	0	1	3	3	3	3	17
	k36	3	0	1	1	1	0	0	1	0	3	1	1	12
	k37	3	0	9	1	3	0	3	3	3	3	1	1	30
	k38	9	0	3	1	3	0	3	3	3	3	1	1	30
	k39	9	0	3	1	3	0	3	3	3	3	1	1	30
	k40	9	0	9	1	9	3	3	3	3	9	3	1	53
	k41	9	0	9	3	9	3	9	9	9	9	3	1	73
	k42	9	0	9	3	9	3	9	9	9	9	3	1	73
	k43	3	0	9	3	9	9	1	9	9	9	3	1	65
	k44	3	0	9	1	9	9	1	3	9	9	3	1	57
	k45	3	0	3	1	3	9	1	3	9	9	3	1	45
	k46	9	0	3	1	3	3	9	3	9	9	9	1	59
	k47	9	0	3	1	9	3	9	3	9	9	1	1	57
	k48	1	0	9	1	1	9	9	3	9	9	9	3	63
	k49	1	0	0	0	0	9	9	0	9	1	1	1	31
	k50	1	0	0	0	0	9	9	0	9	1	1	1	31
	k51	1	0	0	0	0	3	1	0	3	0	0	1	9
	k52	1	0	0	0	0	3	3	1	3	0	0	1	12
	k53	3	0	9	3	9	9	3	3	9	9	3	3	63
	k54	3	0	9	3	9	9	3	3	9	9	3	3	63
	Sum	268	5	130	49	133	226	212	125	261	214	103	86	
	%	15	0.3	7.2	2.7	7.3	12	12	6.9	14	12	5.7	4.7	

Figure 6.4: LPD-2 MIM

6.5 Result analysis MFD

First, the top modularity drivers, shown in Table 6.4, are analyzed. This way, it can be checked if the expected benefits are the actual potential benefits when applying modularity. It can be seen that for both the FuAD and LPD-2 l_9, l_6, l_1, l_7, and l_{10}, although in a slightly different order, form the top-5. When comparing it to the challenges the RNLN faces, it can be seen the possible mitigation of 'Maintenance & Upgrades' will mainly result in a potential benefit in service and maintenance, excluding upgrades. The difference is that an upgrade could require significant changes in the vessel, rather than just replacing the current system with a new one. An example is the replacement of the old 127 mm-canon for an upgraded version, which resulted in a 3-deck deep project [59]. Therefore, a system that is easy to change does not necessarily simplify future upgrading. Furthermore, the three modularity drivers purchase, common unit, and process and/or organisation indicate the challenges for the 'high design and production time for small series' and 'high economic costs for small series' can be mitigated by the application of modularity. This indicates that using systems across the fleet will result in increased scale advantages.

Table 6.4: Top modularity drivers

FuAD			**LPD-2**		
Rank	**Modularity driver**	**Score**	**Rank**	**Modularity driver**	**Score**
1	l_9; Purchase	266(15%)	1	l_1; Different specification	268(15%)
2	l_6; Common unit	262(14%)	2	l_9; Purchase	261(14%)
3	l_1; Different specification	236(13%)	3	l_6; Common unit	226(12%)
4	l_{10}; Service and maintenance	220(12%)	4	l_{10}; Service and maintenance	214(12%)
5	l_7; Process and/or organisation	208(11%)	5	l_7; Process and/or organisation	212(12%)
Total points		1833	Total points		1812

The top-5 most potential modular systems are formulated in Table 6.5. Again, much overlap between the FuAD and LPD-2 can be seen. These are systems that can be used, possibly in more or less advanced versions, on multiple vessel types across the fleet. This can be achieved by less advanced components in the system, while the interface remains the same, making it suitable as a module. These results indicate increased scale advantages as well; the ability to use similar systems across the fleet results in high-potential modules.

Table 6.5: Top systems

FuAD			**LPD-2**		
Rank	**System**	**Score**	**Rank**	**System**	**Score**
1	k_{31}; Horizon surveillance radar	73	1	k_{40}; Horizon surveillance radar	73
1	k_{37}; Air surveillance radar	73	1	k_{41}; Air surveillance radar	73
3	k_{35}; Surface-to-surface missile	71	3	k_{42}; Tracking radar	65
4	k_{32}; Tracking radar	65	4	k_{47}; Heavy machineguns	63
5	k_{36}; Heavy machineguns	63	4	k_{52}; Electronic Support Measures	63
5	k_{49}; Electronic Support Measures	63	4	k_{53}; Electronic Counter Measures	63
5	k_{50}; Electronic Counter Measures	63			
Total points		1833	Total points		1812
Average points per system		36.66	Average points per system		33.56

6.6 Discussion & Conclusion MFD

This section will start with the discussion in subsection 6.6.1. Next, the conclusion is formulated in subsection 6.6.2.

6.6.1 Discussion

First of all, it must be kept in mind that the MFD already assumes the use of modularity, and only checks how systems could benefit from modularity rather than questioning if modularity improves it at all. In this thesis, MFD is used to identify the high-potential modular systems, which can be used in decision-making to use modularity.

When applying the MFD, it is important to keep in mind how modular systems are already. An example is the Vertical Launching System (VLS, k_{34}), which is designed to handle any missile type in any cell, making it an extremely flexible system [35]. Since this is already a modular system, there are very few benefits to making it modular. The high score in the MFD comes from strong commonality and organizational advantages coupled with commonality, and the medium score is from purchase, separate testing, maintainability, and upgradability. It is important to understand that these benefits have already been achieved since the VLS is a modular system that can be bought off the shelf while being ready for usage [35]. So even though the VLS is already a modular system with proven benefits in system flexibility [35], it does not come out of the MFD as a potentially good module. Therefore, using the MFD will indicate which non-modular systems could benefit from modularity while modular systems can give invalid results.

6.6.2 Conclusion

When looking at both the modularity drivers and high-potential modular systems, it can be seen the expected benefits are a result of the wider use of systems across the fleet, which increases scale advantages. With on average 36.66 points per system for the FuAD and 33.56 points for the LPD-2, the FuAD seems to be more suitable for modularity application. When looking at commonality across vessel types, this conclusion is reasonable. The LPD-2 has more unique functions, such as the task of conducting amphibious operations and providing hospital facilities, while the FuAD shares more common systems across different frigate types, such as weapon systems.

Most results are in line with the possible mitigations, while the possible mitigation of 'Maintenance & Upgrades' will mainly result in a potential benefit in maintenance, and not necessarily upgrades. The difference is that an upgrade could require significant changes in the vessel's construction, rather than just replacing the current system with a new one. For this reason, modularity will also not necessarily improve short-term adaptability, since it is not guaranteed a system can easily be replaced by another one.

7

Framework AHP

The next step in the framework is to apply the AHP method. Where the MFD focuses on identifying high-potential modular systems based on modularity drivers, the AHP focuses on identifying them based on their reciprocal importance during naval operations. By identifying the most important functions of the vessel with the AHP and combining this with the results from the MFD, an indication for high-potential modules can be retrieved. MFD identifies high-potential modules based on modularity drivers, while AHP can identify them based on their reciprocal importance during naval operations. When an MOP is identified as highly important after AHP application, and its accompanying system has a high score in the MFD, this indicates modularity can improve the design. The coupling of systems to MOPs consists of multiple steps. First, the MOP will be coupled to functions for the FuAD and LPD-2. By using the DPM for FuAD and LPD-2, these functions can be coupled to its accompanying systems. This way, an MOP can be coupled to specific systems.

First, the properties of the AHP are formulated in section 7.1. Next, the computation of the pairwise comparison matrices is discussed in section 7.2, after which the results are analyzed in section 7.3. The chapter ends with a conclusion and discussion in subsection 7.4.2.

7.1 Define properties AHP

The first step is to identify the vessel's OMOEs, MOEs, and MOPs. The level of detail should be considered well because enough detail should be present to gain sufficient results, while too much detail will result in an abundance of large matrices. These large matrices are cumbersome to complete because they must be filled in manually. To keep the matrices coherent, not every function is translated into an MOP. The MOPs will focus on the naval operations, which makes a naval vessel unique. General functions required for a vessel (j_1 - j_{17}), such as the hotel facilities, are left out of the MOP overview. Functions accompanying basic vessel command operations (j_{18}, j_{19}, j_{21}, j_{23}) are combined in MOP1 'Vessel command capability'. The mission-related functions are translated into more detailed MOPs. An example for FuAD is the translation from the function 'To neutralize long-range threats through the air' (j_{36}) to MOP14 'Long-range air defense'. The OMOEs for FuAD are the overall mission effectiveness on top, and the Task Force Command & Control and Task Force Escort operations on the second level. The MOEs are split into Command, Control, ASW, ASuW, and AAW. The MOPs are the functions required to conduct the operations mentioned as MOE. The overview of the OMOEs, MOEs, and MOPs can be seen in respectively Table 7.1, Table 7.2, and Table 7.3. The reason the LPD-2 has an OMOE 'Others' and the FuAD does not, is that the LPD-2 has multiple secondary tasks that it is designed for, such as hospital facilitation, self-defense, and sea-basing. Self-defense is put as a secondary task since an amphibious vessel usually operates within a fleet, which should neutralize threats before it reaches the amphibious vessel. Since these are secondary tasks, a 'other' category is made to make a clear division between secondary and primary tasks. The FuAD is only designed for its primary tasks and does therefore not include an OMOE 'others'.

An overview of these parameters is shown in the MOP breakdown structure in Figure 7.1 and Figure 7.2 for respectively the FuAD and the LPD-2. When computing the breakdown trees, it is important to think about the distribution of the parameters in the structure. For example, when comparing the MOPs accompanied by the MOE ASuW, it could be a choice to compare the importance of the detection systems and the weapon systems under one MOE. However, the vessel cannot defend itself if a threat cannot be detected or when a threat can be detected but not neutralized. Therefore, the MOPs used for detection can be compared to their reciprocal importance while the neutralization MOPs should be rated in a separate matrix. Therefore, this thesis will split the MOEs ASW (MOE3), ASuW (MOE4), and AAW (MOE5) into detection and neutralization components (MOEX.1 and MOEX.2 respectively). To keep the matrices coherent, the MOE detection contains everything until the action for neutralization.

Table 7.1: OMOE overview

OMOE FuAD	**OMOE LPD-2**
OMOE: Overall mission effectiveness FuAD	OMOE: Overall mission effectiveness LPD-2
OMOE1: Task force Command & Control	OMOE1: Task force Command & Control
OMOE2: Task force escort	OMOE2: Amphibious operations
	OMOE3: Others

Table 7.2: MOE overview

MOE FuAD	**MOE LPD-2**
MOE1: Command	MOE1: Command
MOE2: Control	MOE2: Control
MOE3: ASW	MOE3: Landing operations
MOE3.1:Detection	
MOE3.1:Neutralization	
MOE4: ASuW	MOE4: Hospital facilities
MOE4.1:Detection	
MOE4.1:Neutralization	
MOE5: AAW	MOE5: Sea-basing
MOE5.1:Detection	
MOE5.1:Neutralization	
	MOE6: Self-defense
	MOE6.1:Detection
	MOE6.1:Neutralization

Table 7.3: Overall MOP overview

MOP1: Vessel command capability	MOP12: Prevent detection by EW
MOP2: Task force command capability	MOP13: Evade incoming enemy threat by EW
MOP3: Communication capabilities	MOP14: Long-range air defense
MOP4: Detect objects on the surface	MOP15: Short-range air defense
MOP5: Detect objects above the surface	MOP16: Vehicle storage
MOP6: Detect objects under the surface	MOP17: Vehicle LC transferring
MOP7: Underwater ranged weapon	MOP18: Personnel LC transferring
MOP8: Track enemy threat	MOP19: Low-care medical capability
MOP9: Control fired projectile	MOP20: Intensive care capability
MOP10: High impact surface weapon	MOP21: Operating capability
MOP11: Low impact surface weapon	MOP22: Station keeping

The MOPs can be coupled to at least one mission-related function. This is done in Table 7.4. From the mission-related functions, only CBRN protection (FuAD j_{42}, LPD-2 j_{44}) and helicopter operations support (FuAD j_{43}, LPD-2 j_{45}) are left out of the MOPs. This choice has been made because the systems accompanying these functions are out of the scope of this thesis. For CBRN defense, a citadel is used (air-tide outer layer on the vessel) to ensure no intoxicated air comes in and a wetting system is used to wash residues off the vessel. CBRN defense is not part of typical vessel operations but must be present in the event of a CBRN attack to protect the crew. The systems accompanying the helicopter operations support function are the helicopter deck and hanger. These systems must be able to handle different helicopter types and are independent of how the helicopters, or in the future possibly drones, are used. Since the vessel's design is not affected by the type of operations these aircraft perform, while it is a hard requirement the vessel can handle these aircraft [89], the accompanying systems are left out as MOP.

Table 7.4: MOPs and their accompanying functions

MOP	**Accompanying functions FuAD**	**Accompanying functions LPD-2**
MOP1	$j_{18}, j_{19}, j_{21}, j_{23}$	$j_{18}, j_{19}, j_{21}, j_{23}$
MOP2	$j_{38}, j_{39}, j_{40}, j_{41}$	$j_{31}, j_{32}, j_{33}, j_{34}, j_{35}$
MOP3	See note 1	See note 1
MOP4	j_{32}	j_{42}
MOP5	j_{34}	j_{40}
MOP6	j_{29}	j_{38}
MOP7	j_{31}	N/A
MOP8	$j_{30}, j_{31}, j_{33}, j_{35}, j_{36}, j_{37}$ (See note 2)	j_{39}, j_{41}, j_{43} (See note 2)
MOP9	$j_{30}, j_{31}, j_{33}, j_{35}, j_{36}, j_{37}$ (See note 2)	j_{39}, j_{41}, j_{43} (See note 2)
MOP10	j_{33}	j_{43}
MOP11	j_{33}	j_{43}
MOP12	j_{44}, j_{45}, j_{46}	j_{46}, j_{47}, j_{48}
MOP13	j_{46}	j_{48}
MOP14	j_{36}, j_{37}	N/A
MOP15	j_{35}, j_{37}	j_{41}
MOP16	N/A	j_{29}, j_{30}
MOP17	N/A	j_{29}, j_{30}
MOP18	N/A	j_{29}, j_{30}
MOP19	N/A	j_{37}
MOP20	N/A	j_{37}
MOP21	N/A	j_{37}
MOP22	N/A	j_{36}

Note 1: MOP3 (Communication capabilities) is important for almost all mission related functions. Without communication, either between the crew or staff on shore, the vessel cannot operate

Note 2: Tracking the threat and controlling fired projectile are required for every type of neutralization.

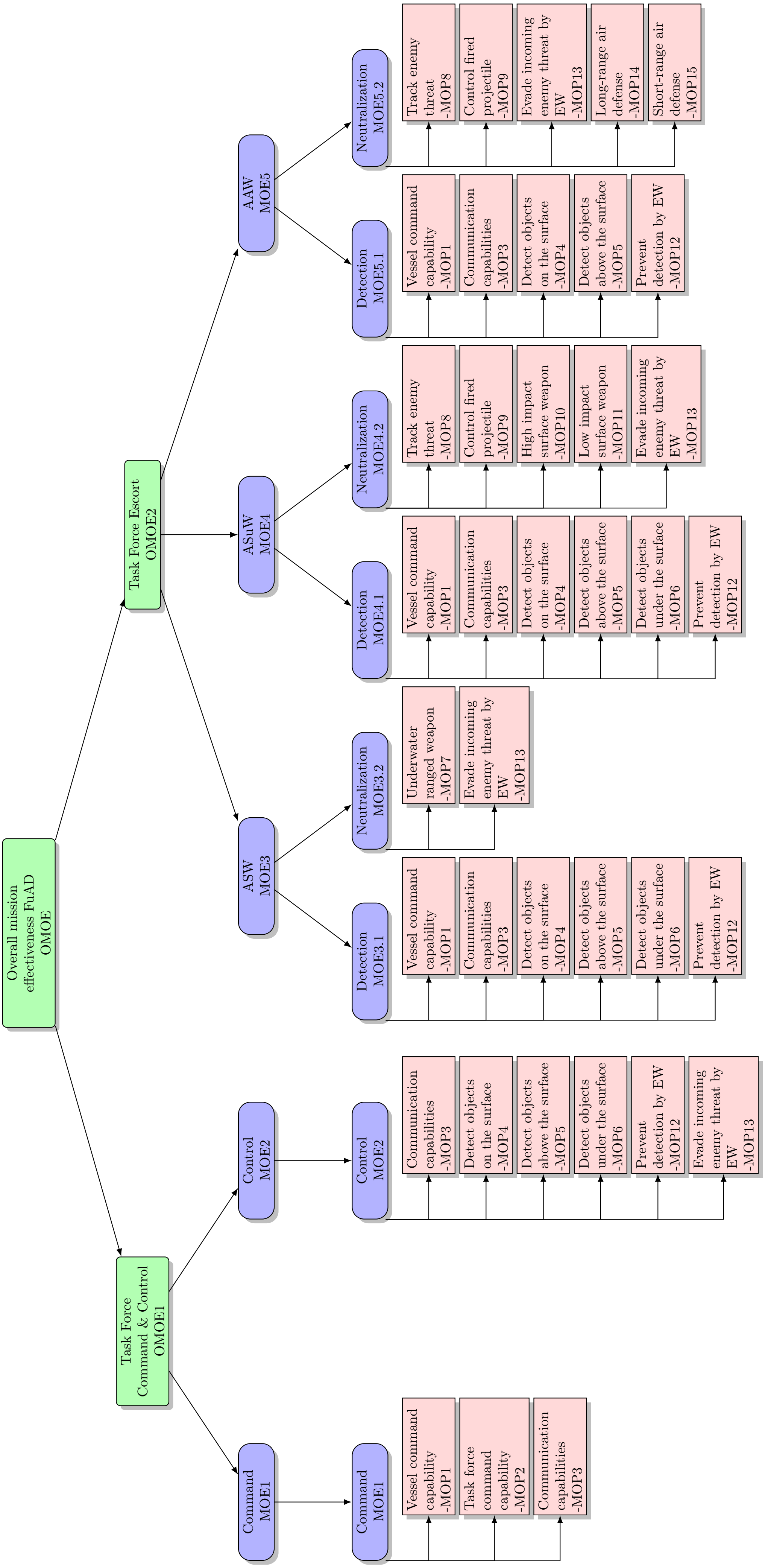


Figure 7.1: MOP Breakdown Structure FuAD

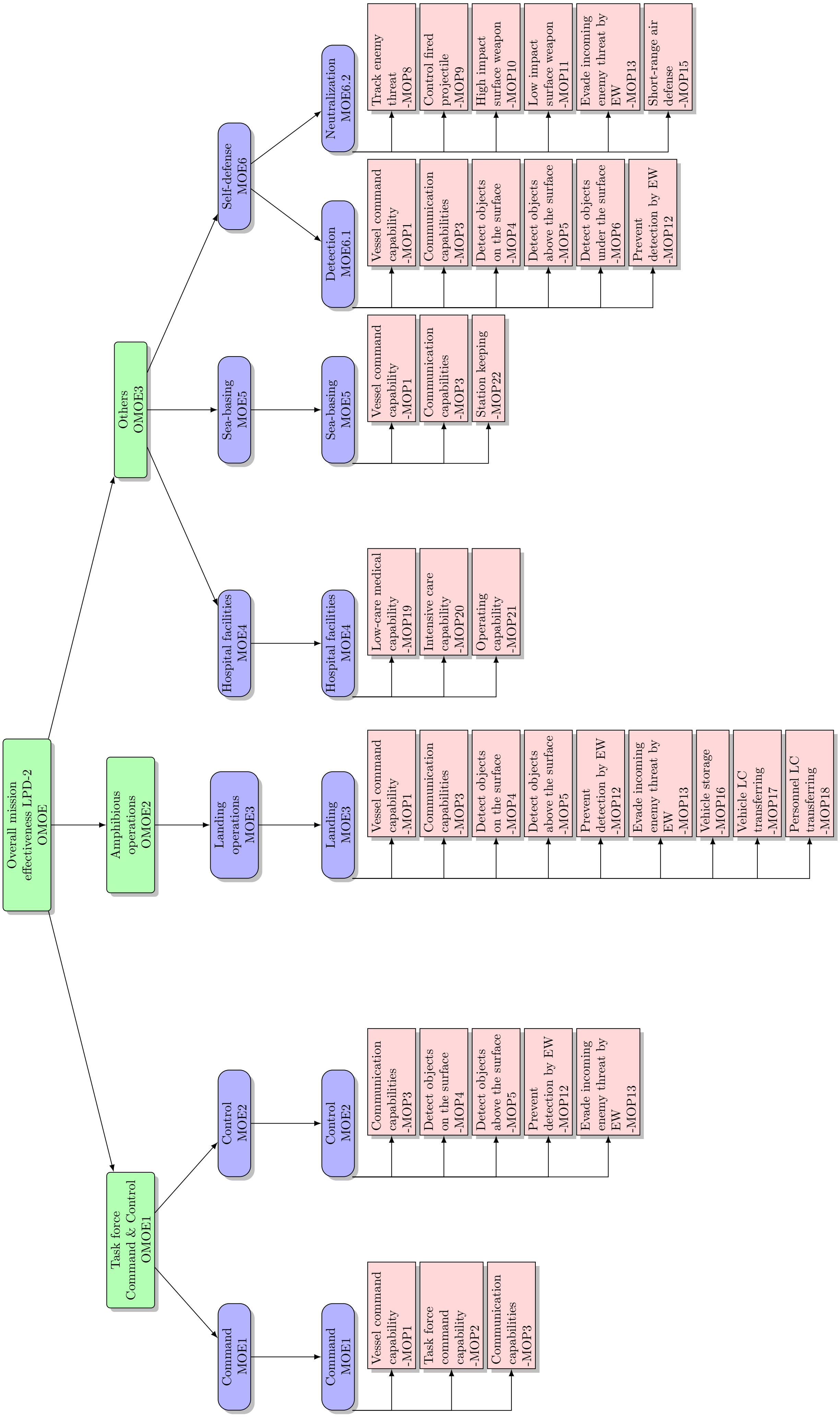


Figure 7.2: MOP Breakdown Structure LPD-2

7.2 Pairwise comparison matrices

The next step is to compute the pairwise comparison matrices derived from the MOP breakdown trees. A junior naval architect (<2 years of experience), naval architect (2-8 years of experience), and senior naval architect (8+ years of experience) from COMMIT were asked to fill in the pairwise comparison matrices using the rating scale shown in Table 7.5.

Table 7.5: Rating scale AHP

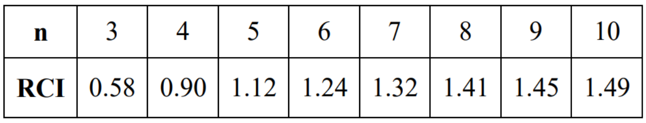
Definition	**Intensity**
1	A and B equally important
2	A is weakly more important than B
3	A is strongly more important than B
4	A is very strongly more important than B
5	A is extremely or absolutely more important than B

The geometric mean of the three matrices is taken to gain valid results for the average values of the AHP [48]. The equation to retrieve the geometric mean can be seen in Equation 7.1. When naval architect 1 prefers A over B by 3 and naval architect 2 prefers B over A by 3 (thus A over B is $\frac{1}{3}$), the geometric mean will be 1 and determine A and B are equally important, while taking the arithmetic mean (the sum of a series of numbers divided by the number of items in that series) will result in a value of ≈ 1.667. It is important to notice the impact when both naval architects agree one parameter is more important than the other but disagree on the rating. When naval architect 1 rates A over B by 3 and naval architect 2 rates it by 5, the arithmetic mean will be 4, while the geometric mean will be ≈ 3.87. This shows that using the geometric mean increases the weight of the lowest value when determining the average.

$$\bar{\mathrm{a}} = \sqrt[n]{a_1 \cdot a_2 \cdots a_n} \tag{7.1}$$

The next step is to assess the quality of the expert opinion in these matrices. This quality assessment can be done by checking each individual matrix for consistency [76]. A matrix is consistent when $a_{i,j} = a_{i,k} \cdot a_{k,j} \; \forall \; i, j, k$ [75]. Since it requires at least three different rows or columns (n>3), a 2x2 matrix cannot be evaluated on consistency. Since pairwise comparison matrices are computed by expert opinion, they are often inconsistent. For example, when looking at Table 7.6, it can be seen $a_{1,3} = \frac{1}{5}$, $a_{1,2} = \frac{1}{3}$, and $a_{2,3} = \frac{1}{2}$. For a consistent matrix, $a_{1,3} = a_{1,2} \cdot a_{2,3} = \frac{1}{5}$. However, in reality, the result is $\frac{1}{3} \cdot \frac{1}{2} = \frac{1}{6} \neq \frac{1}{5}$. This shows the matrix is not consistent. The Consistency Ratio (CR) can indicate how consistent a matrix is. This ratio consists of a Consistency Index (CI) and a Random Consistency Index (RCI) [72]. The CI is calculated using Equation 7.2. In this equation, λ_{max} is the dominant (largest in magnitude) eigenvalue. If the matrix is cardinally consistent, $\lambda_{max} = n$, otherwise $\lambda_{max} > n$. Next, the RCI value for a nxn matrix can be determined from Figure 7.3.

$$CI = \frac{\lambda_{max} - n}{n - 1} \geq 0 \tag{7.2}$$



n	3	4	5	6	7	8	9	10
RCI	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Figure 7.3: The Random Consistency Index (RCI) [72]

With these values, the RC can be calculated by Equation 7.3 A CR of 0.10 or less is considered acceptable [72, 76]. This means the CI is at least 10 times better than the RI. If the CR is larger than 0.1, the experts are asked to revise the relative importance of each objective to improve the judgmental consistency.

$$CR = \frac{CI}{RCI} \tag{7.3}$$

The resulting pairwise comparison matrices, including their accompanying CR, of the OMOE2 Task force Escort and MOE5.2 AAW neutralization from FuAD can be seen in respectively Table 7.6 and Table 7.7. The right column shows the relative weight (W_t) of the components of each matrix. This relative weight is calculated by normalizing the principal eigenvector of the matrix [75]. The Consistency Ratio (CR) is calculated as well to validate the quality of the expert's opinion. All filled-in pairwise comparison matrices for the FuAD and LPD-2 can be found in Appendix D.

Table 7.6: Task force Escort FuAD

OMOE2 Task force Escort	MOE3	MOE4	MOE5	W_t
MOE3 - ASW	1.00	0.33	0.20	0.11
MOE4 - ASuW	3.00	1.00	0.50	0.31
MOE5 - AAW	5.00	2.00	1.00	0.58

C.R. = 0.0032

Table 7.7: AAW neutralization FuAD

MOE5.2 - AAW neutralization FuAD	MOP8	MOP9	MOP13	MOP14	MOP15	W_t
MOP8 - Track enemy threat	1.00	1.00	3.17	1.40	2.44	0.31
MOP9 - Control fired projectile	1.00	1.00	1.40	1.00	1.40	0.22
MOP13 - Evade incoming enemy threat by EW	0.32	0.71	1.00	1.00	1.40	0.15
MOP14 - Long-range air defense	0.71	1.00	1.00	1.00	3.00	0.22
MOP15 - Short-range air defense	0.41	0.71	0.71	0.33	1.00	0.11

C.R. = 0.034

The resulting weights of the OMOEs and MOEs are shown in Table 7.8. The resulting absolute weights of each of the MOPs for its accompanying MOE, so already multiplied by the weight of the accompanying MOE from Table 7.8, are shown in Table 7.9. The resulting relative weight vectors are verified by checking if the sum of all absolute weight values of a certain level is summed up to be the value of the level above. For example, when the top-level has a value of 1, the sum of values of all categories on the second level should equal 1. If a second-level category has a value of 0.5, the sum of the accompanying third-level categories should equal 0.5. An example of this application is by checking if the sum of the weight of the MOPs for the accompanying MOE as shown in Table 7.9 is the same as the weight of this MOE as shown in Table 7.8. A deviation of 0.005 for this value is deemed acceptable since this is caused by rounding off the values to two decimals. The results for the LPD-2 can be found in section D.3.

