Modular Zero-Emission Incident Response Vessel

Concept for a zero-emission, modularized and standardized Incident Response Vessel, with optimized layout and functionalities for new fleet composition of the PoR

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Abstract

This thesis investigates the conceptual design of a zero-emission, modular, and standardized Incident Response Vessel (IRV) for the Port of Rotterdam, aiming to support the port's ambitious sustainability objectives, including a 90% reduction in CO_2 emissions by 2030 and a fully emission-free fleet by 2035. Addressing the challenge of decarbonizing maritime operations, this research explores the integration of alternative fuels, energy modules, and modular design principles to develop a fleet that is resilient and adaptable to future energy technologies.

The study includes an evaluation of various ship design methodologies, focusing on modular design principles and approaches to assess how standardization and modularization can be most effectively applied to the new vessel design. Among the extensive range of system design methods, Modular Function Deployment (MFD) was selected as the optimal approach. Additionally, a comprehensive analysis was conducted on all necessary inputs, tasks, functions, and requirements for an IRV, recognizing that this vessel operates within a niche market and cannot be treated as an off-the-shelf type. Given this specialized role, it was crucial to map out in detail the current systems onboard, identify those no longer needed, and determine future systems essential for continued task performance. This structured analysis was systematically integrated into the thesis and organized to provide a foundation for the MFD model.

Estimates for various alternative energy carriers were developed based on scientific research and data from other sources, identifying potential matches for the Port of Rotterdam. These preliminary estimates offer a reference point for assessing energy needs in the early stages of design. By linking energy demands with specific energy carriers, the study supports the design of various conceptual models. In addition to the developed model, output values were translated into visual sketches, providing concept designs of systems and vessels. These serve as visual aids to support future decision-making, helping guide the port's strategic choices.

The study employs MFD in combination with other ship design methodologies to identify optimal strategies for flexible energy system integration, spatial layout efficiency, and operational effectiveness. MFD is applied here for the first time to IRVs, with a focus on achieving a robust design that supports emission-free technologies, such as electric propulsion and alternative fuels like methanol and hydrogen, without compromising on the functional and operational requirements of the fleet.

The findings indicate that MFD provides a structured and scalable framework that enables the Port of Rotterdam to maintain operational flexibility while addressing both current and anticipated regulatory standards. This research highlights that the swappable battery system presents the most practical solution for immediate implementation, supporting both present-day tasks and future scalability. Additionally, the study suggests that modularity enables easier adaptation to technological advancements, offering a pathway for long-term fleet evolution.

In conclusion, this thesis outlines a feasible strategy for the Port of Rotterdam to transition to a modular, emission-free IRV fleet that meets operational demands while remaining adaptable to emerging energy solutions, thus positioning the port at the forefront of sustainable maritime innovation.

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Nomenclature

Abbreviations

Abbreviation	Definition
AC	Alternating Current
AGV	Automated Guided Vehicles
AED	Automated External Defibrillator
AM	Asset Management
B	Beam (Breath of Ship)
BMS	Battery Management System
CAD	Computer-Aided Design
CAPEX	Capital Expenditures
CFD	Computational Fluid Dynamics
CoB	Center of Buoyancy
CoG	Center of Gravity
ConOps	Concept of Operations
CRL	Community Readiness Level
DC	Direct Current
DBB	Design Building Block
DOD	Depth of Discharge
DPM	Design Property Matrix
DPS	Dynamic Positioning System
DT	Digital Twin
DWT	Dead Weight Tonnage
ESS	Energy Storage System
ESSD	Early Stage Ship Design
ETO	Engineer To Order
GJ	Giga Joule
GM	Metacentric Height
H2	Hydrogen
HFO	Heavy Fuel Oil
H&S	Handling and Storage
HVAC	Heating, Ventilation and Air Conditioning
HVO	Heavy Fuel Oil
ICT	Information and Communication Technology
IM	Induction Machine
IMO	International Maritime Organization
IRV	Incident Response Vessels
KB	Center to Buoyancy
KG	Center to Gravity
kW	Kilowatt
LC	Life Cycle Assessment
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
LOA	Overall Length
LPG	Liquefied Petroleum Gas
LSFO	Low Sulfur Fuel Oil
MARIN	Maritime Research Institute Netherlands
MBSE	Model Based System Design

Abbreviation	Definition
M	Metacenter
MFD	Modular Function Deployment
MIM	Module Indication Matrix
MJ	Mega Joule
MW	Mega Watt
NOx	Nitrogen Oxides
Norled	Norwegian Shipping Company
OPEX	Operating Expenditures
PMM	Product Management Map
PMSM	Permanent Magnet Synchronous Machines
PoR	Port of Rotterdam
P	Propulsion
Ppm	Parts Per Million
QFD	Quality Function Deployment
RoPax	Passenger Car Ferries
RPA	Rotterdam Port Authority (ship names)
SDG	Sustainable Development Goals
SOx	Sulfur Dioxide
STEL	Short-Term Exposure Limit
SWATH	Small-Waterplane-Area Twin Hull
T	Draft Ship
TEU	Twenty Foot Equivalent Unit
TRL	Technology Readiness Levels
TWA	Time Weighted Average
TTW	Tank to Wheel
VoA	Voice of Asset Managers
VoB	Voice of Business
VoC	Voice of Customer
VoE	Voice of Engineer
VoU	Voice of User
WTW	Well to Wheel
ZES	Zero Emission Services

Symbols

Symbol	Definition	Unit
a_{ij}	Eigenvalue	[-]
g	Gravitational Acceleration	[m/s^2]
i	Capabilities	[-]
j	Functions	[-]
k	Technical Solutions	[-]
L_{wl}	Waterline Length	[m]
LOA	Length Over All	[m]
V_s	Ship Velocity	[m/s]
Δ	Displacement	[m^3]
$\eta_{Converter}$	Converter Efficiency	[-]
η_{DC-DC}	DC-DC Converter Efficiency	[-]
η_{em}	Electric Motor Efficiency	[-]
η_{pc}	Propulsion Efficiency	[-]
η_{Total}	Total Total	[-]
ρ	Density	[kg/m^3]

1 Introduction

This chapter provides the context and foundational knowledge for the research topic and introduces the study. It discusses the research scope, main research questions and sub-questions. The thesis outline presents the research gap and focus areas. Section 1.1 offers background on the current energy transition within the maritime industry. Section 1.2 focuses on the Port of Rotterdam, detailing ongoing sustainability improvements and the port's ambition to become the most sustainable port in the world. The scope of the study is addressed in Section 1.3, followed by the research questions in Section 1.4. Section 1.5 outlines the structure of the thesis, and Section 1.6 concludes with an exploration of the research gap and the thesis focus.

1.1. Maritime Industry Context

Global maritime transport contributes approximately 3% to worldwide greenhouse gas emissions, along with significant SOx, NOx, and particulate matter emissions. With expected increases in shipping activity by 2050, emissions per ton-mile from maritime vessels need to be fully decarbonized (net-zero GHG emissions) by 2050 [65], with a strong focus on transitioning to low- or zero-carbon fuels and technologies. These targets reflect a shift in strategy from previous goals, which were less stringent, to align more closely with international climate goals and the urgency of addressing global climate change [162].

Many institutions worldwide examine alternative fuels as potential solutions for decarbonizing maritime transportation. The energy transition is a deep-rooted problem intertwined with fuels, production methods, technology use, energy efficiency, environmental impact over the life cycle, economic feasibility, and the existing policy landscape. Alternative fuels are crucial for reducing emissions in international and local maritime sectors. Over the years, it became clear that there is no single solution for achieving the necessary reductions in greenhouse gas emissions, but in every part of the sector, companies and people need to innovate [67]. The extent of emission reductions varies considerably based on the production methods of each fuel. Fuels produced via carbon-intensive processes do not achieve true decarbonization but transfer emissions throughout the supply chain. A comprehensive, system-wide approach is necessary to develop effective policy frameworks that encourage the adoption of alternative propulsion technologies.

The global shipping industry has significant environmental impacts, yet its progress in sustainability lags behind other sectors. This slower pace of change is due to the industry's long asset lifecycles, which hinder rapid transitions, and the involvement of numerous stakeholders. Electrifying a truck or powering a factory with green wind energy is comparatively straightforward, whereas converting a vessel to operate on hydrogen presents far greater challenges. With increasing environmental concerns, the shipping industry is trying to reduce its environmental impact, which is driven by regulations and market factors. But the shipping sector is more difficult to get a good grip on. Applying traditional environmental performance assessments, such as using a life cycle assessment (LCA) in shipyards, is complex due to the unique complexity of yards. This requires tailor-made approaches to the environmental impacts of ship design and construction [73]. In addition to the fact that shipyards build more unique and complex ships, customer demand is also more specific and demanding. Making the ships more sustainable and bringing new technologies on board. The spatial layout has become more critical than ever, with every square centimeter needing to be utilized efficiently, as alternative energy sources require significantly more space to provide the same amount of energy [135].

1.2. Port of Rotterdam Tomorrow's Sustainable Port

Beyond the global shipping industry lies a complex network of interconnected ports, each playing a critical role in sustainable maritime objectives and heavily relying on one another to achieve these goals. The Port of Rotterdam (PoR) leads in sustainable port operations, striving to balance economic growth with environmental stewardship. To align with the Paris Agreement, PoR has set ambitious targets to reduce greenhouse gas emissions per ton-mile by 75–85% by 2050. Supporting these goals, the port has expanded its renewable energy capacity, increasing wind power from 200 MW in 2016 to 300 MW by 2020, and is actively exploring the use of floating solar panels [19]. These projects exemplify the port's commitment to sustainability.

Innovation in environmental technology is central to the PoR's strategy. The port has implemented energy-efficient LED lighting across its facilities and is advancing CO2 capture and storage solutions. Additionally, PoR repurposes industrial residual heat to potentially heat up to 500,000 homes, demonstrating a commitment to energy efficiency and resource conservation. To encourage greener shipping practices, the port provides financial incentives for vessels that surpass environmental standards.

Social responsibility is another pillar of PoR's sustainability agenda. The port secures jobs through strategic agreements and promotes maritime careers through educational initiatives such as EIC Mainport Rotterdam [19]. Furthermore, PoR maintains green spaces like the Green Gateway and Bird Valley, enhancing local biodiversity and ecological health. These initiatives collectively reinforce PoR's ambition to lead in sustainable port management, embodied in its motto: "Connecting the world. Building tomorrow's sustainable port.".

Achieving a sustainable port requires sustainable fleet management, which drives the need for an emission-free concept design for PoR's vessels. As the port seeks to embody sustainability at all levels, a zero-emission fleet is essential to meeting these comprehensive environmental goals.

Figure 1.1: Connecting the world. Building tomorrow's sustainable port

1.3. Research Scope

In the current energy transition, the PoR has expressed the ambition for the port to become a front runner in the transition to renewable fuels, the reduction of CO2, and more in general contributing to the United Nations 17 Sustainable Development Goals (SDG's). The port authority PoR has set climate goals for between 2025 and 2050 to become completely emission-free. Hence PoR's purpose statement is "Connecting the world. Building tomorrow's sustainable port.". This implies a range of programs, projects, and initiatives covering many areas inside and outside the PoR organization. One of these areas is the complete renewal of PoR's Fleet (of vessels) and making it sustainable.

PoR has committed to the following ”science-based goals” for its fleet:

- Achieve a 75% reduction in CO2 emissions by 2025.
- Achieve a 90% reduction in CO2 emissions by 2030.
- **A 100% emission free fleet by 2035.**

Currently, the PoR Fleet consists of 16 vessels, of which 7 Incident Response Vessels (IRV) (Incident Bestrijdings Vaartuigen IBV) [159] and 6 Patrol Vessels, and three additional ships. As part of wanting to become a front-runner in sustainability, PoR intends to replace these vessels with emission-free versions. Currently, there are no absolute winners regarding the different available emission-free energy sources or carriers applicable for this kind of vessel. To be even more concrete, this type of ship does not yet exist without emissions. Considering the ambition to renew the complete fleet by 2035, this brings up two dilemmas for the PoR. The first dilemma is: How does the PoR prevent choosing a specific energy carrier that the PoR will regret later on? This dilemma goes hand in hand with the second dilemma: How does the PoR prevent ”analysis paralysis” because of not daring to choose an energy carrier? The PoR decided to come up with a concept that provides flexibility to switch to another energy carrier at a later stage. At this moment, emission-free implies energy carriers with a very low energy density. Because of extended charging or bunkering times for low energy density carriers, this is a substantial challenge for vessels with a 24/7 uptime requirement (e.g., the Incident Response and Patrol vessels). Therefore, part of this concept is that energy must recharged on board within 15 minutes or refuel in 15 minutes.

In July 2022, the PoR research the possibility of building new emission-free vessels. The PoR has a fleet of patrol and incident response vessels, which the Harbor Master Division deploys in the day, semi-, and continuous service for management, inspection, and incident response tasks. The fleet also consists of hydrographic measuring vessels and the management vessel. This research mainly looked at the possibilities for sustainability based on the current fleet and current program of requirements and functionalities. Various analyses were carried out in this study, and it became clear that with an emission-free fuel and the same bunker frequency, it is not feasible to continue to implement the current functionality profile.

The start for this thesis arose from the PoR’s newly started fleet renewal program. A conceptually highly standardized and modularized electrically powered vessel must be designed. Based on the basis from which this assignment arose and the various building blocks that can already be collected at the PoR and from the knowledge of TU Delft, a concept can be outlined that helps the PoR determine the direction in which the solution is sought. Doing this makes it much easier to develop confidence in advance that decisions will be made that will not be regretted afterward. It is emphatically pointed out here that this is a concept and idea. It is, therefore, important to realize that it is not about the final solution. However, the final solution may look different due to the imaging and integrated iterations facilitated by the concept. It is not realistic to immediately look for a solution for the entire fleet, including surveyor and other ship types, because the scope of this transition is far too large, but this research can contribute to giving the PoR a step in the right direction so that the continuation of the fleet renewal is much more targeted.

Looking at the current PoR fleet, the Incident Response Vessels, these are converted tugboats on which a water cannon and an extra pump have been installed. At the time these ships were ordered, no systematic thought was given to how these ships were classified, which was not illogical at the time. However, the layout of the current fleet is not efficient at all, and there is also much space on board the ships. This indicates the importance of this research, which will look at the most efficient layout on board the systems on the ships that will be tested against the future-proof functionalities. Because implementing emission-free fuels will also be considered, optimal use of space is all the more important. Due to energy densities, additional systems on board, and safety reasons, integrating emission-free fuels takes much more space and weight than conventional fuels. This means that changing stability on board ships also needs to be considered in addition to re-examining how spaces are designed.

Currently, the ships have different lengths and sizes. The current functionalities will be peeled back and critically assessed in this research. In addition, future-proof functionalities that suit a changing port and technologically changed world are also examined. This may mean that a ship now has certain functionalities that can no longer fit together in the concept design of an emission-free ship. In this way, the future design could have two ships with separate functionalities currently performed by one ship. Finding the best layouts is, therefore, significant in this research. This is also accompanied by the need from the PoR to look at standardized ships in the future fleet. Standardization in building and designing ships refers to using predefined, repetitive designs for components and systems across different contracts to enhance efficiency and reduce costs. It emphasizes creating a system where repeatable designs can be applied to various projects without redesigning each time, thus optimizing the economic principle of standardization in shipbuilding [148]. Therefore, the design of every ship needs to be the same globally, specifically in terms of dimensions and general hulls. In this way, the entire fleet is examined, and thus, fleet renewal is integrated.

The implementation of modular ship design is also included in this research. This happens in two ways. First of all, this research looks at a modular built boat. This means that an energy supply has been added to the ship that is either already electric or is converted into electricity. This ensures that all systems on board the new concept ship are powered by electricity. Consider, for example, extinguishing systems to taps to hotel systems. The thinking behind this method is that the energy source module can be removed if it proves not functional enough. Second of all, the modular ship is implemented in future flexibility. Due to future innovation, there will appear to be a much better energy carrier on the market in a few years. The module is then removed and replaced by this new energy carrier. This hardly requires any intervention in the overall design, and this makes the concept future-proof. If the design must be constructed according to these requirements, it is essential to know which modules there are and how the different modules can best be arranged and located. That is why modular design methods within ship design methods were examined. These methods look at building a ship from modular building blocks.

1.4. Research Questions

A research question and several sub-questions are formulated to evaluate the feasibility and design of concept vessels that can form the base for a future fleet that matches this scope from a technical perspective. The scope of this research is further limited to the conceptual design of a fleet renewal ship. The main question of the research has been formulated to conduct the research within the associated scope:

1.4.1. Main Question

How can a zero-emission, modularized, and standardized Incident Response Vessel (IRV) be designed to serve as a scalable decision-making concept for a fleet, optimizing layout and functionality to meet operational requirements?

1.4.2. Sub-Questions

Next to the main research question, several sub-questions are created in order to help answer the main research question:

1. **sub-question 1:**
   What are the most effective modular design principles for ensuring flexibility in ship energy systems and future-proofing the design?
2. **sub-question 2:**
   Which alternative fuels provide the most viable solution for reducing emissions in the Port of Rotterdam's IRV future fleet?
3. **sub-question 3:**
   How can the existing design of the Port of Rotterdam's Incident Response Vessels be optimized for modularity and zero-emission technology?
4. **sub-question 4:**
   What is the energy demand profile of the IRV fleet, and how can alternative energy modules meet

these demands while ensuring operational efficiency in the future?

5. **sub-question 5:**
   How can Modular Function Deployment (MFD) be applied to optimize the design of a modular, zero-emission IRV for the Port of Rotterdam?
6. **sub-question 6:**
   What modular systems and energy modules can be integrated into the concept design of the new zero-emission IRV fleet?
7. **sub-question 7:**
   How does the fleet composition and modular design can assist in future decision making for the Port of Rotterdam IRV fleet?

1.5. Thesis Outline

This thesis is structured in three parts: the Literature Review, the Model Building, and the Concept Development, and ends with the Conclusions. The different parts are structured in a series of phases, beginning with a comprehensive literature study, followed by model development, energy analysis, and concept visualization. These phases cumulatively contribute to the design of a zero-emission, modular IRV for the Port of Rotterdam, aligning with the sustainability and operational goals of PoR.

The first phase of this research involves a thorough Literature Review, part I, to gather foundational knowledge and input on ship design methodologies, modularization, and energy systems. Various resources are consulted, including online literature databases, published papers, theses, and specific repositories such as those from Trondheim, TU Delft, and IMARES. The literature review aims to establish a methodological framework that supports the research objectives, focusing on three key steps to guide the conceptual and practical aspects of vessel design:

- **Identify Early-Stage Ship Design Methods**
- **Explore Modularization Principles and Design Approaches**
- **Explore Alternative Marine Fuels**

Following the literature review, the research advances to model development in Part II. This model is introduced within a Concept of Operations in Chapter 5. The functions and tasks are detailed in Chapter 6, using a reference vessel to clarify the system components. In Chapter 7, the data and requirements gathered during the initial phase are translated into a functional model. Various functionalities and requirements specific to the operational needs of the Port of Rotterdam are assessed, with a selection process conducted in consultation with the Port to identify which functionalities are to be integrated into the model.

In part II, this reserach also examines the energy requirements for the vessel based on operational profiles. This involves an in-depth analysis of energy demand, building on preliminary estimates from previous studies referenced in Chapter 9. This phase provides the foundation for determining suitable zero-emission energy sources for the IRV. In chapter 10 is the Modular Function Deployment model build. Where all the various input values converge within a model specifically developed for the PoR.

With the energy requirements established, the modular model advances to the development of building blocks and modules in Chapter 11 in part III, the Concept Development. This process culminates in Chapter 12, where concept development occurs. In this chapter, various emission-free concept models are created and modulated represented. These models are tested for operational feasibility, assessing energy efficiency, adaptability, and optimal layout to determine the most effective design for the PoR needs.

The Thesis concludes with a synthesis of the findings in chapter 13, which presents conclusions and recommendations. These insights provide strategic guidance for the Port of Rotterdam's ongoing fleet renewal program, emphasizing modular, zero-emission vessel design as a cornerstone for sustainable port operations. The structure of this thesis is given in Figure 1.2.

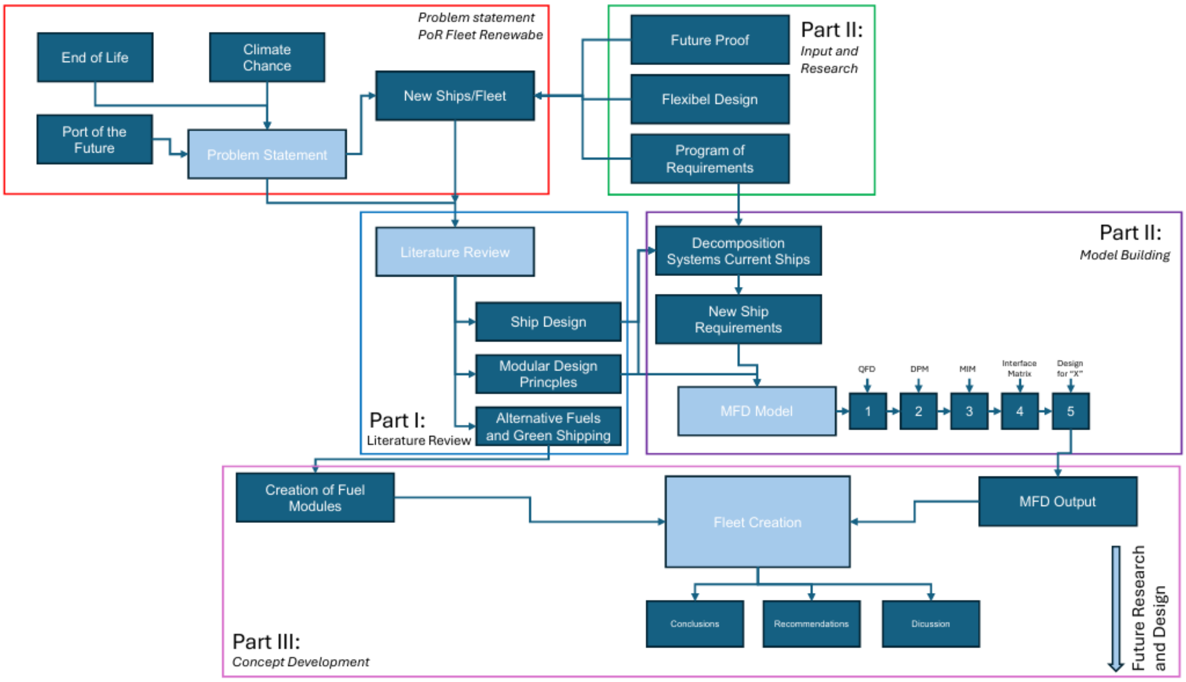


Figure 1.2: Thesis Structure Flowchart. *Created by the author*

This thesis is organized into four main parts, each building upon the previous to systematically address the research questions and create a comprehensive IRV concept for the Port of Rotterdam.

1.6. Research Gap and Thesis Focus

This literature review examines the research gap concerning the application of modular design principles to emission-free vessels in which this study specifically investigates how the port authority can optimally design an emission-free ship that supports all necessary systems and functionalities for an IRV. The transition to a sustainable maritime sector is a major challenge for the Port of Rotterdam and the search for an emission-free fleet. There is steady progress in replacing conventional ships with emission-free alternatives. However, a combination of the modular design principles remains somewhat unexplored. The PoR's request to investigate what an emission-free standardized and modular Incident Response Vessel should and could look like is to serve as a design for the new fleet; therefore, it is a completely new challenge that has never been investigated in this way before. This study focuses on the possibilities of MFD for designing an emission-free ship or fleet, a research area that has received little attention from this perspective.

One of the key components of this research involves unraveling the functional aspects of existing IRV vessels, such as IRV 12, to determine which functions should be retained or could be adapted in the light of zero-emission technologies. This specifically looks at the integration of emission-free energy carriers, such as batteries, methanol (not emission zero), and hydrogen, and implementing these energy carriers in the new ship design. This research will determine whether the current functions of these ships are feasible with the new energy carriers and propose new functional requirements and modularity strategies. By using MFD, it is possible to look at how the systems and functionalities on board are correlated and how they can find a place on board the ship in the future design. The MFD method used in this study follows a five-step process with a primary focus on matching customer requirements with technical solutions and evaluating concept models. This process will result in several conceptual models that cover all functionalities and requirements. This unique use of MFD within the Maritime sector for developing zero-emission ships offers a new angle in shipbuilding to more systematically and pragmatically bring about significant changes in future ship design strategies.

Furthermore, integrating modular systems on board will be explored, with the possibility of future replacement of the energy systems as an essential part of the design. Implementing a modular structure with an energy source that can regulate the entire energy supply on board the ship through electrical cables ensures that the concept design is future-proof. In this way, the possibility of future replacement of energy sources is considered within the design. This approach not only offers flexibility in the use of different energy carriers but also ensures the possibility of adapting to new technologies without major redesigns.

The results of this research will be visualized using Rhinoceros (Rhino) software, creating a three-dimensional model of the conceptual ship consisting of the different modules. This model will serve as a basis for stability calculations and other technical evaluations, which are essential for validating the design and providing insights into feasibility and functionalities.

This research attempts to fill the gap in research into a standardized, modular, emission-free conceptual ship design that can be the foundation of the future fleet. As a result, a new concept design will be created with this new approach and methodology. The modular and standardized concept design will support the Port of Rotterdam in achieving its 2035 sustainability goals. However, it may also have broader implications for future ship design strategies for patrol and firefighting vessels in various ports worldwide, contributing to a more sustainable and adaptable maritime sector globally.

Part I

Literature Review

2
Ship Design

The ship design process bridges the gap between the shipowner's mission profile and the actual construction at the shipyard. This design or gap can be described as using computer models, drawings, and other visual aids to determine how something will function and appear [62]. This makes the ship design a complex process that exist out of multiple stages. The definition of these stages and the number of stages differ in the literature. The different stages in ship designs start at two stages [72] and can go up to six stages depending on the specifications of these stages and the different approaches [71] [86]. Due to the wide range of different approaches, Scheffers' method is used [132], which distinguishes four different stages. The stages can be combined or separated depending on the project's needs.

The stages can be combined or separated depending on the project's needs. To understand the function and operation of the phases, a certain basic knowledge of the different stages of ship design is required [86]. The four different phases are therefore explained. Designing a ship is a process that is repeatedly followed and generally consists of several steps, an iterative process. These steps aim to ensure that the ship meets the established requirements, performance standards, and safety norms set by the ship owner. Although the specific classification may vary depending on the type of ship and the shipyard, the design steps are usually divided into four main phases. According to Scheffers' [132], the key phases are as follows:

- **Concept Design**
- **Preliminary Design**
- **Contract Design**
- **Functional Design and Detail Design**

These four phases generally apply to the design of a newly built ship [110]. The key phases can be divided into four main components of the ship design process. These four phases can be separated or combined to form more or fewer phases. The division or combination of the phases depends on the project's needs [21] [71]. In this report, the focus is currently only on the first two phases: concept design and preliminary design. The emphasis will mainly be on concept design, with a smaller part on preliminary design, referred to as the Early Stage Ship Design (ESSD), as made visible in Figure 2.1. This stage is fundamental to overcoming the challenges of ship design.

During the process, the naval architect examines multiple design options based on the client's requirements, allowing the client to choose a concept to proceed to the contract phase. In budget constraints, only one design solution may be explored. The project's success is closely tied to the experience and expertise of the naval architect. As Andrews [6] emphasizes the way in which a designer selects, develops, and refines initial concepts has a significant impact on the outcome of the ship.

The project's success is ultimately determined by the ship's performance and total costs, as visualized by Mavris and Delaurentis [102]. That model shows that most of the ship's performance and costs are determined during the preliminary design phase, despite limited information being available at that

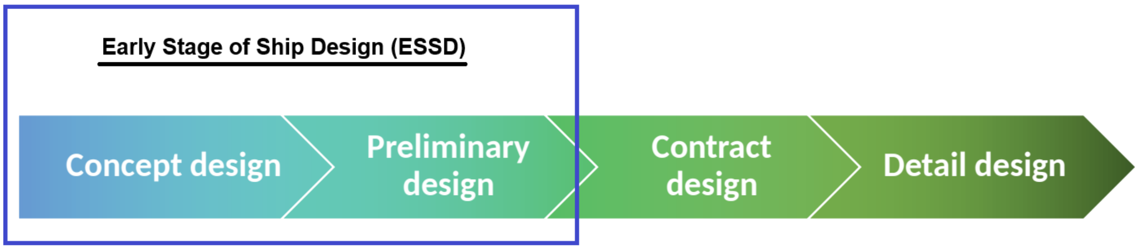


Figure 2.1: General Ship Design Processes [59]

stage. Therefore, it is crucial to have effective design methods during this phase to support the naval architect in making well-informed decisions.

2.1. Design Phases

The different phases of the ship design process exist due to the unique characteristics of each component [4]. The division of the design phases can be specified by specific drawings or documents that must be completed before or at the end of each design phase, and these are known as milestones [132]. The four different phases each have an own characteristics and will be discussed.

2.1.1. Concept Design

The concept phase, also known as the cost and feasibility study phase, is designed to understand the client's or commissioner's requirements. The primary goal is to find the combination of the ship's mission and its key performance characteristics. Important components for this include a clear mission statement and a concept design. This concept design must meet all the requirements set by the owner. However, it is not always possible for all the requirements to be financially or technically feasible. To assess the financial and technical feasibility, a cost estimate is also made in this phase, and a risk assessment is conducted. The end of this phase consists of determining the capacity of the main components on board, such as the required propulsion and an estimate of the total energy consumption [136].

In the design process, one must start by defining the purpose and requirements associated with the ship. This differs per type of ship, but the phase is the same for every different ship. It involves determining elements such as specific operational considerations, range, the speed the ship must be able to achieve, fuel consumption, and cargo and passenger capacity [132]. Once the requirements are clearly defined, design features are translated from the requirements. These design features form the foundation that guides the initial concept designs. The importance of the concept designs is that they meet the client's requirements. This is done through a feasibility study, focusing on innovation and cost-effectiveness [110][121]. In the concept design phase, everything is broadly outlined, and the first shapes of the ship become clear.

2.1.2. Prelimary Design

Once the ship design concept has been developed in the concept phase, the next step is the preliminary design phase. There is no clear boundary between the concept design phase and the preliminary design phase. Both phases are closely linked and, in various methods, are combined or fall into the exact design phase [110]. More refinement from the concept design is needed in the preliminary design, and more technical documentation is needed. In this phase, important design decisions are made through trade-off studies. Decisions in this phase have a significant influence and impact on aspects such as dimensions, overall configuration, and performance. In the preliminary design phase, the costs and risks of the ship are also more clearly defined than in the concept phase [59].

As described in Haben en Jansen, in the preliminary design phase, there are important components of the ship determined [72]. This includes dimensions such as the hull size and the shape of the hull. The General Arrangement (GA) is defined, as well as the crew size. Specifications of mission-critical cargo features are determined, and if it was not fully decided in the concept phase, the propulsion system is reviewed. The first components on board the ship are also broadly described, such as the onboard systems, features on board, electrical load analysis, HVAC load, and deliverables such as line diagrams. These deliverables are still very general and incomplete. At this stage, an evaluation and feedback are again presented to the client in order to refine the design and address important changes and preferences. The final preliminary design is then reviewed against the operational requirements, the client's budget, and legal standards.

If a ship is designed to be emission-free or green-powered, this is determined in the concept phase. However, these decisions are made in the preliminary design phase because this is where the power and emission characteristics of the ship become clear. Based on this, iterations can be performed, or appropriate emission-free propulsion and secondary systems can be considered [135]. In recent years, digitization has increasingly been used through computer-aided design (CAD) [115]. Using CAD systems adds an extra dimension to the preliminary design phase and helps influence the concept design phase. Digital applications and processes make it easier, faster, and more efficient to consider and address design variations.

The preliminary design process of a vessel can be described by the design spiral of (Evans (1959) [41]. Working through the design spiral provides all the different feasibility concept designs needed in this phase. The design spiral is further discussed in section 2.3.1.

2.1.3. Contract Design

The contract design phase comes after the concept design phase and the preliminary design phase. Everything that needs to be on board the ship is finalized in the preliminary design. The contracts' final development and completion occur in the contract design phase. In the research of Scheffers' its been told that this occurs between the shipyard and the future shipowner [132]. In the contract design phase, all technical, legal, and commercial aspects of the ship's or multiple ships' new realization are established. This is important to reach a clear compromise and understanding of the rights, obligations, and expectations among the various parties involved in the project [110].

All the previously discussed components are contractually defined, from the precise description of the hull and the ship's length, the general arrangement of the ship, to estimates of the center of gravity and weight. Ultimately, in this phase, the solution is detailed and analyzed. This analysis forms the basis for determining the contract, the contract description, and the price [37]. The established layout, which can still change after the contract design phase and is thus provisional, forms the basis for contracts for purchases such as materials and equipment [36]. Shipyards often have the own suppliers, which often results in the shipyards taking on most of the work in this phase or working closely with partners. The shipyard has good insight into the ship's producibility and the estimated costs [36].

2.1.4. Detail Design

The final phase of the ship design process is the detailed design phase. After most of the contract has been established in the contract design phase, the final contract design is further refined in this phase. The refinement is done by creating detailed technical drawings and specifications. These serve as the instructions and blueprint for a shipyard that will undertake the realization of the ship. The start of the production of a ship often coincides with the detailed design phase. The development of a detailed design can co-occur with the engineering process, where production techniques play an important role in the production schedule [38] [64].

This final phase covers a large portion of the entire design process. During this phase, the outcomes of the contract design phase are translated into a design that is directly suitable for production. This is done by creating detailed technical specifications and production drawings. Often, this phase runs parallel to the start of shipbuilding, where construction can begin before all technical drawings are fully completed [36].

The literature clarifies the different design phases in which a ship design progresses. The initial phase of the ship design process is important in this thesis, and this is the Early Stage of Ship Design (EESD). EESD will now serve as the overarching term for the Concept Design and Preliminary Design Phase. These two phases represent the early stage of ship design, and the thesis focuses on analyzing the ship's system architecture during this initial phase.

2.2. Early-Stage of Ship Design (ESSD)

In the early stage of ship design, the focus is on the concept and preliminary phases of the design process. In the ESSD, there is a lot of design freedom, which is shown in Figure 2.2 through influence. Initially, costs are still low, and information and problem knowledge are limited. As problem and information knowledge increase over time, the trend shows that design freedom decreases. The decrease in influence on the design in an innovative process over time is related to the increase in the information graph: as more becomes known, decisions are influenced by this information [72]. This freedom is more significant in the early stages because the impact of costs is lower, and less information is known.

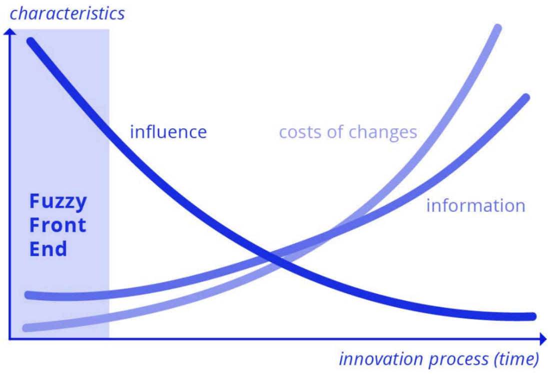


Figure 2.2: Characteristics versus innovation process - Fuzzy Front End [60]

Figure 2.2 shows the representation of the general design process, where the different phases in the ESSD are displayed along the timeline. The pre-milestone phase is also mentioned, during which the requirements are defined. These requirements are often ambiguous and typically change over time. Therefore, understanding the simultaneous impact of requirements, product design variables, and emerging technologies during the concept formulation and development stages is critically important and, until now, elusive [102]. Developing this understanding would greatly improve the process of determining trade-offs and early design activities, as shown in Figure 2.2.

When considering requirements, it's common to think about both the acquisition and design timelines, which share similarities. As Figure 2.2 shows, current practices often establish firm requirements early, limiting design flexibility and locking in a large portion of costs without fully understanding the interaction between requirements, concepts, and technologies. Capturing this interaction provides valuable insights, allowing for more design freedom and better decisions. This research focuses on a new approach to achieve this understanding [102].

Now that the position of the ESSD phase within the design process is being examined, its nature can be described in more detail. An important difference between the early design phase and the later phases in the development of a product or system is that the early phase focuses on clarifying the requirements and defining the design problem, rather than on the technical design work itself [6]. The ESSD phase is considered one of the most important steps in ship design [125], as crucial and costly decisions about the ship's performance are made early in the process. Figure 2.3 shows The inclusion of requirements definition with the design freedom and different design stages.

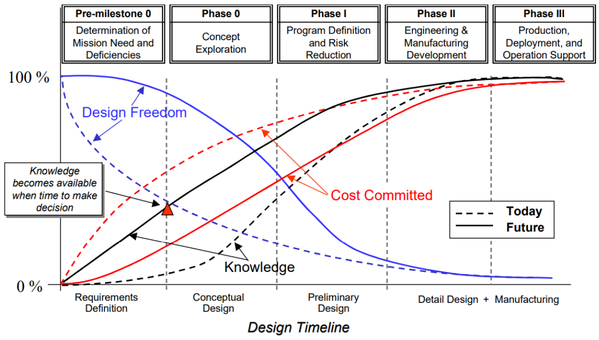


Figure 2.3: Pre-mileston requirements with Design phases [102]

Poor or ill-considered choices can lead to higher costs and undesirable consequences later in the process, as early decisions limit the later design [126]. Most design and cost-related decisions are therefore made in this phase. However, the limited knowledge about the problem and possible solutions poses a significant challenge. The study of Wilcox emphasizes the importance of early knowledge and introducing the correct information early in the process [167]. For better decision-making and improved designs, a good understanding of ship performance is necessary [23], which highlights the need for an effective design process.

This literature review highlights the influence of decisions made in the early stage design of shipping and the great importance. In this phase of ship design, decisions are made that can have the greatest impact on the entire design process and exert the most influence on the lifecycle of the product and ship, but when the most minor information is available [21]. At this moment, the greatest uncertainty is present in the design process. The requirements and the definitions, including tasks, must be clearly defined in order to have an effective and positively influential ESSD.

2.3. Ship Design Methods

In ship design, various systems and processes have been developed over the years. With the rise of digital design tools, these are becoming increasingly advanced, allowing these systems to solve complex problems more easily. From simple to complex, each method has its own philosophy and system. The ship design process, and the most traditional method, was described by Evans in 1959 as the design spiral [41], involving continuous iterations of the ship design in succession. However, over the years, due to developments, more and more new methods have been adopted, each with the specific advantages but also with potential disadvantages or weaknesses in certain areas. This section discusses several important design methods. This literature review examines classical methods and methods that hold potential for complex and green shipping designs.

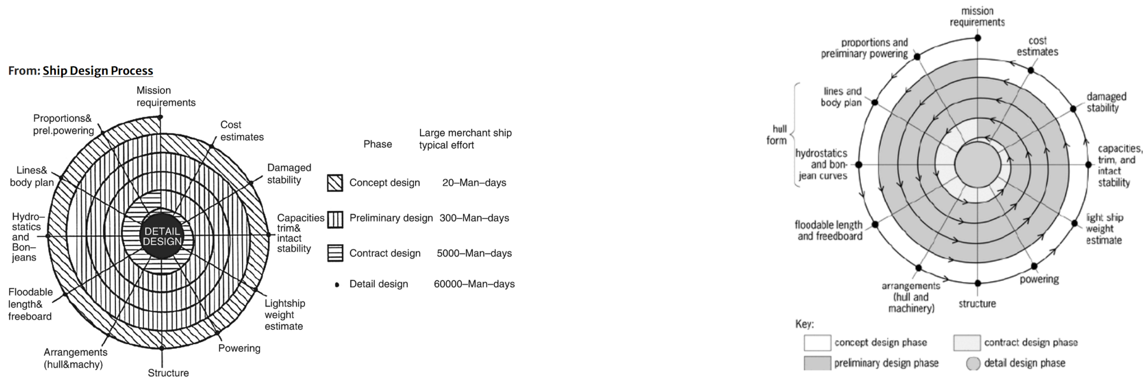
2.3.1. Ship Design Spiral

The ship design spiral, developed by Evans in 1959 [41], was one of the first systematic methods to structure ship design and is shown in Figure 2.4a. It describes an iterative and cyclical process in which the design is refined through various phases until it meets the requirements in the final stage. This approach was the standard in shipbuilding for many years and helped design teams focus on specific areas of the design.

The design spiral follows a point-based approach [41], where one design solution is gradually developed through new insights gained from each iteration. This process helps guide subsequent design decisions. While it was effective for many types of ships [4], it has proven less suitable for complex ships such as warships, as it is not easy to translate mission requirements directly into physical parameters, as is often the case with cargo ships [72] [108].

One of the advantages of the ship design spiral is that it provides a structured and systematic way to improve the design through different phases [108]. This process ensures that designers refine and optimize the choices after each iteration, leading to a detailed and well-tuned final solution [16]. The methodology is suitable for standard ship types where the design is largely predictable.

Despite its advantages, there are significant limitations to the design spiral. Its success heavily depends on a good starting point; a wrong choice can lead to inefficiencies and hinder innovative solutions. Additionally, the sequential nature of the spiral limits flexibility, especially when dealing with unexpected changes. It also reinforces an ”over-the-wall” mentality [142], where communication problems arise due to a lack of interaction between design teams. Modern approaches, such as those of Erikstad and Levander [39] in Figure 2.4b, offer more flexibility and are better suited for complex designs with multiple configurations.



(a) Design spiral, J.H. Evans 1959. [146]

(b) Design spiral Erikstad 2012. [39]

Figure 2.4: Design Spirals in concept, preliminary, contract, and detail design

While design spirals have historically provided a valuable framework for ship design, the evolution of the industry shows that new methods and approaches are needed better to handle the complexity and dynamics of modern ship designs.

2.3.2. System based Design

The literature review covered the ship design spiral, but this method has the drawback that the starting point is often unclear. In current designs and processes, a great deal of collaboration is needed between the shipowners and engineers to reach an optimal design. However, a problem arises in this collaboration, where the ship designers receive requirements but not the plans or the ship’s operational profile to be built. This results in assumptions that are fixed during alternative exploration [126].

When assumptions are made, and the design is fixed based on them, instead of exploring and evaluating potential solutions, attention is focused on a single concept. The solution to this problem came from System-Based Ship Design (SBSD). SBSD is based on the classical ship design spiral but with modifications. In this method, the focus is more on the analysis of functionalities [39]. The operational profile and mission must be clearly defined from the outset. This concerns the ship’s mission, capacity, various tasks, and performance factors. By integrating functionalities, the design spiral can be corrected, reducing the number of loops needed to achieve technically feasible solutions [39].

The SBSD method is effective in early design decisions because it helps to determine the best starting points before the ship design begins. The new design is based on a suitable baseline ship, reducing the number of iterations in later phases [160]. This has resulted in successful designs for standard ships such as container ships, ferries, and cruise ships, where only minor adjustments are needed [39]. Since these ships require little innovation, the design process often revolves around scaling up.

Like the design spiral, SBSD has limitations, such as the fact that new designs depend on existing ships [16]. However, with complex ships, such as naval vessels, more innovation is needed to push beyond the boundaries of existing designs.

2.3.3. Set-based Design

Another design method for ships is set-based design (SBD), where different design alternatives are explored and evaluated in separate design spaces or sets at the same time [163]. This contrasts with prematurely converging on a single isolated solution [139]. The different designs are analyzed and compared only at the end of the process. This is done systematically, where the different design alternatives are compared, focusing on the similarities. The goal is to converge the various options into a single design eventually. This is achieved by comparing the different alternatives on competitive grounds. The design sets are compared and generated using data, where the use of software and data methods plays a significant role [44].

This SBD method emerged as a departure from the traditional design spiral and is actively pursued in the U.S. Navy (David Singer, Doerry, and Buckley 2009). In the Netherlands, under the leadership of Bart van Oers, the SBD method has been extensively studied and applied [155]. This method is not limited by early-stage limited knowledge and predefined costs [72]. Instead, it explores different sets using data and parameters rather than directly creating an optimal solution. In the various sets of data, dominated or unfeasible solutions are eliminated [104].

The SBD method is complemented by MBSE, which will be discussed in Section 2.3.7. This addition enables effective communication about stable elements in the design and which elements will or can change [147]. Besides distinguishing between elements, the focus is also on the participants who assist in the design [104]. All these individual groups and design sets are kept open until the overlaps between feasible and desired components are better understood, after which convergence occurs at these points [35].

The main advantage of the SBD method is that it provides design freedom and flexibility before influential decisions are made [104]. This allows for monitoring various set ranges to manage uncertainties and design decisions while deferring decision-making until the influences are better understood. Important decisions are made once all information is known and alignment is clearly mapped out. The adaptability of the SBD method is also high because no significant decisions have been made in the early design phase. This allows for quick adaptation in case of changes and provides more flexibility in later design phases due to the postponement of decisions [101].

A key challenge with Set-Based Design (SBD) is correctly defining individual sets and managing the design spaces over time [52]. Although much research has been done, little attention has been paid to understanding how these design spaces are formed in the early stages. Additionally, the decision-making process for reducing sets during design is complex, as changing variable sets affects design relationships. This dynamic makes it difficult to understand the consequences of set changes [139] [104], and the adjustments are often heuristically determined by a chief engineer. Unlike for example the automotive industry, the U.S. Navy does not have extensive databases to support this process [104].

2.3.4. Modulair Design

Modular design is a modern approach in shipbuilding that divides the ship into blocks, sections, and modules [39]. It is considered a strategic method to manage various forms of complexity, such as structural and behavioral complexity. By breaking the more extensive system into self-sufficient, smaller modules that are combined according to specific rules, naval architects can design more flexibly and efficiently [48].