Table 7.8: OMOE and MOE weight results FuAD

OMOE	Overall mission effectiveness FuAD	1.00
OMOE1	Task force Command & Control	0.26
MOE1	Command	0.13
MOE2	Control	0.13
OMOE2	Task force escort	0.74
MOE3	ASW	0.081
MOE3.1	Detection	0.057
MOE3.2	Neutralization	0.023
MOE4	ASuW	0.23
MOE4.1	Detection	0.15
MOE4.2	Neutralization	0.076
MOE5	AAW	0.43
MOE5.1	Detection	0.25
MOE5.2	Neutralization	0.18

Table 7.9: MOP weight results FuAD

	MOE1	MOE2	MOE3.1	MOE3.2	MOE4.1	MOE4.2	MOE5.1	MOE5.2	Total
MOP1	0.033	0	0.014	0	0.035	0	0.045	0	0.13
MOP2	0.050	0	0	0	0	0		0	0.050
MOP3	0.048	0.049	0.014	0	0.036	0	0.051	0	0.20
MOP4	0	0.028	0.0087	0	0.035	0	0.025	0	0.096
MOP5	0	0.028	0.0088	0	0.021	0	0.087	0	0.15
MOP6	0	0.011	0.0069	0	0.0069	0	0	0	0.025
MOP7	0	0	0	0.018	0	0	0	0	0.018
MOP8	0	0	0	0	0	0.016	0	0.054	0.070
MOP9	0	0	0	0	0	0.017	0	0.038	0.055
MOP10	0	0	0	0	0	0.021	0	0	0.021
MOP11	0	0	0	0	0	0.0079	0	0	0.0079
MOP12	0	0.0082	0.0046	0	0.018	0	0.044	0	0.075
MOP13	0	0.0070	0	0.0056	0	0.015	0	0.027	0.054
MOP14	0	0	0	0	0	0	0	0.039	0.039
MOP15	0	0	0	0	0	0	0	0.020	0.020

7.3 Result analysis AHP

The results from Table 7.8 has been rewritten to retrieve the final ranking of the MOPs, which is formulated in Table 7.10. When conducting the AHP on different vessel types, the results indicate which MOPs are the most important for each vessel type. Comparing the AHP results of varying vessel types indicates which important functions share commonality. In Table 7.10, it can be seen that MOP3 (communication capabilities) is the most important MOP for both FuAD and LPD-2. The naval architect can explore the possibilities of designing the accompanying systems, or components of the system, as a module to make them more easily applicable for both vessel types. Another reason the accompanying systems of the most important MOPs could be designed as a module is to reduce maintenance time by making a module easily replaceable. If the system is destroyed during naval operations, the vessel cannot continue its operations as required. When the system is designed as a module that a new one could easily replace, the vessel can continue its operations faster.
W_t calculations?

Table 7.10: Results AHP

FuAD			**LPD-2**		
MOP		%	**MOP**		%
MOP3:	Communication capabilities	19.85	MOP3:	Communication capabilities	25.34
MOP5:	Detect objects above the surface	14.51	MOP1:	Vessel command capability	11.01
MOP1:	Vessel command capability	12.67	MOP18:	Personnel LC transferring	9.35
MOP4:	Detect objects on the surface	9.63	MOP17:	Vehicle LC transferring	7.36
MOP12:	Prevent detection by EW	7.45	MOP16:	Vehicle storage	7.15
MOP8:	Track enemy threat	7.03	MOP5:	Detect objects above the surface	6.99
MOP9:	Control fired projectile	5.49	MOP4:	Detect objects on the surface	6.79
MOP13:	Evade incoming enemy threat by EW	5.40	MOP2:	Task force command capability	5.90
MOP2:	Task force command capability	4.99	MOP12:	Prevent detection by EW	3.82
MOP14:	Long-range air defense	3.90	MOP21:	Operating capability	3.43
MOP6:	Detect objects under the surface	2.46	MOP13:	Evade incoming enemy threat by EW	3.33
MOP10:	High impact surface weapon	2.11	MOP20:	Intensive care capability	2.42
MOP15:	Short-range air defense	1.95	MOP19:	Low-care medical capability	2.42
MOP7:	Underwater ranged weapon	1.78	MOP22:	Station keeping	1.27
MOP11:	Low impact surface weapon	0.79	MOP6:	Detect objects under the surface	1.18
			MOP15:	Short-range air defense	0.60
			MOP8:	Track enemy threat	0.59
			MOP9:	Control fired projectile	0.42
			MOP11:	Low impact surface weapon	0.34
			MOP10:	High impact surface weapon	0.27
	Total	100		Total	100

First of all, it is important to note that the ranking focuses on the main operations of the vessels, while the lower-ranked MOPs are still indispensable for the ability to complete their missions. An example is MOP15, the 'Short-range air defense' which has an AHP score of 1.95% and 0.60% for respectively FuAD and LPD-2. The reason for the low score is that the long-range air defense, either carried out by the vessel itself or by the escorting vessels, should intercept incoming threats before they become a short-range threat. However, in the case a threat comes through, each vessel must be able to protect itself. The same reasoning is behind the relatively low-scoring surface weapons (MOP10 and MOP11). The vessel's main tasks do not contain surface warfare, but they must be able to do so. Therefore, the AHP can help to give insights into the most important MOPs of a vessel, but the lower-scoring MOPs cannot be neglected.

It is particularly interesting when the accompanying systems of a high-scoring MOP score high on the MFD. An example from the FuAD is MOP5 'Detect objects above the surface', which can be coupled to function j_{34} 'To detect threats through the air', which in its turn is coupled to system k_{37}, the 'Air surveillance radar'. The high ranking of MOP5 on the AHP shows the importance of a working air surveillance radar. If the radar is destroyed during naval operations, the vessel cannot continue its operations as required. Therefore, the vessel can continue its operations faster if the radar is an easily replaceable module. The MFD results for the FuAD, shown in Figure 6.3, show that the air surveillance radar is already a high-potential modular system based on modularity drivers. Since both results show possible advantages of modular designing, the air surveillance radar is particularly interesting for investigating modular applications. By developing this ranking for the naval architect, the AHP can improve insights into the importance of the vessel's functions and accompanying systems to identify systems that have high potential as modular designs based on their reciprocal importance during naval operations.

7.4 Discussion & Conclusion AHP

This section will start with the discussion in subsection 7.4.1. Next, the conclusion is formulated in subsection 7.4.2.

7.4.1 Discussion

The AHP can identify important MOPs that share commonality across the fleet. However, this does not mean the system as a whole can be designed as a module. An example is MOP3 ‘communication capabilities’. The required layout of the system, such as the placement of the satellite dishes and antennas, are vessel-dependent so they do not interfere with other systems [89]. Therefore, components of the system might be suitable for modularity, while the system as a whole needs to be adjusted for each vessel type.

When working with expert opinion, it is important to validate their expertise and results. The method used in this thesis is the consistency ratio CR, used for every individual matrix. By applying the requirement the CR needs to be below 0.10, indicating the matrix is 10 times more consistent than a random matrix, consistency is checked. When the CR exceeds 0.10, the naval architect is asked to revise his opinion. During this thesis, the CR remained under 0.10 for every independent matrix. When working with large data sets, data from naval architects who do not deliver consistent matrices can be left out of the AHP inputs. The resulting relative weight vectors are verified by checking if the sum of all absolute weight values of a certain level is summed up to be the value of the level above. A deviation of 0.005 for this value is deemed acceptable since this is caused by rounding off the values to two decimals.

7.4.2 Conclusion

First, the ‘overall measures of effectiveness’ (OMOEs), ‘measures of effectiveness’ (MOEs), and ‘measures of performance’ (MOPs) have to be formulated. The MOPs can be coupled to functions and systems computed during the MFD. A junior naval architect, naval architect, and senior naval architect from COMMIT were asked to fill in the pairwise comparison matrices, ranking the reciprocal importance of OMOEs, MOEs, and MOPs. The results are implemented by taking the geometric mean of their inputs. This ensures opposite valuation by naval architects will result in an ‘equally important’ output. Comparing the AHP results of varying vessel types indicates which important functions share commonality. The naval architect can explore the possibilities of designing the accompanying systems, or components of the system, as a module to make them more easily applicable for both vessel types. Another reason the accompanying systems of the most important MOPs could be designed as a module is to reduce maintenance time by making a modular system easily replaceable. If an important system is destroyed during naval operations, the vessel cannot continue as required. With an easily replaceable module, the vessel can continue its operations faster.

The results show communication capabilities is the most important MOP for both FuAD and LPD-2. In this case, the MOP cannot be coupled to specific accompanying functions. The second highest ranking MOP for FuAD is MOP5 ‘Detect objects above the surface’, which can be coupled to function j_{34} ‘To detect threats through the air’, which in turn is coupled to system k_{37}, the ‘Air surveillance radar’. This shows the importance of a working air surveillance radar. The MFD results for the FuAD show that the air surveillance radar is already a high-potential modular system based on modularity drivers. When both the MFD and AHP show possible advantages of modular designing, the system is particularly interesting for investigating modular applications. By developing this ranking for the naval architect, the AHP can improve insights into the importance of the vessel’s functions and accompanying systems, which can help select systems as high-potential modules. It is important to note that the ranking focuses on the main operations of the vessels, while the lower-ranked MOPs are still indispensable for the ability to complete their missions. The AHP can give insights into the most important MOPs of a vessel, but the lower-scoring MOPs cannot be neglected.

8
Framework Knowledge Based Engineering

This chapter will address the Knowledge Based Engineering (KBE) model. The KBE model can be used to test the technical impact of modular system design based on the MFD and AHP analysis. Upgraded systems in the future can require increased volume, weight, or required electric power. Implementing these possible increases in the KBE model by creating different configurations for each modular system, valuable insights will be created for the naval architect into the impact of future upgrades on the design. With these insights, better estimations can be made of the additional requirements caused by upgrades in early-stage ship design. This can result, for instance, in applying larger power- or volume margins. By analyzing the technical impact of making systems modular, an assessment can be made of the technical feasibility of modules.

The KBE model will implement a Python script in Rhino, resulting in a 3D model of the design. This thesis will use the existing Python script with four corresponding parent hulls and will implement the required parameters of the vessel and its systems in this model. The Python script, used in the course 'Design of Complex Specials', part of the Design track from the master Marine Technology at TU Delft, is retrieved from A.A. Kana (personal communication, October 4, 2024). This script generates a design in Rhino based on input from the designer, consisting of a parent hull, the hull's dimensions, and optionally the hull's weight and volume blocks. Different systems can be added to the vessel by adding volume blocks to the Python insertion. Parameters such as displacement, estimated draft, and GM can be calculated with the weights and volumes of these blocks and the vessel's hull. The Python script requires a 'parent hull', which is a hull design imported from a different Rhino file, which can be modified by adjusting the dimensions.

When applying different modular configurations, it can be investigated how the vessel's parameters change. This way, the technical impact is assessed. By assessing the technical impact, possible design changes due to future upgrades can be addressed in the concept exploration phase of the design. These insights aim to create a better understanding of the impact of modularity and to help create more future-proof designs.

First, the vessel selection for the KBE model case study will be discussed in section 8.1. Next, the HLPs will be selected and described in section 8.2. The computation and results of the KBE model are discussed in section 8.3. The chapter is finalized with a discussion and conclusion in section 8.4.

8.1 Vessel selection

Due to the time-intensive process, the KBE model will be applied to one vessel type. The process is time-intensive because parameters such as the vessel's dimensions and weight, possible modular configurations of systems, engine room layout and systems, and volume blocks with accompanying weight and dimensions need to be identified for each vessel type.

The choice has been made to use the FuAD as a reference for the KBE model since it has more potential for modularity according to the higher MFD score compared to the LPD-2 case, even though the FuAD has fewer systems. This indicates the FuADs systems have a higher potential for modular application. This is caused by the wider diversity of weapon systems on the frigate, which can be used on different vessel types as well to increase scale advantages, such as the tomahawk cruise missiles on submarines or the canon on the ASWF. Therefore, the choice has been made to use the FuAD as a reference vessel for the KBE model.

8.2 High Level Primitive (HLP) selection

This section discusses the systems selected as HLPs and will give qualitative descriptions of these systems. To show how the KBE model can highlight changes in the design, HLPs are selected which are expected to change at least one of the following parameters; the vessel's weight, stability, or required electric power. Modular variants of the systems will increase the system's weight by 2 times since equipment that would usually be integrated and optimized within the design should now be part of the module. The vessel's GM is taken into account to ensure the vessel will remain sufficiently stable. The electric power increase is chosen since a significant increase in electric power will result in higher power delivery requirements. This will result in larger, heavier equipment for the engine room, which can lead to increased vessel dimensions.

The first system identified as an HLP is the air surveillance radar. An example of the radar used in the RNLN, the SMART-L, is shown in Figure 8.1. This system has the highest score on the MFD (Table 6.5), is identified to fulfill an important function according to the AHP (Table 7.10), and is expected to change the vessel's GM due to its high placement on top of the superstructure.

Figure 8.1: SMART-L radar [53]

The weight of the antenna is taken and increased in different configurations to indicate what future upgrades could implicate. The antenna size is not changed, since the antenna needs to rotate at 12 rpm at all times, and a larger size could hinder this [23]. Besides, the antenna will remain rectangular shaped on top of the vessel, so there are no size limitations based on the placement on the vessel and no volume margins are required. Due to the high placement on the vessel, the weight is expected to have the largest influence on the GM, although the weight is relatively low. The specifications of the SMART-L and a potential modular air surveillance radar are shown in Table 8.1.

Table 8.1: SMART-L specifications

Parameter	**SMART-L [23]**	**Modular air surveillance radar**
Antenna weight [kg]	8000	16000
Required electric power [kW]	100	250
Antenna size (LxBxH) [m]	9.2 x 4.4 x 3.7	9.2 x 4.4 x 3.7

The second system chosen as an HLP is the laser directed energy weapon (LDEW) since this system is a likely upgrade in the near future. The UK is currently testing an LDEW called 'DragonFire', as shown in Figure 8.2, which can be used from shore and on naval vessels [15]. The UK's defence secretary Grant Shapp mentions the LDEW 'has the potential to revolutionise the battlespace by reducing the reliance on expensive ammunition, while also lowering the risk of collateral damage.' To indicate how much cheaper it is; where missiles cost at least thousands of pounds per shot, the UK's LDEW only costs £10 per shot [15]. It must be noted this is only the cost of electric power, the costs of the system itself are not included in this cost estimation. Another advantage is the accuracy of a laser. The UK's LDEW can hit 'a £1 coin from a kilometre away' [15]. However, this system will significantly increase the required electric power of the vessel. When looking at the UK's LDEW it can be seen the system consists of a 50kW laser with the ability to scale its fire-power levels in the future [16]. An example of this power increase is the newest 500 kW laser from Lockheed Martin [50]. Therefore, the report will work with a laser that requires 500 kW. Since the vessel should be able to defend itself from all sides, a laser will be placed on the front and rear end of the vessel. An additional advantage is redundancy; when one system fails, the vessel will have an additional laser. No weight of the system can be found online. Therefore, it is assumed the LDEW will have the same weight as the air defense system it will replace, which is the Rolling Airframe Missile (RAM). As a reference system, the United States Navy's RIM-116 Rolling Airframe Missile (RAM) is used, weighing approximately 5 tons [96]. The configurations for the LDEW are shown in Table 8.2.

Table 8.2: LDEW specifications

Parameter	**Non-modular LDEW**	**Modular LDEW**
Weight [t]	5	10
Required electric power [kW]	500	500

Figure 8.2: UK's DragonFire [16]

8.3 Model computation

Most of the vessel's dimensions have already been formulated in Table 5.1. An added vessel parameter is the estimation of the height of the vessel's hull, which will be the main deck. Naval Technology [66] mentions that the forecastle-deck, typically one deck above the main deck, is at 13.6 meters, and Marineschepen.nl [54] mentions the deck height is 3 meters, so this would mean the main deck is at a height of 10.6 meters. Therefore, the model based on the LCF will have a height of 10.6 meters. The tanktop is estimated to be 1.5 meters high, while the other decks are 3 meters high. The engine room must have a height of two decks since the diesel engines and gas turbines are higher than the 3-meter deck height [22, 102]. Furthermore, the LCF has four generators, each generating 1,650 kW [57]. The structural weight, which consists of the hull and superstructure weight, is estimated at 2600 tonnes. The engine room weight is estimated at 650 tonnes. The additional systems are estimated at 2800 tonnes, with a center of gravity (COG) (X,Y,Z) = (60, 0, 7.5). This will be added to the LCF reference model as a point mass at the COG. The total weight of the LCF reference model is 6050 tonnes, which is the same as the displacement from Table 5.1.

The block coefficient (C_b) for naval vessels is typically around 0.55 [6, 74]. The Python script comes with four parent hulls. The parent hull with a C_b closest to 0.55 is deemed most suitable. This results in a parent hull with a C_b of 0.56 since the other parent hulls all have larger values for their C_b. The estimated weights are checked by COMMIT to ensure realistic, but not exact, values are used. The approximations are made with a ± 5% range. The data used for the LCF reference model, the weight estimations, and retrieved dimensions and volumes from the model can be seen in Table 8.3.

Table 8.3: Data for LCF model

From open sources	
Displacement	6050 [t]
LOA	144 [m]
B	18.8 [m]
D	10.6 [m]
T_{Design}	5.1 [m]
Installed propulsive power	49800 [kW]
Installed generator power	6720 [kW]
From estimations, deemed representative by COMMIT	
Construction weight (Hull + superstructure)	2600 [t]
Engine room weight	650 [t]
Other weight	2800 [t]
From Rhino model estimations	
LWL	140 [m]
Beam WL	14.75 [m]
T	5.4 [m]
GM	1.636 [m]
Total hull volume	17000 [m^3]
Engine room volume	3300 [m^3]
Fuel storage volume	400 [m^3]

The output of the KBE model for the LCF reference vessel can be seen in Table 8.4. A complete overview of the KBE model's output is shown in Appendix E. It can be seen the LCF reference model's T_{Design} differs from the estimated draft from the Python model. The draft in the Python model is estimated with the vessel's mass, dimensions, and $\mathrm{C_b}$ by Equation 8.1. Since the $\mathrm{C_b}$ is based on literature and not on the actual frigate, the value for the estimated draft is expected to differ from the T_{Design}. The Rhino model is verified by checking the different outcomes and comparing the values. It was found the total weight of the vessel and the displacement differ; the displacement is less than the vessel's weight. When comparing the volume under the waterline at the given estimated draft, and multiplying this volume by the density of salt water (ρ=1.025 $\frac{\mathrm{ton}}{m^3}$), the weight of the vessel is retrieved. Therefore, the weight of the vessel will be used as displacement value, and not the output 'displacement'. After consulting naval architects at COMMIT, the value for the GM is deemed acceptable as long as it will be in the range of 1.4 and 1.8 meters and the output from the KBE model is deemed suitable.

Table 8.4: Output KBE model LCF reference model

Weight [t]	6050
GM [m]	1.636
Draft [m]	5.4
Displacement [t]	5929
COB (x,y,z) [m]	67.89, 0.00, 3.25

$$\text{Estimated draft [m]} = \frac{\text{Displacement}}{\text{LWL} \cdot \text{Beam WL} \cdot C_b \cdot \rho} \tag{8.1}$$

The required volume for fuel storage for the FuAD reference model can be estimated by Equation 8.2. The weight of the storage is included in the structural weight and extension of the storage will mostly result in added fuel weight since only the sides of the fuel tanks will be prolonged. Since the fuel is not part of the lightship weight, the additional weight of the fuel storage is not separately calculated. The fuel storage density aims to show the naval architect an increase in engine room power will lead to increased fuel requirements.

$$\text{Fuel storage density} = \frac{\text{Fuel storage volume}}{\text{Installed power}} = \frac{400}{39000 + 10800 + 6720} \approx 0.0071\ \frac{m^3}{kW} \tag{8.2}$$

The next step is to estimate the required propulsive power. This is done assuming the FuAD reference model power supply is the same as for the LCF, which is a Combined Diesel Or Gas (CODOG) power supply [54, 66].

The required propulsive power can be estimated by the admiralty constant, which is, according to Wärtsilä [105], 'a coefficient used in the preliminary estimations of the power required in a new design to attain the desired speed'. The admiralty constant can be calculated using Equation 8.3, where Δ = displacement in tonnes, V = speed in knots, and P = shaft power in kW.

$$C = \frac{\Delta^{\frac{2}{3}} \cdot V^3}{P} \tag{8.3}$$

All calculations are done for two cases since the vessel will use either its gas turbines to reach its maximum speed of 30 kn or its diesel engines for its cruising speed of 18 kn. Therefore, the estimations will be made for both the gas turbines and diesel engines with their accompanying speeds. The admiralty constants for these cases are shown in respectively Equation 8.4 and Equation 8.5.

$$C_{gas} = \frac{\Delta^{\frac{2}{3}} \cdot V_{max}^3}{P_{gas}} = \frac{6050^{\frac{2}{3}} \cdot 30^3}{39000} \approx 230 \tag{8.4}$$

$$C_{diesel} = \frac{\Delta^{\frac{2}{3}} \cdot V_{cruise}^3}{P_{diesel}} = \frac{6050^{\frac{2}{3}} \cdot 18^3}{10800} \approx 180 \tag{8.5}$$

The FuAD reference model will result in an increased length of 16 m (11.1%) and an increased beam of 2.2 meters (11.7%) while keeping the C_b the same. Since the hull form will change in relatively the same proportions, the admiralty constant will be used to estimate the required propulsive power for the FuAD reference model. This is done for the gas turbines and diesel engines in respectively Equation 8.6 and Equation 8.7.

$$P_{gas} = \frac{\Delta^{\frac{2}{3}} \cdot V_{max}^3}{C_{gas}} = \frac{10000^{\frac{2}{3}} \cdot 30^3}{230} \approx 54500\ kW \tag{8.6}$$

$$P_{diesel} = \frac{\Delta^{\frac{2}{3}} \cdot V_{cruise}^3}{C_{diesel}} = \frac{10000^{\frac{2}{3}} \cdot 18^3}{180} \approx 15000\ kW \tag{8.7}$$

The crew size of the FuAD compared to the LCF will decrease from 174 [63] to 150 [71], while the additional personnel spots will increase from 28 [63] to 70 [71]. The additional electric power consumption compared to the LCF is unknown. Since personnel remains roughly the same, and the additional electric power consumption is unknown, it is assumed the initial electric power supply will remain 6720 kW. This will result in a total power requirement of 76720 kW. The estimated fuel storage volume can be calculated using Equation 8.8.

$$\text{Fuel storage volume} = 0.0071\ \frac{m^3}{kW} \cdot 76720\ \text{kW} \approx 550\ m^3 \tag{8.8}$$

The weight of the structure will be estimated by the weight density for the hull of the LCF reference model and scaling it to the FuAD reference model. Since the dimensions, design draft, and C_b are known, the volume of the new hull can be retrieved from Rhino. With the application of the weight density on this volume, the weight of the construction can be estimated. The construction weight density of the LCF reference model is calculated using Equation 8.9.

$$\text{Construction weight density} = \frac{\text{Construction weight}}{\text{Hull volume}} = \frac{2600}{17000} \approx 0.153\ \frac{t}{m^3} \tag{8.9}$$

With the dimensions of the FuAD reference model, the hull's volume is retrieved from the Rhino model, resulting in a 20750 m^3 hull. With this hull volume and the construction weight density, an estimation can be made for the construction weight of the FuAD reference model. The construction weight for the FuAD reference model is calculated using Equation 8.10.

$$\text{Construction weight FuAD} = 0.153\ \frac{t}{m^3} \cdot 20750\ m^3 \approx 3200\ t \tag{8.10}$$

The next step is to determine the engine room power layout for the FuAD reference model. Two layouts of the engine room will be made. One layout for the initial design and one layout for the higher energy demands by the LDEWs. Since the vessel has a CODOG propulsion system, the additional electric power needs to be delivered by the generators. When electric power is used in the propulsive power generation, the additional power required by future upgrades such as the laser can be delivered by this electric propulsive power. The initial FuAD reference model retrieves 6720 kW from generators and since the lasers will require 1000 kW, additional generators or generators with increased delivered power are required. In the case a new generator is added, two generators should be installed because of redundancy. Therefore, it is preferred to use generators with increased power.

With a power increase of 1000 kW for the lasers and 150 kW for the modular air surveillance radar, 1150 kW of additional electric power is required. This means an additional 575 kW per generator. As a result, it is possible to upgrade all four generators instead of placing additional generators in the engine room. Two engine room configurations will be made; one for the initial design and one for the design with LDEWs. An overview of the power generation systems for the LCF and comparable suitable systems for the FuAD reference model can be seen in Table 8.5.

Table 8.5: Overview power generation systems

	Diesel engine (DE)	**Gas turbine (GT)**	**Generator (GEN)**
LCF reference model			
Model	Wärtsilä 16V26 [102]	Rolls Royce Spey SM 1A [22]	Wärtsilä-Deutz D620 V12 [103]
Power [kW]	5400	19500	1640
Dimensions (LxBxH) [m]	9.752 x 2.990 x 3.711	7.5 x 2.285 x 3.39	2.920 x 1.450 x 2.040
Weight [t]	68.8	25.7	5
Number installed	2	2	4
FuAD reference model			
Configuration 1			
Model	Wärtsilä 16V32 [104]	GE LM2500+ [27]	Wärtsilä-Deutz D620 V12 [103]
Power [kW]	8000	30200	1640
Dimensions (LxBxH) [m]	7.735 x 3.020 x 3.595	7.16 x2.74 x 3.05	2.920 x 1.450 x 2.040
Weight [t]	74.5	23	5
Number installed	2	2	4
Configuration 2			
Model	Wärtsilä 16V32 [104]	GE LM2500+ [27]	Wärtsilä-Deutz D620 V16 [103]
Power [kW]	8000	30200	2240
Dimensions (LxBxH) [m]	7.735 x 3.020 x 3.595	7.16 x2.74 x 3.05	3.400 x 1.450 x 2.100
Weight [t]	74.5	23	6
Number installed	2	2	4

It must be noted the Wärtsilä-Deutz D620 is only the engine of the generating set. The generating set used for the LCF cannot be found. However, the weight of the generating set is included in the engine room weight. To indicate a possible weight increase, a comparable generating set from Wärtsilä, the W25 series, is used [106]. However, this generating set uses an in-line dual-fuel engine, while the Wärtsilä-Deutz D620 is a V-engine using diesel. Therefore, the length difference will not be taken into account and only the weight will be used. The specifications of the W25 series are shown in Table 8.6. It can be seen that an increase of approximately 800kW in power, which is the case in the FuAD reference model, results in 10 tonnes of additional weight for the generating set. Therefore, the four generators for configuration 2 will result in an additional weight increase of 40 tonnes.

Table 8.6: Wärtsilä W25 series [106]

Engine type	Eng. kW	Weight
6L25	2070	38
7L25	2415	44
8L25	2760	49
9L25	3105	52

The engine room layout used for the LCF reference model and the FuAD reference model is shown in Figure 8.3. The dashed line is a watertight compartment to ensure redundancy. The generators are split up on both sides of the propulsion to decrease the chances all four generators are destroyed by leakage or a weapon hit. The gas turbines are 0.5 meters wider for the FuAD reference model than the type installed in the LCF reference model. Since two gas turbines are installed next to each other, the FuAD reference model will require at least 1 meter additional beam. At the tanktop at 1.5 meters height, where the foundation of the engine room will be, the FuAD reference model has a beam of 11.4 meters, compared to 10 meters for the LCF reference model. This way, it is verified that the engine room layout will fit in the FuAD reference model. However, the dimensions of the engine room will change.

The length of the 2 diesel engines, 2 gas turbines, and 2 generators (since two of the generators are next to the gas turbines) for the FuAD reference model compared to the LCF reference model is 2.4 meters shorter for configuration 1 and 1.9 meters shorter for configuration 2. By taking only the decreased length from the engine room length, the margins for auxiliary systems and space for movement within the engine room are retained. The total weight for these configurations will increase from 209 to respectively 215 and 219 tonnes. The engine room volume will decrease from 3300 m^3 to respectively 3180 and 3230 m^3. With an average construction weight density of 0.153 $\frac{t}{m^3}$, this will result in a decrease of respectively 18.4 and 10.7 tonnes of construction weight. With an increase of respectively 6 and 10 tonnes due to the power generation systems, the engine room weight will remain approximately the same. Since the heavier equipment would most likely lead to reinforced local construction, the weight of 650 tonnes for the engine room will be contained for configuration 1. To indicate the impact of changing the generators in configuration 2, the added weight of 1 tonne per generator and 10 tonnes per generating set is taken into account, resulting in an engine room weight of 694 tonnes for configuration 2.

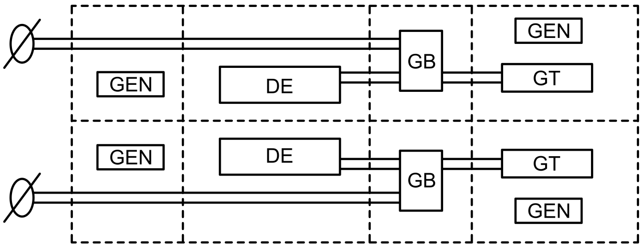


Figure 8.3: Engine room layout

It is assumed the length of the initial FuAD reference model is based on configuration 1 without the additional electric power supply by more powerful generators. As a result, the vessel's length will be extended by 0.5 meters for configuration 2. This choice has been made to investigate the impact of such a small change on the design under the consumption the vessel's space is already optimized and the extended equipment will not fit in the current design. The FuAD reference vessel's dimensions for the superstructure, placement of the SMART-L, and placement of the LDEW are estimated using a concept design figure from Marineschepen.nl [55]. With a length of 160 m [71], other dimensions, such as the length and height of the superstructure, the placement of the SMART-L radar, and the placement of a future laser are estimated by retrieving and scaling the reciprocal distances from Rhino.

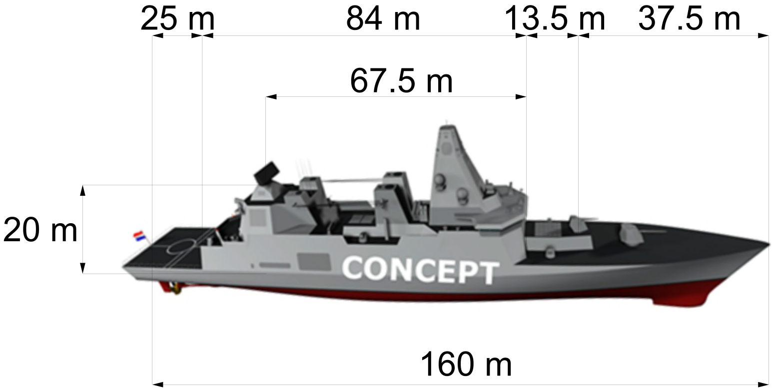


Figure 8.4: Dimension estimations FuAD (adjusted from Marineschepen.nl [55])

The newly installed propulsive power will be 16,000 kW from diesel engines and 60,400 kW from gas turbines, resulting in a total of 76,400 kW installed propulsive power. The admiralty constant from Equation 8.3 can be rewritten to calculate the maximum displacement for this installed power. This is shown in Equation 8.11 for the gas turbines and in Equation 8.12 for the diesel engines. This results in a maximum displacement of 11500 tonnes for the gas turbines and 10975 tonnes for the diesel engines. This thesis will therefore assume that the propulsive power systems for the FuAD reference model are acceptable as long as the displacement of the vessel will remain under 10975 tonnes.

$$\Delta_{gas} = \sqrt[\frac{2}{3}]{\frac{P \cdot C}{V^3}} = \sqrt[\frac{2}{3}]{\frac{60400 \cdot 230}{30^3}} \approx 11500 \text{ tonnes} \tag{8.11}$$

$$\Delta_{diesel} = \sqrt[\frac{2}{3}]{\frac{P \cdot C}{V^3}} = \sqrt[\frac{2}{3}]{\frac{16000 \cdot 180}{18^3}} \approx 10975 \text{ tonnes} \tag{8.12}$$

The hull's volume for configuration 2, with the increased length of 0.5 meters due to the changed generator size, is increased by 65 m^3. With the new hull volume for configuration 2, and the construction weight density of 0.153 $\frac{t}{m^3}$, the construction weight will increase by 10 tonnes. As mentioned before, the 4 tonnes from the increased weight of the generators is taken into consideration as well. The LDEW is not included in configuration 1 since the initial design uses the Rolling Airframe Missile (RAM). The weight of the RAMs is included in the 'other weight' category with 5 tonnes per system. For configuration 2, the LDEW is included. The weight of the LDEW, estimated at 5 tonnes per system, is subtracted from the 'other weight' category so total displacement stays correct.

The 'other weight' will be the total displacement of the FuAD subtracted with the weight of the structure, the SMART-L radar, and the engine room. This 'other weight' will be placed at the same relative COGx as the one from the LCF reference model, which means it will be placed at ($\frac{60}{144}$ =) 42% LBP of the x direction. The Y coordinate remains at 0.00 since the vessel is symmetrical around the x-axis. However, when computing the FuAD reference model with a COGz of 'other weight' at the same height as the LCF reference model at 7.5 meters, the GM for the FuAD reference model will be over 3 meters. Since the GM for the LCF reference model is 1.636 meters and a GM between 1.4 and 1.8 meters is deemed acceptable according to naval architects from COMMIT, the COGz for the 'other weight' volume block for the FuAD reference model will be shifted until the design has a GM of approximately 1.636 meters. This value for the GM is found by an iterative process at exactly 9.25 meters, resulting in a COG of (67, 0, 9.25) for the 'other weight' category. The parameters for the configurations are shown in Table 8.7.

Table 8.7: Data initial FuAD model

	Configuration 1	Configuration 2
Displacement [t]	10000	10062
LOA [m]	160	160.5
B [m]	21	21
LWL [m]	155	156
Beam WL [m]	17.5	17.5
T [m]	6.5	6.5
GM [m]	1.636	1.633
Installed propulsive power [kW]	70000	70000
Installed generator power [kW]	6720	8960
Engine room volume [m^3]	3180	3230
Fuel storage volume [m^3]	550	560
Engine room weight [t]	650	694
Construction weight [t]	3200	3210
SMART-L weight [t]	8	16
LDEWs [t]	0	10
Other weight [t]	6142	6132

The initial design and a design with a modular air surveillance radar are made in the KBE model with configuration 1 with the assumption the upgraded radar's additional power can be delivered by the original generators. This assumption is made to investigate a relatively small change, a weight addition of 8 tonnes but on a high point on the vessel, on the initial design. Two models, one with non-modular LDEWs and a modular air surveillance radar and one with modular LDEWs and a modular air surveillance radar, will be designed in the KBE model using configuration 2. This way, the impact of making a non-modular system modular can be assessed. The resulting Rhino model for configuration 2 is shown in Figure 8.5 and the KBE output from Python can be seen in Table 8.8. The outputs from the Rhino models for configuration 1 and the complete output of the Python model for both configurations are shown in Appendix E.

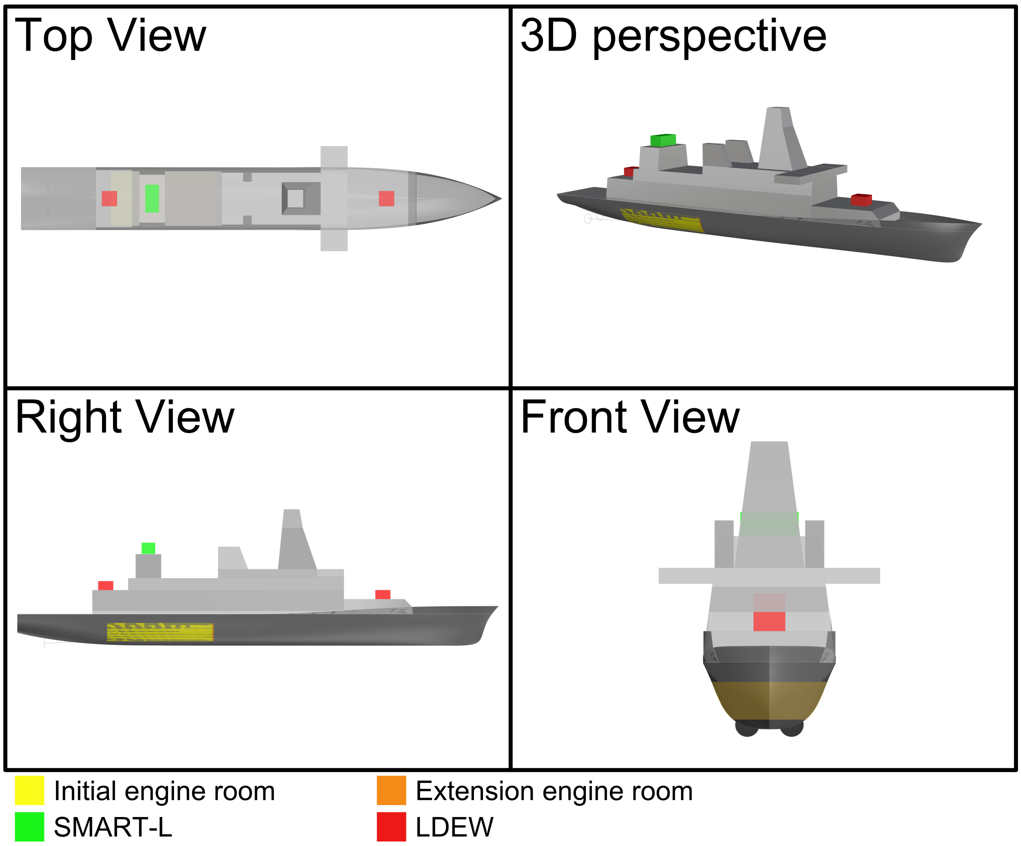


Figure 8.5: FuAD reference model including LDEW and SMART-L Rhino

Table 8.8: Output KBE model FuAD reference model

Model	Configuration 1 Initial design	Configuration 1 Modular SMART-L	Configuration 2 Initial LDEWs and modular SMART-L	Configuration 2 Modular LDEWs modular SMART-L
Weight [t]	10000	10008	10062	10072
Displacement [t]	9896	9889	9902	9894
GM [m]	1.636	1.616	1.633	1.622
Draft [m]	6.5	6.5	6.5	6.5
COB (x,y,z) [m]	74.53, 0.00, 3.95	74.53, 0.00, 3.95	74.77, 0.00, 3.94	74.78, 0.00, 3.94

From the output in Table 8.8, it was found that a larger weight of systems leads to a smaller displacement. The estimated draft is calculated using this displacement, which leads to a heavier design with less draft. For this reason, the draft is given with 1 decimal.

It can be seen in the impact of a modular SMART-L radar, which doubles the system's weight to 16 tonnes, on the FuAD reference model is limited. It leads to a decrease of the GM by 0.02 meters despite its height placement on the vessel and no changes in the vessel's draft and COB. The impact of modular LDEWs, which doubles the system's weight to 10 tonnes per system, on the FuAD reference model is limited as well. The GM will decrease by 0.01 meter while the draft remains the same and the COB shiftst 0.01 meter in x direction. For both cases, the GM remains well within the 1.4-1.8 meter range that is deemed acceptable. The draft remains the same and the COB due to modularity will only shift 0.01 meters. Since the total weight of the vessel remains under 10970 tonnes, the selected power supply systems remain suitable. This indicates a modular SMART-L and modular LDEWs will be feasible.

8.4 Discussion & Conclusion KBE

This section will start with the discussion, including verification and validation of the model, in subsection 8.4.1. Next, the conclusion is formulated in subsection 8.4.2.

8.4.1 Discussion

The potential increase in electric power demand must be targeted during the concept exploration phase. When looking at the laser, the power delivery required by the generators is significant. Since two generators must be able to supply the vessel with electric power, the two lasers, consuming 1000 kW in total, will consume 30% of the two generators' power supply of 3360 kW. By recognizing this increase in the concept design phase, the engine room layout can be changed so sufficient power is installed. Otherwise, there is a risk a future system cannot be installed without major refits of the power supply, which could be limited by the available space in the vessel. However, the risk of estimating future power demand is that it could be overestimated, and too much power is installed in the vessel, resulting in higher economic costs. Besides, the new machinery for the engine room is selected based on their technical performance. As formulated before, this thesis will not consider the economic impact. This means that the systems selected in this thesis are technically suitable, but could be extremely expensive.

Verification
The Rhino model is verified by checking the different weight outcomes and comparing the values to calculations. It was found the total weight of the vessel and the displacement differ; the displacement is less than the vessel's weight. When comparing the volume under the waterline at the given estimated draft, and multiplying this volume by the density of salt water (ρ=1.025 $\frac{\text{ton}}{m^3}$), the weight of the vessel is retrieved. Therefore, the weight of the vessel will be used as displacement value, and not the output 'displacement'. This difference will be discussed during the validation as well.

Bart van den einden 16 jan 12:00 Marco flöck 28 jan 14.00
Validation
The first step to validate the KBE model is to check if the input weights are equal to the output weight of the vessel. This way, it is checked if the required vessel is actually built as a 3D model. By analyzing the output, it was found the data in the 'Ship Mass Output' table matches the weight inputs of the volume blocks and hull. However, the 'Stability' output table shows a different value for the vessel's displacement. By an iterative process, it was found a larger weight of systems increases the vessel's weight but decreases the vessel's displacement. This indicates an inaccurate value for the vessel's displacement. The deviation is shown in Table 10.2. Since the deviation remains <2%, and weight estimations are made with a 5% deviation, the results are still considered valid. However, it is important the underlying Python script is investigated in more detail to check how this error is caused.

Table 8.9: Displacement deviation FuAD reference model

Weight [t]	Displacement [t]	Absolute deviation [t]	Relative deviation [%]
10000	9896	104	1.04
10008	9889	119	1.19
10062	9902	160	1.59
10072	9894	178	1.77

The use of the new machinery in the engine room is validated by calculating the maximum displacement of the vessel with the specific power delivery, and to make sure the total displacement will never exceed this value. If the displacement becomes larger, new machinery is required. The maximum displacement is calculated for both the vessel's maximum and cruise speed, and the lowest value is taken as a boundary. The dimensions of the new machinery and the FuAD reference model are validated as well. At the tanktop at 1.5 meters height where the engine room's foundation is built, the FuAD has a beam of 11.4 meters, compared to 10 meters for the LCF reference model. The new machinery requires 1 meters additional beam for the FuAD reference vessel compared to the LCF reference vessel. Therefore, it is validated that the engine room layout will fit in the FuAD reference model.

Another difference that needs to be highlighted is the difference between LCF's and FuAD's T_{Design} and estimated draft from the KBE model. With the vessel's mass, dimensions, and C_b, the draft is estimated in the Python model. This is done using Equation 8.1. Since the C_b is based on literature and not on the actual frigate's design, the value for the estimated draft is expected to differ from the T_{Design}. The larger difference for the FuAD reference vessel compared to the difference in the draft of the LCF reference vessel is most likely caused by a larger C_b for the actual FuAD. These differences are deliberated with naval architects from COMMIT and are deemed reasonable due to the difference in C_b. Therefore, the estimated draft from the KBE is considered valid.

8.4.2 Conclusion

The KBE model is used to map the technical impact and assess the feasibility of making systems modular. The model consists of a Python script implemented in Rhino. This results in a model that delivers a visual representation besides the output of the Python model. From this output, the vessel's dimensions, weight, GM, estimated draft, and COB can be retrieved. By analyzing the changes, the impact of modularity can be assessed and it can be checked if the design remains within its margins as required by the naval architect.

The first step in this model is to select systems as HLPs. This is done by combining the MFD results, indicating which systems are high-potential modules, and the AHP results, indicating the most important systems of the vessel. For the case study, performed on the FuAD as reference vessel, the resulting AHPs are an air surveillance radar and Laser-Directed Energy Weapons (LDEWs). The LCF is taken as a starting point, after which it was scaled to the FuAD dimensions. The application of LDEWs results in a significant increase in electric power demand. Therefore, the FuAD reference model is made in two configurations; one for the initial design and one for the design that requires more electric power. As a result, more powerful generators are required and the vessel needs to be extended by 0.5 meters to make it fit. For the first configuration, the SMART-L air surveillance radar was first implemented non-modular and then as a module, and for the second configuration, the LDEW was first implemented non-modular and then as a module. This way, an assessment could be made of the impact of making these systems modular. It was found that the weight was slightly increased, the draft remained the same, and the GM stayed in a range of 1.616-1.636 meters, keeping it well within the acceptable range of 1.4-1.8 meters. With these results, the SMART-L and LDEWs are deemed feasible modules.

9

Evaluation effectiveness modules

This chapter will formulate a final evaluation of the effectiveness of modular systems compared to their non-modular variant. This will be done with an AHP assessment. First, the properties of the pairwise comparison matrices are described in section 9.1. Next, the results are analyzed in section 9.2. THe chapter ends with a discussion and conclusion in section 9.3.

9.1 Properties pairwise comparison matrices

When formulating the OMOEs, MOEs, and MOPs, the possible mitigations of modularity, as described in subsection 3.2.2, will be taken into account. The same method as described in chapter 7, the AHP, will be used. By using the AHP, the intentions of the end user will determine the outcome. When the focus will be on economic costs, a different ranking will occur than when the end user will focus on operational downtime. The formulated OMOEs are shown in Table 9.1.

Table 9.1: OMOEs evaluation effectiveness modules

OMOE	Overall system effectiveness
OMOE1	Air surveillance radar
OMOE2	LDEW

The assessment of the naval vessel's effectiveness is based on the top-5 modularity drivers from Table 6.4. The formulated MOEs can be seen in Table 9.2. The MOEs are related to the top-5 modularity drivers in the following ways:

- *Purchase*; The accompanying MOEs (MOE1 & MOE6) aim to identify the initial purchase costs. This will be an estimation of the price per system. Scale advantages will take a part in this since a larger number of systems required will most likely bring the purchase price per system down.
- *Common unit*; The accompanying MOEs (MOE2 & MOE7) aim to identify the importance of commonality across the fleet is identified. High commonality across the fleet could reduce design times for different vessel types since systems have already been designed for other vessel types.
- *Different specification*; The accompanying MOEs (MOE3 & MOE8) aim to identify the ability to quickly change system types, for example, to change an LDEW to a RAM.
- *Service and maintenance*; The accompanying MOEs (MOE4 & MOE9) aim to identify how long a vessel will be docked for maintenance caused by the accompanying system. When a module is easily replaceable by a new system, maintenance can be done onshore and the vessel can quickly sail out with a new system. This would decrease the docking time during maintenance.
- *Process and/or organisation*; The accompanying MOEs (MOE5 & MOE10) aim to identify the number of systems that are required to keep operations running. When the choice is made for quickly changing systems to shorten maintenance time, additional systems are required that can replace the systems on board. These systems need to be bought and maintained, bringing significant economic costs for this option.

Table 9.2: MOEs evaluation effectiveness modules

OMOE1 Air surveillance radar	
MOE1	Purchase costs
MOE2	Common use across the fleet
MOE3	Quick changing of systems
MOE4	Maintenance time in dock
MOE5	Number of systems required
OMOE2 LDEW	
MOE6	Purchase costs
MOE7	Common use across the fleet
MOE8	Quick changing of systems
MOE9	Maintenance time in dock
MOE10	Number of systems required

As MOP, the non-modular and modular variant of a system will be compared to each other. This way, an evaluation can be made on the effectiveness of modularity. The formulated MOPs are shown in Table 9.3. The resulting MOP breakdown tree is shown in Figure 9.1.

Table 9.3: MOPs evaluation effectiveness modules

MOP1	Non-modular Air surveillance radar
MOP2	Modular Air surveillance radar
MOP3	Non-modular LDEW
MOP4	Modular LDEW

The pairwise comparison matrices are filled in by a naval architect with expertise in frigates at COMMIT. The same method will be applied as in section 7.2 for the computation and validation of the matrices. All resulting pairwise comparison matrices are shown in Appendix F. The results are shown in Table 9.4.

Table 9.4: MOP weight results modules

	MOE1	MOE2	MOE3	MOE4	MOE5	MOE6	MOE7	MOE8	MOE9	MOE10	Total
MOP1	0.082	0.027	0.013	0.021	0.030	0.000	0.000	0.000	0.000	0.000	0.174
MOP2	0.041	0.014	0.026	0.064	0.015	0.000	0.000	0.000	0.000	0.000	0.160
MOP3	0.000	0.000	0.000	0.000	0.000	0.066	0.039	0.061	0.029	0.054	0.249
MOP4	0.000	0.000	0.000	0.000	0.000	0.033	0.117	0.183	0.058	0.027	0.418

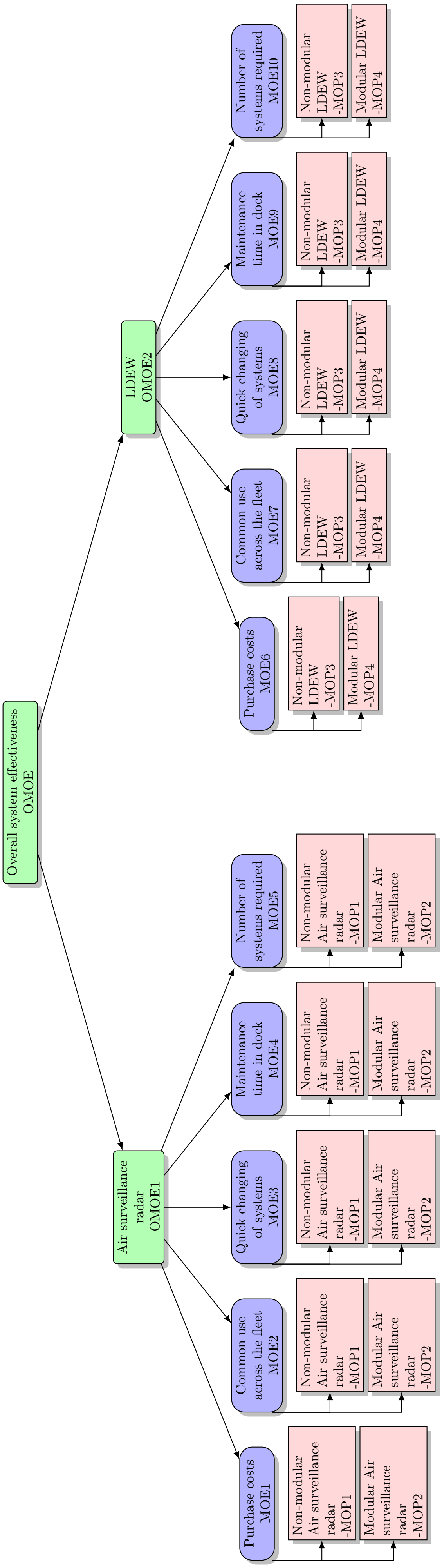


Figure 9.1: Evaluation KBE FuAD

9.2 Result analysis

When analyzing the results, it is not only important to look at the final ranking but also to compare each non-modular system to its modular variant. The final ranking can help prioritize more important systems, but comparing non-modular systems to their modular variants will determine if the system's effectiveness can be increased. This is formulated as the reciprocal importance, focusing on the type of system. This value is calculated by adding the absolute importance value for the MOPs of one system type and calculating the share of each MOP to this value. Therefore, the sum of the reciprocal importance of one system type adds up to 100%. The results are shown in Table 9.5

Table 9.5: Results system effectiveness

System	MOP	Absolute importance	Reciprocal importance	Outcome
LDEW	MOP4 - Modular LDEW	41.8%	62.7%	Modular
	MOP3 - Non-modular LDEW	24.9%	37.3%	
Air surveillance radar	MOP1 - Non-modular Air surveillance radar	17.4%	52.1%	Non-modular
	MOP2 - Modular Air surveillance radar	16.0%	47.9%	

From the absolute importance, it can be seen the LDEW has a higher impact on the overall system effectiveness than the air surveillance radar. To draw conclusions in relation to modularity, it is important to look at the reciprocal importance, where the non-modular and modular solution of a system is compared to each other. For the LDEW, it can be seen the modular variant is preferred, while the non-modular air surveillance radar is slightly preferred. This difference is caused by the high weight of the 'common use across the fleet' and the 'quick changing of systems' for the LDEW, while the air surveillance radar has a low weight for these categories, in which modular systems can clearly be an outcome.

This also indicates the different applications of these types of systems and the way the RNLN could benefit from modularity. For the air surveillance radar, the purchase costs have the largest weight. The quick changing of systems scores low, because there are no different air radars used for a specific vessel type, the most suitable radar is used at all times. Therefore, there is no need to quickly change the system for another type. On the contrary, the quick changing of systems for the LDEW has the highest weight since different systems can be used on board as anti-air weapons, and when threats change adaptability in weapon systems can generate benefits. The common use across the fleet also scores relatively high for the LDEW and low for the air surveillance radar. Since every vessel needs to defend itself against air threats, each vessel type could benefit from the LDEW, increasing the common use across the fleet, while for the air surveillance radar, since the FuAD is an air defender, it will be the most advanced version of the radar compared to other vessel types. Therefore, it will be a radar specifically for the FuAD, which is too advanced, and thereby too expensive, for other vessel types.

The results show the importance of looking at the intentions of the end user. The LDEW results show that the focus is on adaptability rather than purely the economic aspect, while the air surveillance radar does not require high adaptability, and therefore the focus is on the economic aspect. These results show that even though a system scores high on the MFD, its function scores high on the AHP, and is deemed technically feasible in the KBE, it does not need to mean it will improve the vessel or the organizational process. This shows the importance of assessing if a feasible modular system improves the design compared to a non-modular solution.