In the modular design process, ships are divided into smaller, independent modules. These modules can be recombined in different ways, leading to various end products [126]. This approach is supported by a product platform strategy, where standardization and customization go hand in hand. This allows multiple stages of the design process to be executed in parallel, significantly reducing the time and resources required for construction [46].

Modular design offers several advantages. It allows the reuse of previous designs, making the design process more efficient. By using modular components, structural complexity becomes more manageable, which is essential when designing ships with various subsystems [137]. Additionally, it increases design flexibility, making it easier to adapt to market dynamics. This results in shorter lead times and lower costs [126].

Although modular design has its advantages, there are also challenges. The method works best when designing product families but loses efficiency when dealing with unique, individual products. This is because the standardization within modules is less applicable to single designs. Moreover, managing hidden interactions between modules requires careful planning to avoid unexpected complications [46].

2.3.5. Holistic Design

Holistic ship design is an approach where the ship is viewed as a single entity, taking into account the interdependencies between various factors. This design model aims to balance functionality, performance, and efficiency by integrating all aspects of a ship into the design process. The goal is to find optimal design solutions that meet the specific requirements of the ship, the owner, and the environment in which the ship will operate.

In holistic ship design, an optimization algorithm is applied, where the ship's key specifications and load cases are known in advance. Then, through exploration, various design solutions are pursued. This approach requires a comprehensive analysis of factors such as stability, propulsion, and operational efficiency, with the interrelationships between subsystems playing a crucial role [122]. Modern techniques like data analysis and predictive models can further enhance this process by improving optimization algorithms, leading to more efficient and accurate designs [82] [111].

Holistic design offers several advantages. First, it can lead to a better-integrated design, where all parts of the ship work harmoniously, resulting in improved performance and efficiency. Additionally, using data-driven optimization algorithms and predictive models allows for faster and more accurate identification of optimal design solutions. This lowers total costs and shortens the lead time for the design and construction process. It also helps anticipate complex interactions between systems, making the design more reliable [111].

Despite the advantages of holistic ship design, there are challenges. It requires extensive integration of different disciplines, which can lead to complex decision-making processes and a greater need for collaboration between designers, engineers, and other stakeholders. Implementing optimization algorithms and data models can place high demands on the computing power and data infrastructure of design organizations. Furthermore, it depends on the availability and accuracy of data, which can sometimes be a limiting factor, especially in the early design phases [82].

2.3.6. Design Building Block

The Design Building Block (DBB) method is an approach in ship design where the process is divided into separate building blocks or modules. These modules represent various components and systems of the ship, allowing for a flexible and structured design methodology. The use of Computer-Aided Design (CAD) plays a key role in applying this method, enabling the management and more efficient processing of complex designs.

In the DBB method, predefined modules are developed that represent different components and systems of the ship. These modules can be integrated into the design process, creating a structured and repeatable approach. By using CAD software, designers can easily modify and combine these modules, resulting in a systematic design process [155]. The modular nature of DBB allows for breaking down the complex nature of ship designs into manageable parts, significantly simplifying the design process [5].

An advantage of the DBB method is the increased flexibility in the design process. By dividing ships into individual modules, designers can quickly make changes without having to revise the entire design. Additionally, CAD software makes it possible to handle large amounts of data, enhancing accuracy and efficiency. This approach can also contribute to shorter lead times and lower costs, as modules can be reused across different projects [4]. Moreover, the modular nature of DBB offers opportunities for innovation by developing new modules and easily integrating them into existing designs.

Despite the advantages, there are challenges in applying the DBB method. The reliance on CAD software and advanced ICT systems is not always feasible. Additionally, careful execution of data and module processing is essential to avoid errors, which requires extra time and expertise. Managing large amounts of data, such as big data, can be problematic if the processing systems are not properly set up. This makes the method highly dependent on the availability of advanced technology and the proper implementation of digital tools [5] [82].

2.3.7. Model-based Systems Engineering (MBSE)

Model-Based Systems Engineering (MBSE) is a method within systems engineering that uses models as the primary tool for designing, analyzing, and managing complex systems. This contrasts with traditional Document-Based Systems Engineering (DBSE), which mainly relies on text and diagrams. MBSE offers a structured approach to managing the increasing complexity of modern systems, such as ships, by using models that integrate the various aspects of the system [134].

The MBSE method breaks down complex systems into smaller subsystems, where each subsystem is defined within a model. This model serves as a central database, capturing all requirements, functions, system architecture, and verification and validation steps [76]. This enables different design teams from multiple disciplines to collaborate effectively within the same system model, streamlining data analysis and design exploration [25]. MBSE is particularly useful in the early design phases, where it helps establish a robust system architecture and predict future system behaviors [123].

MBSE offers several advantages. It enhances consistency, precision, and traceability in the design, as every change in the model immediately provides insight into its impact on the overall system. This makes decision-making simpler and more effective, as changes can be accurately evaluated [147]. Additionally, it improves stakeholder communication and shortens design time by providing detailed information early in the process. MBSE also helps reduce design errors and integrates subsystems more efficiently [123].

Despite its many advantages, there are challenges in implementing MBSE. It requires significant investment in technical infrastructure and staff training to apply the methodology effectively. Moreover, setting up and maintaining a model that integrates all subsystems and data [84] can be time-consuming and complicated. MBSE is also highly dependent on the accuracy and completeness of the data entered into the model, making the process vulnerable to errors if the data is not well-managed [97].

2.3.8. Digital Twin Supported Design

A digital twin (DT) is a representative approach within model-based systems engineering (MBSE) that supports the ship design process. It provides a digital representation of a physical ship and serves as a tool for making design decisions. This technique is increasingly used in modern ship designs, particularly because of its advantages in optimization and lifecycle management, as demonstrated by studies on green ship design [92].

A digital twin is a virtual version of a physical ship connected to the physical product through a real-time data stream. By performing simulations on the DT, ship designers can analyze and optimize various design variants [8]. This applies not only during the design phase but also throughout the operational lifespan of the ship. The DT acts as a data-driven system that performs operational simulations and supports future decision-making [39].

The use of a DT in ship design offers multiple benefits. It allows designers to perform more accurate simulations, enabling design challenges to be addressed early and solutions to be tested more quickly. This leads to lower operational costs (OPEX) and reduced emissions, as demonstrated by Nikolopoulos and Boulougouris (2020) [111]. Moreover, integrating a DT with a systems-based approach in the early design stages accelerates assessment and evaluation processes, making the overall design process more efficient [18].

Although a DT offers significant advantages, there are also challenges. Its implementation requires advanced ICT infrastructure and continuous data streams between the physical and digital products, which add extra costs and technical complexity. Furthermore, a DT is not a standalone design method but a complement to existing techniques, meaning its effectiveness largely depends on how well it is integrated into existing processes [109].

2.4. Concluding Remark Different Design Methods

The exploration of various ship design methodologies in Chapter 2 has highlighted the benefits and challenges associated with each approach, especially in the context of developing a modular, zero-emission IRV for the PoR. Traditional methods, such as the Ship Design Spiral, offer a structured approach to functional decomposition and early-stage design, which can clarify functional requirements and guide the initial phases of development. However, these methods often lack the flexibility and lifecycle perspective essential for a modular vessel concept, which must accommodate both current and future technological advancements.

Model-Based Systems Engineering and Digital Twin technologies provide a more integrated approach, allowing for real-time data analysis and simulation across the vessel's lifecycle. These methods facilitate a deeper understanding of system interactions and enable continuous improvements throughout the operational life of the IRV. Despite the technical complexity and resource investment required to implement these methods, the ability to support sustainable, adaptable vessel designs underscores the relevance of the IRV project's goals. The adaptability provided by such advanced digital tools aligns with the Port of Rotterdam's objective to integrate sustainable solutions into its fleet management.

The PoR aims to implement a modular and standardized ship design if feasible. This chapter discusses various ship design methodologies that could potentially align with this goal. To deepen understanding of modularity and standardization, further exploration is required. Model-Based Systems Engineering, Digital Twin, and Modular Design are the most suitable approaches for this study due to the potential for future flexibility and given the modular approach of these methods, which aligns with the PoR requirements. Other methods are less appropriate, as they involve making fixed design choices prematurely.

Transitioning into Chapter 3, the focus will shift from evaluating individual design methodologies to examining modular design principles and strategies as this aligns best with the identified ship design methods, particularly with the PoR request to design a modular vessel. This next chapter will explore how modularity and standardization can enhance the IRV's adaptability and efficiency. By building on the foundational design methods outlined here, Chapter 3 will establish a framework for modularization that supports streamlined maintenance, rapid reconfiguration, and future scalability. This transition from broad design methodologies to specific modular strategies will reinforce the IRV's potential to meet evolving operational and environmental demands.

3
Modular Design Principles and Strategies

This chapter describes the different modular design principles and strategies. Chapter 3 consists of 5 sections that all contribute to answering the first sub-question of this research:

- *What are the most effective modular design principles for ensuring flexibility in ship energy systems and future-proofing the design?*

In this chapter, the focus will be on identifying the most effective modular design principles that enable adaptability, particularly in energy systems. These principles will ensure that ships can transition smoothly between different energy carriers and layouts, helping future-proof vessel designs in a fast-changing technological landscape.

The literature study investigates the core principles and strategic advantages of modular design in shipbuilding, focusing on how these concepts can enhance the adaptability and efficiency of both vessel construction and operations. Modular design is critical for improving the integration of advanced technologies while allowing for simplified modifications and upgrades in response to evolving technical and operational requirements. The analysis will explore the role of modular strategies in optimizing ship construction processes and forming the foundation for the design of IRVs.

When applied to shipbuilding, the modular design methodology creates an all-around architecture supporting innovations' rapid incorporation. Given the dynamic nature of technological advancements in the maritime industry, this flexibility is essential. Modularity enables easier integration of new systems and facilitates retrofitting existing vessels, ensuring that ships can adapt over the ship's lifecycle. Consequently, modular design holds significant potential for IRVs, allowing for swift adaptation to new operational challenges and future-proofing the vessels.

3.1. Standardization and Modularization

The development of a highly standardized and modularized electric-powered vessel is one of the requirements for the Port of Rotterdam. Standardization involves implementing technical standards that reduce production costs and ensure compatibility, while modularization divides a system into independent modules that can be reused across different designs. These two concepts complement ship design, providing strategic benefits such as cost efficiency, flexibility, and streamlined production. This section explores how these approaches can be applied to optimize shipbuilding for the PoR.

3.1.1. Standardization

Standardization refers to applying universal specifications to ensure uniformity and compatibility in ship components [78]. This practice enhances production efficiency, reduces costs, and ensures operational safety [80]. Shipbuilders often reuse components across projects, which saves time and resources. However, expanding standardization to larger ship designs beyond smaller components remains challenging. For example, Damen's multipurpose tugboats [9] and Artemis' hydrofoil ferries [165] demonstrate how modular ship types can be built using standardized designs. This approach reduces the total cost of ownership and supports sustainable development [7].

3.1.2. Modularization

Modularization refers to designing products using common, interchangeable components to create variations and increase production flexibility. Modular designs enhance efficiency by quickly replacing parts and adapting to market demands [63]. Modularization is particularly advantageous for shipbuilding, where complex systems can be divided into simpler, independent modules [133]. Key characteristics of modular design include closed functional units, defined interfaces, and subsystems with lower complexity than the overall design [75].

Modular construction involves dividing the product into distinct product modules, each representing a specific functional unit. When these modules are assembled, the modules form a complete system. A product module can be characterized by the following properties [75]:

- **A product module is a subsystem with lower complexity than the overall system of which the module is a part.**
- **A module is a closed functional unit**
- **A module is a spatially closed unit**
- **A module has well-defined and obvious interfaces**

3.1.3. Integral versus Modular Design

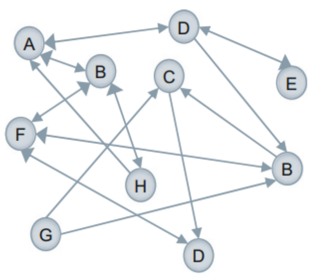
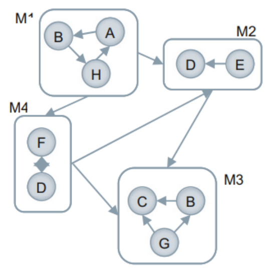
Ship designs must balance the need for performance with flexibility. Integral designs offer high performance but lack flexibility, while modular designs allow for easier adaptation to technological changes and customer needs [47]. In the current conceptual phase of ship design for the PoR, modular design offers the best balance between performance and adaptability, allowing for potential future upgrades to fuel and propulsion systems. Table 3.1 highlights the key differences between integral and modular design approaches.

3.1.4. Types of Modularization

Modular design plays a critical role in engineering, with Fixson [45] identifying four distinct types of modularity: product, process, organizational, and innovation modularity. Building on this framework, modularity within product families has been further categorized into three critical perspectives: functionality, technological solutions, and physical structures, leading to the concepts of **functional**, **technical**, and **physical** modularity [140].

- **Functional modularity** is based on the significance of functional requirements for different user groups, each with unique needs. This categorization is purely functional and does not consider other aspects, remaining solution-neutral.
- **Technical modularity** focuses on the technical viability of design solutions, assessing the interdependence of design elements needed to meet specific functional requirements, irrespective of the physical implementation.
- **Physical modularity** centers on manufacturability, with module connections and physical interactions as key concerns. The diversity of interfaces and the presence of a central unit define the types of physical modularity, which include:
  - **Sectional modularity**
  - **Bus modularity**
  - **Slot modularity**
    - *Combinatorial modularity*
    - *Component-swapping modularity*

Table 3.1: Key differences between integral and modular design [46]

	Integral Design	Modular Design
Performance	Can be trimmed for higher/highest performance (e.g., size, weight)	Typically compromises on performance (e.g., over-sizing)
Product definition	Complex mapping from functional elements to physical elements and/or interfaces between elements are coupled. Interfaces poorly defined	Each physical element implements one or a few functional elements in the entirety. Interfaces between elements are not coupled. Requires 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 architecture are typically in eras of a completely new technology development.	Modular architectures are typically superior if technologies overshoot mainstream customer requirements.
Organization, 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.
Example		

    * *Component-sharing modularity*
  - **Cut-to-fit modularity**
  - **Mix modularity**

Sectional modularity uses standardized interfaces to connect modules, while bus modularity connects modules to a central unit via a standard bus interface. Combinatorial and component-swapping modularity lack global interfaces, but some modules share local interfaces. In combinatorial modularity, modules with compatible slots connect, whereas component-swapping modularity attaches modules to a central unit through slots. Cut-to-fit modularity, used in shipbuilding, modifies the midsection without altering the bow or stern [140].

3.1.5. Integrating Standardization and Modularization in Ship Design

Integrating standardization and modularization is essential for the Port of Rotterdam's new fleet. By designing ships using modular components based on standardized frameworks, the fleet can operate more efficiently and adapt to future energy supply and propulsion systems innovations. This approach ensures flexibility while optimizing operational efficiency and reducing costs [137].

3.2. Comparing different Modular Design Principles

Previous studies have evaluated various modular design principles. Comparative research has included the work of Zahid (2012) [75] and Nepal (2005) [128], which analyzed different modular strategies in both theoretical and practical contexts. These studies highlight the different types of modularity, such as functional, technical, and physical, and the corresponding approaches to ship design. The principles and methods that emerged from these studies provide a framework for standardizing ship modules, which can be reused across different vessel types or operational profiles, leading to reduced costs and construction times. The modularity principles are derived from the modular, model-based systems engineering ship design methodologies discussed in Chapter 2, as well as related approaches aimed at establishing modularity within the design.

The literature review includes a comprehensive comparison of modular design methods and assesses the applications to modern shipbuilding. This review lays the foundation for selecting the optimal modular design strategy to be applied to IRV development. Specifically, it explores the types of modularization, such as product modularity, process modularity, and technical modularity, and how these concepts can streamline shipbuilding. The modular design strategies discussed in this section will serve as the basis for defining the modular architecture of the IRV concept.

The methods to be discussed include:

1. **Pahl and Beitz method**
2. **Matrix based methods**
3. **Functional flow heuristics**
4. **Group technology-based approach**
5. **Consideration of technology complexity**
6. **Modular functional deployment (MFD)**
7. **Modularity matrix method**
8. **Quantitative functional modeling method**
9. **Product modularization for life cycle engineering**
10. **Developing modular products for testability**
11. **Modularity operation of systems based on maintenance consideration**
12. **QFD-based modular product design**

- **Pahl and Beitz Method**
  The Pahl and Beitz method is a systematic design approach that emphasizes decomposing complex systems into distinct functional modules [119]. It starts with a functional analysis, breaking down a product into primary functions and sub-functions. The core principle of this method is to create functional modules that simplify the assembly and production processes while ensuring each module performs a specific function with minimal interaction with others. This approach enhances flexibility in design and eases assembly, though it may increase part complexity due to reduced opportunities for functional integration. The Pahlz and Beitz engineering design is a system engineer design approach.

  The Pahl and Beitz method is a well-established systematic approach focusing on functional decomposition. It breaks down complex systems into sub-functions, facilitating the design of modular systems that are easier to assemble and produce. While this method is excellent for ensuring functional clarity, it does not emphasize the product's lifecycle or provide robust tools for aligning modular architecture with customer needs and business drivers [161]. In the context of the IRV project, where lifecycle considerations such as maintenance, upgrades, and energy efficiency are crucial, the Pahl and Beitz method lacks the necessary strategic foresight.
- **Matrix-Based Methods**
  Matrix-based methods, such as the Design Structure Matrix (DSM), are used to visualize and analyze dependencies between system components. This method involves decomposing the system, documenting interactions between elements, and clustering those elements into logical groups. By organizing elements in a matrix, designers can identify potential modular structures by grouping components that share strong interactions [124].

  Matrix-based methods, like the DSM, Excel at visualizing component interactions and clustering elements into logical groups based on the dependencies [27]. These methods are beneficial for managing complexity in large systems and ensuring that highly interconnected components are clustered together. However, while DSM is valuable for visualizing interdependencies, it does not inherently guide decisions on which functions or components should be modularized based on strategic drivers such as sustainability, lifecycle costs, or customer requirements. This limitation makes it less suited for projects where strategic modularization is critical, as with the IRV.

- **Functional Flow Heuristics**
  Functional flow heuristics focus on how functions flow across different system components. This approach organizes the product into logical sequences of functions, allowing for the identification of modules that align with these flows. It emphasizes continuity and coherence in product design, ensuring that each function is supported efficiently across modules [61].

  Functional flow heuristics are useful for identifying how functions are distributed across system components, ensuring that the design supports logical sequences of operations. This method is particularly effective for ensuring operational coherence [129]. However, it falls short in guiding how to structure modules for ease of production, lifecycle management, or future upgrades, which are critical concerns for a vessel operating in a rapidly evolving technological landscape.
- **Group Technology-Based Approach**
  The group technology-based approach identifies similarities in product components and groups them into families. This approach aims to maximize the standardization of parts by forming modules with common functions. It leverages shared components across multiple products to achieve economies of scale in production and assembly, promoting design efficiency [107].

  The group technology approach emphasizes standardization by grouping similar components into families. This method is highly effective for achieving economies of scale in production by reusing components across different products [10]. However, it focuses primarily on production efficiency and does not address the evolving needs of lifecycle engineering, maintenance, or sustainability considerations. This method, originating in 1966, is outdated and no longer suitable as a representative approach for contemporary applications.
- **Consideration of Technology Complexity**
  This method involves structuring products based on the technology's complexity. It evaluates the technological interdependencies and complexity within the system to divide the product into modules that minimize complexity at the integration stage [13]. This approach helps manage technological risks and ensures the system is easier to update and maintain. The method was first published around the turn of the century and has been used in various settings over the past twenty years [17].

  This approach evaluates the technological complexity of a system and structures modules to minimize integration challenges. While this method helps manage high-tech systems, it does not provide a robust framework for aligning modules with customer needs or lifecycle strategies. In the IRV project, where aligning the modular architecture with future-proof technologies and stakeholder demands is critical, this method alone is insufficient [151].
- **Modular Function Deployment (MFD)** MFD is a method that connects customer needs to product architecture through functional clustering and strategic drivers. The MFD process involves five steps: clarifying customer requirements, identifying functional requirements, assigning modules, defining interfaces, and optimizing the product for lifecycle considerations [55]. This method emphasizes the alignment of business, technical, and customer needs in modular design, ensuring that modules can be optimized for production, maintenance, and future updates.

  Modular Function Deployment (customer needs and strategic business drivers. It follows a structured five-step process:

  1. Clarifying customer requirements
  2. Identifying functional requirements
  3. Assigning modules
  4. Defining interfaces
  5. Optimizing the design for lifecycle and strategic considerations

  The strength of MFD lies in its ability to prioritize functions based on customer and business needs, ensuring that the modules not only perform the technical roles but are also designed for ease of production, maintenance, and future upgrades [138]. For the IRV, where sustainability, zero emissions, and operational flexibility are critical, MFD's focus on aligning modular architecture with lifecycle considerations and future adaptability is invaluable.

- **Modularity Matrix Method** The modularity matrix method involves mapping the interactions between components in a matrix to identify logical clusters or modules. By visualizing the interactions between components, this method highlights which elements can be grouped into modular units with minimal interdependencies, thus simplifying product design and improving maintainability [143].

  The modularity matrix method is similar to matrix-based methods but focuses specifically on identifying cluster components that can form logical modules. While this method helps identify modular boundaries based on component interdependencies, it does not offer tools for integrating customer needs or lifecycle strategies into the modularization process [12]. This makes it less applicable for projects like the IRV, where customer needs and sustainability are key drivers.
- **Quantitative Functional Modeling Method** Quantitative functional modeling uses mathematical and simulation techniques to model the functional performance of systems. This approach quantifies functional dependencies and relationships within a product, enabling designers to optimize the distribution of functions across modules [51]. The goal is to enhance system performance while maintaining modularity.

  Quantitative functional modeling uses mathematical techniques to optimize the distribution of functions across modules. This method is precious in scenarios where precise performance metrics are crucial [50]. However, it does not inherently account for lifecycle considerations, customer alignment, or business strategy, making it less applicable to projects where adaptability and future-proofing are essential.
- **Product Modularization for Life Cycle Engineering** This principle focuses on designing modular products for production and the entire product lifecycle, including maintenance, upgrades, and disposal. The key idea is to create modules that are easy to replace, update, or recycle, ensuring that the product remains sustainable and adaptable. This is often used in industries where long product life and sustainability are critical [20].

  This method emphasizes designing modular products throughout the product lifecycle, including production, maintenance, upgrades, and disposal [54]. It aligns closely with sustainability goals, making it relevant for projects like the IRV. However, it does not offer a structured framework for linking these lifecycle considerations with customer requirements or strategic business drivers like MFD does.
- **Developing Modular Products for Testability** This method emphasizes designing modular products that can be easily tested during production and operation. It ensures that each module can be tested independently, simplifying the testing process and increasing product reliability [14]. The approach also allows for quicker identification and isolation of faults within individual modules.