9.3 Discussion & Conclusion

This section will start with the discussion in subsection 9.3.1. Next, the conclusion is formulated in subsection 9.3.2.

9.3.1 Discussion

It must be noted the effectiveness assessment is based on expert opinion before a technical design of the system's non-modular and modular configuration is made. The expert opinion will remain relevant since the potential benefits of a system depend on the intentions of the end user, which can be seen as an opinion. One design can be more effective for one country, and less effective for another one, depending on their intentions with the design. Due to the limited time for this thesis, no technical design of the systems themselves could be made. Future research could expand this framework by making detailed designs of each system's configuration, so the technical impact can be studied in more detail.

When working with expert opinion, it is important to validate their expertise and results. The method used in this thesis is the consistency ratio CR, used for every individual matrix. By applying the requirement the CR needs to be below 0.10, indicating the matrix is 10 times more consistent than a random matrix, consistency is checked. When the CR exceeds 0.10, the naval architect is asked to revise his opinion. During this thesis, the CR remained under 0.10 for every independent matrix. When working with large data sets, data from naval architects who do not deliver consistent matrices can be left out of the AHP inputs. The resulting relative weight vectors are verified by checking if the sum of all absolute weight values of a certain level is summed up to be the value of the level above.

9.3.2 Conclusion

When formulating the OMOEs, MOEs, and MOPs, the possible mitigations of modularity are taken into account. After the computation of the pairwise comparison matrices, filled in by a naval architect with expertise in frigates at COMMIT. When evaluating the results, it is important to focus on the reciprocal importance of the non-modular and modular variant of a system. For the LDEW, the modular variant is preferred, while the non-modular air surveillance radar is slightly preferred. This difference is caused by the high weight of the 'common use across the fleet' and the 'quick changing of systems' for the LDEW, while the air surveillance radar has a low weight for these categories. These results show the importance of looking at the intentions of the end user. The LDEW results show that the focus is on adaptability rather than purely the economic aspect, while the air surveillance radar does not require high adaptability, and therefore the focus is on the economic aspect. These results show that even though a system scores high on the MFD, its function scores high on the AHP, and is deemed technically feasible in the KBE, it does not need to mean it will improve the vessel or the organization process. This shows the importance of assessing if a feasible modular system improves the design compared to a non-modular solution.

10

Conclusion & Recommendations

This thesis describes the development of a framework for the concept design phase to investigate the impact of modularity with respect to a non-modular solution and assess if modular systems would improve the vessel. The framework is applied during a case study on naval combatants of the RNLN. First, the conclusion is given in section 10.1. Next, the discussion is formulated in section 10.2. This chapter will end with a recommendation for future research in section 10.3.

10.1 Conclusion

This thesis has developed a framework, which can be used by the naval architect during the concept exploration phase, that aims to give a structured way to assess which systems have a high potential to be modular and evaluate the technical impact on the design of modular systems. When a system is a feasible module, the last step is to assess the impact on the vessel's effectiveness to check if the modular system will actually improve the vessel, or if the non-modular solution is preferred. The main research question of the thesis is:

How can the decision-making for modular systems in naval vessel design be performed in a structural way and evaluated on its effectiveness compared to a non-modular solution?

To answer this question, a literature review has been performed to gain valuable insights into modularity. The conclusions of this literature review, including the answers to the research questions formulated in the introduction, are formulated in subsection 10.1.1. The conclusions of the developed framework are formulated in subsection 10.1.2. The final conclusion of this thesis, focusing on the applicability of the framework, is formulated in subsubsection 10.1.2.a.

10.1.1 Literature review

Throughout the literature review, valuable insights into modularity are gained. The research questions, as formulated in the introduction, will be answered in the following subsubsections.

10.1.1.a ***RQ-1: Which type of missions are performed by the RNLN naval vessels?***

From the spectrum of conflict, it became visible that the environment in which a naval vessel must be able to operate can differ from little to no force on the low end, to lethal force on the high end of the spectrum. The naval vessels must be able to survive on the high end of the spectrum, while they would most likely operate on the lower end of the spectrum most of the time. The fundamentals of maritime operations show the diverse types of operations a naval vessel can counter, such as maritime assistance (low end of the spectrum), maritime security operations (low to middle end of the spectrum), and maritime combat operations (high end of the spectrum). A naval vessel's operational profile has high uncertainty since the operations that need to be performed in the future are unknown. This uncertainty makes it hard to determine a detailed representative operational profile of a naval vessel during the design process. Therefore, this report will focus on the main capabilities the Dutch naval vessels are designed for at the high end of the spectrum as shown in Table 10.1.

Table 10.1: Vessel type capability matrix

	Landing	AAW	ASuW	ASW	Supply
Submarine			X		
LPD	X				
LCF		X	X		
ASWF			X	X	
M-Frigate		X	X	X	
OPV			X		
JSS					X
CSS					X

10.1.1.b *RQ-2: Which design drivers influence the vessel's performance and how can this be evaluated in terms of effectiveness?*

Naval vessels need to be adaptable since the future area of operation is unknown and technology is advancing rapidly. Important naval vessel design drivers are the offensive capabilities, survivability, mobility, range, and endurance. These design drivers influence each other, which makes it impossible to design an optimal vessel for every single design driver at once. To gain insights in a vessel's performance, an effectiveness assessment must be made. This is not a straightforward process since expert opinion will remain highly important. Therefore, the development of a method to qualify this opinion is required. A promising method is the analytical hierarchy process (AHP). By creating a hierarchical overview, the level of influence can be distinguished. This results in the overall measure of effectiveness (OMOE) at the top level, measure of effectiveness (MOE) at the middle level, and measure of performance (MOP) at the bottom level. Numerical values on performance can be retrieved by wargaming, which is extremely time-consuming, or by applying pairwise comparison matrices. With the use of expert opinion, the reciprocal importance of elements can be rated. By using the principal eigenvector and normalizing the result, a numerical value of relative importance can be retrieved. This method can help the designer gain critical insights into the reciprocal importance of different functions of naval vessels.

10.1.1.c *RQ-3: What is the state-of-the-art in modularity and how would this be applicable to naval vessels?*

Different types of modularity can be applied to naval vessels. The first type is geometrical modularity, which aims to design standardized generic parts of the vessel, such as hotel facilities, to reduce the design time and enable parallel production. The next type is payload modularity, which aims to make it relatively easy to (re)place systems on board vessels. The challenge with this modularity type is the required ability of the platform to handle multiple systems. A modularity type not involving the platform is mission modularity, which aims to bring mission-related equipment onto the vessel. This is often achieved by standardized TEU container spots with electrical connections for cooling on board. The last type is software modularity, which aims to create the possibility of running different systems on the same software. This way, a plug-and-play principle is created. Modular systems have the advantage of being decoupled systems. This way, changes in functionality only impact the element that carries the function and the modules can be developed by independent research teams that work in parallel. As a result, future updates can be designed more easily and the design process can be accelerated. However, applying a modular architecture will typically result in compromises on performance since overdesign will be inevitable. Therefore, it is important to clearly understand the challenge that needs to be mitigated, and then determine if modularity is a suitable method to do so.

When looking at different methods for modularity application, it is important to first define the required output. For naval vessels, the functional requirements and design parameters are often fixed meaning the modularity method should not apply changes to the vessel's design itself. Modularity drivers play an important role and can be defined as 'expected benefits'. The goal is to find a method that gives an indication of potential modular systems for different modularity drivers. Since the expert opinion is of high importance in the design process of naval vessels, it is important the tool will not define modules but rather return an indication, which leaves the actual decision to the designers. Modular Function Deployment (MFD) will indicate high-potential modules for each corresponding modularity driver while leaving the final decisions to the designer. Therefore, MFD has a high potential to be applied to complex naval vessels.

10.1.1.d *RQ-4: What are the main challenges in naval vessel design for the RNLN and how could modularity mitigate these challenges?*

Designing naval vessels comes with specific challenges, besides the difficulty of assessing their effectiveness as discussed before. For the RNLN, designers face challenges in the vessel's complexity, maintenance & upgrades, short-term adaptability, high design and production time for small series, and high economic costs for small series. For vessels that require a flexible design and face changing requirements, modular design can be used as a method to mitigate these challenges. It can decrease a vessel's complexity by using standardized interfaces that can handle various systems, and the application of modules can ease the maintenance and upgrade costs and time. When modules are relatively exchangeable, short-term adaptability is increased since the vessel's configuration can be changed without the need for major refits. For the last two challenges, modularity enables the ability to use modules on more vessel types, which increases the number of vessels to which it can be applied. A larger application will decrease the relative costs since it is already designed but can be used for more purposes. This will also reduce the design and production time since parts of the future vessel (the already existing modules) are already designed.

Another advantage of reusing modules among multiple vessels is the possibility of using Knowledge Based Engineering (KBE). The KBE model consists of parametric building blocks, called 'High Level Primitives' (HLPs). These HLPs can incorporate and reuse relevant knowledge. This way, KBE can be used to investigate changes in these parameters when changing non-modular systems into modular variants.
97

10.1.2 Developed framework

The developed framework aims to give the naval architect guidance on applying modularity or not. When a system scores high on the MFD, it indicates the system would benefit from modularity. When its accompanying function scores high on the AHP, it indicates the system fulfills an important function. The technical impact of making the system modular can be assessed with the KBE model. If the technical impact is deemed acceptable, the system can be labeled as a 'feasible' module. The final effectiveness assessment will indicate if the feasible module actually improves the vessel's design or the organizational process. The flowchart of the framework is shown in Figure 10.1.

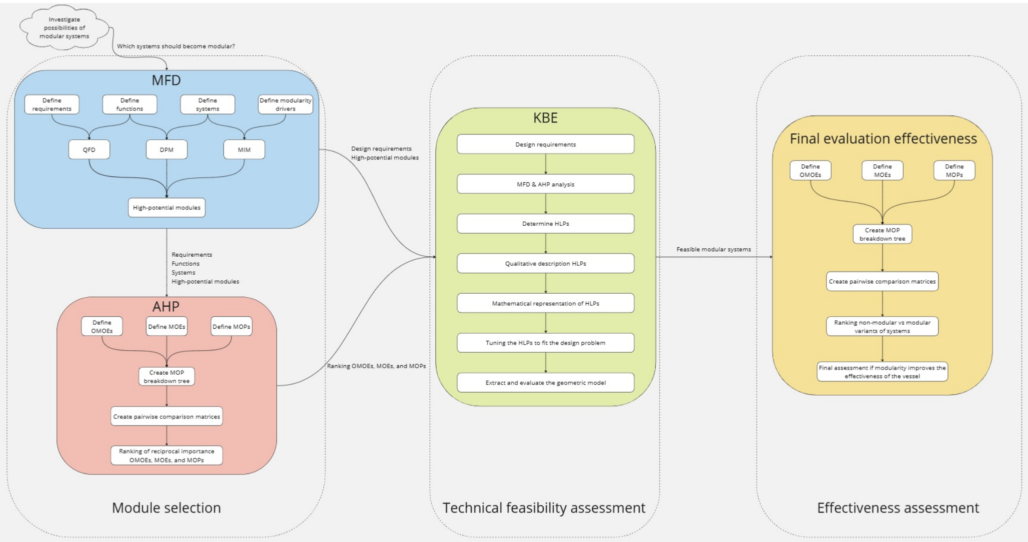


Figure 10.1: Flowchart framework

During the case study, the MFD and AHP of the framework will be applied to two large surface vessels from the RNLN. These are a landing platform dock (LPD-2) and a future air defender (FuAD). Due to the time-intensive process, the KBE will be applied only to the FuAD.

When looking at both the modularity drivers and high-potential modular systems, it can be seen the expected benefits are a result of the wider use of systems across the fleet, which increases scale advantages. With on average 36.66 points per system for the FuAD and 33.56 points for the LPD-2, the FuAD seems to be more suitable for modularity application. When looking at commonality across vessel types, this conclusion is reasonable. The LPD-2 has more unique functions, such as the task of conducting amphibious operations and providing hospital facilities, while the FuAD shares more common systems across different frigate types, such as weapon systems. Most results are in line with the possible mitigations computed during the literature review, while the possible mitigation of 'Maintenance & Upgrades' will mainly result in a potential benefit in maintenance, and not necessarily upgrades. The difference is that an upgrade could require significant changes in the vessel's construction, rather than just replacing the current system with a new one.

The AHP results show communication capabilities is the most important MOP for both FuAD and LPD-2. In this case, the MOP cannot be coupled to specific accompanying functions. The second highest ranking MOP for FuAD is MOP5 'Detect objects above the surface', which can be coupled to function j_{34} 'To detect threats through the air', which in turn is coupled to system k_{37}, the 'Air surveillance radar'. This shows the importance of a working air surveillance radar. The MFD results for the FuAD show that the air surveillance radar is already a high-potential modular system based on modularity drivers. When both the MFD and AHP show possible advantages of modular designing, the system is particularly interesting for investigating modular applications. By developing this ranking for the naval architect, the AHP can improve insights into the importance of the vessel's functions and accompanying systems, which can help select systems as high-potential modules.

It is important to note that the ranking focuses on the main operations of the vessels, while the lower-ranked MOPs are still indispensable for the ability to complete their missions. The AHP can give insights into the most important MOPs of a vessel, but the lower-scoring MOPs cannot be neglected.

The KBE model is used to map the technical impact and assess the feasibility of making systems modular. The model consists of a Python script implemented in Rhino. This results in a model that delivers a visual representation besides the output of the Python model. From this output, the vessel's dimensions, weight, GM, estimated draft, and COB can be retrieved. By analyzing the changes, the impact of modularity can be assessed and it can be checked if the design remains within its margins as required by the naval architect. The first step in this model is to select systems as HLPs. This is done by combining the MFD results, indicating which systems are high-potential modules, and the AHP results, indicating the most important systems of the vessel. For the case study, performed on the FuAD as reference vessel, the resulting AHPs are an air surveillance radar and Laser-Directed Energy Weapons (LDEWs). The LCF is taken as a starting point, after which it was scaled to the FuAD dimensions. The application of LDEWs results in a significant increase in electric power demand. Therefore, the FuAD reference model is made in two configurations; one for the initial design and one for the design that requires more electric power. As a result, more powerful generators are required and the vessel needs to be extended by 0.5 meters to make it fit. For the first configuration, the SMART-L air surveillance radar was first implemented non-modular and then as a module, and for the second configuration, the LDEW was first implemented non-modular and then as a module. This way, an assessment could be made of the impact of making these systems modular. It was found that the weight was slightly increased, the draft remained the same, and the GM stayed in a range of 1.616-1.636 meters, keeping it well within the acceptable range of 1.4-1.8 meters. With these results, the SMART-L and LDEWs are deemed feasible modules.

The last part of the framework consists of an effectiveness evaluation using the AHP. The pairwise comparison matrices were filled in by a naval architect with expertise in frigates at COMMIT. When evaluating the results, it is important to focus on the reciprocal importance of the non-modular and modular variant of a system. For the LDEW, the modular variant is preferred, while the non-modular air surveillance radar is slightly preferred. This difference is caused by the high weight of the 'common use across the fleet' and the 'quick changing of systems' for the LDEW, while the air surveillance radar has a low weight for these categories. These results show the importance of looking at the intentions of the end user. The LDEW results show that the focus is on adaptability rather than purely the economic aspect, while the air surveillance radar does not require high adaptability, and therefore the focus is on the economic aspect. These results show that even though a system scores high on the MFD, its function scores high on the AHP, and is deemed technically feasible in the KBE, it does not need to mean it will improve the vessel or the organization process. This shows the importance of assessing if a feasible modular system improves the design compared to a non-modular solution.

10.1.2.a Final conclusion

The framework can be applied to a wide variety of vessels, including commercial vessels. The framework uses generally applicable methods, and by combining them in a structural way the decision-making on whether to use modularity or not can be improved. For naval vessels, the effectiveness depends on the intentions of the end user. By qualifying the expert opinion using AHP, both by identifying the most important functions and the final evaluation, this intention is integrated into the framework. This also personalizes the outcome: based on the intentions of the end-user, completely different outcomes can be retrieved from this framework. After computing the framework for a specific vessel type, the results can partially be applied to other vessel types, within the same organization due to the end-user intentions mentioned above, as well. If a modular system is preferred over the non-modular variant, this implies the other vessel types will also benefit from this system as a module. Since this system is already defined as an HLP in the KBE model, the system can easily be imported into another design. The hull form can be easily changed as well since this already is an external Rhino file imported into the Python file. These factors make the framework applicable to a wide variety of different vessel types.

10.2 Discussion

When applying the MFD, it is important to keep in mind how modular systems are already. An example is the Vertical Launching System, which is designed to handle any missile type in any cell, making it an extremely flexible system. Since this is already a modular system, there are very few benefits to making it modular. The high score in the MFD comes from strong commonality and organizational advantages coupled with commonality, and the medium score is from purchase, separate testing, maintainability, and upgradability.

It is important to understand that these benefits have already been achieved since the VLS is a modular system that can be bought off the shelf while being ready for usage. So even though the VLS is already a modular system with proven benefits in system flexibility, it does not come out of the MFD as a potentially good module. Therefore, using the MFD will indicate which non-modular systems could benefit from modularity while modular systems can give invalid results. In this thesis, only the VLS had contradictory results.

The AHP can identify important MOPs that share commonality across the fleet. However, this does not mean the system as a whole can be designed as a module. An example is MOP3 ‘communication capabilities’. The required layout of the system, such as the placement of the satellite dishes and antennas, are vessel-dependent so they do not interfere with other systems. Therefore, components of the system might be suitable for modularity, while the system as a whole needs to be adjusted for each vessel type. Besides, it must be noted the effectiveness assessment is based on expert opinion before a technical design of the system’s non-modular and modular configuration is made. The expert opinion will remain relevant since the potential benefits of a system depend on the intentions of the end user, which can be seen as an opinion. One design can be more effective for one country, and less effective for another one, depending on their intentions with the design.

For the KBE model, it is important the potential increase in electric power demand is targeted during the concept exploration phase. When looking at the laser, the power delivery required by the generators is significant. Since two generators must be able to supply the vessel with electric power, the two lasers, consuming 1000 kW in total, will consume 30% of the two generators’ power supply of 3360 kW. By recognizing this increase in the concept design phase, the engine room layout can be changed so sufficient power is installed. Otherwise, there is a risk a future system cannot be installed without major refits of the power supply, which could be limited by the available space in the vessel. However, the risk of estimating future power demand is that it could be overestimated, and too much power is installed in the vessel, resulting in higher economic costs. Besides, the new machinery for the engine room is selected based on their technical performance. As formulated before, this thesis will not consider the economic impact. This means that the systems selected in this thesis are technically suitable, but could be extremely expensive.

Verification

During the AHP, the resulting relative weight vectors are verified by checking if the sum of all absolute weight values of a certain level is summed up to be the value of the level above. A deviation of 0.005 for this value is deemed acceptable since this is caused by rounding off the values to two decimals.

The Rhino model from the KBE model is verified by checking the different weight outcomes and comparing the values to calculations. It was found the total weight of the vessel and the displacement differ; the displacement is less than the vessel’s weight. When comparing the volume under the waterline at the given estimated draft, and multiplying this volume by the density of salt water (ρ=1.025 $\frac{\text{ton}}{m^3}$), the weight of the vessel is retrieved. Therefore, the weight of the vessel will be used as displacement value, and not the output ‘displacement’. This difference will be discussed during the validation as well.

Validation

The results of the AHP are validated using the consistency ratio (CR) for every individual matrix. By applying the requirement the CR needs to be below 0.10, indicating the matrix is 10 times more consistent than a random matrix, consistency is checked. When the CR exceeds 0.10, the naval architect is asked to revise his opinion. During this thesis, the CR remained under 0.10 for every independent matrix. When working with large data sets, data from naval architects who do not deliver consistent matrices can be left out of the AHP inputs.

The first step to validate the KBE model is to check if the input weights are equal to the output weight of the vessel. This way, it is checked if the required vessel is actually built as a 3D model. By analyzing the output, it was found the data in the ‘Ship Mass Output’ table matches the weight inputs of the volume blocks and hull. However, the ‘Stability’ output table shows a different value for the vessel’s displacement. By an iterative process, it was found a larger weight of systems increases the vessel’s weight but decreases the vessel’s displacement. This indicates an inaccurate value for the vessel’s displacement. The deviation is shown in Table 10.2. Since the deviation remains $<$2%, and weight estimations are made with a 5% deviation, the results are still considered valid. However, it is important the underlying Python script is investigated in more detail to check how this error is caused.

Table 10.2: Displacement deviation FuAD reference model

Weight [t]	Displacement [t]	Absolute deviation [t]	Relative deviation [%]
10000	9896	104	1.04
10008	9889	119	1.19
10062	9902	160	1.59
10072	9894	178	1.77

The use of the new machinery in the engine room is validated by calculating the maximum displacement of the vessel with the specific power delivery, and to make sure the total displacement will never exceed this value. If the displacement becomes larger, new machinery is required. The maximum displacement is calculated for both the vessel's maximum and cruise speed, and the lowest value is taken as a boundary. The dimensions of the new machinery and the FuAD reference model are validated as well to ensure the new engine room's dimensions will fit in the vessel's hull.

Another difference that needs to be highlighted is the difference between LCF's and FuAD's T_{Design} and estimated draft from the KBE model. With the vessel's mass, dimensions, and $\mathrm{C_b}$, the draft is estimated in the Python model. This is done using Equation 8.1. Since the $\mathrm{C_b}$ is based on literature and not on the actual frigate's design, the value for the estimated draft is expected to differ from the T_{Design}. The larger difference for the FuAD reference vessel compared to the difference in the draft of the LCF reference vessel is most likely caused by a larger C_b for the actual FuAD. These differences are deliberated with naval architects from COMMIT and are deemed reasonable due to the difference in C_b. Therefore, the estimated draft from the KBE is considered valid.

10.3 Recommendations for future research

This thesis has built the start of a framework for decision-making concerning the application of modular systems. In this section, future research is discussed which could improve or extend this framework.

Add detailed technical designs of systems to the KBE model
Due to the limited time for this thesis, no detailed technical design of the systems themselves could be made. Future research could expand this framework by making detailed designs of each system's configuration, so the technical impact can be studied in more detail.

Enable automatic generation of designs
Another way to improve the KBE model is to enable the automatic generation of different configurations. An important factor in achieving this is to include an automated design of the engine room that matches the required power output, both for the propulsive power and the electric power demanded by the vessel's systems. By automating the process, a more advanced vessel with multiple modular and non-modular configurations can be assessed.

Include wargaming in the effectiveness assessment
In this framework, the effectiveness of the vessel and its systems is evaluated based on expert opinion. In the final evaluation, faster maintenance is selected as an important design driver for the LDEW by the expert. When wargaming is included in the effectiveness assessment, a better estimation of the vessel's performance during combat operations can be made. One of the aspects that could be useful is to track how many times a system gets destroyed during these combat simulations. When a system gets destroyed often, it can shift more weight to fast maintenance than when it seems to survive the combat simulations often.

Economic impact
This thesis focused on the technical impact of the design while leaving the economic costs out. Future research could investigate how the costs of modular systems could estimated and implemented in the model. This could be done in the final evaluation of the modular systems since now only an estimation of an expert is used.

11

Personal reflection

The last year of working on my thesis has been an exciting, challenging journey. Working at COMMIT has really been a pleasure and the cooperation between COMMIT and TU Delft has been great. Especially the difference in points of view worked out great since COMMIT would focus on the context from a naval point of view, while TU Delft would focus from an academic point of view.

In the beginning, it was clear I would work on modularity, but the exact problem definition was unknown. One of the reasons was that modularity was some buzzword everyone talked about, but the exact definition and opinions were lacking. The only thing that was sure about my topic, is that it would have something to do with applying modularity and the vessel's effectiveness. This made the start of the literature review a bit hard since a research gap had to be found. Along the way, it became clear that modularity was assumed to improve a vessel's design, without comparing it to a non-modular solution. When this became a clear research gap, it became easier to continue the thesis since this gave more guidance.

Personally, I feel that the framework I have developed can really improve the decision-making with regard to the choice of modularity. By shifting the focus of modularity from the detailed design phase, with the focus on how modularity could be implied, to the concept exploration phase answering the question if modularity should be implied. By applying this framework, with their own intentional use of the vessel in mind, the naval architect can gain different insights into the application of modularity and the potential benefits it can offer. By using the framework, the naval architect can check if the benefits they have in mind could actually be gained by modularity. The last step, the evaluation of the effectiveness, aims to give naval architects a wake-up call to keep asking themselves if they are actually improving the vessel, or if they go along with the trend of applying modularity.

I experienced working on the thesis like solving a puzzle of which the exact outcome was unknown in the beginning. I feel like I got the pieces together and built something I am proud of and which can be used by naval architects when designing vessels.

References

[1] Alcott, B. (2005). Jevons' paradox. *Ecological Economics*, 54(1):9–21. `https://doi.org/10.1016/j.ecolecon.2005.03.020`.

[2] Andersen, R., Brunoe, T. D., and Nielsen, K. (2022). Module drivers in product development: A comprehensive review and synthesis. *Procedia CIRP*, 107:1503–1508. `https://doi.org/10.1016/j.procir.2022.05.182`.

[3] Andrews, D. (2001). Adaptability – the key to modern warship design. In *International Conference WARSHIP'01, Future Surface Warships.*

[4] Andrews, D. (2017). *Encyclopedia of Maritime and Offshore Engineering - Warship Design.* John Wiley & Sons. `https://doi.org/10.1002/9781118476406.emoe305`.

[5] Andrews, D. (2019). The multi role combatant - jack of all trades, master of none? In *Warship 2019: Multi-Role Vessels, 1.*

[6] Bahadori, A. (2014). *Cathodic Corrosion Protection Systems.* Gulf Professional Publishing, Boston.

[7] Baldwin, C. Y. and Clark, K. B. (2006). *Modularity in the Design of Complex Engineering Systems*, pages 175–205. Springer Berlin Heidelberg, Berlin, Heidelberg. `https://doi.org/10.1007/3-540-32834-3_9`.

[8] Bello, L. and Segovia, C. (2020). Evolution and present of modularity in warships. In *International Ship Design & Naval Engineering Congress.* `https://doi.org/10.1007/978-3-030-35963-8_17`.

[9] Brekke, Ø. (2012). *Modular Capabilities on Offshore Support Vessels.* Master's thesis, Norwegian University of Science and Technology. `https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/238186`.

[10] Brown, A. (2013). Application of operational effectiveness models in naval ship concept exploration and design. *Ciencia y tecnología de buques*, 7. `https://doi.org/10.25043/19098642.80`.

[11] Brown, A. and Salcedo, J. (2003). Multiple-objective optimization in naval ship design. *Naval Engineers Journal*, 115. `https://doi.org/10.1111/j.1559-3584.2003.tb00242.x`.

[12] Cambridge Dictionary (n.d.). *Neutralization.* Retrieved October 9, 2024, from `https://dictionary.cambridge.org/dictionary/english/neutralization`.

[13] Charisi, N. (2019). *Parametric Modelling Method based on Knowledge Based Engineering: The LNG Bunkering Vessel Case.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid:5321df04-39e6-4128-9eec-c3adcac8a68a?collection=education`.

[14] Choi, M. (2018). *Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context.* PhD thesis, Norwegian University of Science and Technology. `https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2566084`.

[15] Defence Science and Technology Laboratory (2024a). *Advanced future military laser achieves UK first.* Retrieved November 11, 2024, from `https://www.gov.uk/government/news/advanced-future-military-laser-achieves-uk-first`.

[16] Defence Science and Technology Laboratory (2024b). *Laser power moves a step closer for UK defence.* Retrieved November 11, 2024, from `https://www.gov.uk/government/news/laser-power-moves-a-step-closer-for-uk-defence`.

[17] Dick, J. and Hull, E. (2017). *Requirement Engineering.* Springer, 4 edition.

[18] Dion, E. (2017). *Synergy: A Theoretical Model of Canada'S Comprehensive Approach.* iUniverse.

[19] Duchateau, E. (2016). *Interactive evolutionary concept exploration in preliminary ship design.* PhD thesis, Delft University of Technology. `https://doi.org/10.4233/uuid:27ff1635-2626-4958-bcdb-8aee282865c8`.

[20] Erikstad, S. (2009). *Modularisation in Shipbuilding and Modular Production.* Trondheim, Norway, Marintek.

[21] Erikstad, S. O. (2019). *A Holistic Approach to Ship Design: Volume 1: Optimisation of Ship Design and Operation for Life Cycle.* Springer International Publishing, Cham. `https://doi.org/10.1007/978-3-030-02810-7_10`.

[22] Forecast international (2016). Rolls-royce industrial spey. `https://www.forecastinternational.com/archive/disp_pdf.cfm?DACH_RECNO=1245`.

[23] Forecast International (2019). *S1850M.* Retrieved November 20, 2024, from `https://www.forecastinternational.com/archive/disp_pdf.cfm?DACH_RECNO=1359`.

[24] Forti, A., Ramos, C., and Muniz, J. (2022). Integration of the design structure matrix (dsm) and modular function deployment (mfd) methods applied to mass customization aiming product modularization: a case study on heavy vehicle suspension. `https://doi.org/10.21203/rs.3.rs-1848068/v1`.

[25] Fuchs, C. and Golenhofen, F. J. (2019). *Mastering Disruption and Innovation in Product Management.* Springer.

[26] Gale, P. (1975). Margins in naval surface ship design. *Naval Engineers Journal*, 87(2):174–188. `https://doi.org/10.1111/j.1559-3584.1975.tb03728.x`.

[27] General Electric (2017). Lm2500+ marine gas turbine. `https://www.geaerospace.com/sites/default/files/datasheet-lm2500plus.pdf`.

[28] Gurbuz, H. G. and Tekinerdogan, B. (2018). Model-based testing for software safety: a systematic mapping study. *Software Quality Journal*, 26:1327–1372. `https://doi.org/10.1007/s11219-017-9386-2`.

[29] Habben Jansen, A. (2020). *A Markov-based vulnerability assessment of distributed ship systems in the early design stage.* PhD thesis, Delft University of Technology. `https://doi.org/10.4233/uuid:f636539f-64a5-4985-b77f-4a0b8c3990f4`.

[30] Hölttä-Otto, K., Tang, V., and Seering, W. (2003). Modularizing product architectures using dendrograms. `https://www.researchgate.net/publication/37595148_Modularizing_Product_Architectures_Using_Dendrograms`.

[31] Hvam, L., Herbert-Hansen, Z. N. L., Haug, A., Kudsk, A., and Mortensen, N. H. (2017). A framework for determining product modularity levels. *Advances in Mechanical Engineering*, 9(10):1–14. `https://doi.org/10.1177/1687814017719420`.

[32] Janssen, M. (2024). Consulted: 27-2-2024. Deputy head of AMS, COMMIT.

[33] Jiao, R. and Tseng, M. (2000). Fundamentals of product family architecture. *Integrated Manufacturing Systems*, 11. `https://doi.org/10.1108/09576060010349776`.

[34] Joergensen, S. N. (2013). *Developing Modular Manufacturing Architectures.* PhD thesis, Aalborg University. `https://vbn.aau.dk/ws/portalfiles/portal/549511916/Developing_Modular_Manufacturing_System_Architectures_Steffen_Nordahl_Joergensen_phd_thesis_print_file_2_.pdf`.

[35] John Hill (2023). *US increases MK41 vertical launching system production.* Retrieved August 30, 2024, from `https://www.naval-technology.com/news/us-increases-mk41-vls-production/?cf-view`.

[36] Kana, A., Shields, C., and Singer, D. (2016). Why is naval design decision-making so difficult? In *Warship 2016: Advanced Technologies in Naval Design, Construction, and Operation.*

[37] Kanellopoulou, A., Kytariolou, A., Papanikolaou, A., Shigunov, V., and Zaraphonitis, G. (2019). Parametric ship design and optimisation of cargo vessels for efficiency and safe operation in adverse weather conditions. *Journal of Marine Science and Technology*, 24. `https://doi.org/10.1007/s00773-018-00620-1`.

[38] Kao, I. (2021). *Knowledge Based Engineering (KBE) automatic layout generation framework for modular offshore wind service vessels: Towards a Brand-New Multi-Model Generator for Modular OSV Product Families.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3A34162956-baa5-49b6-984a-719cfd5d833a`.

[39] Karreman, J. (2022a). Doorbraak in dossier vervanging m-fregatten. Marineschepen.nl. `https://marineschepen.nl/nieuws/Doorbraak-in-dossier-vervanging-M-fregatten-230620.html`.

[40] Karreman, J. (2022b). In 2027 eerste nederlandse fregat met tomahawk. Marineschepen.nl. `https://marineschepen.nl/nieuws/Marine-krijgt-Tomahawk-kruisvluchtwapen-040423.html#:~:text=Nederland%20gaat%20in%20de%20VS,wachten%20in%20verband%20met%20aanpassingen`.

[41] Karremann, J. (2022). *Marine wil op korte termijn grote zwaarbewapende schepen met enkele bemanningsleden.* Retrieved August 1, 2024, from `https://marineschepen.nl/nieuws/TRIFIC-nieuw-plan-voor-zwaarbewapende-laagbemande-schepen-231122.html`.

[42] Karremann, J. (2023). *Twee nieuwe marineschepen voor meer slagkracht en beter beeld dreiging op Noordzee.* Retrieved August 1, 2024, from `https://marineschepen.nl/nieuws/Marine-wil-twee-nieuwe-schepen-inzetten-voor-beter-beeld-dreiging-Noordzee-081223.html`.

[43] Karremann, J. (2024). *Amfibische Transportschepen krijgen mogelijk doorlopend dek.* Retrieved August 4, 2024, from `https://marineschepen.nl/nieuws/Meer-details-Amfibische-Transportschepen-090424.html`.

[44] Keane, R. and Tibbits, B. (1996). A revolution in warship design: Navy-industry integrated product teams. *Journal of Ship Production*, 12(4):254–268.

[45] Khezri, R. and Mahmoudi, A. (2020). Review on the state-of-the-art multi-objective optimisation of hybrid standalone/grid- connected energy systems. *IET Generation Transmission Distribution*, 14:4285 – 4300. `https://doi.org/10.1049/iet-gtd.2020.0453`.

[46] Kitchenham, B., Pearl Brereton, O., Budgen, D., Turner, M., Bailey, J., and Linkman, S. (2009). Systematic literature reviews in software engineering – a systematic literature review. *Information and Software Technology*, 51:7–15. `https://doi.org/10.1016/j.infsof.2008.09.009`.

[47] Knegt, S. (2018). *Winning at sea: Developing a method to provide insight in early stage naval fleet design requirements.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3Af5de21cd-dc49-42dc-a17e-2b6ec9a6bca8`.

[48] Krejčí, J. and Stoklasa, J. (2018). Aggregation in the analytic hierarchy process: Why weighted geometric mean should be used instead of weighted arithmetic mean. *Expert Systems with Applications*, 114:97–106. `https://www.sciencedirect.com/science/article/pii/S0957417418303981`.

[49] Le Poole, J. J. (2018). *Integration of aboard logistic processes in the design of logistic driven ships during concept exploration.* Master's thesis, Delft University of Technology. `http://resolver.tudelft.nl/uuid:d104572f-6337-4c20-b719-f1cf44c986e6`.

[50] Lockheed Martin (2023). *Lockheed Martin to Scale Its Highest Powered Laser to 500 Kilowatts Power Level.* Retrieved November 14, 2024, from `https://news.lockheedmartin.com/2023-07-28-Lockheed-Martin-to-Scale-Its-Highest-Powered-Laser-to-500-Kilowatts-Power-Level#:~:text=BOTHELL%2C%20Wash.%2C%20July%2028,Office%20of%20the%20Under%20Secretary`.

[51] Manley, D. (2018). The nato drive to mission modularity. In *Warship 2018: Procurement of Future Surface Vessel, 1.*

[52] Marineschepen.nl (2023a). City- en vlissingenklasse mijnenbestrijdingsvaartuigen (belgië en nederland). Marineschepen.nl. `https://marineschepen.nl/schepen/vlissingen.html`.

[53] Marineschepen.nl (2023b). *SMART-L radar.* Retrieved December 2, 2024, from `https://marineschepen.nl/dossiers/smart-l.html`.

[54] Marineschepen.nl (2024a). *De Zeven Provinciënklasse fregatten.* Retrieved August 2, 2024, from `https://marineschepen.nl/schepen/zeprov.html`.

[55] Marineschepen.nl (2024b). *Eerste beeld nieuwe fregatten.* Retrieved November 20, 2024, from `https://marineschepen.nl/nieuws/Eerste-beeld-nieuwe-fregatten-100424.html`.

[56] Marineschepen.nl (2024c). *Johan de Witt Landing Platform Dock.* Retrieved August 2, 2024, from `https://marineschepen.nl/schepen/johandewitt.html`.

[57] Military Factory (2019). *HNLMS De Zeven Provincien (F802).* Retrieved November 17, 2024, from `https://www.militaryfactory.com/ships/detail.php?ship_id=hnlms-de-zeven-provincien-f802-guided-missile-destroyer-netherlands`.

[58] Ministerie van Defensie (2023a). *Defensie in zee met bouwers nieuwe Anti Submarine Warfare fregatten.* Retrieved November 29, 2023, from `https://www.defensie.nl/actueel/nieuws/2023/06/29/defensie-in-zee-met-bouwers-nieuwe-anti-submarine-warfare-fregatten`.

[59] Ministerie van Defensie (2023b). *Vervanging 127 millimeter-kanon is complexe modificatie.* Retrieved August 26, 2024, from `https://magazines.defensie.nl/materieelgezien/2023/09/vervanging-127-millimeter-kanon-is-complexe-modificatie`.

[60] Ministerie van Defensie (2023c). *Zr.Ms. Holland meert aan in Cyprus.* Retrieved February 6, 2024, from `https://magazines.defensie.nl/defensiekrant/2023/46/01_cyprus_46`.

[61] Ministerie van Defensie (2024). *Twee nieuwe scheepstypes op tekentafel.* Retrieved August 2, 2024, from `https://magazines.defensie.nl/materieelgezien/2024/02/twee-nieuwe-scheepstypes-op-tekentafel#:~:text=Het%20zijn%20twee%20van%20de,OceanGoing%20Patrol%20Vessels%20(OPV)`.

[62] Ministerie van Defensie (n.d.a). *Amfibisch transportschip (LPD).* Retrieved August 4, 2024, from `https://www.defensie.nl/organisatie/marine/materieel/schepen/amfibische-transportschepen`.

[63] Ministerie van Defensie (n.d.b). *Luchtverdedigings- en commandofregat (LCF).* Retrieved August 6, 2024, from `https://www.defensie.nl/onderwerpen/materieel/schepen/luchtverdedigings--en-commandofregatten-lcf`.

[64] Ministerie van Defensie (n.d.c). *Mijnenjagers.* Retrieved February 29, 2024, from `https://www.defensie.nl/onderwerpen/materieel/schepen/mijnenjagers`.

[65] Ministry of Defence (2014). Fundamentals of maritime operations: Netherlands maritime military doctrine. `https://english.defensie.nl/downloads/publications/2014/02/13/netherlands-maritime-military-doctrine`.

[66] Naval Technology (2003). *De Zeven Provincien Class (LCF).* Retrieved November 12, 2024, from `https://www.naval-technology.com/projects/dezeven/?utm_source=&utm_medium=15-4898&utm_campaign=&cf-view`.

[67] Nieuwenhuis, J. J. (2013). *Evaluating the appropriateness of product platforms for Engineered-To-Order ships.* PhD thesis, Delft University of Technology. `https://doi.org/10.4233/uuid:8d3cf609-2adc-461b-b61c-ed3affc9ac31`.

[68] Parsons, M. A., Robinson, K. M., Kara, M. Y., Stinson, N. T., Snyder, D. J., Woodward, D. C., and Brown, A. J. (2020). Application of a distributed system architectural framework to naval ship concept and requirements exploration. *NAVAL ENGINEERS JOURNAL*, 132(4):105–124. `https://www.sciencedirect.com/science/article/pii/S0950584908001390`.

[69] Pawling, R. J. (2017). *Encyclopedia of Maritime and Offshore Engineering - Introduction—What Makes a Warship?* John Wiley & Sons. `https://doi.org/10.1002/9781118476406.emoe305`.

[70] Perun (2024). Us navy procurement disasters - the littoral combat ship and zumwalt class destroyer. [Video]. Youtube. `https://www.youtube.com/watch?v=odS3Kn5oGl0&t=8s`.

[71] Peruzzi, L. (2024). *Euronaval 2024 – tkMS presents the Meko A-400 AMD.* Retrieved November 19, 2024, from `https://www.edrmagazine.eu/euronaval-2024-tkms-presents-the-meko-a-400-amd`.

[72] Piantanakulchai, M. and Saengkhao, N. (2003). Evaluation of alternatives in transportation planning using multi-stakeholders multi-objectives ahp modeling. *Proceedings of the Eastern Asia Society for Transportation Studies*, 4.

[73] Piperakis, A. S. (2013). *An Integrated Approach to Naval Ship Survivability in Preliminary Ship Design.* PhD thesis, University College London. `https://www.researchgate.net/publication/313566821_An_Integrated_Approach_to_Naval_Ship_Survivability_in_Preliminary_Ship_Design`.

[74] Rawson, K. and Tupper, E. (2001). *Basic Ship Theory.* Butterworth-Heinemann, Oxford, fifth edition edition.

[75] Saaty, R. (1987). The analytic hierarchy process—what it is and how it is used. *Mathematical Modelling*, 9(3):161–176. `https://doi.org/10.1016/0270-0255(87)90473-8`.

[76] Salomon, V. and Gomes, L. (2024). Consistency improvement in the analytic hierarchy process. *Mathematics*, 12:828. `https://www.researchgate.net/publication/378911244_Consistency_Improvement_in_the_Analytic_Hierarchy_Process`.

[77] Schank, J. F., Savitz, S., Munson, K., Perkinson, B., McGee, J., and Sollinger, J. M. (2016). *Designing Adaptable Ships - Modularity and Flexibility in Future Ship Designs.* RAND Corporation. `https://doi.org/10.7249/RR696`.

[78] Schulten, P., Geertsma, R., and Visser, K. (2017). Energy as a weapon, part ii. In *EAAW VII Symposium Proceedings.*

[79] Simpson, T., Maier, J., and Mistree, F. (2001). Product platform design: Method and application. *Research in Engineering Design*, 13:2–22. `https://doi.org/10.1007/s001630100002`.

[80] Simpson, T. W., Jiao, J., Siddique, Z., and Hölttä-Otto-Otto, K. (2014). *Advances in Product Family and Product Platform Design.* Springer.

[81] Smit, R. J. (2019). *Modular Platform: Towards a Product Family for a Series of Navy Support Vessels.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3A6f8b90ea-ec59-4da2-8980-68b8e4dfbbec?collection=education`.

[82] Smith, D. R. (2019). Multi-role vessels: Design, manning & cost drivers. In *Warship 2019: Multi-Role Vessels, 1.*

[83] Stjepandić, J., Wognum, N., and Verhagen, W. J. (2015). *Concurrent Engineering in the 21st Century.* Springer.

[84] Streng, J. E. (2021). *Alternative Energy Carriers in Naval Vessels: Design Options and Implications for RNLN Large Surface Vessels.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3A47e02b82-5a0f-4eba-8092-f2e10b5c6845?collection=education`.

[85] Streng, J. E. (2024a). Consulted: 16-2-2024. Naval architect, COMMIT.

[86] Streng, J. E. (2024b). Consulted: 22-3-2024. Naval architect, COMMIT.

[87] Streng, J. E. (2024c). Consulted: 27-6-2024. Naval architect, COMMIT.

[88] Streng, J. E. (2024d). Consulted: 01-8-2024. Naval architect, COMMIT.

[89] Streng, J. E. (2024e). Consulted: 16-10-2024. Naval architect, COMMIT.

[90] Streng, J. E., Duchateau, E., and Jansen, A. H. (2024a). Consulted: 02-8-2024. Naval architects, COMMIT.

[91] Streng, J. E., Duchateau, E., and Logtmeijer, R. (2024b). Consulted: 27-2-2024. Naval architects, COMMIT.

[92] Streng, J. E. and Krikke, E. (2024). Consulted: 12-3-2024. Naval architects, COMMIT.

[93] Tummers, J., Kassahun, A., and Tekinerdogan, B. (2019). Obstacles and features of farm management information systems: A systematic literature review. *Computers and Electronics in Agriculture*, 157:189–204. `https://doi.org/10.1016/j.compag.2018.12.044`.

[94] Tvedt, H. (2012). *Modular approach to offshore vessel design and configuration.* Master's thesis, Norwegian University of Science and Technology. `https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/238192?locale-attribute=no`.

[95] UK Ministry of Defence (2022). maritime modularity concept. `https://assets.publishing.service.gov.uk/media/63dcece38fa8f57fc8061089/Maritime_Modularity_Concept.pdf`.

[96] United States Navy (2021). *RIM-116 Rolling Airframe Missile (RAM).* Retrieved December 6, 2024, from `https://www.navy.mil/Resources/Fact-Files/Display-FactFiles/Article/2168961/rim-116-rolling-airframe-missile-ram/`.

[97] Van den Berg, S. (2018). *Low carbon shipping - a decision support tool for the implementation of co*$_2$ *reducing measures.* Master's thesis, Delft University of Technology. `https://repository.tudelft.nl/record/uuid:b758d9f7-63a0-4ba0-ba97-d7345f46a38e`.

[98] Van der Maat, C. (2024). *Beantwoording feitelijke vragen A-brief 'Vervanging LCfregatten' en 'Bewapening maritieme lucht- en raketverdediging'.* Ministerie van Defensie.

[99] Van Oers, B., Takken, E., Duchateau, E., Zandstra, R., Cieraad, S., Bruijn, W., and Janssen, M. (2018). Warship concept exploration and definition at the netherlands defence materiel organisation. *Naval Engineers Journal*, 130:61.

[100] Van Oers, B. J. (2011). *A Packing Approach for the Early Stage Design of Service Vessels.* PhD thesis, Delft University of Technology. `https://repository.tudelft.nl/islandora/object/uuid%3A6be7582c-63b1-477e-b836-87430bcfb43f`.

[101] Walton, D. (1997). *Appeal to expert opinion: Arguments from authority.* University Park, PA: Penn State University Press.

[102] Wärtsilä (2006). *Wärtsilä 26 technology review.* Retrieved November 17, 2024, from `https://www.wartsila.com/docs/default-source/product-files/engines/ms-engine/wartsila-o-e-w-26-tr.pdf`.

[103] Wärtsilä (2009). *Wärtsilä Deutz marine engines.* Retrieved November 17, 2024, from `https://quantiparts.com/tech-support/deutz/TBD620/1-engine%20leaflet/D620_leaflet.pdf`.

[104] Wärtsilä (2013). *WÄRTSILÄ 32 PRODUCT GUIDE.* Retrieved November 17, 2024, from `https://www.coordinador.cl/wp-content/uploads/2019/05/Anexo-Informe-T%C3%A9cnico-PPyD-Central-Cenizas.pdf`.

[105] Wärtsilä (n.d.a). *Admiralty coefficient, Admiralty constant.* Retrieved November 19, 2024, from `https://www.wartsila.com/encyclopedia/term/admiralty-coefficient-admiralty-constant`.

[106] Wärtsilä (n.d.b). *Generating sets.* Retrieved December 12, 2024, from `https://www.wartsila.com/marine/products/engines-and-generating-sets/generating-sets/wartsila-gensets`.

[107] Yao, H., Xu, Z., Hou, Y., Dong, Q., Liu, P., Ye, Z., Pei, X., Oeser, M., Wang, L., and Wang, D. (2023). Advanced industrial informatics towards smart, safe,and sustainable roads: A state of the art. *Journal of Traffic and Transportation Engineering (English Edition)*, 10(2):143–158. `https://doi.org/10.1016/j.jtte.2023.02.001`.

A

Literature review approach

This appendix will discuss the published work analysis in section A.1 and the literature review approach in section A.2.

A.1 Published work analysis

This section aims to analyze trends in research involving modular vessels to show the subject's relevance. This is done by analyzing the published work on Scopus to make sure peer-reviewed sources are used. Besides, Scopus can create simple overviews of the subject area, document type, and country of research which can be used for analysis. Therefore, Scopus will be used for the general published work analysis. During the literature review, it was discovered work had been classified, either by commercial companies or governments, while other published work could not be found by people who did not attend certain conferences. Therefore, only an analysis can be done to investigate global trends in research involving modular vessels.

To start with, sources were searched which included '(ship OR vessel) AND (modular OR modularity)' in the title, keywords, or abstract. It was found that the combination of 'vessel AND (modular OR modularity)' also resulted in medical publications about blood vessels. Therefore, the results were limited to publications in the fields of Engineering, Energy, Materials Science, Environmental Science, Mathematics, and Computer Science. These areas were deemed relevant after analyzing the results in every category to make sure the published work involved the maritime industry. The results from the period 2000-2023 were analyzed to ensure the results show published work of completed years and are (relatively) up-to-date. The three most researched areas, in respective order Engineering, Energy, and Computer Science, will be plotted to analyze trends. After this analysis, a more specific analysis of naval vessels is done by searching for '(ship OR vessel) AND (modular OR modularity) AND (navy OR naval)'.

The results for the general analysis is shown in Figure A.1 and the analysis focused on naval vessels in Figure A.2. The general Figure A.1, focusing on modularity in vessels in general, tends to show an upcoming trend in research towards modularity in vessels, while no real trends can be seen in Figure A.2. On the naval analysis, the peak in publications in the period 2004-2007 is caused by publications from the 'Jane's International Defence Review', which published respectively 4, 8, 12, and 13 publications during this period. Scopus stopped the coverage of this review after 2007, which caused a drop in publications. This example also shows the limited results shown in Scopus compared to the actual published articles on modularity focused on naval vessels. Therefore, the actual trends can best be retrieved by modularity in vessels in general. For this reason, trend lines are only included in Figure A.1. These trend lines show an increase in publications involving modularity on vessels, indicating increased interest in the subject.

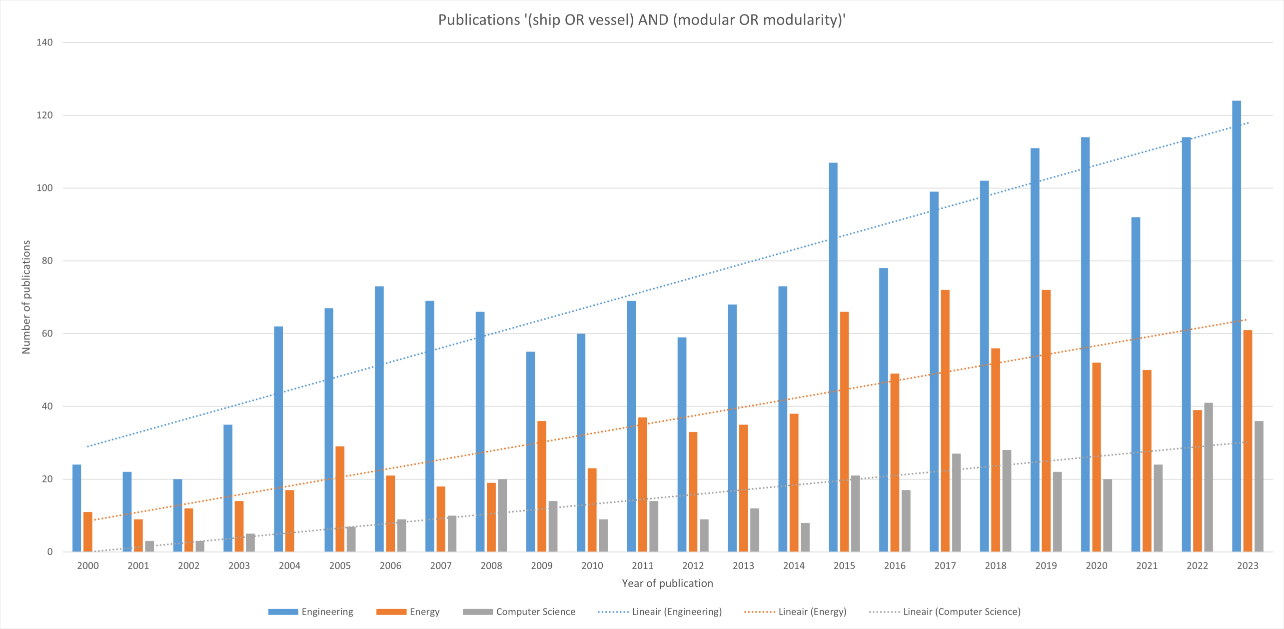


Figure A.1: Published works per year in the areas of Engineering, Energy, and Computer Science including '(ship OR vessel) AND (modular OR modularity)' in the title, abstract, or keywords indexed on Scopus (2000-2023)

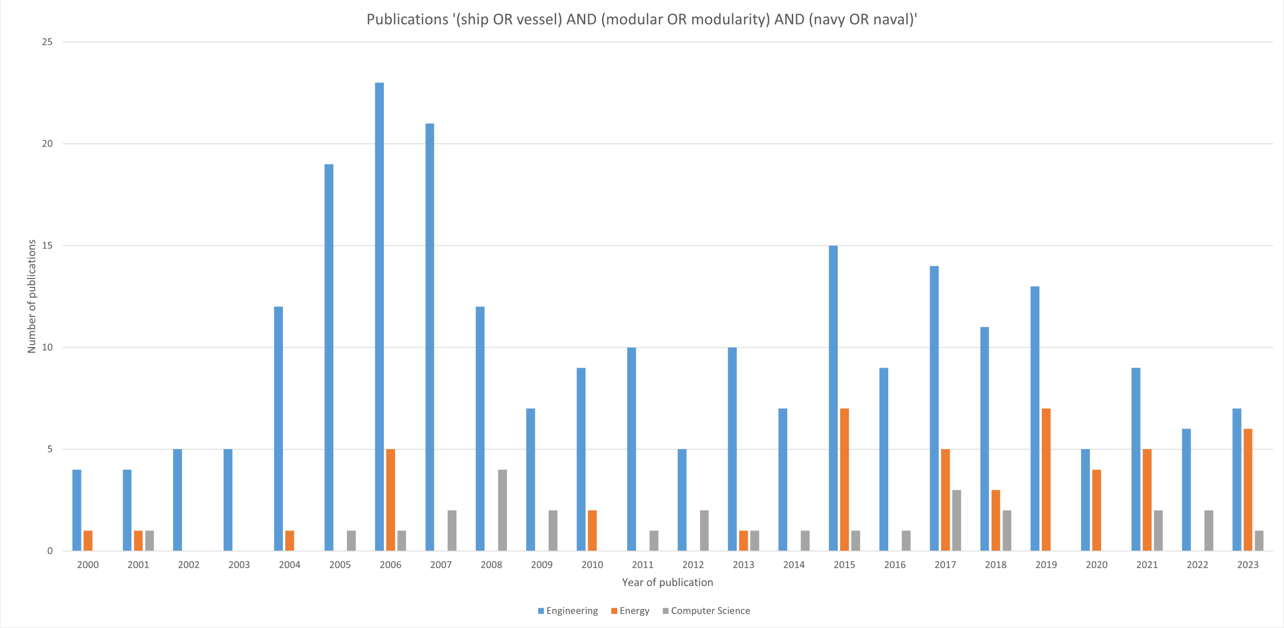


Figure A.2: Published works per year in the areas of Engineering, Energy, and Computer Science including '(ship OR vessel) AND (modular OR modularity) AND (navy OR naval)' in the title, abstract, or keywords indexed on Scopus (2000-2023)

A.2 Literature review approach

This section will discuss the literature review approach, quality assessment of sources used for the literature study, and formulate the research questions. This report follows the method for a literature review proposed by Kitchenham et al. [46]. First, the main research questions (RQs) will be determined. Next, suitable criteria (C) will be specified. At last, the quality index (QI) will be identified. Each part will be explained further in the subsections below. Such an approach is needed to filter out unsuitable articles and to have a guideline on the scientific value of an article. To find these scientific sources, Google Scholar, TU Delft repository, and Scopus were used.