  Designing for testability ensures that each module can be independently tested, improving reliability and reducing testing costs [58]. While this is important for production and operation, it is a narrow focus compared to the broader goals of lifecycle management, adaptability, and customer alignment, which are more critical in the IRV project.
- **Modularity Operation of Systems Based on Maintenance Consideration** This principle focuses on modular design from a maintenance perspective. It involves structuring systems so modules can be easily removed, replaced, or repaired without disrupting the entire system [53]. This approach is beneficial in industries with costly equipment downtime, such as maritime or aerospace applications.

  This method ensures that modular systems are easy to maintain and upgrade. While maintenance is a critical lifecycle consideration [74], this method does not provide a framework for integrating customer needs or business strategy, making it less comprehensive than MFD for projects like the IRV, where both operational flexibility and lifecycle management are essential.

- **QFD-Based Modular Product Design** Quality Function Deployment (QFD)-based modular design integrates customer requirements into the product design process [1]. QFD maps customer needs onto design characteristics and helps prioritize which functions should be modularized based on the importance to the customer. This ensures that the modular architecture reflects customer preferences and enhances product-market fit.

  The QFD-based modular design integrates customer requirements into the modularization process, ensuring that the modular architecture reflects customer preferences [131]. This method is valuable for meeting customer needs but lacks the structured approach to lifecycle optimization and strategic alignment found in MFD. While QFD is essential for customer satisfaction, the IRV project demands a more comprehensive approach incorporating production, maintenance, and future adaptability.

3.3. Evaluation Framework for Modular Design Methodologies

Table 3.3 offers a comprehensive assessment of 12 different modular design methodologies evaluated across five critical criteria relevant to complex system design. Each methodology has been scored numerically from 1 to 5, with 1 representing poor performance and 5 representing excellent performance. Table 3.2 shows the score structure including the colors. These scores are complemented by color-coded circles, visually representing the assessment. The color scheme ranges from red (poor performance) to green (excellent performance), helping to quickly convey the relative strengths of each method across the various criteria.

The five criteria that are used to evaluate the modular design methodologies are applicability to ship design, flexibility and customization, complexity management, efficiency in design and production, and support for innovation and technology integration. By summing the scores across these criteria, the table provides an overall score for each methodology, allowing for easy comparison of the relative strengths. This table gives a visual understanding of how the different methods perform in this concept design phase of the IRVs.

Table 3.2: Legend for Score Colors

Symbol	Score Description
● (red)	1 - Poor performance
● (orange)	2 - Below-average performance
● (yellow)	3 - Average performance
● (blue)	4 - Above-average performance
● (green)	5 - Excellent performance

Table 3.3: Assessment of Modular Design Methodologies. *Created by the author*

Methodologies	Applicability to Ship Design	Flexibility and Customization	Complexity Management	Efficiency in Design and Production	Support for Innovation and Technology Integration	**Total Score**
Pahl and Beitz Method [119]	4 ●	3 ●	3 ●	4 ●	3 ●	**17**
Matrix-Based Methods [124]	5 ●	3 ●	4 ●	3 ●	3 ●	**18**
Functional Flow Heuristics [61]	3 ●	4 ●	3 ●	3 ●	5 ●	**18**
Group Technology-Based Approach [107]	2 ●	3 ●	2 ●	2 ●	2 ●	**11**
Consideration of Technology Complexity [13]	4 ●	5 ●	4 ●	4 ●	5 ●	**22**
Modular Functional Deployment (MFD) [55]	5 ●	4 ●	5 ●	5 ●	4 ●	**23**
Modularity Matrix Method [143]	3 ●	3 ●	4 ●	3 ●	4 ●	**17**
Quantitative Functional Modeling Method [51]	3 ●	4 ●	3 ●	5 ●	5 ●	**20**
Product Modularization for Life Cycle Eng. [20]	2 ●	3 ●	3 ●	3 ●	3 ●	**14**
Developing Modular Products for Testability [14]	3 ●	3 ●	2 ●	3 ●	3 ●	**14**
Modularity Operation Based on Maintenance [53]	3 ●	4 ●	3 ●	4 ●	3 ●	**17**
QFD-Based Modular Product Design [1]	5 ●	4 ●	5 ●	4 ●	4 ●	**22**

3.4. Concluding Remark

Modular Function Deployment (MFD) was selected as the most suitable method for designing the IRVs for the PoR due to its holistic and systematic approach to modularization. MFD offers several advantages that align with the project's needs, including customer-centric design, lifecycle management, platform flexibility, and long-term adaptability. This section outlines the key reasons for choosing MFD over other modular design methodologies.

1. **Systematic and Visual Methodology** MFD provides a structured and systematic approach visualized through a graphical table, improving understanding and management of the modularization process. This clarity is essential in ship design's complex and interdisciplinary domain, ensuring that all stakeholders have a coherent view of the design process and outcomes. The visualization aspect of MFD ensures that decisions are transparent and aligned with strategic project goals [153].
2. **Customer-Centric Flexibility** A core feature of MFD is its strong foundation in Quality Function Deployment and the integration of QFD in the MFD, which ensures a high level of customer orientation. This customer-centric approach is precious for the Port of Rotterdam, as it ensures that the design of the IRV aligns closely with the operational requirements of the Port. Furthermore, the flexibility inherent in the MFD process enables the design to adapt to changing market needs and future technological advancements, making it a future-proof solution [81].
3. **Platform Flexibility and Versatility** MFD supports comprehensive platform management, enabling designers to create a versatile set of modules that can be configured into different product variants. This is particularly beneficial in the shipbuilding industry, where various ship types can share common systems and components. MFD contributes to operational and production efficiency by optimizing resource use and simplifying maintenance. For the IRV, this means that different vessel types can share common modules, further enhancing flexibility and reducing costs [87].
4. **Lifecycle Considerations** MFD places a strong emphasis on lifecycle management, ensuring that the designed modules are optimized for initial production, as well as for maintenance, upgrades, and disposal. This is aligned perfectly with the sustainability goals of the IRV, which must not only be efficient in production but also adaptable to future changes in technology and operational demands. MFD ensures that each module can be upgraded or replaced, making the vessel adaptable over its lifespan [55].
5. **Strategic Alignment and Long-Term Adaptability** The MFD method integrates technical and strategic drivers, ensuring the modular architecture is aligned with broader organizational goals such as zero emissions and cost efficiency. This is crucial for the IRV project, as it balances the operational flexibility required for different emergency scenarios with long-term sustainability. Furthermore, MFD's focus on future adaptability makes it particularly relevant for the IRV, where advancements in green technologies, such as energy storage and propulsion systems, will likely necessitate upgrades in the near future [151].
6. **Enhanced Learning and Process Understanding** MFD facilitates a better understanding of the entire modularization process through its structured approach, helping to transition from ad hoc decisions to a disciplined and systematic design process. This structured method increases the efficiency and effectiveness of the design team, ensuring that key decisions are made with a clear understanding of the impact on the overall system [144].

In summary, MFD was chosen as the most suitable modular design method for the IRV project because it offers the most framework for developing a modular design that balances technical, customer, and strategic considerations and a complete method. MFD ensures that the vessel is designed to meet current operational needs and remains adaptable to future technological advancements. Its focus on lifecycle management, platform flexibility, and strategic alignment makes MFD uniquely suited to the complex, future-oriented goals of the IRV project and it can address the requirements of an individual vessel as well as a fleet.

3.5. Modular Function Deployment

With a Modular Functional Deployment project, a core project team must always be considered. This core stream must always be multidisciplinary, which is clarified by Kono and Lynn [83] and by Wheelwright and Clark [24]. The core teams must participate in assessing the functionalities and have all own knowledge and specialization. Each person is a representative of the relevant area of responsibility, and these can be divided into Voice of the Customer (VoC), Voice of the Engineer (VoE), and Voice of the Business (VoB). The Voice of the customer is a key input for product definition and establishing the value proposition of a product design [55]. This Voice is typically represented by a sales or marketing function, but in the case of the PoR, more the operational department. The Voice of Engineering collects inputs from engineering, people with knowledge of manufacturing, etc. to execute the value-driven process to design a suitable product for the customer. The engineering, research, or designers define this Voice. Voice of the Business are the shareholders, corporate officers or others involved in the corporate governance and determine which direction and value is important for the success of the design per product or ship and the company as a whole. The project manager, program manager, or platform manager represents the Voice of the Business for an MFD project.

MFD organizes the product data, information, and knowledge collected by the team into a collection of matrices known as the Product Management Map (PMM), as shown in Figure 3.1. Each vote is recorded in a different matrix to generate the modular product design [137]. Iterations are needed at each step to manage the trade-offs between different votes.

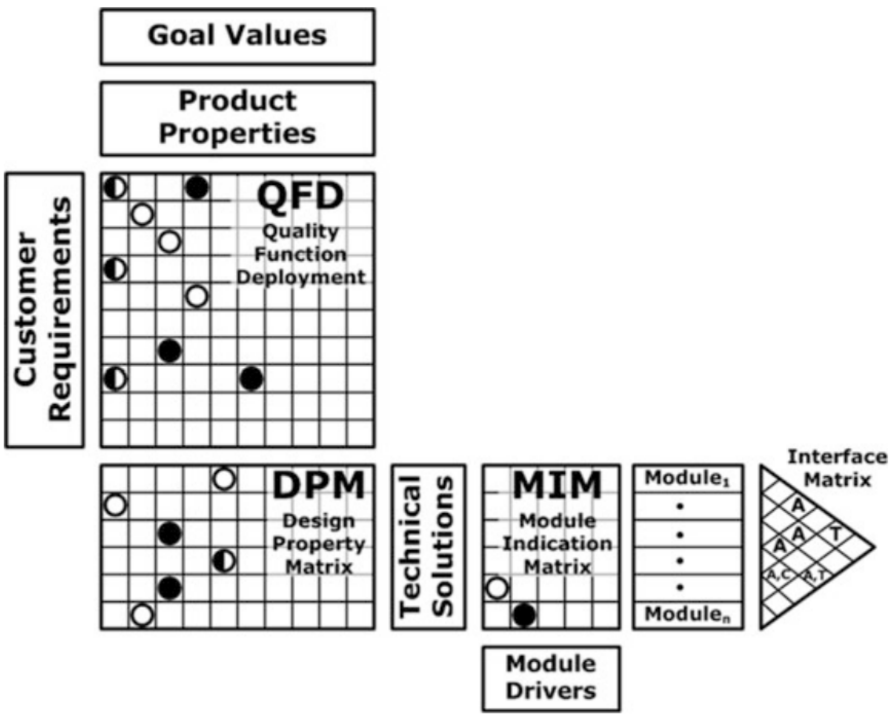


Figure 3.1: Product management Map [137]

3.5.1. MFD 5 Steps

MFD consists of five basic steps [55] as shown in Figure 3.2. These steps clarify how the MFD works and how all design steps and processes work. The input comes from the existing product and the new ideas including the decided changes. During the POR, the current ships will be peeled off to see which parts, functionalities, and systems should remain; this forms the existing product descriptions. The new ideas arise from the new program of requirements and the new emission-free drive methods. The decided changes are drawn up throughout the fleet renewal program and included in the model. The MFD consists of the following steps: Clarify Customer Requirements, Select Technical Solutions, Generate Concepts, Evaluate Concepts, and Improve Modes [137]. The outcome is a Modular Product Design from which the concept design can be formed most efficiently. The steps will be explained.

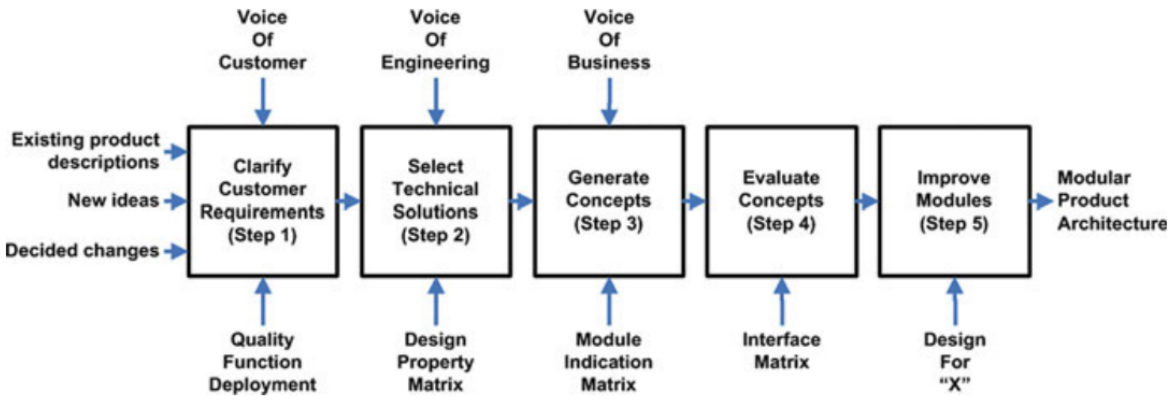


Figure 3.2: Modular Function Deployment [137]

Step 1 - Clarify Customer Requirements

- The first step is to create the Quality Function Development Matrix (QFD) that outlines the customer and operational requirements by mapping them against the production characteristics. The product and design features are measurable and controllable entities that are the building blocks of the product. At the core of the QFD is a correlation matrix that illustrates the customer's and operational requirements and how a product is designed to fulfill these needs [46]. The philosophy of QFD aligns closely with the principle that design should be driven by function, or in other words, "form follows function." The purpose of the QFD is to translate a customer's subjective requirements into objective criteria that can be measured. The resulting data can be used to design and build a concept ship [46].
  - The QFD is a method to convert customer expectations and requirements into products.
  - The QFD depends on a goal-oriented, interdisciplinary approach.
  - Factors that influence and coherence are systematically prioritized, quantified and displayed.
  - The total QFD is an iterative process and follows an iterative approach.
- In the QFD, DPM, and MIM matrix, a rating scale is used to enumerate the value of impact, defined in Figure 10.2.

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

Figure 3.3: Value an impact score of QFD, DPM and MIM [130]

Step 2 - Select Technical Solutions

- The product's functional requirements are determined by analyzing the functionalities. So that these requirements can be used for technical solutions that, in turn, shape the product properties. It can also be examined here whether the technical solutions need to be evaluated and developed based on the evaluation criteria (i.e., product properties) generated in the first step of the MFD. The results of these decisions are modeled in a Design Properties Matrix (DPM) [112]. This matrix indicates the relationship between product properties and technical solutions. DPM then becomes the representation of the Voice of Engineering.
- In the MIM matrix and in the DPM matrix, a rating scale is used to enumerate the value of impact, defined in Figure 10.2.
- In Appendix B several example questions are shown that help discusses and map the different functions and modularity drivers.

Step 3 - Generate Concepts

- In the third step, a unique feature of Modular Job Development is emphasized. Unlike other design approaches, the MFD incorporates a company's strategic intent into product design. This shows the Module Drivers and the strategic reason why such a module must be set up or built. The Module Drivers are drawn up in a Module Indication Matrix, and these Drivers are applied to technical solutions [137]. The company's strategy is examined with associated technical solutions, forming the basis for transferring to a module. The Voice of the Business is established by merging the MIM and the DPM and this allows for the ignoring of module concepts.

Step 4 - Evaluate Concepts

- In the fourth step, the modules and the concepts are reviewed and evaluated. This is done by looking at how these are physically or otherwise connected to each other. This linking of modules is done with the help of standardized module interfaces. In modular product construction, these interfaces are represented by an agreement or contract. Evaluating the different interfaces is very important to enable simultaneous engineering and ensure the concept's flexibility, among other things. The interface matrix identifies and displays the type and analysis of the types of interfaces.
- Every module concept will be evaluated in step 4 in the Interface Matrix. In this research, there are four important physical interfaces that will be used in the model, which are attachment, transfer, spatial, and command and control [34]:

  - *Attachment interface*: This interface is connected physically. By connecting the parts of the module to one another or to put the pieces together.
  - *Transfer interface*: Acts as a pathway for the transfer of power or media between modules.
  - *Command and control interface*: Establishes the method by which the condition of a component is monitored and manipulated by other components.
  - *Spatial interface*: Defines the separation between modules, specifying the space and volume that a component may occupy.

  Figure 3.4 refers to the classification of interfaces types in the Interface Matrix.

Denotation	Interaction taxonomy
A	Attachment
T	Transfer
S	Spatial
C	Command & control

Figure 3.4: Interface matrix indicators [130]

Step 5 - Improve Modules

- As a final step, the concept will be improved in the fifth step. This is done using the DFX approaches. This stands for Design For "X". In this thesis, this could be design in order to be an operational IRV design ready for shipbuilding processes [137]. In step 5, each module's specifications are written with associated technical information, market and operational requirements, and the business strategy [46]. The detailed design of the various components placed in modules can begin from here. However, by going through all the steps of this MFD, all building blocks are extracted in an optimal way, and the concept ship can be designed. From here, the blocks will be used in a 3D CAD system, as will be explained in Chapter 12.

3.5.2. Type of Voices in MFD Representing Stakeholder in Design Processes

Three stakeholder viewpoints, known as the Voices, are essential to MFD's product development life cycle. These are already discussed but are explained again here for the overview of this literature review. These Voices include the client's needs, the engineer's design and manufacturability considerations, and the corporate entity's strategic imperatives.

1. **The Voice of the Customer (VoC)** is very important as this Voice focuses on understanding and translating the diverse needs and preferences closely linked to the different segments in the market. This step translates customer requirements into quantifiable customer values. These then shape the characteristics of the product and are expressed in tailor-made product properties [137]. This process is not carried out in isolation but is significantly influenced by different insights from the operations, sales and also marketing departments. This ensures that the end product meets the quality expectations and the cost considerations of the intended user.
2. In **the Voice of the Engineer (VoE)** the tangible reality of product creation emerges. This Voice brings technical pragmatism to the fore. This emphasizes the importance of manufacturability and the integration of product modules. By selecting technical solutions that physically express product properties, engineers bridge the gap between what customers desire and what can actually be produced [137]. Using a DPM, the relationship between desired product functions and feasible technical solutions is investigated and optimized, with important contributions from technology, production, quality, and supply chain.
3. Finally, **the Voice of the Business (VoB)** takes a strategic look at the entire modular product development process. The VoB reflects the company's strategic initiatives and is concerned with how product design aligns with business objectives [137]. Through the MIM, module drivers are linked to technical solutions, so that the strategic goals of the company become interwoven into the architecture of the product. This Voice incorporates the directives of shareholders and those on corporate governance, and determines product configurations that will move the company forward, ensuring that the product not only meets market demand, but also drives the company's success.

3.5.3. Concluding Remark Modular Design Principles and Strategies

This chapter provided an in-depth analysis of standardization and modularization, which are prioritized by the Port of Rotterdam. It distinguishes between integral and modular design approaches and explores their applications in ship design. Various design methods aligned with modular design principles were reviewed, with twelve distinct methods evaluated based on the literature.

The application of MFD has proven instrumental in shaping a modular architecture for the IRV. By systematically aligning the IRV's design with customer and operational requirements, MFD enables the vessel to meet current demands while remaining adaptable to future needs. Integrating key modularity drivers, such as functional decomposition, customer-oriented design, and lifecycle flexibility, ensures a comprehensive approach to modularization that supports operational efficiency and sustainability objectives.

An important benefit of MFD is its ability to incorporate a wide range of stakeholder perspectives, from operational requirements to strategic sustainability goals. This allows the IRV's design to be both technically robust and adaptable to the Port of Rotterdam's zero-emission mandates. By employing tools like the QFD matrix and the Module Indication Matrix MIM, the IRV design can adapt to diverse emergency response scenarios, facilitating rapid reconfiguration and reducing response times through standardized, easily replaceable modules.

This thesis applies MFD to design a future-proof, zero-emission fleet for the Port of Rotterdam by ensuring that each vessel's modular design can adapt to emerging energy technologies. MFD enables a systematic approach to match operational requirements with technical solutions, covering all necessary tasks and functions within a scalable, standardized fleet design. This adaptability reduces risks associated with early technology commitments, providing the Port with a flexible path to decarbonization. As a novel application in maritime design, MFD offers a structured framework that can significantly influence sustainable shipbuilding strategies.

Moving forward, Chapter 4 explores the essential aspect of energy solutions that align with the modular IRV's design. This exploration addresses the vessel's energy demands, emphasizing zero-emission technologies. The modular framework established in Chapter 3 sets the stage for evaluating various green energy sources, such as hydrogen, methanol, and battery systems which are essential in meeting the Port's environmental goals while supporting the operational flexibility introduced by MFD. This transition to Chapter 4 highlights the need for compatible, sustainable fuel solutions that seamlessly integrate into the IRV's modular architecture, thereby enabling the vessel to adapt to emerging technologies and fuel systems over its lifecycle.

4 Alternative Fuels and Green Shipping

This chapter describes the different alternative fuels and green shipping. Chapter 4 consists of five sections that all contribute to answering the second sub-question of this research:

- *Which alternative fuels provide the most viable solution for reducing emissions in the Port of Rotterdam's IRV future fleet?*

Several types of zero-emission or green fuels are being considered as potential energy sources for IRV vessels in the future. Ongoing research is investigating a variety of alternative fuels; however, diesel remains a formidable competitor due to its high energy density, compact storage requirements, ease of refueling and transfer, and its ability to remain in a liquid state across varying temperature ranges [42]. In contrast, alternative fuels present distinct challenges, as they exhibit different physical and chemical properties, which may complicate the storage, handling, and efficiency compared to diesel.

In the search for alternative fuels, several critical properties must be considered, including energy density, storage conditions, ease of handling, and the environmental impact of the lifecycle. These factors will play a crucial role in determining the feasibility of each fuel as a sustainable alternative to diesel.

4.1. Current Global Fleet and Order Book

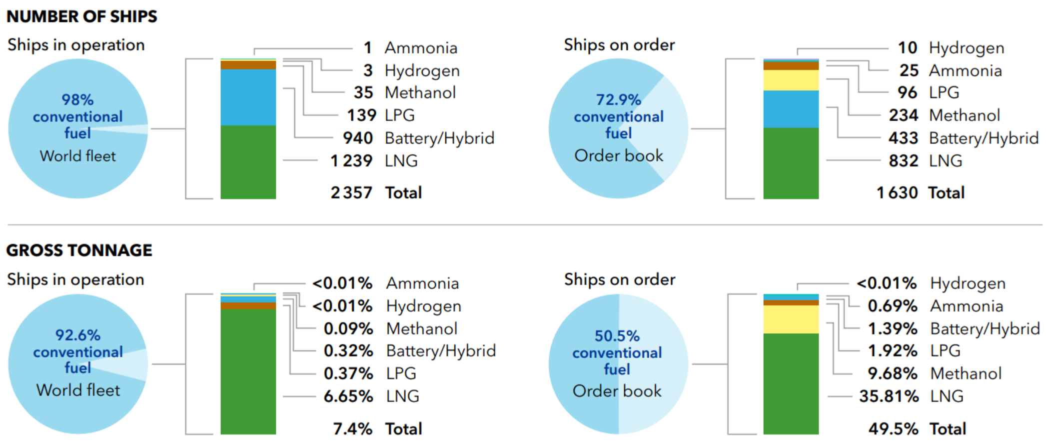


Figure 4.1: Alternative fuel uptake in the world fleet in number of ships (upper Figure) and gross tonnage (lower Figure), as of june 2024 [33]

To understand the current global fleet, Figure 4.1 can look at DNV data. As of June 2024, 7.4% of vessels by gross tonnage are running on alternative fuels, with 49.5% of new orders capable of doing so. However, only 2% of active ships and 27.1% [33] of new builds by vessel count use alternative fuels, indicating larger ships favor dual-fuel solutions. This shows the ongoing transition to alternative fuel technologies, with larger methanol-powered ships expected by 2030 [33].