The list of sources used for the literature study can be seen in Table A.1. This list is computed in chronological order of when the articles were read. To start with, a list of around 30 sources has been compiled. After applying the QI, 24 sources were deemed suitable for the analysis. Whenever possible useful references were found in these sources, they were read as well and assessed according to the QI. Afterward, the gaps in research in this list are analyzed. The next step is to specifically look for sources who did research into these subjects. If these sources cannot be found after an intensive search, the conclusion can be drawn there is a general gap in research. After adding useful sources found in sources from the original list and searching for new sources in the identified gaps in the original list, a final list of 46 sources was computed for the analysis.

To start with, useful sources were retrieved by colleagues at COMMIT. Additional information was retrieved by Google Scholar, TU Delft repository, and Scopus. To start with some general information, the Dutch MoD's maritime doctrine [65] was read to gain insights into the type of operations the RNLN conducts. Next, literature was retrieved about the effectiveness assessment of naval vessels. This was done by searching for 'Naval AND (Vessel OR Ship) AND Effectiveness AND Assessment'. Next, an analysis of modularity on naval vessels is done by searching for '(ship OR vessel) AND (modular OR modularity) AND (navy OR naval)'. When only little information was found, the search was expanded to more general information by using the keywords '(ship OR vessel) AND (modular OR modularity)'.

In subsection A.2.1 the main research questions are formulated. Next, in subsection A.2.2 inclusion and relevance criteria are discussed, together with quality assessment criteria for the scientific sources.

Table A.1: Categorisation of selected papers for review

ID	Paper reference	Year	Type	Main country of research
#1	Andrews [5]	2019	Conference paper	United Kingdom
#2	Smith [82]	2019	Conference paper	United Kingdom
#3	Streng [84]	2021	MSc thesis	The Netherlands
#4	Knegt [47]	2018	MSc thesis	The Netherlands
#5	Smit [81]	2019	MSc thesis	The Netherlands
#6	Kao [38]	2021	MSc thesis	The Netherlands
#7	Brown [10]	2013	Journal article	United States
#8	Brown and Salcedo [11]	2003	Journal article	United States
#9	Parsons et al. [68]	2020	Journal article	United States
#10	Andersen et al. [2]	2022	Journal article	Denmark
#11	Andrews [3]	2001	Conference paper	United Kingdom
#12	Andrews [4]	2017	Book	United Kingdom
#13	Bello and Segovia [8]	2020	Conference paper	Colombia
#14	Dion [18]	2017	Book	Canada
#15	Erikstad [20]	2009	Book	Norway
#16	Forti et al. [24]	2022	Journal article	Brazil
#17	Fuchs and Golenhofen [25]	2019	Book	Germany
#18	Gale [26]	1975	Journal article	United States
#19	Gurbuz and Tekinerdogan [28]	2018	Journal article	The Netherlands
#20	Habben Jansen [29]	2020	PhD Thesis	The Netherlands
#21	Hölttä-Otto et al. [30]	2003	Journal article	Australia
#22	Kana et al. [36]	2016	Conference paper	The Netherlands
#23	Keane and Tibbits [44]	1996	Journal article	United States
#24	Kitchenham et al. [46]	2009	Journal article	United Kingdom
#25	Le Poole [49]	2018	MSc thesis	The Netherlands
#26	Manley [51]	2018	Journal article	United Kingdom
#27	Nieuwenhuis [67]	2013	PhD Thesis	The Netherlands
#28	Pawling [69]	2017	Book	United Kingdom
#29	Piperakis [73]	2013	PhD Thesis	United Kingdom
#30	Saaty [75]	1987	Journal article	United States
#31	Schank et al. [77]	2016	Book	United States
#32	Schulten et al. [78]	2017	Conference paper	The Netherlands
#33	Simpson et al. [80]	2014	Book	United States
#34	Simpson et al. [79]	2001	Journal article	United States
#35	Stjepandić et al. [83]	2015	Book	Germany
#36	Tummers et al. [93]	2019	Journal article	The Netherlands
#37	Van Oers et al. [99]	2018	Journal article	The Netherlands
#38	Van Oers [100]	2011	PhD Thesis	The Netherlands
#39	Joergensen [34]	2013	PhD Thesis	Denmark
#40	Choi [14]	2018	PhD Thesis	Norway
#41	Brekke [9]	2012	MSc Thesis	Norway
#42	Jiao and Tseng [33]	2000	Journal article	China
#43	Duchateau [19]	2016	PhD Thesis	The Netherlands
#44	Tvedt [94]	2012	MSc Thesis	Norway
#45	Erikstad [21]	2019	Journal article	Norway
#46	Hvam et al. [31]	2017	Journal article	Denmark

A.2.1 Main research questions

The possible questions arising on naval vessel research may cover a range from global to specific tasks. The following 4 questions will help define the research done on designing naval vessels and applying modularity, and this way identify the research gaps:

RQ-1	Which type of missions are performed by the RNLN naval vessels, and what is their operational profile?
RQ-2	Which design drivers influence the vessel's performance and how can this be evaluated in terms of effectiveness?
RQ-3	What is the state-of-the-art in modularity and how would this be applicable to naval vessels?
RQ-4	What are the main challenges in naval vessel design for the RNLN and how could modularity mitigate these challenges?

A.2.2 Inclusion and relevance criteria

For a proper review of the scientific contributions, additional selection needs to be done. This selection criteria should go in-depth into the content of the contribution itself, rather than selecting it on the presence of certain keywords.

C-1 Full text is available in English (*inclusion*);
C-2 Content is classified (*exclusion*);

Criterion C-1 led to the exclusion of 82 Chinese, 11 Russian, 58 unidentified, 34 German, 7 French, 6 Spanish, 4 Italian, 3 Korean, 2 Japanese, 1 Portuguese, 1 Polish, and 1 Croatian articles. The amount of sources excluded by criterion C-2 is unknown since classified content can not be analyzed online. This criterion is mentioned because of the documents retrieved by COMMIT, of which several could be used to gain valuable insights but could not be used in the literature study due to classification.

After applying the inclusion criteria, it is important to assess the quality of the scientific contributions found. The quality assessment criteria proposed by Gurbuz and Tekinerdogan [28] is used as a suitable example, adapted to the subject of this report. This means the following quality index (QI) needs to be answered:

QI-1 Are the aims of the study clearly stated?
QI-2 Are the scope and context of the study clearly defined?
QI-3 Are the variables used in the study likely to be valid and reliable?
QI-4 Is the research process adequately documented?
QI-5 Are all the study's research questions answered?
QI-6 Are negative findings and weaknesses presented?
QI-7 Are the main findings stated clearly in terms of creditability, validity and reliability?
QI-8 Do the conclusions relate to the aim of the purpose of the study?

Answering these questions can lead to a certain score, as proposed by Tummers et al. [93]. If the index is fully satisfied, 1 point will be given. A partially satisfied index will lead to 0.5 points and 0 points will be given if the index is not satisfied at all. The maximum score a scientific contribution can achieve is 8 points, and the QI assessment will be passed if the contribution scores at least 4 points. This QI assessment will ensure only high-quality contributions will be used for the literature review. The resulting values for the QI can be seen in Figure A.3. It must be noted that sources that were deemed of low quality were left out of the analysis and are thus not shown in this figure. The relatively high amount of sources scoring a QI value of 8 can be explained by the amount of Master- and PhD theses used, which often retrieve the full score.

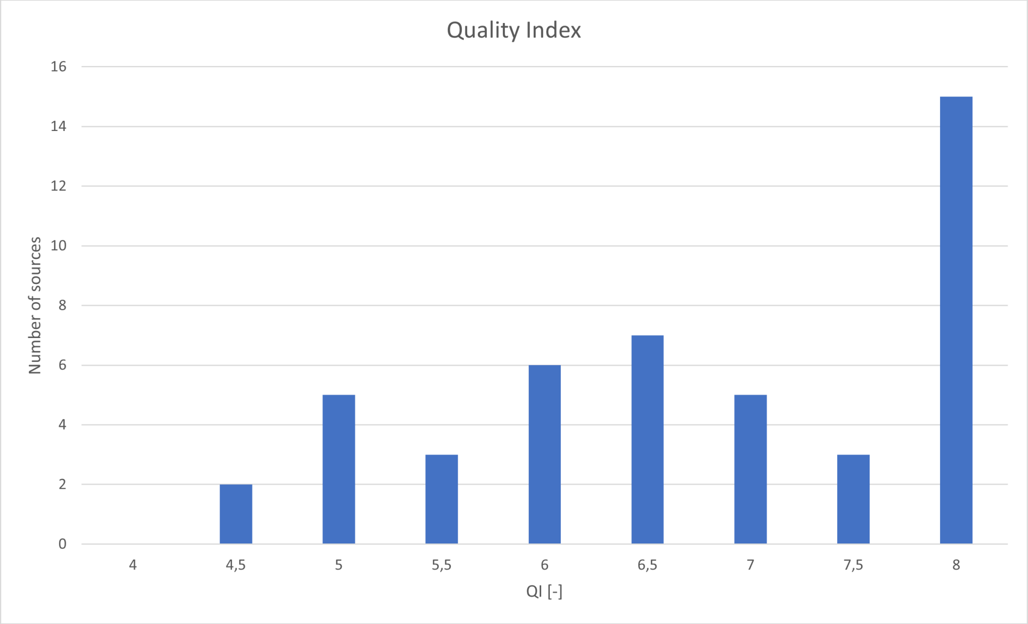


Figure A.3: Quality Index values

B

Example of application of the AHP

The example described here is used by Saaty [75]. The author has a teenage son who graduated from high school last year and the AHP model is used to select the college of his choice. He was accepted by Swarthmore College, Northwestern University, the University of Michigan, Vanderbilt University, and Carnegie-Mellon University (two blocks from his home). Since they all have around the same costs, it was left out of the hierarchy. He has an artistic temperament and writes with his right hand in a hooked position, implicating that he is "right-brained". After the analysis, he chose Northwestern University, which had a slightly lower reputation and academic environment compared to Swarthmore College, but Northwestern University appealed more to his nature. At Northwestern, he selected a room facing Lake Michigan, combining a convivial 4-year vacation site with his study. To summarize his outlook: as far as location was concerned, the farther away from home the better. The university's reputation was slightly more important than academics (personalized attention, size of the classes), and ambiance (how happy he felt at the place) was a little more important than both location and academics. The hierarchy is shown below in Fig. 2.

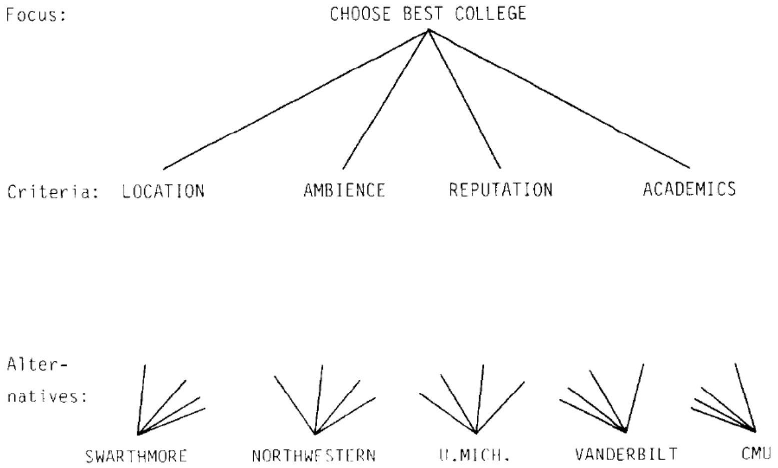


Figure B.1: Hierarchy for choosing a college [75]

The preferences mentioned above are judged according to Table 2.4. The question is asked how the value on the left side of the table is more or less important than the value on the top of the table. The reciprocal value is then automatically entered for the transpose. To gain valuable insights, it is important to clarify from the beginning what the focus of the hierarchy is and how the elements on the following levels either serve this focus or are a consequence of certain choices. The resulting table for the relations of the criteria is shown below:

Focus	Location	Ambience	Reputation	Academics
Location	1	1/7	1/5	1/5
Ambiance	7	1	2	3
Reputation	5	1/2	1	1
Academics	5	1/3	1	1

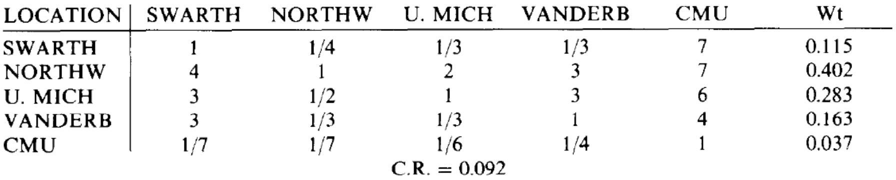
The first step to get the values in this matrix is to compare the location to the ambiance. The question is: "How much more is location preferred over ambiance?". The ambiance is preferred very strongly (7 times) over location. A matrix is said to be consistent if $a_{ij}a_{jk}, = a_{ik}, \forall\ i,\ j,\ k$. Note that this matrix is inconsistent. To show this the next example can be used: (ambiance, reputation) = 2, while (reputation, academics) = 1, therefore to be consistent (ambiance, academics) = (ambiance, reputation) x (reputation, academics) = (2) x (1) = 2. But in the matrix, it has the value 3. Thus the value entered in the (2,4) position is larger than it should be to be consistent, but we then enter the reciprocal value 1/3 in the (4,2) position and note that $1/3 < 1/2$.

The relevance of this observation is that while one value exceeds the corresponding consistent value, its reciprocal is less than the reciprocal of the consistent value, which will compensate in a minor way. When a positive reciprocal matrix of order n is consistent, the principal eigenvalue has the value n. When it is inconsistent, the principal eigenvalue exceeds n and its departure from n serves as a measure of inconsistency by forming the consistency ratio (C.R.) of this difference to the average of the corresponding differences from n of the principal eigenvalues. The C.R. is an indication of how consistent a matrix is.

The next step is to derive the scale of priorities (or weights). This can be derived by using the principal eigenvector of the matrix and then normalizing the result. This is called the local derived scale before weighting by the priority of its parent criterion. After weighting, it is called the global derived scale. When conducting this method on the matrix mentioned above, the following result (with an inconsistency ratio of 0.02) is retrieved:

$$(\text{Location, Ambience, Reputation, Academics}) = (0.053, 0.491, 0.238, 0.213)$$

The next step is to compare the alternatives for each criterion, resulting in four matrices (one for each criterion). The matrix concerning location is shown below as an example, in which Wt is the vector of relative weights:



LOCATION	SWARTH	NORTHW	U. MICH	VANDERB	CMU	Wt
SWARTH	1	1/4	1/3	1/3	7	0.115
NORTHW	4	1	2	3	7	0.402
U. MICH	3	1/2	1	3	6	0.283
VANDERB	3	1/3	1/3	1	4	0.163
CMU	1/7	1/7	1/6	1/4	1	0.037

C.R. = 0.092

This can be done for ambiance (2), reputation (3), and academics (4) as well. This gives the following vectors:
(2) (SWARTH, NORTHW, U. MICH, VANDERB, CMU) = (0.034, 0.539, 0.250, 0.121, 0.056);
(3) (SWARTH, NORTHW, U. MICH, VANDERB, CMU) = (0.521, 0.235, 0.147, 0.038, 0.059);
(4) (SWARTH, NORTHW, U. MICH, VANDERB, CMU) = (0.564, 0.209, 0.132, 0.040, 0.055).

When the consistency ratio exceeds 0.10 the judgments made before often need reevaluation. To retrieve the overall priority scale matrix coupling the alternatives to the criteria should be multiplied by the vector of the criteria reciprocal importance as follows:

$$\begin{pmatrix} 0.115 & 0.034 & 0.521 & 0.564 \\ 0.402 & 0.539 & 0.235 & 0.209 \\ 0.284 & 0.250 & 0.147 & 0.132 \\ 0.163 & 0.121 & 0.038 & 0.040 \\ 0.037 & 0.056 & 0.059 & 0.055 \end{pmatrix} \cdot \begin{pmatrix} 0.053 \\ 0.491 \\ 0.238 \\ 0.218 \end{pmatrix} = \begin{pmatrix} 0.270 \\ 0.387 \\ 0.201 \\ 0.086 \\ 0.055 \end{pmatrix} \tag{B.1}$$

This gives a final priority of 0.387 for Northwestern University with Swarthmore University as runner-up with a priority of 0.270. The overall consistency of these judgments is obtained as a ratio of sums of weighted inconsistency indices to the corresponding sums of weighted random indices.

C

LPD-2 requirements, functions, systems, and modularity drivers

C.1 Requirements LPD-2

Table C.1: Requirements LPD-2

I	Requirement
Vessel	
i_1	The vessel operates at a cruising speed of 15 kn.
i_2	The vessel needs to reach a maximum speed of 19 kn.
i_3	The vessel needs to be able to operate independently for 30 days.
i_4	The vessel will have a range of 5.000 nm at cruising speed.
i_5	The vessel needs to be inherently stable.
i_6	The vessel's seakeeping needs to be sufficient for typical operations.
Hotel	
i_7	The operators shall be able to drink/eat.
i_8	The operators shall be able to sleep/rest.
i_9	The operators shall be able to control air properties.
i_{10}	The operators shall be able to do laundry.
i_{11}	The operators shall be able to do sanitary needs.
Safety	
i_{12}	The operators shall be able to detect emergency situations.
i_{13}	The operators shall be able to extinguish a fire.
i_{14}	The operators shall be able to abandon the vessel.
i_{15}	The operators shall be able to rescue a person fallen in the water.
Operations	
i_{16}	The operators shall be able to navigate safely and securely, at all times.
i_{17}	The operators shall be able to operate systems remotely.
i_{18}	The operators shall be able to maintain the vessel's systems.
i_{19}	The operators shall be able to maneuver with the vessel.
i_{20}	The operators shall be able to do station keeping.
i_{21}	The operators shall be able to (un)load and store cargo/supplies.
Additional Mission related requirements	
Amphibious operations	
i_{22}	The vessel shall be able to support amphibious operations with a battalion of marines and equipment.
i_{23}	The vessel shall be able to support amphibious operations without the availability of a port.
Command & Control	
i_{24}	The vessel shall be able to communicate with the fleet and land-based command.
i_{25}	The vessel shall be able to host the 400 pax staff for large-scale operations up to 50.000 pax.
Sea basing & Strategic transport	
i_{26}	The operator shall be able to (un)load cargo at sea.
Others	
i_{27}	The vessel shall be able to provide emergency hospital facilities for 100 patients.
i_{28}	The vessel shall be able to protect itself against threats under the surface.
i_{29}	The vessel shall be able to protect itself against threats through the air.
i_{30}	The vessel shall be able to protect itself against small surface threats.
i_{31}	The vessel shall be able to protect itself against CBRN threats.
i_{32}	The vessel shall be able to support helicopter operations.
i_{33}	The vessel shall be able to conduct electronic warfare.

C.2 Functions LPD-2

Table C.2: Functions LPD-2

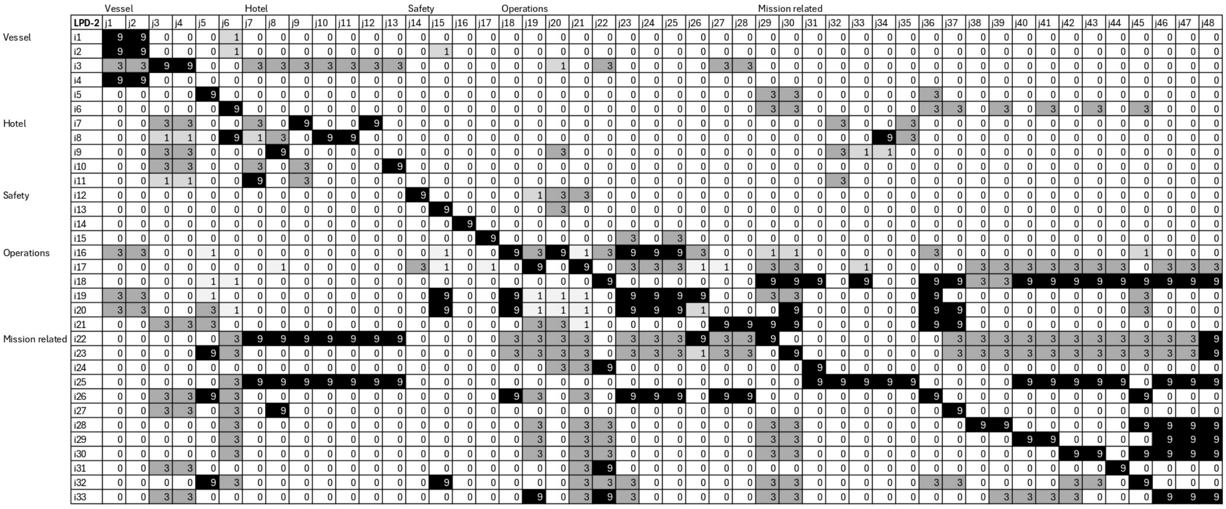
J	Function
Vessel	
j_1	To provide mechanical/electrical power.
j_2	To transfer energy generated by the prime mover to the propulsor.
j_3	To generate electric power for the electric consumers.
j_4	To distribute the electrical power.
j_5	To secure stability.
j_6	To secure sufficient seakeeping for typical operations.
Hotel	
j_7	To treat grey and black water.
j_8	To control the air properties.
j_9	To provide fresh water.
j_{10}	To provide sleeping facilities.
j_{11}	To provide facilities for leisure possibilities.
j_{12}	To provide restaurant facilities.
j_{13}	To provide laundry possibilities.
Safety	
j_{14}	To inform the crew of an emergency/critical situation.
j_{15}	To support rescue operations at sea.
j_{16}	To provide multiple alternatives for abandoning the vessel.
j_{17}	To support crew for extinguishing and detecting a fire.
Operations	
j_{18}	To provide the crew with navigational data.
j_{19}	To provide the crew control over systems remotely.
j_{20}	To back-up the electric power system during a black out.
j_{21}	To provide the crew systems information.
j_{22}	To provide the crew space and tools for doing maintenance/repair work.
j_{23}	To alter course if commanded to.
j_{24}	To create a force in transversely direction for movement.
j_{25}	To forestall drifting away due to wind or current.
j_{26}	To provide draught data.
j_{27}	To (un)load cargo/supplies.
j_{28}	To store and secure cargo/supplies.
Additional Mission related functions	
Amphibious operations	
j_{29}	To support amphibious operations with a battalion of marines and equipment.
j_{30}	To support amphibious operations without the availability of a port.
Command & Control	
j_{31}	To communicate with the fleet and land-based command.
j_{32}	To provide workspace for 400 pax.
j_{33}	To provide a joint operation room.
j_{34}	To provide additional sleeping facility for officers.
j_{35}	To provide a flag officers mess.
Sea basing & Strategic transport	
j_{36}	To (un)load cargo/supplies at sea.
Others	
j_{37}	To provide emergency hospital facilities for 100 patients.
j_{38}	To detect threats under the surface.
j_{39}	To neutralize incoming threats under the surface.
j_{40}	To detect threats through the air.
j_{41}	To neutralize close-range threats through the air.
j_{42}	To detect threats on the surface.
j_{43}	To neutralize the source of surface threat when in range of weapon systems.
j_{44}	To protect itself against CBRN threats.
j_{45}	To support helicopter operations.
j_{46}	To detect RF emissions.
j_{47}	To intercept communication.
j_{48}	To jam.