Energy for propulsion and other systems on board a ship can be provided in various ways. Figure 4.2 illustrates a simplified representation of energy sources used for ship propulsion. These are the most commonly employed options at present. The maritime industry must transition away from red, conventional carbon-based fuels while green energy sources offer powerful alternatives to help reduce greenhouse gas emissions. It is also essential to have efficient energy carriers on board, as these transport the energy needed for the ship's propulsion.

4.2. Ship Fuel-tilisation Comparison

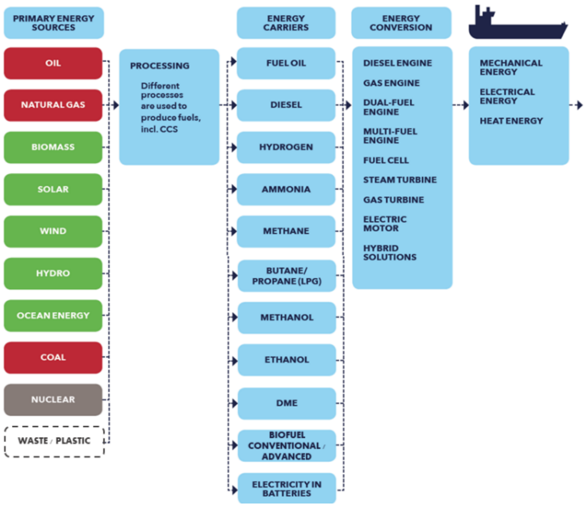


Figure 4.2: Simplified illustration of the chain from energy sources to mechanical energy for marine propulsion [3]

When considering various zero-emission or carbon-neutral fuels, in addition to oil, natural gas, and bioenergy, potential options include hydrogen, ammonia, electricity, and methanol (as an e-fuel). To assess the potential of these fuels, the IMO [67] evaluates the Technology Readiness Levels (TRLs) based on data provided by Lloyd's Register Maritime Decarbonisation Hub [95]. In Figure 4.3, the Zero Carbon Fuel Monitor examines technology readiness from multiple perspectives, offering insights into the viability of alternative fuels.

		Resources			Production			Bunkering & Ports			Ship			
Fuel		TRL	IRL	CRL	TRL	IRL	CRL	TRL	IRL	CRL	TRL H&S	TRL P	IRL	CRL
Ammonia	E-ammonia	7	2	4	5	2	5	4	1	1	5	6	2	2
Ammonia	Blue ammonia	5	2	2	5	2	4	4	1	1	5	6	2	2
Electrification	Electrification (batteries)	7	2	4	9	2	2	7	2	2	5	9	2	2
Hydrogen	E-hydrogen	7	2	2	5	2	5	5	2	1	7	7	2	2
Hydrogen	Blue hydrogen	7	2	2	5	2	4	7	2	1	7	7	2	2
Methanol	Bio-methanol	7	2	2	3	3	2	6	2	2	9	9	3	3
Methanol	E-methanol	7	3	4	4	3	2	6	2	2	9	9	3	3

Figure 4.3: 2023 IMO technology readiness marine fuels from Lloyds Registers [95]

Figure 4.3 represents the Technology Readiness Levels (TRL) for various fuels. Each fuel is evaluated based on its resources, production, bunkering infrastructure, ports, and vessels. The Investment Readiness Level (IRL) and Community Readiness Level (CRL) are also considered. TRL also includes assessments of handling and storage (TRL H&S) and propulsion (TRL P). Each fuel has its strengths and weaknesses; however, ammonia ranks the lowest in overall readiness, while electrification and methanol score the highest, followed by hydrogen.

4.3. Gravimetric and Volumetric Densities

The energy storage capacity of a fuel can be expressed in terms of both volumetric and gravimetric energy densities. A fuel with high volumetric and gravimetric energy density requires less space and weight for storage, which is particularly advantageous for ships. The suitability of a fuel for different types of vessels and the operations is partly determined by its energy density. These energy densities for various fuels are illustrated in Figure 4.4, where alternative fuels are compared against diesel, which serves as the reference fuel.

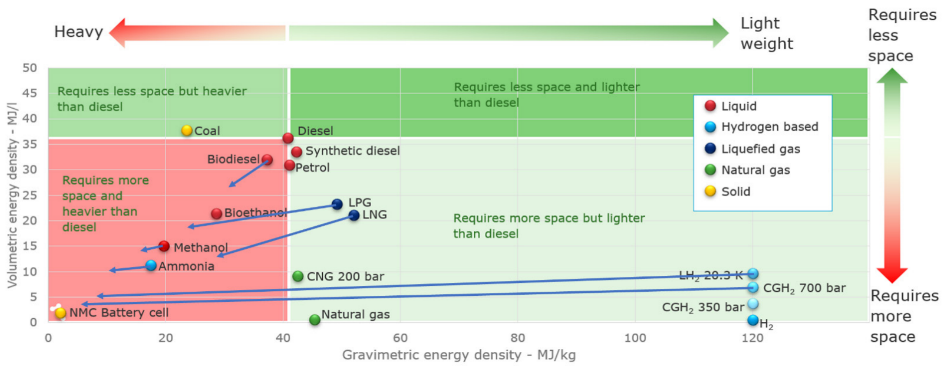


Figure 4.4: Comparision Alternative Fuels versus Diesel [3]

Another notable aspect in the graph of alternative fuels is the blue arrows, which indicate the impact of storage systems on both gravimetric and volumetric energy density. These values are approximate and should be interpreted accordingly. As shown in Figure 4.4, all alternative fuels (hydrogen, methanol, ammonia, methane, and bio/synthetic diesel) have a lower volumetric energy density than diesel. Regarding gravimetric energy density, only hydrogen and methane (LNG) exhibit significantly higher values. However, due to the storage requirements of these gases, they may still require more space and weight compared to diesel [3].

The reduction in volumetric and gravimetric energy density for gaseous alternative fuels is addressed in detail in Part II of the report. Among the alternatives, only biodiesel and synthetic diesel closely match the favorable properties of fossil diesel, with a slight decrease in volumetric energy density and a marginal increase in gravimetric energy density for synthetic diesel (FT-diesel). Methanol and ammonia, on the other hand, experience substantial reductions in volumetric energy density by 60% and 65%, respectively [3]. The impact on gravimetric density is also significant, with a reduction of approximately 50% [3].

It is important to recognize that Figure 4.4 only illustrates the properties of the fuels and no systems. When storage tanks and required systems are factored in, the energy density profile changes significantly for some fuels, especially those that must be stored under undercooled, cryogenic, or pressurized conditions, such as hydrogen and LNG. For instance, hydrogen's energy density drops considerably when storage systems are included, with gravimetric densities falling below 10 MJ/kg for liquid hydrogen (LH2), including storage, compared to approximately 120 MJ/kg for the fuel alone. Similarly, LNG's gravimetric energy density is around 25 MJ/kg, and its volumetric energy density is about 223 MJ/L when accounting for storage systems, compared to approximately 50 MJ/kg and 21 MJ/L for the fuel alone.

Taking both fuel density and storage systems into account, the endurance of a ship—how frequently it must refuel—depends on the chosen fuel, regardless of the vessel's size. Refueling frequency can range from a few hours to several months, depending on the fuel type. It is important to note that HVO, LNG, and LPG are fossil-based fuels, while methanol and ammonia, when produced with CO2, and hydrogen and electricity, depending on the energy source for production, are considered fully renewable fuels [15].

4.4. Comparative analysis of Energy Sources and Technologies

Figure 4.5 provides a comparative analysis of several energy carriers: hydrogen, methanol, battery electric, and ammonia based on the energy densities, production costs, and storage feasibility. These factors are critical when evaluating the suitability of different fuels for maritime applications, particularly in the design of zero-emission vessels Davis et al. [28].

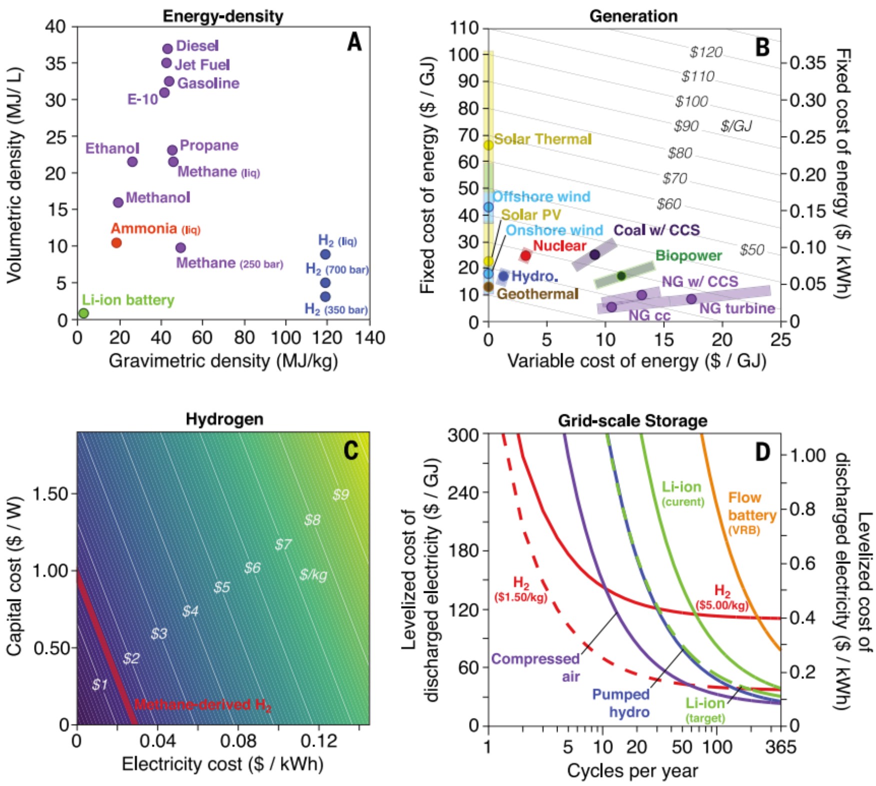


Figure 4.5: Gravimetrische energy density [28]

Figure 4.5.A illustrates the energy density of various fuels, highlighting hydrogen's high gravimetric energy density (120 MJ/kg), which makes it attractive for long-range shipping where weight is a critical factor. However, its low volumetric energy density poses storage challenges, requiring either high-pressure or cryogenic storage solutions. In contrast, methanol and ammonia offer a better balance between gravimetric and volumetric energy density, making them more space-efficient. Lithium-ion batteries, though heavily used in electric systems, have the lowest energy density, which limits the application to short-range vessels due to the size and weight constraints.

Figures 4.5.B and 4.5.C address the cost of energy production and hydrogen generation. Due to its established infrastructure, methanol remains a cost-effective fuel, whereas green hydrogen production is highly dependent on electricity prices. Hydrogen produced through electrolysis becomes more expensive as electricity costs rise, with methane reforming still being the cheaper, albeit more carbon-intensive, option. Ammonia, which can be synthesized from green hydrogen, also holds promise for maritime applications, although its production and storage costs are still relatively high.

Figure 4.5.D highlights the leveled cost of electricity discharge for various storage technologies. Battery systems are currently the most expensive for large-scale storage, but future cost reductions are expected to improve competitiveness. Hydrogen storage remains costly due to its low volumetric density and the infrastructure required to contain it safely. Ammonia, while cheaper to store than hydrogen, requires careful handling due to its toxicity. However, its higher volumetric density makes it a viable alternative for ships needing substantial onboard energy storage.

Hydrogen's high energy density makes it suitable for long-range vessels, while methanol offers a more practical storage solution at lower costs. With its balance of volumetric density and zero-carbon combustion, Ammonia holds potential for large-scale adoption, though handling and storage remain challenges. Lithium-ion batteries, although well-established, are currently best suited for short-range maritime applications due to the lower energy density and higher costs. This comparative analysis provides a solid foundation for evaluating the technical and economic feasibility of different energy carriers in pursuing sustainable, zero-emission vessels.

4.4.1. Safety Alternative Fuels

Using alternative fuels and battery systems in maritime applications introduces various safety challenges related to health risks, flammability, reactivity, and storage. Understanding these risks is critical for ensuring safe ship operations and protecting crew and the environment. The following sections evaluate the safety profiles of different fuel types and battery technologies, focusing on the health impacts, flammability, reactivity with materials, and safe storage practices onboard vessels. This analysis is essential for selecting and implementing suitable energy sources for zero-emission shipping.

Health Concerning Safety

Health issues can arise from fuel leaks or improper handling. This study focuses on the effects of exposure to various substances on humans and the environment. Such exposure can occur through inhalation of gases at specific concentrations or direct skin contact with the substance. Figure 4.6 presents a table and graphs outlining the safety risk levels of alternative fuels; batteries are not included in this Figure.

Substance	Health	Flammability	Reactivity
Ammonia	3	1	0
Hydrogen	0	4	0
Gasoline	1	3	0
LPG	1	4	0
Natural Gas	1	4	0
Methanol	1	3	0

0=No hazard, 4=Severe hazards

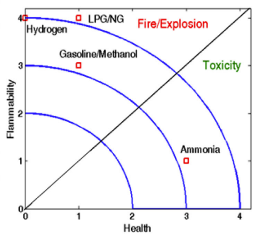


Figure 4.6: Health, Flammability, Reactivity per fuel type [152]

Battery systems, particularly lithium-ion batteries, are dangerous because of exposure to harmful chemicals during leaks or fires. Hazardous chemicals like lithium and electrolytes can escape in the event of battery damage or improper handling, leading to potential inhalation or skin contact risks. Lithium-ion batteries, while non-toxic in regular use, can emit toxic gases such as hydrogen fluoride when exposed to extreme temperatures. This can pose serious health risks in confined spaces such as ships [11].
ammonia is considered the most hazardous fuel for health due to its high toxicity. Even at low air concentrations, serious health issues can occur, with levels above 300 ppm that occur and are dangerous. European regulations set an 8-hour Time-Weighted Average (TWA) of 20 ppm and a Short-Term Exposure Limit (STEL) of 50 ppm [117], which are relatively low compared to methanol, which has a TWA of 200 ppm [118] and no specific STEL established.

Methanol, a liquid at atmospheric pressure and room temperature, poses risks through skin or eye contact or ingestion. Ingesting 20 ml of methanol can be fatal, and smaller amounts may cause blindness [42]. Environmentally, ammonia can affect biodiversity through acidification and eutrophication, though

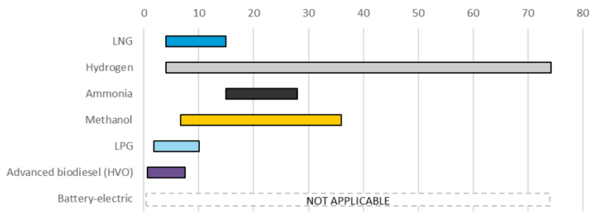


Figure 4.7: Flammability limits for different fuels [volume % in air]. A wide range indicates a fuel that is flammable under several conditions [3]

only with significant emissions [40]. Methanol, being biodegradable, has a limited environmental impact, with minimal risk of groundwater contamination [70].

Hydrogen is non-toxic, and inhaling small amounts of hydrogen gas poses no health risks. However, high concentrations can displace oxygen and cause asphyxiation. Similarly, natural gas (about 9% methane) is non-toxic but can act as an asphyxiate at high concentrations, with a TWA of 1000 ppm [169].

4.4.2. Flammability and Toxicity Alternative Fuels

The flammability and potential for thermal runaway in lithium-ion batteries are widely discussed in safety analyses of battery systems for marine applications. Specialized firefighting techniques and risks associated with toxic smoke from burning batteries are outlined in maritime safety regulations and battery industry standards [88].

The flammability of a fuel refers to how easily it ignites, the intensity of its combustion, the heat released, the spread of fire, and the production of smoke and toxic gases during combustion [90]. Ammonia has the lowest flammability risk among alternative fuels due to its slow reaction characteristics, requiring 2-3 times more energy to ignite than hydrocarbons, and its low laminar burning velocity [40]. Its narrow flammability range makes it less volatile than methanol or hydrogen, though ammonia vapor is flammable and can explode upon ignition.

Methanol is highly flammable with a non-luminous flame, producing no smoke when burning [70]. This makes methanol fires harder to detect but offers health advantages (no smoke inhalation) and better visibility for rescue operations. Methanol's flammability is similar to diesel [96], but fires can be easily extinguished with water due to its solubility [79].

Hydrogen has the most comprehensive flammability range, making it prone to ignition at various concentrations. While sensitive to detonations, it has a high auto-ignition temperature, making spontaneous combustion difficult without an external source. Overall, hydrogen is the most flammable and hazardous of alternative fuels [103].

Reactivity Alternative Fuels

Reactivity in batteries relates to how they respond to overcharging, physical impact, or extreme temperatures. Lithium-ion batteries are particularly reactive under these conditions, as they can generate significant amounts of heat, leading to what is known as thermal runaway[98]. In this state, the electrolyte within the battery can decompose, releasing flammable gases and triggering combustion. Additionally, contact with certain metals can induce reactions that further accelerate battery degradation or failure.

Reactivity refers to how fuels interact with materials in systems like pipelines and storage tanks. This report examines the materials aboard ships that may react with each alternative fuel. Pure ammonia is corrosive to brass, copper, and zinc alloys but has minimal effects on standard steels, with stainless steel being the best option [152].

Methanol is corrosive to certain alloys, rubbers, resins, and plastics due to its electrical conductivity. Aluminum and titanium alloys should be avoided, and stress corrosion cracking (SCC) in weld zones is a concern [105].

Hydrogen can cause metal embrittlement, particularly in steel, due to hydrogen atom diffusion, known as hydrogen embrittlement [103]. It also reacts with lithium, chlorine, iodine, and barium.

Safe Storage

Safe storage of batteries is crucial for maritime applications, given the confined nature of ship environments. Battery systems should be stored in well-ventilated compartments to prevent the accumulation of flammable gases. Proper temperature regulation is essential, as excessively high and low temperatures can degrade battery performance and safety. Implementing stringent monitoring systems that track battery temperatures, charge levels, and potential faults is critical to mitigate risks such as overheating and thermal runaway [93]. Batteries are typically stored in specialized battery rooms that may be located below decks, depending on the ventilation and cooling systems required to manage heat and safety [94]. The design should account for fire safety and ventilation needs, but placement below the deck is feasible if proper precautions are taken.

Methanol is a flammable liquid that presents specific safety risks in storage. A flash point of 11°C requires careful temperature control to prevent fire hazards. Methanol is toxic, and leaks can result in inhalation risks or skin contact hazards [105]. It is also prone to corrosion, so storage tanks must be made of resistant materials such as stainless steel. Adequate ventilation is essential to prevent the buildup of methanol vapors in enclosed spaces [79]. Methanol is typically stored in stainless steel or coated mild steel tanks and can be placed below decks, but due to flammability, it is preferred to store it above decks [94].

Hydrogen is highly volatile and poses serious safety challenges during storage. Its wide flammability range (4-75%) and low ignition energy make it highly susceptible to ignition [103]. Hydrogen is often stored as compressed gas or a cryogenic liquid at temperatures below -253°C [169]. Given hydrogen's small molecular size, leaks are difficult to detect and can accumulate in poorly ventilated areas, increasing explosion risks. Hydrogen is often stored above the deck to ensure adequate ventilation and reduce explosion risk. Storing hydrogen below decks is generally avoided unless extensive safety measures, such as ventilation and gas detection, are implemented [94].

Ammonia is a highly toxic gas that becomes liquid under pressure or at low temperatures, requiring specialized storage systems. Although it has a relatively low flammability compared to other fuels, ammonia can still form explosive mixtures in the right conditions (16-25% in air) [40]. Storage vessels must be made from materials like stainless steel to resist corrosion, and systems must include continuous monitoring for leaks due to ammonia's toxic nature. Ventilation and containment are critical to preventing hazardous exposures. Ammonia is stored either under pressure or in refrigerated tanks, with secondary containment measures such as pressure release systems or drip trays. Regulations require systems for leak detection, and venting [94], making above-deck placement preferable in current designs.

4.5. Concluding Remark Fuel-utilisation Comparison

This section's comparative analysis of alternative fuels underscores the complexity of selecting an optimal energy source for the IRV in alignment with the PoR sustainability goals. Each fuel option presents distinct advantages and challenges regarding energy density, storage requirements, safety, and environmental impact. While hydrogen offers superior gravimetric energy density and potential for zero emissions, its storage constraints, particularly in high-pressure or cryogenic forms, pose significant design challenges for maritime applications. Methanol, on the other hand, provides a more balanced solution with manageable storage demands and a higher volumetric energy density than batteries, though it still necessitates safety considerations due to toxicity and flammability.

Battery-electric systems stand out for the simplicity and high efficiency in short-range, low-power applications. However, the low energy density makes them unsuitable for extended operations without frequent recharging or swapping, which limits the viability for longer-duration missions. Ammonia also emerges as a promising alternative, offering a stable liquid fuel with moderate energy density and low flammability. Nonetheless, the infrastructure required for its use remains underdeveloped, and its toxicity necessitates strict handling protocols.

The transition to Chapter 5 builds on these insights by exploring how each fuel option aligns with the IRV's energy requirements and operational profile by going to to model building part. Part II, Model Building, will delve into a more detailed analysis of the specific energy modules and storage configurations necessary to integrate these fuels into a modular vessel design. This next step is important for balancing the IRV's energy demands with the spatial, safety, and logistical constraints identified in Chapter 9, ultimately guiding the selection of the most viable fuel systems for a sustainable and adaptable IRV concept.

Part II

Model Building

5
Concept of Operations for Model Building

This chapter establishes the fundamental objectives, methods, and the model developed in this thesis for designing a modular, zero-emission IRV for the Port of Rotterdam. Including the approach to develop an operational and sustainable new vessel type for the port that is 24/7 available, capable of fast charging and adaptability to future fuel technologies. The chapter guides the model building process to align with the port's zero-emission target and fleet renewal, and establishes a structured approach for vessel design done in this thesis.

5.1. Purpose and Overview

This Concept of Operations (ConOps) chapter provides an overview of the design approach for developing a zero-emission, modular IRV to support the Port of Rotterdam's fleet renewal goals. To do this, a model was created that fits the Concept of Operations and is set out in a roadmap here in this chapter. This roadmap clarifies the systematic approach used in this model building process and ensures that every design decision is aligned with the assignment.