C.3 Systems LPD-2

Table C.3: Systems LPD-2

K	System
Vessel	
k_1	Hull structure
k_2	Mechanical power generation architecture
k_3	Electrical power generation architecture
k_4	Ballast system
k_5	Active stabilisation system
Hotel	
k_6	Fresh water system
k_7	Cabin
k_8	Climate control system
k_9	Plumbing drainage system
k_{10}	Day room
k_{11}	Galley
k_{12}	Laundry facilities
Safety	
k_{13}	Rescue boat & life raft
k_{14}	Fire fighting system
k_{15}	Emergency alarm system
Operations	
k_{16}	Emergency electrical power generation system
k_{17}	Navigation systems
k_{18}	Engineering control system
k_{19}	Command information centre
k_{20}	Workshop facilities
k_{21}	Propulsor
k_{22}	Transmission system
k_{23}	Ship control system
k_{24}	Bow thruster
k_{25}	Switchboard
k_{26}	Cargo handling system
k_{27}	Hold/deck
k_{28}	Cargo securement
Additional Mission related systems	
Amphibious operations	
k_{29}	Well deck
k_{30}	Vehicle deck
k_{31}	Davit crane
Command & Control	
k_{32}	Communication system
k_{33}	Office rooms
k_{34}	Joint operation room (JOR)
k_{35}	Flag officers mess
Sea basing & Strategic transport	
k_{36}	Dynamic Positioning capability (DP-2)
Others	
k_{37}	Medical equipment
k_{38}	Operating room
k_{39}	Intensive care units
k_{40}	Sonar
k_{41}	Horizon surveillance radar
k_{42}	Air surveillance radar
k_{43}	Tracking radar
k_{44}	Fire control radar
k_{45}	Decoys
k_{46}	Surface-to-air missile
k_{47}	Laser
k_{48}	Heavy machineguns
k_{49}	CBRN Citadel
k_{50}	Pre-wetting system
k_{51}	Helicopter deck
k_{52}	Hanger
k_{53}	Electronic Support Measures
k_{54}	Electronic Counter Measures

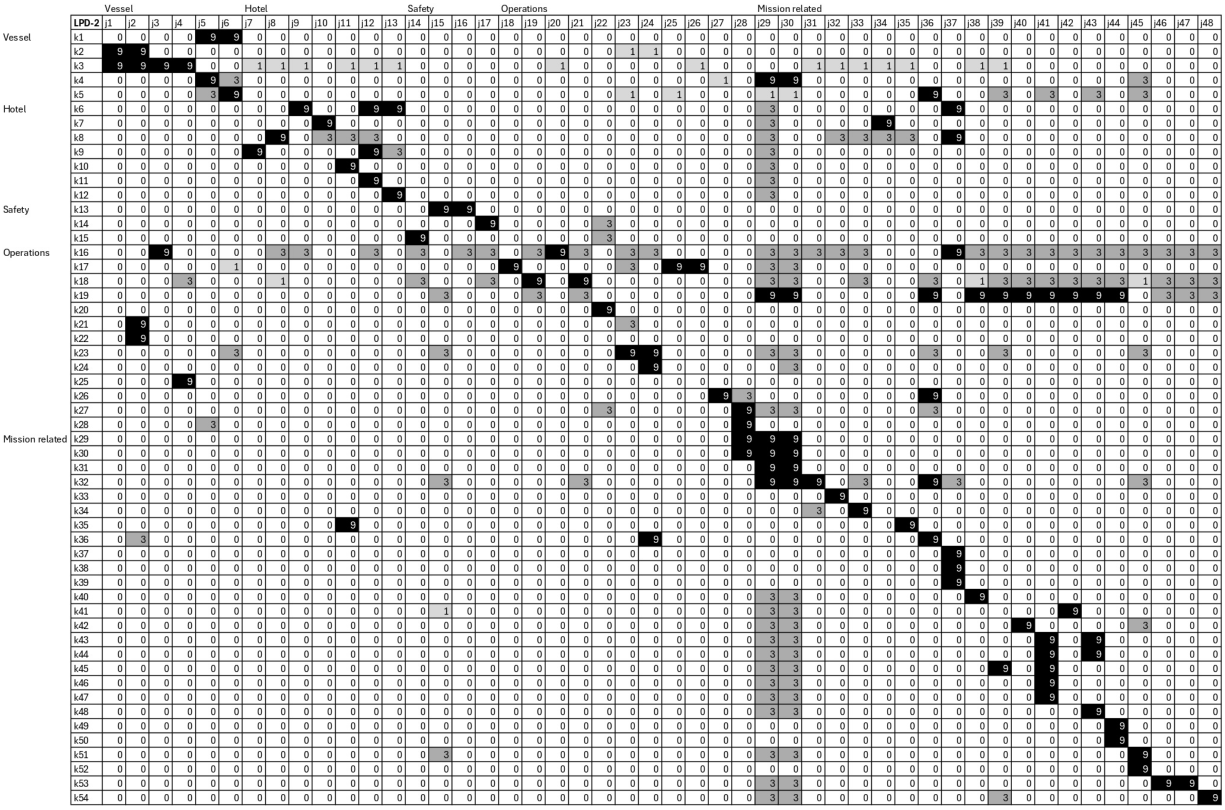
C.4 QFD LPD-2



		Vessel						Hotel							Safety				Operations											Mission related																			
	LPD-2	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16	j17	j18	j19	j20	j21	j22	j23	j24	j25	j26	j27	j28	j29	j30	j31	j32	j33	j34	j35	j36	j37	j38	j39	j40	j41	j42	j43	j44	j45	j46	j47	j48
Vessel	i1	9	9	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i2	9	9	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i3	3	3	9	9	0	0	3	3	3	3	3	3	3	0	0	0	0	0	0	1	0	3	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i4	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i5	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
	i6	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	3	3	0	3	0	3	0	3	0	3	0	0	0
Hotel	i7	0	0	3	3	0	0	3	0	9	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0
	i8	0	0	1	1	0	9	1	3	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0
	i9	0	0	3	3	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i10	0	0	3	3	0	0	3	0	3	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i11	0	0	1	1	0	0	9	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safety	i12	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	1	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Operations	i16	3	3	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	9	3	9	1	3	9	9	9	3	0	0	1	1	0	0	0	0	0	3	0	0	0	0	0	0	0	0	1	0	0	0
	i17	0	0	0	0	0	0	0	1	0	0	0	0	0	3	1	0	1	0	9	0	9	0	3	3	3	1	1	0	3	3	0	0	1	0	0	0	0	3	3	3	3	3	3	3	0	3	3	3
	i18	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	9	9	9	0	9	0	0	9	9	3	3	9	9	9	9	9	9	9	9	9
	i19	3	3	0	0	1	0	0	0	0	0	0	0	0	0	9	0	0	9	1	1	1	0	9	9	9	9	0	0	3	3	0	0	0	0	0	9	0	0	0	0	0	0	0	0	3	0	0	0
	i20	3	3	0	0	3	1	0	0	0	0	0	0	0	0	9	0	0	9	1	1	1	0	9	9	9	1	0	0	0	9	0	0	0	0	0	9	9	0	0	0	0	0	0	0	3	0	0	0
	i21	0	0	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	1	0	0	0	0	0	9	9	9	9	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0
Mission related	i22	0	0	0	0	0	3	9	9	9	9	9	9	9	0	0	0	0	3	3	3	3	0	3	3	3	9	3	3	9	0	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	9
	i23	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	3	3	3	3	0	3	3	3	1	3	3	0	9	0	0	0	0	0	0	3	3	3	3	3	3	3	3	3	3	3	9
	i24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	9	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	i25	0	0	0	0	0	3	9	9	9	9	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	9	9	0	0	0	0	9	9	9	9	9	0	9	9	9
	i26	0	0	3	3	9	3	0	0	0	0	0	0	0	0	0	0	0	9	3	0	3	0	9	9	9	0	9	9	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	9	0	0	0
	i27	0	0	3	3	0	3	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
	i28	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	9	9	0	0	0	0	0	9	9	9	9
	i29	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	9	9	0	0	0	0	9	9	9
	i30	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	3	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	9	9	0	9	9	9	9
	i31	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	i32	0	0	0	0	9	3	0	0	0	0	0	0	0	0	9	0	0	0	0	0	3	3	3	0	0	0	0	0	3	3	0	0	0	0	0	3	3	0	0	0	0	3	3	0	9	0	0	0
	i33	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	3	9	3	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	3	3	3	3	0	0	0	9	9	9

Figure C.1: QFD LPD-2

C.5 DPM LPD-2



		Vessel						Hotel							Safety				Operations											Mission related																			
	LPD-2	j1	j2	j3	j4	j5	j6	j7	j8	j9	j10	j11	j12	j13	j14	j15	j16	j17	j18	j19	j20	j21	j22	j23	j24	j25	j26	j27	j28	j29	j30	j31	j32	j33	j34	j35	j36	j37	j38	j39	j40	j41	j42	j43	j44	j45	j46	j47	j48
Vessel	k1	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k2	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k3	9	9	9	9	0	0	1	1	1	0	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
	k4	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0
	k5	0	0	0	0	3	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1	0	0	0	0	0	9	0	0	3	0	3	0	3	0	3	0	0	0
Hotel	k6	0	0	0	0	0	0	0	0	9	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
	k7	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k8	0	0	0	0	0	0	0	9	0	3	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	3	3	3	0	9	0	0	0	0	0	0	0	0	0	0	0
	k9	0	0	0	0	0	0	9	0	0	0	0	9	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k10	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k11	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k12	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Safety	k13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k15	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Operations	k16	0	0	9	0	0	0	0	3	3	0	0	3	0	3	0	3	3	0	3	9	3	0	3	3	0	0	0	0	3	3	3	3	3	0	0	0	9	3	3	3	3	3	3	3	3	3	3	3
	k17	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	9	9	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k18	0	0	0	3	0	0	0	1	0	0	0	0	0	3	0	0	3	0	9	0	9	0	0	0	0	0	0	0	3	3	0	0	3	0	0	3	0	1	3	3	3	3	3	3	1	3	3	3
	k19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	3	0	3	0	0	0	0	0	0	0	9	9	0	0	0	0	0	9	0	9	9	9	9	9	9	9	0	3	3	3
	k20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k21	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k22	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k23	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	9	9	0	0	0	0	3	3	0	0	0	0	0	3	0	0	3	0	0	0	0	0	3	0	0	0
	k24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k25	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	3	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0
	k27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	9	3	3	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
	k28	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mission related	k29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	0	0	0	0	9	9	9	0	3	0	0	9	3	0	0	0	0	0	0	0	3	0	0	0
	k33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k34	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	k35	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0
	k36	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0
	k37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
	k38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
	k39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0
	k40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0
	k41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0
	k42	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	9	0	0	0	0	3	0	0	0
	k43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	9	0	9	0	0	0	0	0
	k44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	9	0	9	0	0	0	0	0
	k45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	9	0	9	0	0	0	0	0	0	0
	k46	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0
	k47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0
	k48	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0
	k49	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	k50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0
	k51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0
	k52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0
	k53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	9	0
	k54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	9

Figure C.2: DPM LPD-2

D

All pairwise comparison matrices

This appendix shows all pairwise comparison matrices for the FuAD in section D.1 and for the LPD-2 in section D.2. The results are shown in section D.3

D.1 FuAD pairwise comparison matrices

Table D.1: OMOE FuAD

OMOE FuAD	OMOE1	OMOE2	W_t
OMOE1 - Task force Command & Control	1	0.3536	0.2612
OMOE2 - Task force Escort	2.8284	1	0.7388

C.R. = N/A

Table D.2: Task force Command & Control FuAD

OMOE1 Task force Command & Control	MOE1	MOE2	W_t
MOE1 - Command	1	1	0.5
MOE2 - Control	1	1	0.5

C.R. = N/A

Table D.3: Task force Escort FuAD

OMOE2 Task force Escort	MOE3	MOE4	MOE5	W_t
MOE3 - ASW	1	0.3333	0.2	0.1095
MOE4 - ASuW	3	1	0.5	0.3090
MOE5 - AAW	5	2	1	0.5816

C.R. = 0.003185

Table D.4: Command FuAD

MOE1 - Command FuAD	MOP1	MOP2	MOP3	W_t
MOP1 - Vessel command capability	1	0.6250	0.7143	0.2506
MOP2 - Task force command capability	1.5811	1	1	0.3817
MOP3 - Communication capabilities	142	1	1	0.3678

C.R. = 0.001192

Table D.5: Control FuAD

MOE2 - Control FuAD	MOP3	MOP4	MOP5	MOP6	MOP12	MOP13	W_t
MOP3 - Communication capabilities	1	3	2.4444	3.5	4.5	4.5	0.3776
MOP4 - Detect objects on the surface	0.3333	1	1	3.5	4	4	0.2099
MOP5 - Detect objects above the surface	0.4082	1	1	3.5	4	4	0.2144
MOP6 - Detect objects under the surface	0.2887	0.2887	0.2887	1	1.4	2	0.0822
MOP12 - Prevent detection by EW	0.2236	0.25	0.25	0.7071	1	1.4	0.0625
MOP13 - Evade incoming enemy threat by EW	0.2236	0.25	0.25	0.5	0.7071	1	0.0532

C.R. = 0.02963

Table D.6: ASW FuAD

MOE3 - ASW FuAD	MOE3.1	MOE3.2	W_t
MOE3.1- Detection	1	2.449	0.7101
MOE3.2 - Neutralization	0.4082	1	0.2899

C.R. = N/A

Table D.7: ASW Detection FuAD

MOE3.1 - ASW Detection FuAD	MOP1	MOP3	MOP4	MOP5	MOP6	MOP12	W_t
MOP1 - Vessel command capability	1	1.4	1.4	1.75	1.75	3	0.2482
MOP3 - Communication capabilities	0.7071	1	2	2	1.75	3.5	0.2470
MOP4 - Detect objects on the surface	0.7071	0.5	1	0.6325	1.5714	2.4444	0.1519
MOP5 - Detect objects above the surface	0.5774	0.5	1.5811	1	1	2	0.1530
MOP6 - Detect objects under the surface	0.5774	0.5774	0.6325	1	1	1	0.1196
MOP12 - Prevent detection by EW	0.3333	0.2887	0.4082	0.5	1	1	0.0802

C.R. = 0.02305

Table D.8: ASW Neutralization FuAD

MOE3.2 - ASW Neutralization FuAD	MOP7	MOP13	W_t
MOP7 - Underwater ranged weapon	1	3.1623	0.7597
MOP13 - Evade incoming enemy threat by EW	0.3162	1	0.2403

C.R. = N/A

Table D.9: ASuW FuAD

MOE4 - ASuW FuAD	MOE4.1	MOE4.2	W_t
MOE4.1- Detection	1	2	0.66667
MOE4.2 - Neutralization	0.5	1	0.3333

C.R. = N/A

Table D.10: ASuW Detection FuAD

MOE4.1 - ASuW Detection FuAD	MOP1	MOP3	MOP4	MOP5	MOP6	MOP12	W_t
MOP1 - Vessel command capability	1	1	1	2	3.875	2	0.2295
MOP3 - Communication capabilities	1	1	1	2	5	2	0.23805
MOP4 - Detect objects on the surface	1	1	1	1.75	5	2	0.2318
MOP5 - Detect objects above the surface	0.5	0.5	0.5774	1	3.875	1.4	0.1402
MOP6 - Detect objects under the surface	0.2582	0.2	0.2	0.2582	1	0.3333	0.0456
MOP12 - Prevent detection by EW	0.5	0.5	0.5	0.7071	2.8284	1	0.1147

C.R. = 0.006257

Table D.11: ASuW neutralization FuAD

MOE4.2 - ASuW neutralization FuAD	MOP8	MOP9	MOP10	MOP11	MOP13	W_t
MOP8 - Track enemy threat	1	1	0.7143	1.4	1.75	0.2086
MOP9 - Control fired projectile	1	1	0.7143	1.4	2	0.2183
MOP10 - High impact surface weapon	1.4142	1.4142	1	3	1.4	0.2768
MOP11- Low impact surface weapon	0.7071	0.7071	0.3333	1	0.25	0.1035
MOP13 - Evade incoming enemy threat by EW	0.5774	0.5	0.7071	3.8730	1	0.1927

C.R. = 0.06421

Table D.12: AAW FuAD

MOE5 - AAW FuAD	MOE5.1	MOE5.2	W_t
MOE5.1- Detection	1	1.4142	0.5858
MOE5.2 - Neutralization	0.7071	1	0.4142

C.R. = N/A

Table D.13: AAW Detection FuAD

MOE5.1 - AAW Detection FuAD	MOP1	MOP3	MOP4	MOP5	MOP12	W_t
MOP1 - Vessel command capability	1	1	2.4444	0.4444	0.8	0.1781
MOP3 - Communication capabilities	1	1	1.4	1	1	0.2015
MOP4 - Detect objects on the surface	0.4082	0.7071	1	0.3333	0.5	0.0990
MOP5 - Detect objects above the surface	2.2361	1	3.1623	1	3	0.3456
MOP12 - Prevent detection by EW	1.2247	1	2	0.3333	1	0.1758

C.R. = 0.03725

Table D.14: AAW neutralization FuAD

MOE5.2 - AAW neutralization FuAD	MOP8	MOP9	MOP13	MOP14	MOP15	W_t
MOP8 - Track enemy threat	1	1	3.1667	1.4	2.4444	0.3057
MOP9 - Control fired projectile	1	1	1.4	1	1.4	0.2222
MOP13 - Evade incoming enemy threat by EW	0.3162	0.7071	1	1	1.4	0.1501
MOP14 - Long-range air defense	0.7071	1	1	1	3	0.2194
MOP15 - Short-range air defense	0.4082	0.7071	0.7071	0.3333	1	0.1098

C.R. = 0.03394

D.2 LPD-2 pairwise comparison matrices

Table D.15: OMOE LPD-2

OMOE LPD-2	OMOE1	OMOE2	OMOE3	W_t
OMOE1 - Task force Command & Control	1	0.7071	2	0.3431
OMOE2 - Amphibious operations	1.4142	1	2.8284	0.4853
OMOE3 - Others	0.5	0.3536	1	0.1716

C.R. = 0.000

Table D.16: Task force Command & Control LPD-2

OMOE1 Task force Command & Control	MOE1	MOE2	W_t
MOE1 - Command	1	0.7071	0.4142
MOE2 - Control	1.4142	1	0.5858

C.R. = N/A

Table D.17: Command LPD-2

MOE1 - Command LPD-2	MOP1	MOP2	MOP3	W_t
MOP1 - Vessel command capability	1	0.4	0.4	0.1695
MOP2 - Task force command capability	2.4495	1	1	0.4152
MOP3 - Communication capabilities	2.4495	1	1	0.4152

C.R. = 0.000

Table D.18: Control LPD-2

MOE2 - Control LPD-2	MOP3	MOP4	MOP5	MOP6	MOP12	MOP13	W_t
MOP3 - Communication capabilities	1	3.5	3	3.875	4.5	3.5	0.3995
MOP4 - Detect objects on the surface	0.2887	1	0.7143	3	2.4444	2.4444	0.1607
MOP5 - Detect objects above the surface	0.3333	1.4142	1	3.875	3.1667	3.875	0.2192
MOP6 - Detect objects under the surface	0.2582	0.3333	0.2582	1	0.5	0.7143	0.0589
MOP12 - Prevent detection by EW	0.2236	0.4082	0.3162	2	1	2	0.0919
MOP13 - Evade incoming enemy threat by EW	0.2887	0.4082	0.2582	1.4142	0.5	1	0.0699

C.R. = 0.03953

Table D.19: Landing LPD-2

MOE3 - Landing LPD-2	MOP1	MOP3	MOP4	MOP5	MOP12	MOP13	MOP16	MOP17	MOP18	W_t
MOP1 - Vessel command capability	1	0.7143	2.8333	2.8333	4	4	1	1	0.8	0.1432
MOP3 - Communication capabilities	1.4142	1	2.4444	4	4.5	4.5	2	1.4	1	0.1889
MOP4 - Detect objects on the surface	0.3536	0.4082	1	3	1.75	2	0.3333	0.3333	0.25	0.064
MOP5 - Detect objects above the surface	0.3536	0.25	0.3333	1	1.4	1.75	0.25	0.25	0.2222	0.0426
MOP12 - Prevent detection by EW	0.25	0.2236	0.5774	0.7071	1	1	0.2222	0.2222	0.2	0.0349
MOP13 - Evade incoming enemy threat by EW	0.25	0.2236	0.5	0.5774	1	1	0.2222	0.2222	0.2	0.0337
MOP16 - Vehicle storage	1	0.5	3.1623	3.8730	4.4721	4.4721	1	1	0.7143	0.1474
MOP17 - Vehicle LC transferring	1	0.7071	3.1623	3.8730	4.4721	4.4721	1	1	0.7143	0.1517
MOP18 - Personnel LC transferring	1.2247	1	3.8730	4.4721	5	5	1.4142	1.4142	1	0.1927

C.R. = 0.01350

Table D.20: Others LPD-2

OMOE-3 Others LPD-2	MOE4	MOE5	MOE6	W_t
MOE4 - Hospital facilities	1	2	1.75	0.4820
MOE5 - Sea-basing	0.5	1	1	0.2528
MOE6 - Self-defense	0.5774	1	1	0.2652

C.R. = 0.001982

Table D.21: Hospital facilities LPD-2

MOE-4 Hostpital facilities LPD-2	MOP19	MOP20	MOP21	W_t
MOP19 - Low-care medical capability	1	1	0.7143	0.2929
MOP20 - Intensive care capability	1	1	0.7143	0.2929
MOP21 - Operating capability	1.4142	1.4142	1	0.4142

C.R. = 0.000

Table D.22: Sea-basing LPD-2

MOE-5 Sea-basing LPD-2	MOP1	MOP3	MOP22	W_t
MOP1 - Vessel command capability	1	0.7143	1	0.2929
MOP3 - Communication capabilities	1.4142	1	1.4	0.4142
MOP22 - Station keeping	1	0.7071	1	0.2929

C.R. = 0.000

Table D.23: Self-defense LPD-2

MOE-6 Self-defense LPD-2	MOE6.1	MOE6.2	W_t
MOE6.1 - Detection	1	0.8	0.4495
MOE6.2 - Neutralization	1.2247	1	0.5505

C.R. = N/A

Table D.24: Detection LPD-2

MOE6.1 -Detection LPD-2	MOP1	MOP3	MOP4	MOP5	MOP12	W$_t$
MOP1 - Vessel command capability	1	0.8	0.8	0.8	1.4	0.1860
MOP3 - Communication capabilities	1.2247	1	1	1	1.4	0.2190
MOP4 - Detect objects on the surface	1.2247	1	1	0.7143	1.4	0.2043
MOP5 - Detect objects above the surface	1.2247	1	1.4142	1	2	0.2521
MOP12 - Prevent detection by EW	0.7071	0.7071	0.7071	0.5	1	0.1386

C.R. = 0.00414

Table D.25: Neutralization LPD-2

MOE6.2 - Neutralization LPD-2	MOP8	MOP9	MOP10	MOP11	MOP13	MOP15	W$_t$
MOP8 - Track enemy threat	1	1.75	2.4444	1.4	2	1	0.2358
MOP9 - Control fired projectile	0.5774	1	1.75	1.4	1	1	0.1685
MOP10 - High impact surface weapon	0.4082	0.5774	1	1	1.4	0.2857	0.1082
MOP11 - Low impact surface weapon	0.7071	0.7071	1	1	1.4	0.5714	0.1345
MOP13 - Evade incoming enemy threat by EW	0.5	1	0.7071	0.7071	1	0.5	0.1124
MOP15 - Short-range air defense	1	1	3.4641	1.7321	2	1	0.2405

C.R. = 0.02310

D.3 LPD-2 results

The results for the LPD-2 are shown in Table D.26. These results are analyzed in section 7.3.

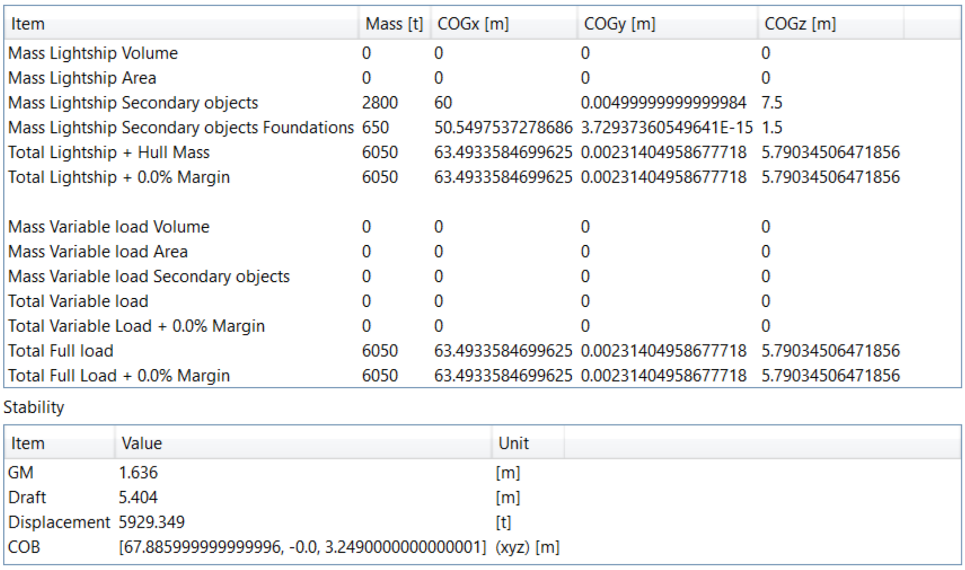
Table D.26: Results AHP LPD-2

	MOE1	MOE2	MOE3	MOE4	MOE5	MOE6.1	MOE6.2	Total	%
MOP1	0.024095	0	0.069511	0	0.012705	0.003805	0	0.110115	11.01152
MOP2	0.05902	0	0	0	0	0	0	0.05902	5.902034
MOP3	0.05902	0.080297	0.09167	0	0.017967	0.00448	0	0.253434	25.34343
MOP4	0	0.03231	0.031411	0	0	0.004179	0	0.0679	6.789984
MOP5	0	0.044058	0.020681	0	0	0.005156	0	0.069895	6.9895
MOP6	0	0.011829	0	0	0	0	0	0.011829	1.182948
MOP7	0	0	0	0	0	0	0	0	0
MOP8	0	0	0	0	0	0	0.005906	0.005906	0.59064
MOP9	0	0	0	0	0	0	0.004222	0.004222	0.422185
MOP10	0	0	0	0	0	0	0.002711	0.002711	0.271078
MOP11	0	0	0	0	0	0	0.00337	0.00337	0.337043
MOP12	0	0.011829	0.016941	0	0	0.002835	0	0.038239	3.823901
MOP13	0	0.018463	0.016383	0	0	0	0.002817	0.033252	3.3252
MOP14	0	0	0	0	0	0	0	0	0
MOP15	0	0	0	0	0	0	0.006025	0.006025	0.60254
MOP16	0	0	0.071543	0	0	0	0	0.071543	7.15431
MOP17	0	0	0.073617	0	0	0	0	0.073617	7.361651
MOP18	0	0	0.093525	0	0	0	0	0.093525	9.352529
MOP19	0	0	0	0.02422	0	0	0	0.02422	2.42195
MOP20	0	0	0	0.02422	0	0	0	0.02422	2.42195
MOP21	0	0	0	0.034252	0	0	0	0.034252	3.425155
MOP22	0	0	0	0	0.012705	0	0	0.012705	1.270452

E

Output KBE model

E.1 LCF reference model



Item	Mass [t]	COGx [m]	COGy [m]	COGz [m]
Mass Lightship Volume	0	0	0	0
Mass Lightship Area	0	0	0	0
Mass Lightship Secondary objects	2800	60	0.00499999999999984	7.5
Mass Lightship Secondary objects Foundations	650	50.5497537278686	3.72937360549641E-15	1.5
Total Lightship + Hull Mass	6050	63.4933584699625	0.00231404958677718	5.79034506471856
Total Lightship + 0.0% Margin	6050	63.4933584699625	0.00231404958677718	5.79034506471856
Mass Variable load Volume	0	0	0	0
Mass Variable load Area	0	0	0	0
Mass Variable load Secondary objects	0	0	0	0
Total Variable load	0	0	0	0
Total Variable Load + 0.0% Margin	0	0	0	0
Total Full load	6050	63.4933584699625	0.00231404958677718	5.79034506471856
Total Full Load + 0.0% Margin	6050	63.4933584699625	0.00231404958677718	5.79034506471856

Stability

Item	Value	Unit
GM	1.636	[m]
Draft	5.404	[m]
Displacement	5929.349	[t]
COB	[67.885999999999996, -0.0, 3.2490000000000001]	(xyz) [m]