Before engaging in model building, a literature review was conducted in Chapter 2, 3 and 4 to examine:

1. **Ship Design Methods:** Exploring traditional and advanced methods of ship design to identify the approach most suitable for the unique demands of modular and emission-free vessels.
2. **Modular Design Methods:** Investigating various modular construction techniques to ensure the design could support future adaptability and facilitate flexible fleet renewal.
3. **Alternative Energy Carriers:** Analyzing potential zero-emission energy carriers in the shipping industry, including hydrogen, methanol, and electric solutions, that could enable PoR's sustainability goals.

This literature study provided the fundamental knowledge needed to meet the requirements of PoR for a fleet that can be modular as well as standardized and how to design an optimized layout ship for a fleet. It also allows the identification of methods and systems that are most suitable for creating adaptable vessels and hereby delimits the research to the use of Modular Ship Design, MFD method and the alternative fuels: electric, hydrogen and methanol.

5.2. Goal of Model Building

The primary goal of the Port Model Building Section is to design an ESSD shipbuilding method to assist in the decision making of fleet renewal. It is a large complex interconnected problem and therefore insights provide future possibilities. A modular design method is tested on this type of ships, which has not been done before and concepts are developed with the output. This model building approach focuses on the following objectives:

- **Achieving Emission Reductions**: In line with PoR's sustainability targets of a 75% CO_2 reduction by 2025 and a 90% reduction by 2030, the IRV must incorporate zero-emission energy sources and design principles. The fleet will be operating at zero emissions by 2035, which marks an ambitious milestone compared to the rest of the world.
- **Modular and Future-Proof Design**: Addressing PoR's concern about "regret" in selecting a single energy technology, the IRV will feature a modular framework that allows for flexibility in fuel choice and research of modularity systems. This adaptable design provides the capability to integrate alternative fuels or new energy modules as they become feasible, mitigating the risk of technological obsolescence. The modular design methodology also covers all tasks of the vessel or vessels.
- **High Operational Uptime**: Given that PoR's fleet operates on a 24/7 schedule for tasks including management, inspection, and emergency response, the IRV must be able to recharge onboard within 15 minutes. This requirement influences both the energy module configuration and the operational layout, ensuring the vessel maintains uptime without compromising on functionality. The layout and standardization of the vessels enhances operations and management.

The significance of this research and of developing this model lies in its ability to accommodate the entire fleet, encompassing diverse functionalities and operational tasks through various technical and solution-oriented approaches. After initial adjustments, the model is expected to provide a robust framework that can be adapted and expanded over time. Currently, it primarily focuses on red ships, but is evolving to incorporate the entire fleet across all task categories and mixed configurations. This approach allows the model to assess the impact of emerging energy carriers on a uniform fleet structure and optimize systems and tasks.

5.3. Methodology and Approach

To achieve these design objectives, this model-building process adopts a structured, multi-step methodology, tailored to address both the operational and sustainability requirements specific to the IRV. The methodology includes:

- **Needs Analysis**: Initial analysis identifies core operational needs and "nice-to-have" features for the IRV. This analysis covers the vessel's core functions, including firefighting and incident response, which PoR has identified as critical to its fleet operations. This was done by analyzing current, new and future systems.
- **Energy Case Study**: A focused energy options analysis evaluates the feasibility of zero-emission fuels such as hydrogen, methanol and battery electric systems. This case study looks at fuel efficiency, storage needs and fuel handling and loading constraints, ensuring that the selected energy source is as aligned as possible to zero-emission sailing, high uptime and fast onboard charging capabilities.
- **Modular Function Deployment (MFD)**: By applying the MFD methodology, all tasks, capabilities and functions are reviewed and systematically evaluated. So that the fleet, or ships, are covering all tasks of the different ship designs. MFD identifies the design process essential modules and key functions, and structures the IRV layout around modular principles that allow flexible upgrades.

The output values of the MFD building blocks, modules, and various clusters, in combination with the energy modules, form the foundation for Concept Development in part III. Based on these model outputs, several sketches of the vessels are created in various configurations.
The IRV design is based on a task-based approach that defines specific vessel functions that match the operational requirements and achieve zero emission sailing. The primary tasks and functional requirements such as firefighting, incident response and inspection tasks are mapped and used. The energy requirements under operational conditions are considered and fuel types and storage configurations will be considered to find the optimal balance between emission reduction, space usage and charging

speed. The entire steps and input values are structured and classified in the MFD method and this provides the building blocks for concept designs. The research and the adoption of a standardized vessel type is essential for streamlining maintenance, operations, and construction processes, underscoring the importance of standardization in achieving these efficiencies.

5.4. Outline of Model Building

This ConOps chapter serves as an essential introduction to the model-building process, establishing clear goals, methodology, and PoR-specific contextual needs. It orients readers to the purpose and design objectives of the IRV model, providing a structured foundation for the modular, zero-emission design choices that follow. Through this approach, each chapter in the model-building section contributes cohesively to the overall mission of a future-proof, sustainable fleet for the Port of Rotterdam.

The model-building section begins with an introduction to the IRVs in Chapter 6, offering an overview of their roles, responsibilities, and operational significance within the PoR fleet. This includes a detailed distinction between different vessel types and their specific functions within the fleet's operations.

In Chapter 7, a reference vessel is presented to provide an example of a comparable ship within the current fleet. Although this vessel is not yet modular or standardized and continues to operate on conventional fuels, it fulfills a substantial portion of the current operational requirements. Understanding these vessels is essential for gaining insights into their functions and the onboard systems they incorporate.

Chapter 8 examines the systems desired by the Port for incorporation into the new vessels. This analysis is based on a comprehensive review of the requirements program for the new ships, drawing partly from the specifications of existing vessels while also considering future needs. Feedback from fleet personnel, who possess extensive experience with the current onboard systems, highlights operational challenges encountered with the existing fleet. Each oversight made during the design phase, even if unnoticed in the development process, will impact the vessel's 30-year operational lifespan, underscoring the critical importance of this requirements program.

The collection of all requirements has been completed, synthesizing diverse inputs to formulate a structured set of requirements. This includes considerations of customer values, essential needs, and desirable features, forming the foundational basis for the input into the MFD model. This framework clarifies design priorities and aids in making trade-offs in critical design decisions.

As a preliminary step in ship design, it is essential to assess the potential future energy needs of the IRV vessels. This assessment provides crucial insights into the impacts of alternative energy sources within the design process. While precise energy consumption forecasts down to the kilowatt-hour are not necessary and not done in this research, it is important to derive reliable estimates that offer a representative indication of the future vessel's requirements.

The model-building section concludes with the MFD model, which integrates all relevant information. Since the output values from this model serve as foundational building blocks for the ship design, specific fuel options are excluded at this stage; instead, they will be introduced as input in Part 3, focused on concept development. The MFD model forms the basis for the import program and is designed to be adaptable and editable for future revisions. In this model, all input data are compiled within an Excel framework, enabling the alignment of operational tasks and requirements with corresponding technical systems and solutions. Following the modeling phase, the various input values are used for concept development, serving as the basis for modularization and visualization of the results, which will be detailed in Part III.

5.5. Concluding Remark

To conclude Chapter 5, this section has outlined the foundational objectives, methodologies, and strategic context essential for the development of a modular, zero-emission IRV for the Port of Rotterdam.

This model, initially designed to gather and utilize input data, can then be employed to establish correlations and organize systems for an optimal layout of the vessels and fleet, supporting the conceptual design phase of this thesis. This systematic and comprehensive approach can be expanded as needed, allowing for adjustments and extensions to the model.

This structured approach, rooted in modularity and adaptability, provides a cohesive framework for the subsequent model-building chapters, offering a foundational structure to which the following chapters can consistently refer. To fully understand the function of an Incident Response Vessel, particularly within the context of the Port of Rotterdam, the necessary information will be introduced and discussed in Chapter 6.

6
Introduction of Incident Response Vessels

This chapter describes the current Incident Response Vessels and the tasks of these vessels, which will are very important for the operation of these ships including the future of the ship design. Chapter 6 consists of 5 sections that all contribute to answering the third sub-question of this investigation:

- *How can the existing design of the Port of Rotterdam's Incident Response Vessels be optimized for modularity and zero-emission technology?*

To develop future-proof, zero-emission vessels, assessing and optimizing existing designs is compelling and essential. This chapter investigates the current layout and systems of the Port of Rotterdam's Incident Response Vessels, focusing on how the current systems can be introduced to support new designs with new technologies. By systematically deconstructing the existing designs, this chapter aims to identify areas for improvement that will reduce emissions and enhance operational flexibility, efficiency, and operation ability.

6.1. Current Fleet PoR

The PoR, therefore, has a major responsibility in the energy transition. In the case of incidents and patrols, the PoR also includes the Rotterdam Port Authority. The port of Rotterdam has 16 different vessels from its fleet under its management. To gain a clearer understanding of these various vessels of the Port of Rotterdam and the operational profiles, these vessels can be divided into two types of ships: Blue and Red subsequently referred to as Blue ships and Red ships in this thesis. The Asset Management department manages the fleet, referred to as AM Fleet. The AM Fleet manages vessels for various departments of the PoR, and the vessels are specifically designed and built for specific tasks.

The Blue ships are primarily intended for enforcement tasks and do not have firefighting equipment like the Red ships. Smaller in size and not designed for offshore operations, they mainly operate in coastal or inland waters. There is a preference to build offshore and non-offshore Blue ship identically because these ships perform the same tasks but operate in different waters.

The Red ships are designed for incident response tasks, such as combating fires at sea or other emergencies. Equipped with special equipment such as fire suppression systems, fire monitors, and a substantial amount of extinguishing agents, these ships are larger to accommodate this equipment and are suitable for offshore operations.

Essentially, the Red ships is primarily focused on incident response in the port. In contrast, the Blue ships are designed for enforcement tasks in coastal and inland waters. Additionally, two PoR fleet vessels focus on surveying the port's seabed. The final vessel in the fleet is the *Nieuwe Maze*, which serves as the official representation ship of the port. Moving forward, the primary focus will be on the Red and Blue vessels, as these vessels are the core operational fleet, all the ships of the current fleet are made visible in Appendix A.

6.2. Overview Tasks of the Vessels

The Port of Rotterdam Authority operates a diverse fleet of vessels, each designated for specific tasks within the port. The tasks of the vessels are categorized into three primary groups based on the assigned functions, represented by the colors Red, Blue, and Green. Each category corresponds to distinct operational roles and responsibilities. Table 6.1 outlines the key differences between these vessel types and the respective functions, providing a foundational overview of the current fleet and for the design and development of a new incident response vessel.

Table 6.1: Primary Tasks and Specific Functions of Ships Based on Color

Task Color	Primary Tasks	Specific Functions
Red	Incident response and assistance	Incident response and assistance, source control of fire and emissions, containment of water pollution
Blue	Detection, enforcement, and sanctioning	Detection and enforcement, sanctioning, supervision, and registration
Green	Support and logistical tasks	Assistance and search & rescue, information point for port users, logistical and representative tasks, medical assistance

It is important to note that "green" tasks are performed by all vessels. Blue and Red vessels carry out green tasks as part of the operations. However, Red and Blue vessels are distinguished by specialized roles: Red vessels are equipped for firefighting with extinguishers and water cannons, whereas Blue vessels are not. Figure 6.1 illustrates the interaction between green tasks and the Red and Blue vessels, highlighting that task overlap occurs vertically between task categories rather than horizontally between Red and Blue vessels.

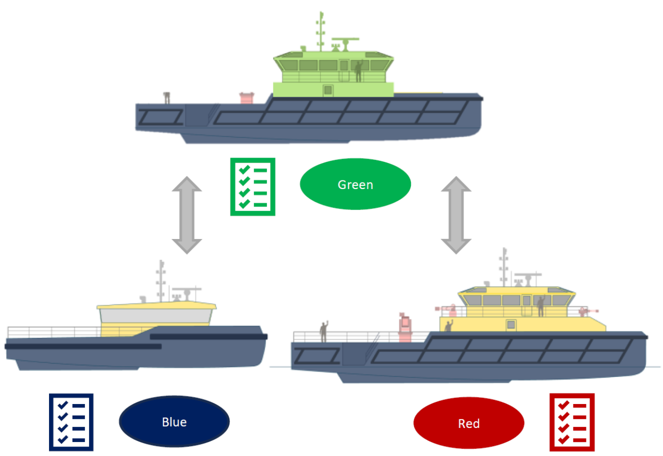


Figure 6.1: Green tasks and Blue and Red ships - Current state. *Created by the author*

6.3. Color-Coded Task Framework for PoR Fleet Operations

Red ships are primarily focused on incident management and emergency response. The primary function of rapid response vessels is to be the first to arrive at an incident site and provide assistance with firefighting and emergency response operations. The tasks include incident management and emergency response, source control of fires and emissions, and containment of water pollution. These ships are equipped to respond quickly to emergencies, such as fires and emissions of hazardous substances. The different assets have advanced firefighting systems, including pumps, fire cannons, and foam systems. These ships can effectively contain and clean up water pollution using oil booms.

Blue ships focus on detection, enforcement, and sanctioning. The tasks include detection and enforcement, sanctioning, and surveillance and registration. These ships conduct patrols and ensure the enforcement of port rules and regulations. The Blue Ships have the authority to record violations and impose sanctions. Blue ships are equipped with surveillance, registration, and enforcement systems, including smaller cranes and cells for temporary detention.

Green tasks are within the operational package executed by the red and blue ships. The green tasks fulfill a wide range of support and logistic tasks. Specifically, the responsibilities include assisting and conducting search and rescue operations, serving as an information point for port users, and handling logistical and representative duties. Additionally, the ships are responsible for offering traffic instructions, transporting materials and personnel, and participating in events and promotional activities. Furthermore, ships assigned to green tasks are equipped with medical equipment, including automated external defibrillators (AEDs), offering limited medical assistance and stabilizing individuals in emergencies.

The red, blue, and green vessels operating within the Port of Rotterdam are each assigned distinct tasks and equipped with specialized systems tailored to the primary functions. A comprehensive understanding of these functional differences is essential for designing a new incident response vessel capable of effectively addressing the diverse needs and challenges encountered within the port. Figure 6.2 illustrates the distribution of red and blue vessels across the designated red, blue, and green task categories. Figure 6.2 highlights the specific vessels assigned to each task and the corresponding operational areas. It becomes evident that both vessel types share responsibilities for the green tasks. In contrast, the red and blue tasks are exclusive to the respective vessel categories, with no overlap in these specialized functions.

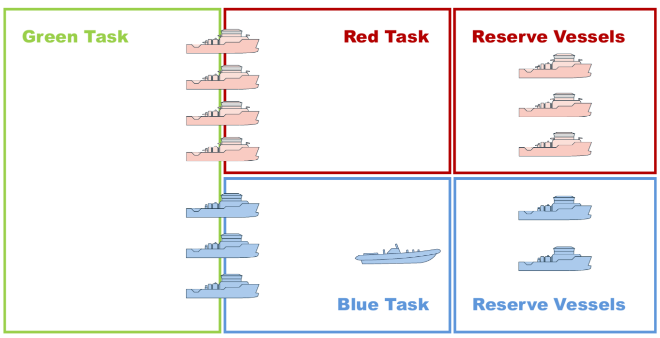


Figure 6.2: Fleet composition in 2024. *Created by the author*

6.4. Operational Area

The Port of Rotterdam's vessels utilize three designated berthing areas, which are critical for docking operations and must be considered preconditions in the new fleet's conceptual design. Due to the limited availability of berthing spots, constrained by long-term contracts, adding new docking locations is not feasible. The dimensions and specific variables of these three existing berths: *Eemhaven*, *De Madroelhaven*, and *Pistoolhaven* are essential factors, as vessels operate from these locations and serve different areas within the port. Figure 6.3 illustrates the geographical positioning of these berthing areas.

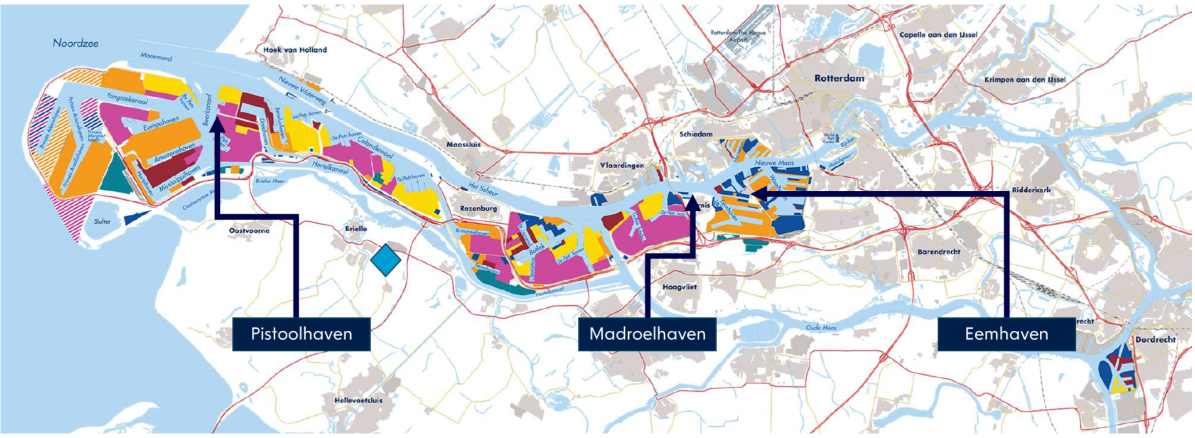


Figure 6.3: The three main berthing and mooring locations for the operational vessels of the Port of Rotterdam. *Created by the author*

With the three key berthing locations now identified for vessel operations within the port, it is essential to define the corresponding operational areas. The Port of Rotterdam spans approximately 50 kilometers in total width [32]. The central maintenance and outage facility is located at *Eemhaven*, while the primary operational sites are at *Pistoolhaven* and *Madroelhaven*. The port's jurisdiction is divided into two main zones: the *Europoort* zone, where the Western Fleet is stationed, and the city zone, where the Eastern Fleet operates from *Madroelhaven*, see Figure 6.4. Although *Dordrecht* is technically a separate zone, it is serviced by a stationed vessel RPA01, with the local fire department managing firefighting operations. *Dordrecht* will not be taken into account for this research. Each main zone consistently deploys two Red vessels and at least one Blue vessel, depending on shift rotations.

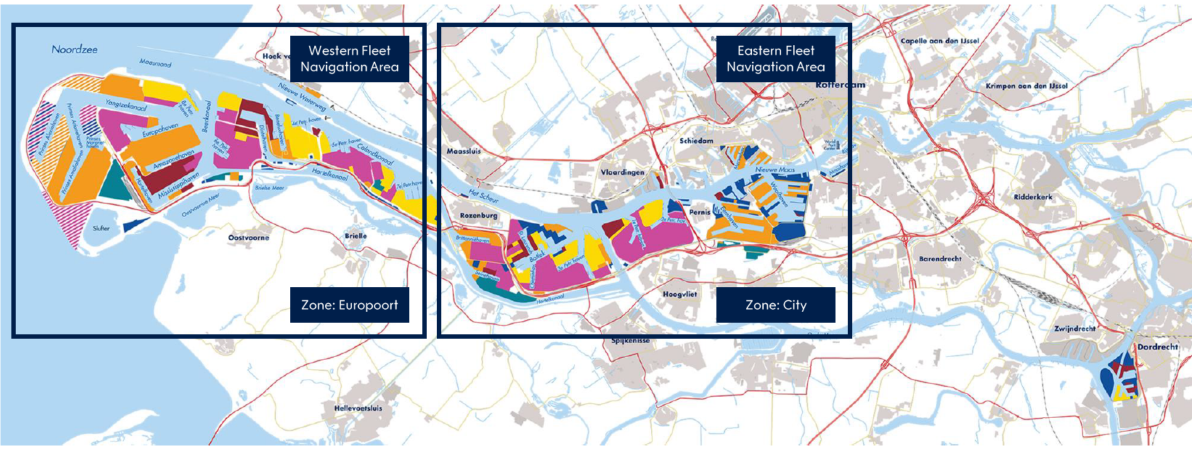


Figure 6.4: Zone *Europoort* and Zone City. *Created by the author*

The division of operational zones is based on a combination of factors determined through decision-making processes by the PoR and the DHMR in recent years. Although this arrangement may present certain limitations in the future, the current zoning structure remains fixed. The allocation of personnel across these zones is also relatively stable. The Western and Eastern Fleets are each equipped with at least two Red vessels to ensure they meet the required capacity to deliver 90 cubic meters of water per minute during emergencies. This capacity has been established through a formal agreement between the PoR, DHMR, and the regional safety authority and is not subject to change now.

As illustrated in Figure 6.5, the Western Fleet is capable of delivering up to 110 cubic meters of water per minute from *Pistoolhaven*, with the RPA15 contributing 65 cubic meters per minute and the

RPA16 delivering 45 cubic meters per minute. The Eastern Fleet operates with the RPA10 and RPA11, providing 45 cubic meters per minute. Additionally, reserve vessels RPA12 and RPA13, stationed at *Eemhaven*, each deliver 45 cubic meters per minute, while the RPA14 provides 65 cubic meters per minute. Although there is some rotation between the vessels stationed at *Eemhaven* and those assigned to the Western and Eastern Fleets, maintaining the capacity of 110 cubic meters per minute for the Western Fleet remains a priority.

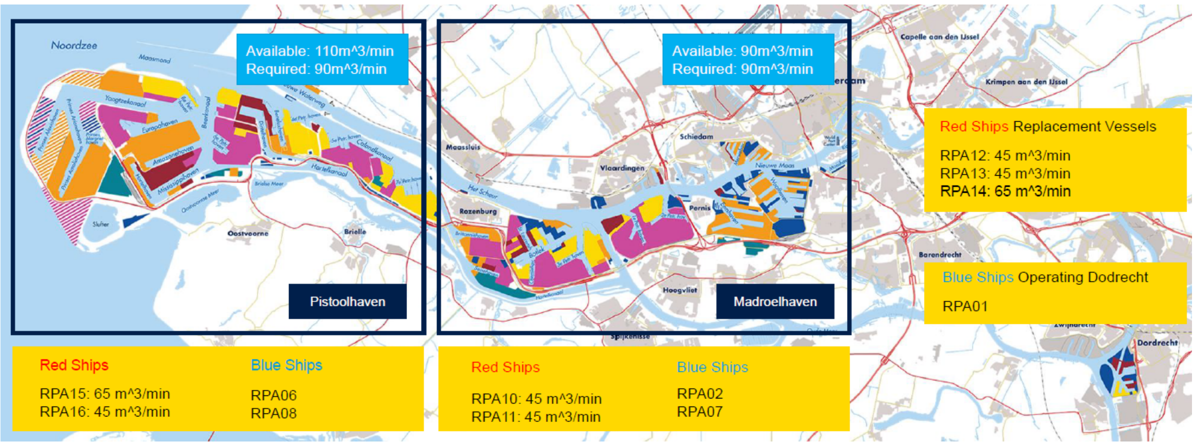


Figure 6.5: Amount of water needed in Western and Eastern Area's of the PoR. *Created by the author*

6.5. Concluding Remark

Based on the analysis, it becomes evident that Red vessels have a more clearly defined and active role, primarily focused on incident response. In contrast, Blue vessels are dedicated to patrol, enforcement, and sanctioning tasks. The Red vessels, stationed across various ports, must meet stringent requirements, including the ability to deliver a minimum water capacity of 90 cubic meters per minute during emergencies. Given the complexity of the operational functions, red vessels offer a compelling starting point for applying ESSD to explore standardized and modular shipbuilding. By successfully designing a standardized Red incident response vessel, which is the more complex of the two, it becomes feasible to adapt the design for the less complex Blue patrol vessels. This justifies prioritizing the Red vessel as the foundational model for the fleet's conceptual design. The primary tasks of the red vessels are:

1. **Incident Response and Assistance**: Red vessels are the primary responders to emergencies within the port, including firefighting, environmental hazard control, and emergency assistance.
2. **Source Control of Fires and Emissions**: These vessels have fire suppression systems, including pumps, water cannons, and foam, to control and extinguish fires. The ships also handle the containment of hazardous emissions.
3. **Containment of Water Pollution**: Red vessels deploy oil booms and other pollution control equipment to contain and clean up water contamination incidents, safeguarding the port's environmental integrity.
4. **Firefighting Systems Operation**: Advanced firefighting systems onboard allow for high-capacity water and foam deployment, ensuring effective response in various emergency scenarios.
5. **Emergency Water Supply**: Red vessels need to deliver up to 90 cubic meters of water per minute per zone, essential for effective firefighting due to concessions.

As the thesis transitions into Chapter 7, the focus shifts to an in-depth examination of a Reference Ship within the existing fleet, providing a benchmark for future IRV designs. This chapter will analyze the current vessel's technical specifications, system requirements, and operational capabilities, identifying elements to inform the new modular, zero-emission framework. Through this exploration, critical insights will be gained into the strengths and limitations of the existing design. This evaluation lays a solid foundation for adapting and enhancing vessel design to meet future operational and environmental standards.

7
Reference Vessel

This chapter analyzes the existing vessel RPA12 within the Port of Rotterdam's fleet, examining its technical specifications, operational role, and system requirements. This chapter provides a detailed assessment of the vessel's capabilities and limitations, focusing on its equipment and onboard systems. By deconstructing the RPA12, the chapter identifies elements that could be adapted or improved in the design of future IRVs to meet evolving operational and environmental standards. The insights gained from this analysis form a benchmark for new vessel designs, ensuring that the updated fleet addresses current needs. This chapter presents the results, the final work can be found in Appendix C where the diagrams are shown.

7.1. Current Red Vessel: RPA12

The operational roles of red ships are well-established, and they play a critical role in port management. The primary functions include rapid response, firefighting, oil spill mitigation, emergency rescue operations, and towing. These vessels are equipped with specialized technologies and are designed for high maneuverability, durability, and fast response times to effectively carry out the tasks within the port environment.

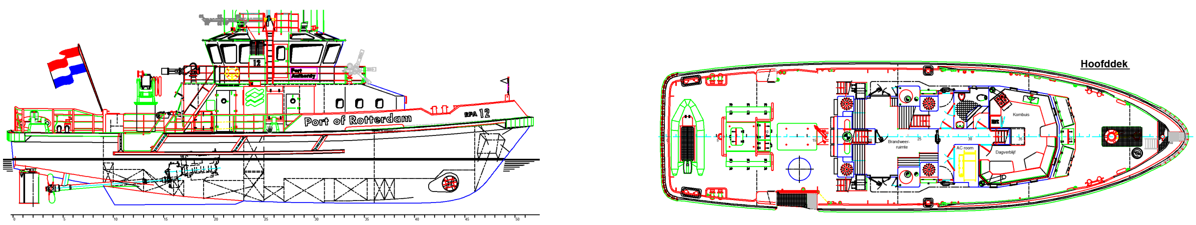
In the context of fleet renewal and the conceptual design of new ships, it is essential to conduct a thorough analysis of the equipment and systems currently installed on board the existing vessels. This analysis helps determine which elements should be retained, discarded, or incorporated into the next generation of red ships. To facilitate this evaluation, the current ships are systematically deconstructed, and the equipment cataloged. Data for this analysis was provided by the Asset Management division of the Port of Rotterdam (AM of PoR).

The vessel under examination is the RPA12, constructed in 1985 and scheduled for replacement starting from 2026. The RPA 10, RPA12, RPA13 and RPA 16, which are part of the same series, are also in operation. These vessels were designed to perform a comprehensive range of tasks and have been optimized to meet the operational demands of the port up to the present day. Figure 7.1 shows the layout's side view and top view.

Table 7.1 presents the key specifications of the current vessel, including its length, width, draft, and displacement, based on data sourced from the Port of Rotterdam's (PoR) database. A minimum crew of three is required to operate and perform its designated tasks. The specifications of the current vessel have been systematically deconstructed, categorized, and analyzed to obtain a comprehensive understanding of the onboard systems.

7.2. Analysis of Requirements on Board of Current Fleet

The PoR has a system in which all function descriptions are listed and described. This is done using codes and subgroups. All ships' components are named so the maintenance can be tracked. The



(a) Sideview Layout **(b)** Topview Layout

Figure 7.1: RPA12 Layout Sketch Damen [26]

Table 7.1: Ship Information RPA12 (Source: PoR)

Feature	Value
Name	RPA 12
Length overall (LOA)	28.82 m
Beam (B)	8.22 m
Depth (D)	3.8 m
Draft (T)	2.55 m
Displacement	372.728 m³
Number of engines	2
Total thrust power	970 kW
Main propellers	2
Bow anchors	1
Number of towing hooks	1

Feature	Value
Rudders	2
Freeboard	127 cm
Year built	1985
Indicative replacement year	2026-2035
Number in service	2
Delta max	372.728 m³
Range	ca. 800 nmi
Crew	Min 3 Persons
Power plant concept	Currently diesel
Number of shafts	2
Bow thrusters	1

function place structure provides all data on board the ships and how the systems are classified. In total, 2419 function places have been identified for all 16 fleet ships. The PoR maintains a database and spreadsheet where this data is stored; however, it has not previously been aggregated, filtered, or visualized. This research was undertaken to provide a clear overview of the 164 different function positions aboard a Red ship RPA12, offering insights into the various systems present on the vessel.

In the Thesis, only Incident Response Vessels (red ships) are considered, specifically the RPA12. Upon examination of the RPA12, 164 function positions remain to be identified. These existing function places must be filtered and classified. In this way, it can be seen how the current systems fit into the new model and concept ship. The codes and naming have been drawn up by the port authority and are adopted. Systematically deconstructing the different systems on board makes it clear which systems there are, which is done in this thesis for the first time. Basic information is listed in Table 7.1.

7.2.1. Primary System Groups

The research conducted to analyse all the current systems on board of the reference ship, is listed in appendix C, the ship's systems are categorized into the following primary groups: hull structure (RPA 12 Casco), electrical installation, auxiliary and accessory equipment, hydraulic installation, incident response systems, navigation and communication systems, propulsion system, and exhaust gas after-treatment installation. A visual representation has been generated for each system, illustrating the system's components down to sub-level and sub-sub-level parts. These representations are provided in the following figures. The primary system groups, as output from the research, are made visible in Figure 7.2.

7.2.2. Concluding Remark from the System Deconstruction

In Appendix C Table C.1 provides a comprehensive overview of the essential systems and the components for conceptualizing an incident response vessel for the Port of Rotterdam. Based on an analysis of current vessels, specifically the RPA 12, the table outlines the fundamental systems to be incorpo-

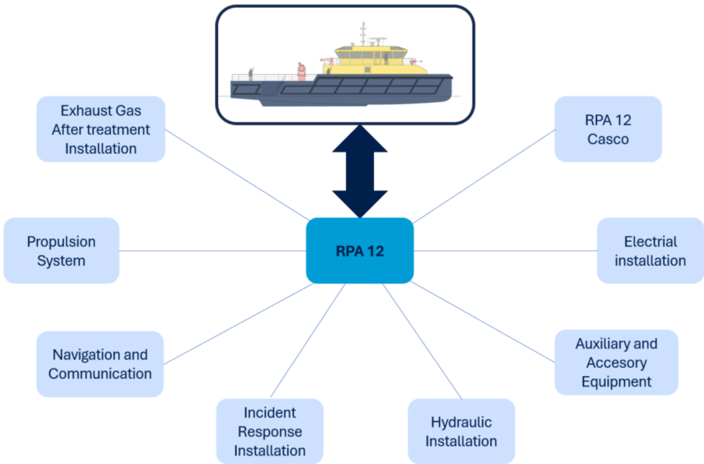


Figure 7.2: Function Descriptions with sub-systems. *Created by the author*

rated into the future model. The analysis identified which systems can serve as technical solutions for the new ship design to perform the same tasks as the current ships. Given the emission-free operation assumption, all diesel and conventional fuel systems have been excluded from this design. So here, nine building blocks with sub-blocks were selected for the new design from the function descriptions of the current ships and are made visible in Figure 7.3.

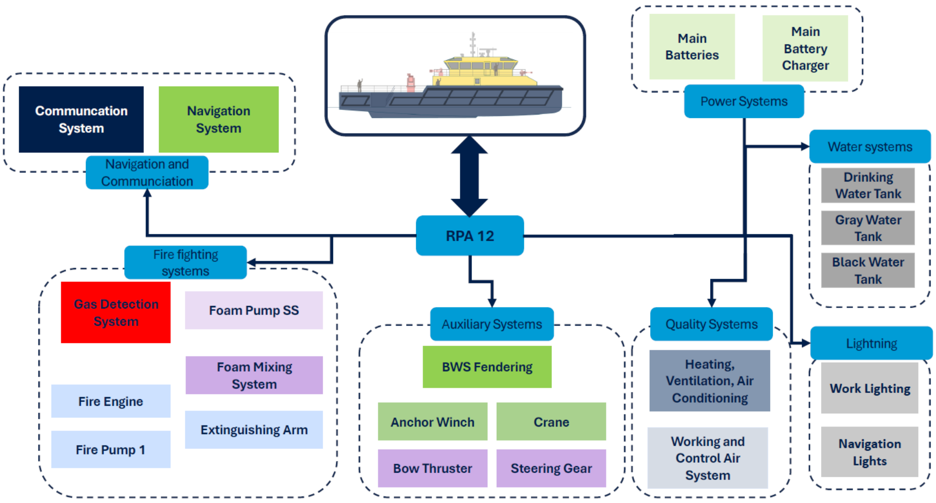


Figure 7.3: Function Descriptions: selected for concept design. *Created by the author*

7.3. System Analysis for Program of Requirements

In addition to stripping down the systems of the current fleet, a team of stakeholders within the Port also drew up a program of requirements. This was used to analyze the configurations and requirements for the next generation of ships. The analysis categorizes findings into three main areas: requirements, functional, and system breakdowns, each important for aligning design with operational needs. The key findings visualized in breakdowns were visualized, with detailed diagrams provided in Appendix C in Section C.3 where the Requirements, Functional, and System Breakdown are given.

7.4. Concluding Remark

By systematically deconstructing the main systems (propulsion, energy storage, emergency response and navigation), a modular framework has been created to improve system independence and interoperability. Having considered the peel-off of current vessels, the future requirements program has now been considered. This analysis informs the application of MFD principles in the following chapters, ensuring that the IRV design meets both functional and emission reduction goals while remaining adaptable for future upgrades. The systems considered in the remainder of this research are listed in Appendix C Table 7.1. The table provides a clear framework for identifying which existing systems can be adapted as technical solutions to meet the operational requirements of the new vessel.

In addition to the deconstruction of systems, the program of requirements has been addressed, with breakdowns created to compile data on all systems, functions, and requirements for the new vessels. This approach ensures that the transition to an emission-free model does not compromise vessel functionality, allowing the future design to perform the same tasks effectively.

In this chapter, the current systems have been deconstructed, and the program of requirements has been analyzed to collectively establish a revised list of requirements based on both existing and desired future systems. These findings will provide new inputs and be incorporated into the subsequent sections of this thesis.

A wide range of information has been gathered and analyzed. To derive input values for the MFD model, all data must be integrated and evaluated to determine its relevance for the system. This process is conducted in Chapter 8, where all the various components are assembled, and critical elements are selected for inclusion in the ESSD.

8
Integrated Design Requirements

This chapter synthesizes the essential requirements and optional features for the design of the new IRV, balancing core functional needs identified in Chapter 7 alongside findings from research and interviews. Additionally, this chapter presents the results of the requirements analysis, which serve as primary inputs for the MFD model, and details the methodology used to establish these requirements. Through this structured approach, design requirements are reprioritized, and the trade-offs made throughout the process are clarified. These results subsequently provide foundational input for the MFD model in the following chapter.

8.1. Design Influences and Input for MFD

Chapter 6 provides an initial overview of the IRV vessels, detailing the distinction between the tasks assigned to the Blue and Red ships and discussing overarching tasks (Green tasks). Operational agreements within this domain are examined, from which core task categories are derived.

In Chapter 7, two critical inputs for the MFD system are presented. First, a deconstruction of the existing systems aboard a reference IRV ship is conducted. This process distinguishes obsolete systems from essential, enduring systems required for current task execution, categorizing them into systems and subsystems to create a comprehensive view of the onboard architecture. Second, in Section 7.3, the program of requirements is systematically reviewed and organized to provide a clear overview of the needs of crew members and stakeholders. All systems are mapped out in the breakdowns in Appendix C, covering new systems, ineffective systems from the current fleet that are slated for removal, and additional systems necessary for task performance. This construction and analysis process enables an assessment of each system's functionality and relevance.

Additionally, interviews with stakeholders and research conducted during the thesis have contributed to a deeper understanding of the vessel systems and task execution requirements. A significant portion of the tasks reflect concessions made with safety regions or are grounded in guiding principles rather than stringent agreements. Interviews with crew members highlight customer values and ”nice-to-have” features, rather than strict requirements or technical specifications.

8.2. Defining Core Requirements from Inputs

To clarify the varying opinions, needs, and preferences, the most critical components for inclusion in the ESSD were identified. Considering all stakeholder inputs, the essential requirements for the MFD model were established. These requirements, along with the associated capabilities and functions, serve as the central inputs for the MFD model. The process of deriving these functions and solutions from customer values is illustrated in Figure 8.1, based on the framework from [141].

In order to find these requirements and capabilities including functions, the pyramid in 8.1 shows how to get there [141] by translating from customer values to functions and solutions.

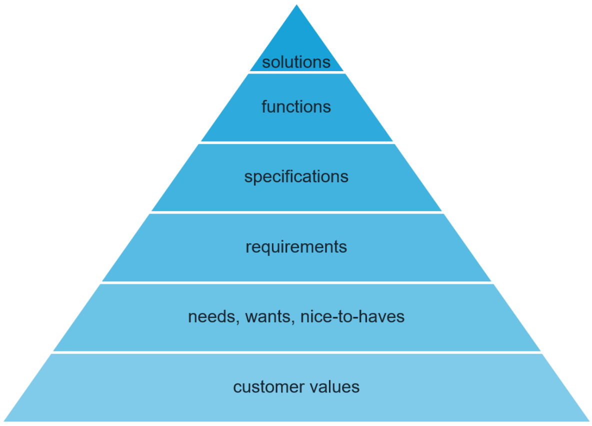


Figure 8.1: Pyramid: from customer values to solutions (Source: Modular5 Slide Deck) & information: [141]

Table 8.1: Customer Values and Development Breakdown

Category	Description
Customer Values	Our customers' core values and priorities underpin the MFD model. These values are critical for understanding customer priorities and are the cornerstone for all subsequent development steps [156].
Needs, Wants, Nice-to-Haves	Customer preferences are categorized by importance, aiding in prioritizing essential features and functions. This categorization is achieved through three breakdowns: the requirement breakdown, the functional breakdown, and the system breakdown.
Requirements	Derived from customer needs and desires, these essential criteria form the basis for further specifications, ensuring the final product aligns with customer expectations [22].
Specifications	Specifications provide detailed descriptions of the requirements, including technical details, offering a clear and actionable plan for the development team to achieve the desired functionality.
Functions	Functions describe the actions or operations the product must perform to meet the specifications, ensuring the product delivers the intended performance.
Solutions	Solutions represent the final design and implementation, encompassing the technical solutions and capabilities required to perform the functions and meet the specifications [141].

The inputs, represented in the pyramid of Figure 8.1, must converge to generate solutions. In this research model, requirements, functions, and capabilities are derived from the available data to encompass all aspects of the concept design [140]. All stakeholder inputs are considered to ensure a comprehensive approach and effectively utilize the MFD model for solution development. The specific stakeholder inputs, or "voices," will be discussed in the following section.

After this section, all input values have been systematically analyzed and documented. These values are based on comprehensive data from the PoR, incorporating insights from the current fleet, crew feedback, port interests, the Program of Requirements, existing systems, and future applications. These requirements have informed the definition of the model's capabilities and functions. To ensure completeness, the relationships and connections between the requirements will be strictly verified and refined. The requirements are presented in Table 8.2 and Table 8.3, with the corresponding input values for the MFD model, capabilities in Table 10.2, and functions in Table 10.3.

8.3. Integrated Requirements:

In this research, all input values were thoroughly analyzed to derive the requirements included in the study. From these requirements, the capabilities and functions serving as inputs for the MFD model were established and based on the inputs from Chapters 6, 7, and Appendix C. The specific capabilities i_n and functions j_n provided as inputs to the MFD model are detailed in Tables 8.2 and 8.3, with corresponding input values, capabilities i_n listed in Table 10.2, and functions j_n outlined in Table 10.3.

Table 8.2: Requirements part 1: New Incident Response Vessel

Nr.	Requirement Component	Requirement Statement
1	Dimensions and Hull Specifications	
1.1	Length	The vessels can not exceed the maximum length of 35 meters.
1.2	Beam (Width)	The vessel can not exceed the maximum beam of 10 meters.
1.3	Draft	The vessel can not exceed the maximum draft of 2.20 meters.
1.4	Air Draft (Crawl height)	The vessel can not exceed the maximum air draft of 9.10 meters if the mast is down.
1.5	Stability	The operators shall be able to secure stability and buoyancy. Sailing and when moored.
1.6	Icebreaking Capabilities	The vessel must be designed to accommodate icebreaking capabilities, requiring specific structural and capacity adjustments to withstand ice conditions.
2	Performance Requirements	
2.1	Speed	The vessel must achieve a maximum 31 km/h (16.75 knots).
2.2	Range	The vessel must be capable of continuous operation for one 8 hour shift without refueling and maintain operational readiness for a minimum of 8 hours at 100% fuel capacity.
2.3	Maneuverability	The vessel must have excellent maneuverability in forward and reverse, with bow thruster power independent of propulsion power and a dynamic positioning system to maintain position with minimal deviation.
2.4	Positioning	The vessel must have a dynamic positioning system for maintaining its position automatically.
2.5	Wind force limitations	The vessel must have no wind force limitations for sea operations and must be operational up to unlimited Bft from all directions.
2.6	Sea state operation	The vessel must be capable of operating in sea states up to Bft 5 and a wave height of approximately 1.5 meters.
2.7	Shallow water	The vessel must be able to sail in water depths of approximately four times its draft.
3	Power and Propulsion	
3.1	Main Propulsion System	The vessel must have a net zero emissions propulsion system.
3.2	Auxiliary Power Systems	The vessel must have a UPS for critical systems with a minimum capacity of 500 kWh.
3.3	Shore Power Capability	The vessel must be capable of connecting to shore power.
3.4	Synchronization	The vessel must have automatic synchronization between generators and shore power.
3.5	Emergency power supply	The vessel must have an emergency power generation system to ensure continuous operation during power failures.
3.6	Interchangeability	The vessel must have modular payload handling capabilities to adapt to different mission requirements quickly.
3.7	Propulsion type	The vessel must be a twin-screw ship with proven functionality.
3.8	Propellers	The propellers must be able to be disengaged.
3.9	Rudders	The vessel must have spade rudders.
3.10	Bow thruster	The bow thruster must rotate 360 degrees and not protrude below the flat plane, ensuring the vessel can remain stationary under wind and current conditions with a working fire cannon, within the desired norm of half the ship's length.

Table 8.3: Requirements part 2: New Incident Response Vessel

Nr.	Requirement Component	Requirement Statement
4	Safety and Incident Response Systems	
4.1	Firefighting Equipment	The vessel must have two large fire pumps (45 m^3/min at 12 bar), one small fire pump (2 m^3/min at 8 bar), and multiple monitors (4 small, 1 large, 1 on firefighting arm).
4.2	Pollution Control	The vessel must have oil booms for water pollution containment.
4.3	Search and Rescue	The vessel must have a rescue boarding platform (drenkelingen instap) at the rear or side.
4.4	Surveying	The operators shall be able to survey the port.
4.5	Storage	The vessel must be able to store firefighting equipment, with a floor area of approximately 10 m^2, ensuring efficient use of the available height.
4.6	Foam system	The vessel must have a foam-forming system with a storage capacity of 9000 liters of foam. That must be able to deliver foam at full capacity (5,000 l/min) with a mixing ratio of 3%, requiring a foam supply for at least 20 minutes, resulting in a necessary storage capacity of 3,000 liters.
4.7	Powder system	The vessel should be equipped with a movable powder extinguisher of 50 kg.
4.8	Safety for operators	It must have safety showers and eye wash stations for handling hazardous materials.
5	Navigation and Communication Systems	
5.1	Navigation	The vessel must have an integrated bridge system with single or two-man operation capability and CCTV for deck and engine room monitoring.
5.2	Communication	The vessel must have a public address system integrated with a loud hailer, suitable communication equipment (C2000 and VHF), and internet connectivity for real-time video streaming and video calls.
6	Environmental Monitoring and Control	
6.1	Sensors	The vessel must be equipped with an e-nose for detecting hazardous substances.
6.2	Climate Control	The vessel must have an HVAC system to maintain ambient conditions within specified limits (cooling to 22ºC in extreme weather) and HEPA filters for recirculating air.
	Deck and Cargo Handling	
7.1	Cranes	The vessel must have a deck crane with a minimum reach of 18 meters and a lifting capacity of 1.5 tons.
7.2	Fendering and Bolding	The vessel must have comprehensive fendering around it and bolders designed to handle maximum tug forces.
7.3	Work Deck	The vessel must have a clear aft work deck of at least 9 meters in length.
8	HVAC and Sanitary Systems	
8.1	HVAC	The vessel must have heating and ventilation systems for all accommodation and operational areas, including proportional noise control and climate management in technical spaces.
8.2	Sanitary Systems	The vessel must have heating and ventilation systems for all accommodation and operational areas, including proportional noise control and climate management in technical spaces.
9	Crew Support and Accommodation	
9.1	Accommodation	The vessel must accommodate a minimum crew of 3 and a maximum of 5, with a day room for 9 people and multifunctional spaces including a pantry and meeting area.
9.2	Health and Safety	The vessel must have safety showers and eye wash stations for handling hazardous materials.
9.3	Drinking and Eating	The operators shall be able to drink and eat.
10	Maintenance and Upgradeability	
10.1	Routine Maintenance	The vessel must have a spacious engine room for maintenance activities.
10.2	Material Use	The vessel must use durable materials such as RVS 316 for moving parts.
10.3	Modularity	The vessel must be able to adapt to future technology changes by being able to switch modules in an easy way.
11	Regulatory Compliance and Certification	
11.1	Compliance	The vessel must meet all relevant maritime regulations and safety standards (SOLAS, MARPOL, ADN proof).
11.2	Certification	The vessel must be certified for inland navigation under the Dutch flag, including Green Award certification.