Figure E.1: Output KBE LCF reference model

E.2 FuAD reference model basis

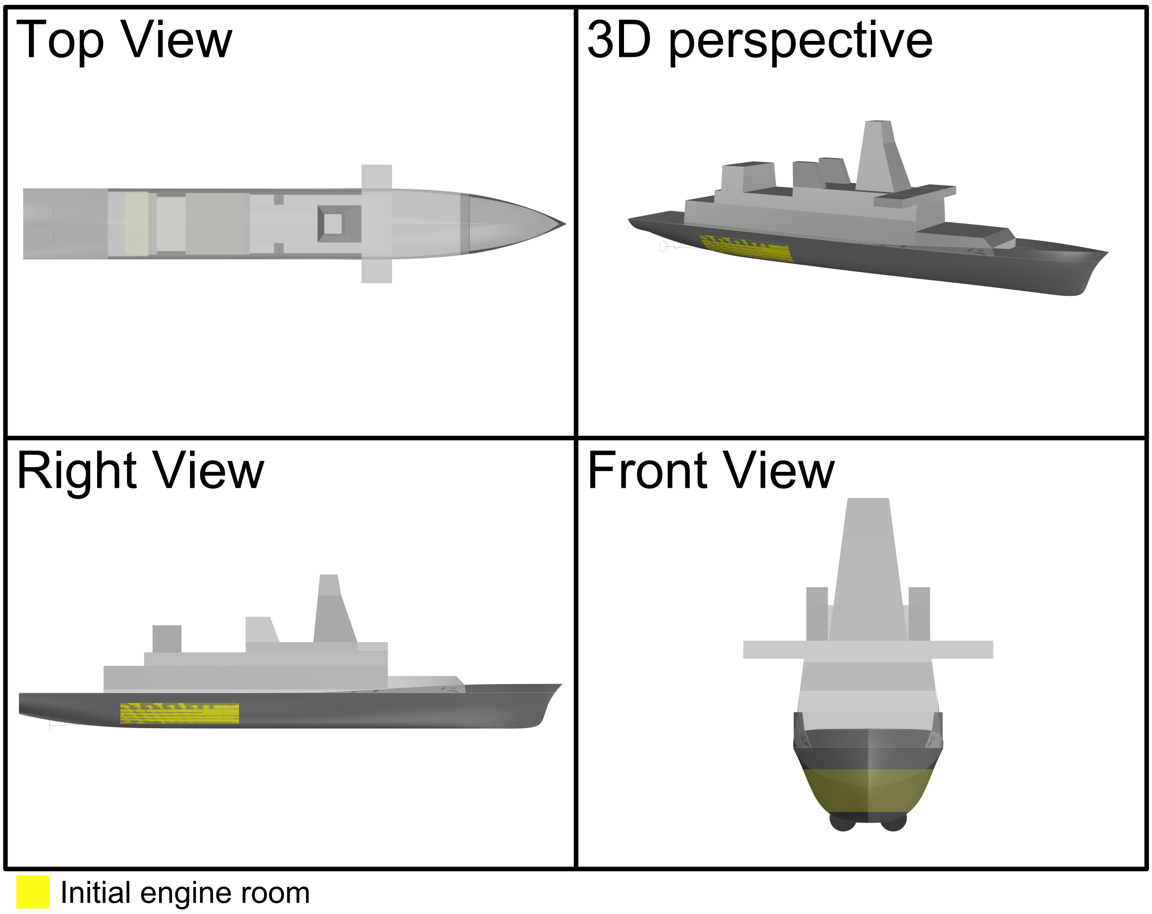
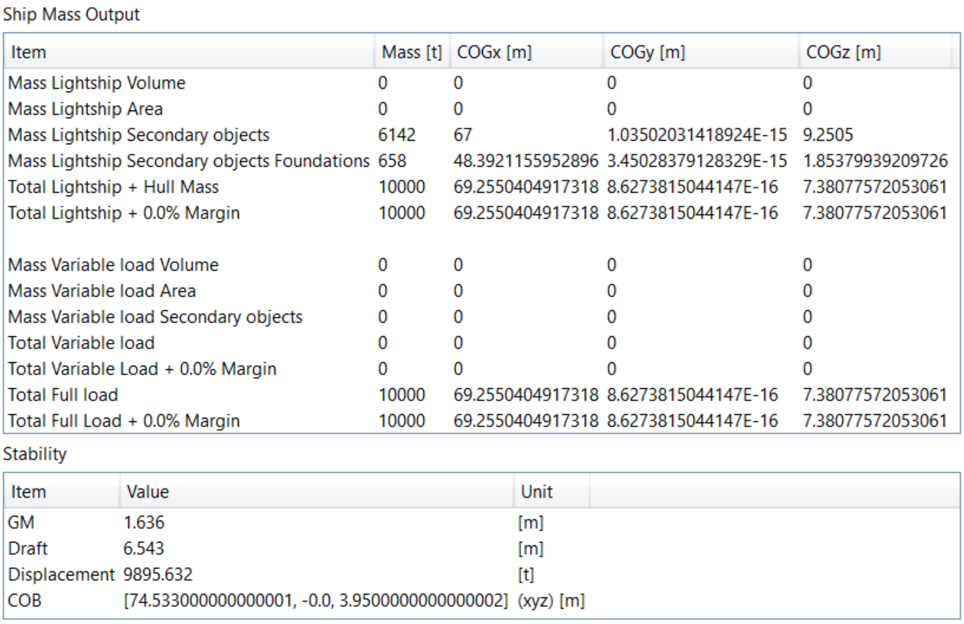


Figure E.2: FuAD reference model Rhino



Ship Mass Output

Item	Mass [t]	COGx [m]	COGy [m]	COGz [m]
Mass Lightship Volume	0	0	0	0
Mass Lightship Area	0	0	0	0
Mass Lightship Secondary objects	6142	67	1.03502031418924E-15	9.2505
Mass Lightship Secondary objects Foundations	658	48.3921155952896	3.45028379128329E-15	1.85379939209726
Total Lightship + Hull Mass	10000	69.2550404917318	8.6273815044147E-16	7.38077572053061
Total Lightship + 0.0% Margin	10000	69.2550404917318	8.6273815044147E-16	7.38077572053061
Mass Variable load Volume	0	0	0	0
Mass Variable load Area	0	0	0	0
Mass Variable load Secondary objects	0	0	0	0
Total Variable load	0	0	0	0
Total Variable Load + 0.0% Margin	0	0	0	0
Total Full load	10000	69.2550404917318	8.6273815044147E-16	7.38077572053061
Total Full Load + 0.0% Margin	10000	69.2550404917318	8.6273815044147E-16	7.38077572053061

Stability

Item	Value	Unit
GM	1.636	[m]
Draft	6.543	[m]
Displacement	9895.632	[t]
COB	[74.533000000000001, -0.0, 3.9500000000000002]	(xyz) [m]

Figure E.3: Output KBE initial FuAD reference model

E.3 FuAD reference model including SMART-L

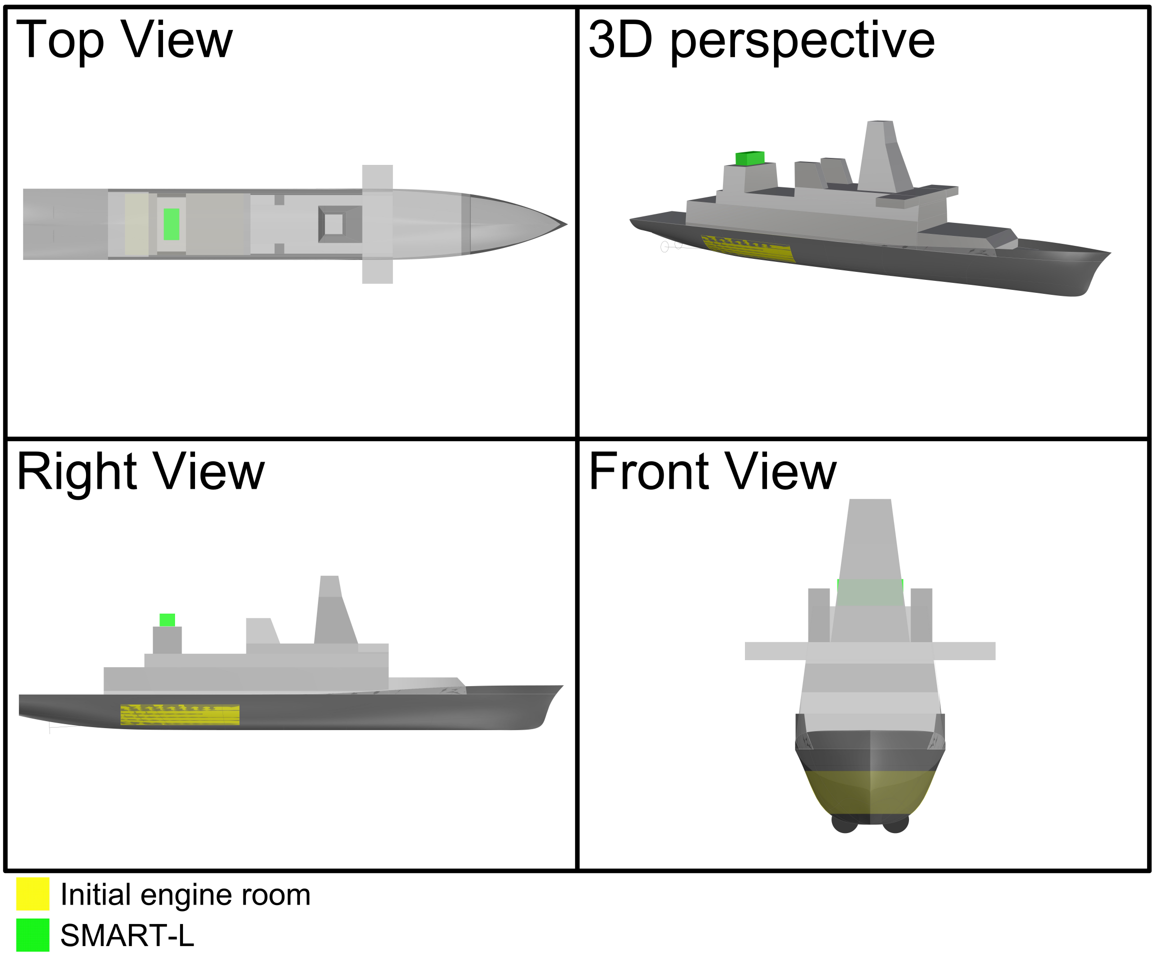
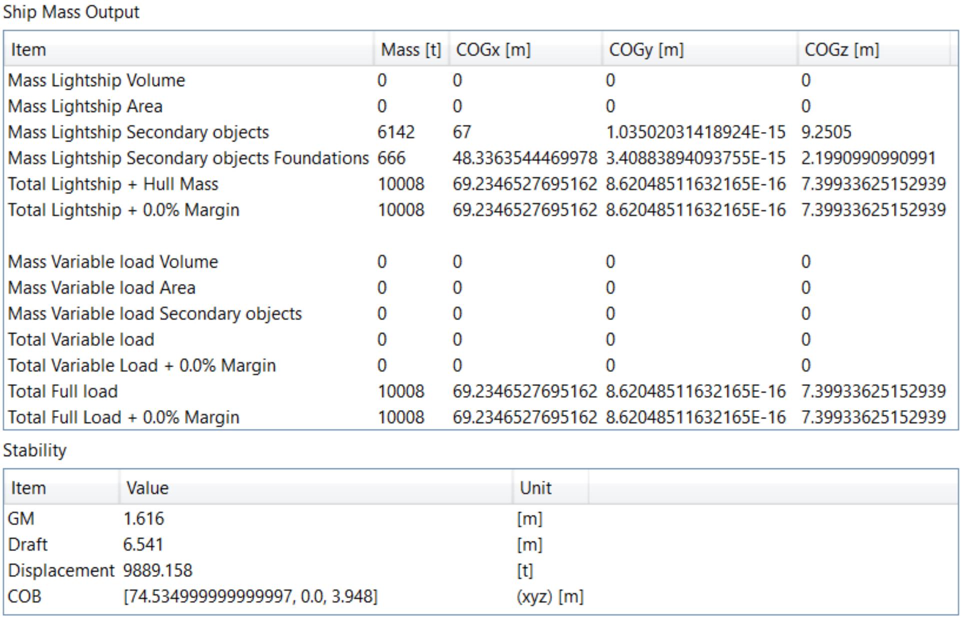


Figure E.4: FuAD reference model including SMART-L Rhino



Ship Mass Output

Item	Mass [t]	COGx [m]	COGy [m]	COGz [m]
Mass Lightship Volume	0	0	0	0
Mass Lightship Area	0	0	0	0
Mass Lightship Secondary objects	6142	67	1.03502031418924E-15	9.2505
Mass Lightship Secondary objects Foundations	666	48.3363544469978	3.40883894093755E-15	2.1990990990991
Total Lightship + Hull Mass	10008	69.2346527695162	8.62048511632165E-16	7.39933625152939
Total Lightship + 0.0% Margin	10008	69.2346527695162	8.62048511632165E-16	7.39933625152939
Mass Variable load Volume	0	0	0	0
Mass Variable load Area	0	0	0	0
Mass Variable load Secondary objects	0	0	0	0
Total Variable load	0	0	0	0
Total Variable Load + 0.0% Margin	0	0	0	0
Total Full load	10008	69.2346527695162	8.62048511632165E-16	7.39933625152939
Total Full Load + 0.0% Margin	10008	69.2346527695162	8.62048511632165E-16	7.39933625152939

Stability

Item	Value	Unit
GM	1.616	[m]
Draft	6.541	[m]
Displacement	9889.158	[t]
COB	[74.534999999999997, 0.0, 3.948]	(xyz) [m]

Figure E.5: Output KBE with modular air surveillance radar

E.4 FuAD reference model including LDEW and SMART-L

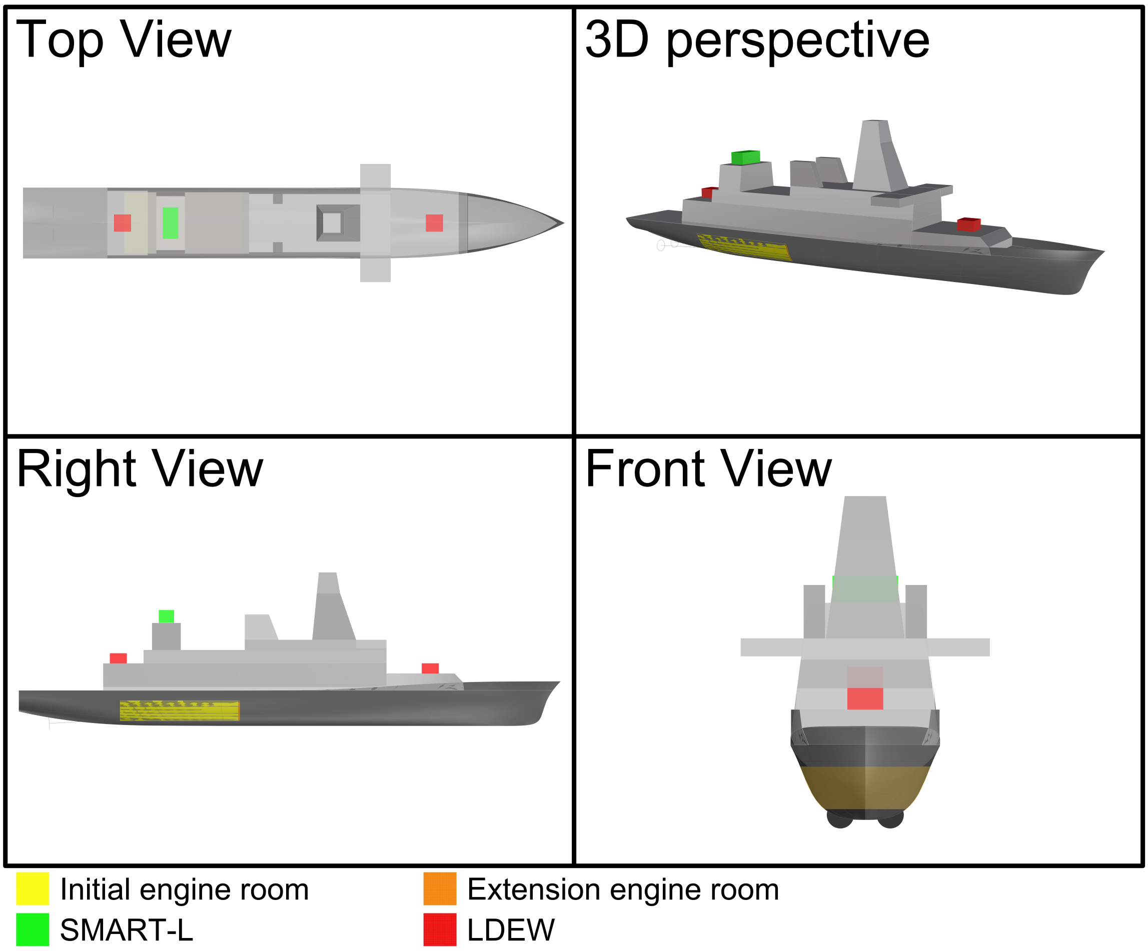
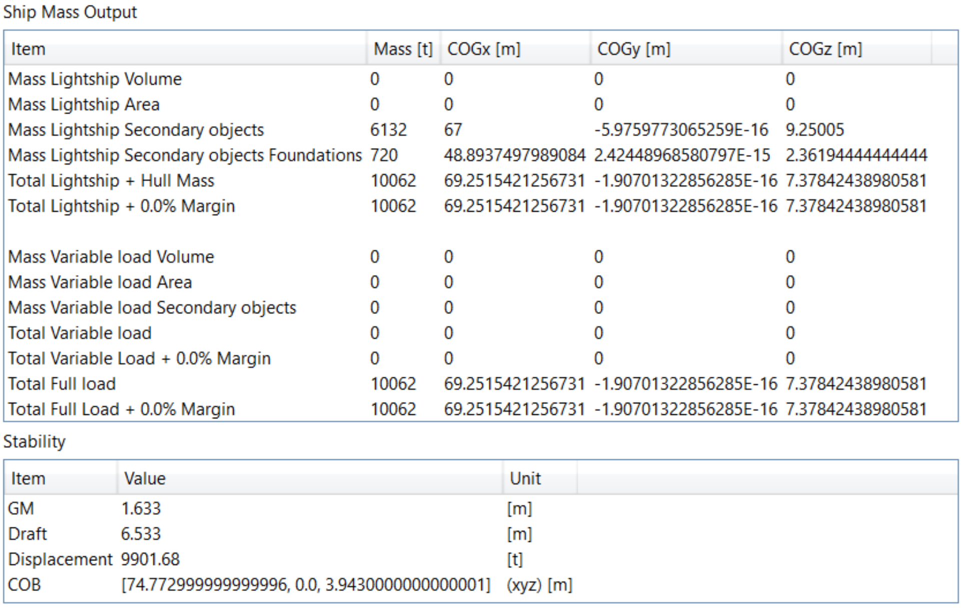


Figure E.6: FuAD reference model including LDEW and SMART-L Rhino



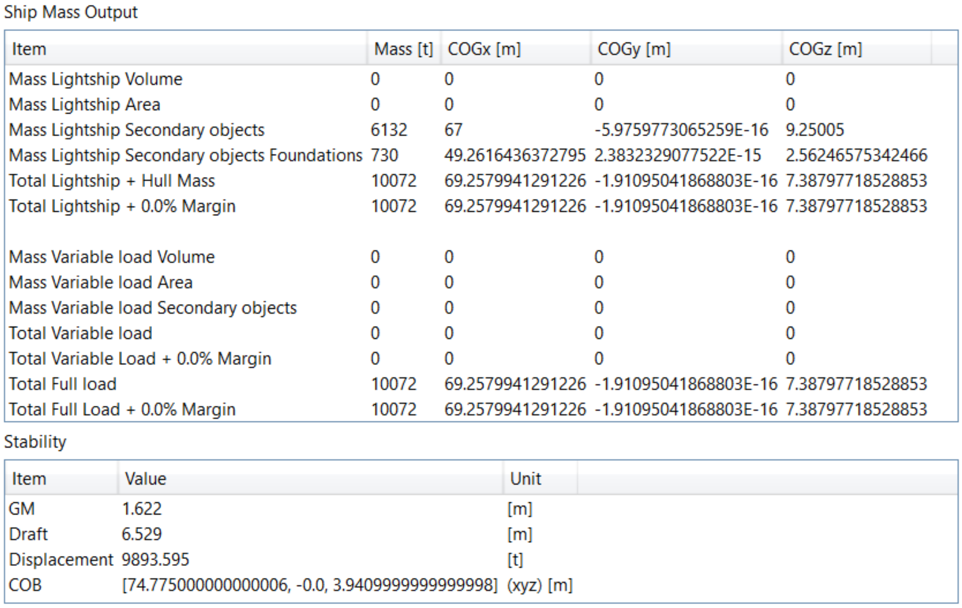
Ship Mass Output

Item	Mass [t]	COGx [m]	COGy [m]	COGz [m]
Mass Lightship Volume	0	0	0	0
Mass Lightship Area	0	0	0	0
Mass Lightship Secondary objects	6132	67	-5.9759773065259E-16	9.25005
Mass Lightship Secondary objects Foundations	720	48.8937497989084	2.42448968580797E-15	2.36194444444444
Total Lightship + Hull Mass	10062	69.2515421256731	-1.90701322856285E-16	7.37842438980581
Total Lightship + 0.0% Margin	10062	69.2515421256731	-1.90701322856285E-16	7.37842438980581
Mass Variable load Volume	0	0	0	0
Mass Variable load Area	0	0	0	0
Mass Variable load Secondary objects	0	0	0	0
Total Variable load	0	0	0	0
Total Variable Load + 0.0% Margin	0	0	0	0
Total Full load	10062	69.2515421256731	-1.90701322856285E-16	7.37842438980581
Total Full Load + 0.0% Margin	10062	69.2515421256731	-1.90701322856285E-16	7.37842438980581

Stability

Item	Value	Unit
GM	1.633	[m]
Draft	6.533	[m]
Displacement	9901.68	[t]
COB	[74.772999999999996, 0.0, 3.9430000000000001]	(xyz) [m]

Figure E.7: Output KBE with non-modular LDEW and modular SMART-L



Ship Mass Output

Item	Mass [t]	COGx [m]	COGy [m]	COGz [m]
Mass Lightship Volume	0	0	0	0
Mass Lightship Area	0	0	0	0
Mass Lightship Secondary objects	6132	67	-5.9759773065259E-16	9.25005
Mass Lightship Secondary objects Foundations	730	49.2616436372795	2.3832329077522E-15	2.56246575342466
Total Lightship + Hull Mass	10072	69.2579941291226	-1.91095041868803E-16	7.38797718528853
Total Lightship + 0.0% Margin	10072	69.2579941291226	-1.91095041868803E-16	7.38797718528853
Mass Variable load Volume	0	0	0	0
Mass Variable load Area	0	0	0	0
Mass Variable load Secondary objects	0	0	0	0
Total Variable load	0	0	0	0
Total Variable Load + 0.0% Margin	0	0	0	0
Total Full load	10072	69.2579941291226	-1.91095041868803E-16	7.38797718528853
Total Full Load + 0.0% Margin	10072	69.2579941291226	-1.91095041868803E-16	7.38797718528853

Stability

Item	Value	Unit
GM	1.622	[m]
Draft	6.529	[m]
Displacement	9893.595	[t]
COB	[74.775000000000006, -0.0, 3.9409999999999998]	(xyz) [m]

Figure E.8: Output KBE with modular LDEW and modular SMART-L

F
Pairwise comparison matrice final AHP

This chapter shows the pairwise comparison matrices of the final evaluation.

Table F.1: OMOE - Overall system effectiveness

OMOE - Overall system effectiveness	OMOE1	OMOE2	W$_t$
OMOE1 - Air surveillance radar	1.00	0.50	0.33
OMOE2 - LDEW	2.00	1.00	0.67

Table F.2: OMOE 1 - Air surveillance radar

OMOE 1 - Air surveillance radar	MOE1	MOE2	MOE3	MOE4	MOE5	W$_t$
MOE1 - Purchase costs	1.00	3.00	3.00	2.00	2.00	0.37
MOE2 - Common use across the fleet	0.33	1.00	1.00	0.50	1.00	0.12
MOE3 - Quick changing of systems	0.33	1.00	1.00	0.33	1.00	0.11
MOE4 - Maintenance time in dock	0.50	2.00	3.00	1.00	2.00	0.26
MOE5 - Number of systems required	0.50	1.00	1.00	0.50	1.00	0.14
	C.R. = 0.015					

Table F.3: OMOE 2 - LDEW

OMOE 2 - LDEW	MOE6	MOE7	MOE8	MOE9	MOE10	W$_t$
MOE6 - Purchase costs	1.00	0.50	0.33	2.00	1.00	0.15
MOE7 - Common use across the fleet	2.00	1.00	0.50	2.00	2.00	0.23
MOE8 - Quick changing of systems	3.00	2.00	1.00	3.00	2.00	0.37
MOE9 - Maintenance time in dock	0.50	0.50	0.33	1.00	2.00	0.13
MOE10 - Number of systems required	1.00	0.50	0.50	0.50	1.00	0.12
	C.R. = 0.050					

Table F.4: TEXT

MOE1 - Purchase costs	MOP1	MOP2	W$_t$
MOP1 - Non-Modular Air surveillance radar	1.00	2.00	0.67
MOP2 - Modular Air surveillance radar	0.50	1.00	0.33

Table F.5: MOE2 - Common use across the fleet

MOE2 - Common use across the fleet	MOP1	MOP2	W$_t$
MOP1 - Non-Modular Air surveillance radar	1.00	2.00	0.67
MOP2 - Modular Air surveillance radar	0.50	1.00	0.33

Table F.6: MOE3 - Quick changing of systems

MOE3 - Quick changing of systems	MOP1	MOP2	W$_t$
MOP1 - Non-Modular Air surveillance radar	1.00	0.50	0.33
MOP2 - Modular Air surveillance radar	2.00	1.00	0.67

Table F.7: MOE4 - Maintenance time in dock

MOE4 - Maintenance time in dock	MOP1	MOP2	W_t
MOP1 - Non-Modular Air surveillance radar	1.00	0.33	0.25
MOP2 - Modular Air surveillance radar	3.00	1.00	0.75

Table F.8: MOE5 - Number of systems required

MOE5 - Number of systems required	MOP1	MOP2	W_t
MOP1 - Non-Modular Air surveillance radar	1.00	2.00	0.67
MOP2 - Modular Air surveillance radar	0.50	1.00	0.33

Table F.9: MOE6 - Purchase costs

MOE6 - Purchase costs	MOP3	MOP4	W_t
MOP3 - Non-Modular LDEW	1.00	2.00	0.67
MOP4 - Modular LDEW	0.50	1.00	0.33

Table F.10: MOE7 - Common use across the fleet

MOE7 - Common use across the fleet	MOP3	MOP4	W_t
MOP3 - Non-Modular Air surveillance radar	1.00	0.33	0.25
MOP4 - Modular Air surveillance radar	3.00	1.00	0.75

Table F.11: MOE8 - Quick changing of systems

MOE8 - Quick changing of systems	MOP3	MOP4	W_t
MOP3 - Non-Modular Air surveillance radar	1.00	0.33	0.25
MOP4 - Modular Air surveillance radar	3.00	1.00	0.75

Table F.12: MOE9 - Maintenance time in dock

MOE9 - Maintenance time in dock	MOP3	MOP4	W_t
MOP3 - Non-Modular Air surveillance radar	1.00	0.50	0.33
MOP4 - Modular Air surveillance radar	2.00	1.00	0.67

Table F.13: MOE10 - Number of systems required

MOE10 - Number of systems required	MOP3	MOP4	W_t
MOP3 - Non-Modular Air surveillance radar	1.00	2.00	0.67
MOP4 - Modular Air surveillance radar	0.50	1.00	0.33