8.4. Concluding Remark

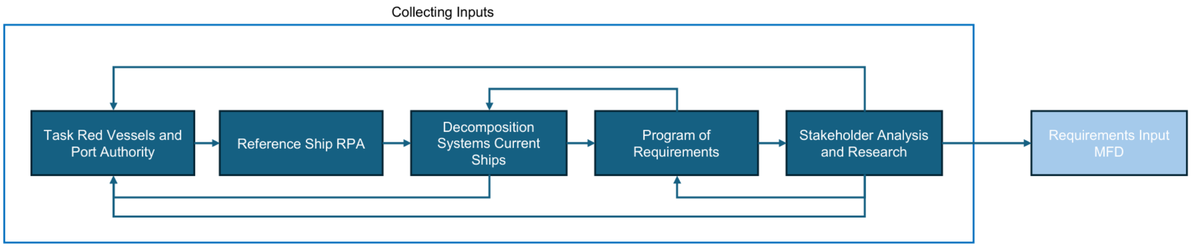


Figure 8.2: Integrated Design Requirements. *Created by the author*

This thesis systematically examines the systems required on board a vessel in conjunction with its operational tasks. Task allocations and vessel classifications are reviewed within the operational domain, considering the applicable requirements. In addition to task analysis, a reference ship was examined to identify existing onboard systems, which are derived from operational needs. This includes a detailed breakdown as well as an analysis of the program of requirements set by PoR. Through stakeholder analysis and interviews, along with feedback loops on findings and investigations, the requirements for the MFD model were ultimately established.The feedback process involved continuous evaluation to identify the most critical systems onboard the vessel, determining which are used most frequently and hold the highest priority. This evaluation was conducted in collaboration with stakeholders from the fleet renewal program to ensure the most accurate and relevant requirements input for the MFD model.

Figure 8.2 illustrates the feedback loop utilized in research and information gathering. Appendix C provide detailed breakdowns and information, covering the range from task-specific analyses to onboard systems and the breakdown analysis of the program of requirements.

A balanced approach was taken to address customer values, needs, wants, ”nice-to-haves,” and core requirements, thereby progressing towards defined specifications, functions, and solutions. This chapter provides the foundational requirements, as outlined in Table 8.2 and Table 8.3, for the development of the MFD model.

The transition to Chapter 9 is closely linked to the foundational elements of this research. Within the MFD model, the system requirements and components necessary to perform each function have now been defined and analyzed. Another critical element is the choice of fuel. Emission-free fuels, with the exception of methanol, present different properties, often being heavier, more voluminous, or less efficient than diesel. Consequently, additional space will be required to accommodate these fuels to meet operational demands. Based on the literature in Chapter 4, foundational components and energy modules are developed and incorporated into the conceptual designs to optimize system integration within the MFD framework, ultimately achieving the most effective design solutions.

9

Energy Analysis and Input

This chapter's energy analysis is based on current ships' sailing profiles and maritime institutions' estimates. Chapter 9 consists of 7 sections that all contribute to answering the fourth sub-question of this research:

- *What is the energy demand profile of the IRV fleet, and how can alternative energy modules meet these demands while ensuring operational efficiency in the future?*

Understanding the energy demand of the Incident Response Vessels is key to integrating the appropriate zero-emission energy systems. This chapter delves into the energy profiles of the IRV fleet, evaluating the operational patterns and power consumption. It will then explore how alternative energy modules, such as battery systems, can be configured to meet these energy demands. The goal is to find solutions that ensure operational efficiency and sustainability without compromising the vessels' capabilities.

9.1. Sailing Profile and Energy Demand Analysis

In July 2022, Kroes Marine investigated the energy analysis and sailing profiles of the Red ships and Blue ships in the Port of Rotterdam fleet [85]. This data forms a guidance in this research, supplemented where necessary. Although energy requirements for the new vessels are not yet defined, data from the existing fleet provides a reliable foundation. It is important to note that this data pertains to older vessels and will be adjusted for new design requirements.

A sailing profile details how a vessel operates at various speeds, including rest, cruising, and maximum speeds. For red and blue vessels, patrol speed, slower than cruising speed, is also critical. The sailing profile directly influences the fuel requirements. Ship speed is often expressed in knots or by the Froude number, a dimensionless quantity used to assess hydrodynamic performance relative to waterline length.

9.1.1. Sailing Profile of Red Vessels

Research has been done in Kroes' study [85] and here is the overview of the functional requirements and sailing profile of the red vessel, including a new section that analyzes energy consumption per shift.

Table 9.1 presents the distribution of sailing profiles for a 200-ton, 35-meter red ship. This vessel is substantial in size, so any additional resources used are advantageous to have onboard. The identified components represent the bare minimum required for an 8-hour operation, despite the vessel's 35-meter length and 200-ton weight. If the vessel were smaller, the need for resupply would be reduced, or the model could be calibrated to allow additional space for systems. The ship spends 20% of its time moored, 60% patrolling, 15% cruising, and 5% at maximum speed. Based on this distribution, propulsion power requirements per day were calculated, resulting in 5480.4 kWh, with auxiliary power estimated at 1003.2 kWh. This brings the total daily energy consumption to 6483.6 kWh.

Table 9.2 presents the power consumption for each sailing profile: Moored, Patrolling, Cruising, and Fast Sailing, covering both the ship's systems and propulsion needs. These values are used in the auxiliary calculations outlined in Table 9.1. The estimates assume continuous operation, 24 hours a day, seven days a week. At a maximum speed of approximately 31 km/h, the total daily energy requirement is 6483.6 kWh, equivalent to 23.34 GJ.

Table 9.1: Usage Profile and Power of a 200 ton Red Vessel: data Kroes Marine [85]

Vessel	v [km/h]	Use/ 24h [%]	P [kW]	P/ day [kWh]	Fn [-]	Aux. [kW]	P/day [kWh]
Moored	0	20				33	158.4
Patrol	15	60	150	2160	0.22	44	633.6
Cruise	22	15	477	1717.2	0.33	44	158.4
Max	31	5	1336	1603.2	0.46	44	52.8
Total/24h			**Prop.**	5480.4		**Aux.** P	1003.2

Table 9.2: Power Consumption of Vessel Systems: data Kroes Marine [85]

Consumer	Moored	Patrolling	Cruising	Fast Sailing
Auxiliary propulsion systems (10 kW)	0.50	2.00	2.00	2.00
Steering and maneuvering (9 kW)	0.00	4.50	4.50	4.50
Fuel and lube oil system (5 kW)	0.75	1.25	1.25	1.25
Firefighting and bilge system (6 kW)	0.30	0.60	0.60	0.60
Ventilation (HVAC) heating (40 kW)	28.00	32.00	32.00	32.00
Navigation/lighting (5 kW)	3.75	3.75	3.75	3.75
Anchoring / mooring (120 kW)	0.00	0.00	0.00	0.00
Total [kW]	33.30	44.10	44.10	44.10

9.1.2. Estimation: Willem Toet

The Kroes report estimated the red ships' power requirement to be $6483.6kWh$ over 24 hours. Table 9.2 provides an estimate for the auxiliary power systems, though it does not represent the total potential energy profile needed for future operations. The PoR aims to transition to fully electric systems in the future, including components like cranes, which are currently hydraulic. Since all onboard systems will be electric, this research has developed its estimate for the energy required for fully electric operations. The analysis considers the ship operating in 3 shifts of 8 hours, ensuring 24-hour availability. Although 8 hours represents one-third of a day, the energy storage capacity is calculated for two-thirds of the daily requirement to future-proof the design, amounting to $4322.4kWh$ per 8-hour shift. The results are presented in Table 9.3. The energy capacity is doubled, allowing for rare but potential use in cases where new system types or backup measures are required. This redundancy addresses potential tank malfunctions or charging system failures, ensuring the ability to maintain 24/7 operational capability.

Table 9.3: New Energy Consumption per Shift

Parameter	Value	Unit
Shift Duration	8.0	hours
Power per Shift	4322.4	kWh
Energy Requirement per Shift	15.56	GJ

9.1.3. Estimations: Marin and Norled

To validate the power estimate developed in this research, the data is compared with estimates from two external sources. The Maritime Research Institute Netherlands (MARIN) [99] analyzed the RPA08, while Norled [114], a Norwegian shipping company involved in maritime electrification, also performed an energy analysis for Port of Rotterdam vessels. This Section compares these external estimates with the self-generated values to assess accuracy by converting the energy and distributing it uniformly across an 8-hour shift.

Table 9.4: Energy and Range Calculations for Various Ships

Calculations	Usable energy [kWh]	Range [h]	Information sailing	Ship information
Norled [114]	2353	3.9	90% slowsteam @15 to 20 km/h	Based on similar ship type
Kroes [85]	6483.6	24.0	Detailed sailing profile	Based on RPA red vessel
Marin [99]	960	8.5	Detailed sailing profile	Based on RPA8 (ca. 150 tons less)
Willem Toet	4322.4	8.0	Estimation	Based on similar ship type

Marin

MARIN conducted an analysis of the RPA08, a blue vessel approximately 150 tons lighter than a red vessel. A sailing profile estimate was made, showing that the vessel primarily operates under sailing conditions. For an 8.5-hour shift, the estimated usable energy requirement is 960 kWh. Adjusting for an 8-hour shift, MARIN estimates the energy requirement to be 903.5 kWh.

Norled

Norled analyzed a similar red vessel that slow-steams for 90% of the time at speeds between 15 and 20 km/h. The focus was on a swappable battery with a capacity of 3920 kWh, providing 2353 kWh of usable energy. Under slow-steaming conditions, this vessel achieves a range of 3.9 hours. When the energy requirement is normalized to an 8-hour shift, the total energy consumption amounts to 4826.7 KWh.

Comparision Energy Consumptions

Table 9.5 presents the various energy consumption estimates for an 8-hour sailing period. Norled's estimate reflects the highest energy requirement, while MARIN's is the lowest, which aligns with MARIN's analysis, which is based on a smaller vessel with fewer systems. To establish a reference point, the average of the estimates was calculated, resulting in an average energy consumption of 3053.5 kWh, as shown in Table 9.5.

Table 9.5: Energy Consumption per Method

Method	Energy Consumption (kWh)	Range [h]
Norled	4826.7	8.0
Willem Toet	4322.4	8.0
Kroes	2161.2	8.0
Marin	903.5	8.0
Average	*3053.4*	*8.0*

The power estimations from Table B are visualized in Figure 9.2, along with the average line. The green areas represent values above the average, while the red areas indicate values below it. Additionally, the percentage deviations from the average for each estimation method have been calculated and are presented in Figure 9.2. Norled's estimate exceeds the average by 58.1%, while Willem Toet's is 41.5% above. In contrast, MARIN falls significantly below the average at -70.4%, and Kroes is also below the average at -29.2%.

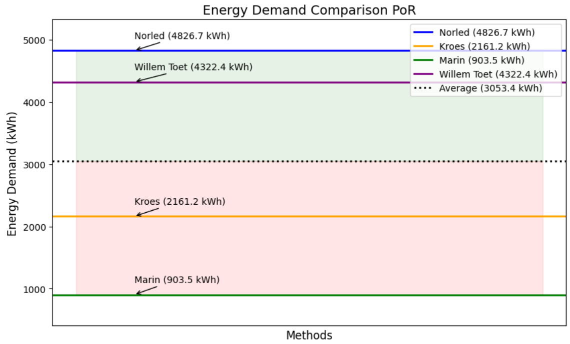


Figure 9.1: First comparison energy calculation Willem Toet versus other sources from literature review. *Created by the author*

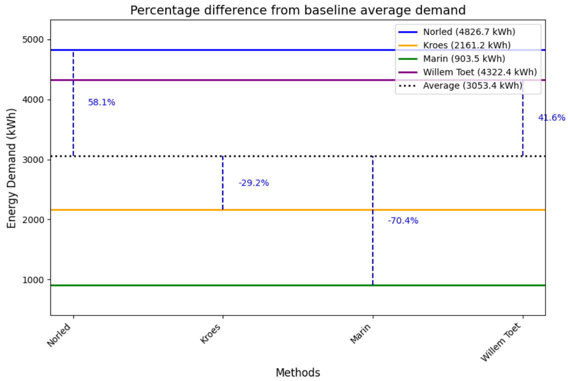


Figure 9.2: Second comparison energy calculation Willem Toet versus other sources from literature review. *Created by the author*

9.1.4. Concluding Remark Energy Analysis

The energy requirement estimate of 4322.4 kWh, calculated for an 8-hour operational shift, establishes a practical baseline for this study's energy consumption analysis. This figure was validated by comparison with other Kroes, MARIN, and Norled estimates. Ensures a realistic evaluation. This value serves as a representative figure for this study. The estimate focuses solely on required energy, while the subsequent Section will account for factors such as efficiencies, battery storage, and other rates.

This estimate provides a foundation for integrating zero-emission energy systems, particularly focusing on energy storage and delivery efficiencies. While this Section primarily addresses raw energy demand, the next steps in the research will expand on this by incorporating considerations for system efficiencies, storage capacity, and potential energy losses during operations. By doing so, the study will offer a more detailed perspective on the technical and logistical challenges of implementing zero-emission solutions within the operational constraints and sustainability objectives of the Port of Rotterdam's fleet renewal goals.

9.2. Comparing Different Marine Fuels

After estimating the energy required for an 8-hour shift, the next step is to assess which energy carriers are most suitable as fuel. Given the limited space on the new vessel designs, fuel density—measured in kg m^{-3} becomes a critical factor. This metric indicates how much mass occupies a given volume. To calculate the space needed to store the required 4322.4 kWh of energy, the three potential fuel types: Methanol, Hydrogen, and Batteries, from the literature study (see Chapter 4) are compared. These is Methanol, Hydrogen, and Battery. Additionally, to relate the density of a fuel to the power that can be extracted from it, the energy density of the fuel should be considered:

- Gravimetric energy density (MJ kg^{-1})
- Volumetric energy density (MJ L^{-1})

9.2.1. Gravimetric and Volumetric Densities of Fuels

The gravimetric and volumetric energy densities are presented in Table 9.6 and Table 9.7, based on data from DNV's Alternative Marine Fuels report [3]. In the tables, 'Gravi' refers to Gravimetric energy density, and 'Vol.' to Volumetric.

Table 9.6: Energy Density and Density of Various Energy Carriers (Part 1) DNV Marine fuels [3]

Type Energy-carrier	Grav. E ρ [MJ/kg]	Vol. E ρ [MJ/l]	Grav. E ρ (lower value) [MJ/kg]
Diesel	45.6	37.8	42.6
Methanol	23	18.2	19.9
Hydrogen (350 bar)	141.7	3	120
Hydrogen (500 bar)	141.7	4.4	120
Hydrogen (700 bar)	141.7	6	120
Hydrogen (-252)	141.7	10.1	120
Ammonia (10 bar / -30°C)	22.5	13.5	18.9
HV100	40.5	37.3	37.8
Bio-LNG (-162°C)	53	24.7	48
Bio-CNG (200 bar)	53	9.5	48
Mierenzuur (hydrazine)	6.2	7.6	5.3
Lithium polymeer NMC	0.8	1.9	0.5

Table 9.7: Energy Density and Density of Various Energy Carriers (Part 2) DNV Marine fuels [3]

Type Energy-carrier	Vol. ρ (lower value) [MJ/l]	Density ρ [kg/m³]
Diesel	35.4	830
Methanol	15.8	792
Hydrogen (350 bar)	2.5	21
Hydrogen (500 bar)	3.7	31
Hydrogen (700 bar)	5	42
Hydrogen (-252)	8.5	71
Ammonia (10 bar / -30°C)	11.3	600
HV100	34.8	880
Bio-LNG (-162°C)	22.4	466
Bio-CNG (200 bar)	8.6	180
Mierenzuur (hydrazine)	6.5	1220
Lithium polymeer NMC	1.7	-

Power is typically measured in kilowatts and energy in kWh. The energy content can be converted from MJ to kWh using the conversion factor 1 kWh $= 3.6$ MJ.

9.2.2. Comparison of Fuel Types

In Section 9.2, an analysis was conducted to compare methanol, hydrogen (at 350 bar), and lithium batteries by calculating the fuel volume required to generate 1 kWh of power. This analysis focuses solely on fuel volume, excluding the additional equipment needed for energy conversion. Table 9.10 and Figure 9.3 indicate that batteries require the most significant volume, while Figure 9.4 shows that batteries also have the highest mass per kWh of energy. Table 9.10 further provides the required onboard volume (in liters) for each fuel to store 1 kWh, accounting for conversion efficiencies of the storage methods. Methanol and hydrogen are closer regarding volume and mass requirements, with methanol exhibiting the highest energy density and requiring the least volume per kWh, while hydrogen has a lower mass.

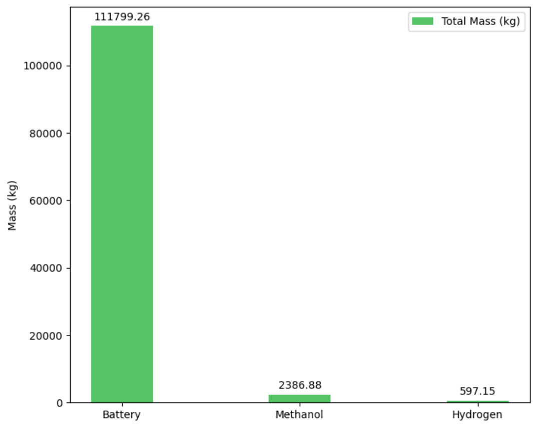


Figure 9.3: Comparison volume: Methanol, Hydrogen (350 bar), Lithium battery. *Created by the author*

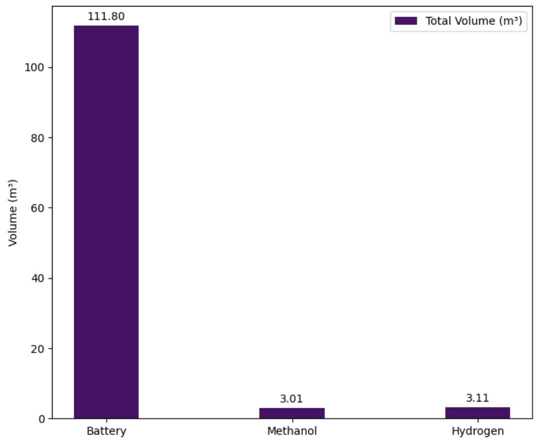


Figure 9.4: Comparison mass: Methanol, Hydrogen (350 bar), Lithium battery. *Created by the author*

Table 9.8: Summary of Differences Between the Three Types of Fuels

Metric	Battery	Methanol	Hydrogen
Energy Density (Wh/L)	125	1516.67	416.67
Conversion Efficiency	90% [168]	30% [116]	50% [29]
Volume for 1 kWh (L)	**8**	**0.66**	**2.4**
Total Mass (kg)	High	Medium	Low
Total Volume (m³)	High	Low	Low

9.3. Power Sources and Energy Modules

The new vessels will require energy to power all onboard systems, including propulsion, auxiliary functions, and equipment such as cranes. The PoR aims to explore the possibility of integrating an energy supply system akin to a "nerve system" throughout the ship. This approach would enhance flexibility for future fuel innovations. The concept involves an energy container, which can either be a detachable or fixed module connected to the ship's electrical system, providing power to all onboard systems. The fuel, stored either in the energy container or a fixed module, would be converted into electricity through onboard energy storage. As illustrated in Figure 9.5, the energy is distributed via a converter to the propulsion and auxiliary systems. This modular design allows for future adaptability, enabling the replacement of onboard energy storage systems while maintaining vessel operations.

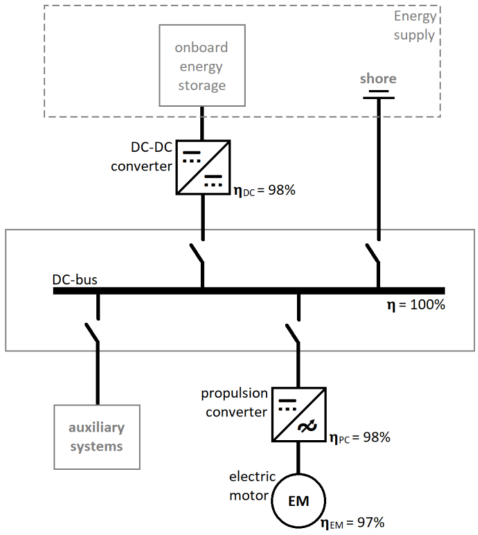


Figure 9.5: Line diagram of the electric propulsion system, including the efficiencies in different components [2]

The rationale for this approach is twofold: it offers future flexibility while maximizing efficiency. An electrical distribution system throughout the vessel is highly efficient and represents the simplest method for distributing energy onboard. Maintaining energy in its electrical form minimizes conversion losses, as each additional conversion, such as through hydrogen, methanol, or fuel cells, introduces further inefficiencies and energy loss. Therefore, a fully electric distribution system is preferred.

The overall efficiency of the electric drive system can be expressed as [2]:

$$\eta_{\text{Total Electric Drive}} = \eta_{\text{Motor}} \times \eta_{\text{Converter}} \times \eta_{\text{DC-DC}} = 97\% \times 98\% \times 95\% = 93\% \tag{9.1}$$

Include an extra energy transfer in the form of hydrogen to the system; the efficiency of the electric drive system will be lower. The overall efficiency of the electric drive system, now including the fuel cell and hydrogen efficiency, can be expressed as:

$$\eta_{\text{Total Hydrogen}} = \eta_{\text{Total Electric Drive}} \times \eta_{\text{Fuel Cell}} \times \eta_{\text{Hydrogen}} \tag{9.2}$$

When integrating a new fuel system for the IRV, it is crucial to manage energy capacities efficiently. As discussed in Section 9.2.2, the volume requirements for alternative fuels are increasing, making space a critical factor in the design. Maximizing efficiency is essential to conserve space. With the concept of energy modules established, we can now examine the application in the different case studies.

9.4. Case study: Energy Modules for Concept Design

Chapter 4 presents a literature review on alternative fuel options for the new IRVs. Three potential fuels, electric, methanol, and hydrogen, were identified as viable options for the Port of Rotterdam. A decision was made after evaluating various energy carriers and the applicability to IRV operations. Four refueling methods were considered, with electric options further divided into an integrated battery system requiring charging and a battery-swapping system. These options are listed below and explained in detail:

1. **Fully Integrated Battery**
2. **Battery Swapping System**
3. **Methanol Energy Module**
4. **Hydrogen Energy Module**

The selection of these four systems, batteries and fuel cells for methanol and hydrogen, reflects the status as the most viable energy carriers currently available. While not entirely emission-free, methanol is included as a comparator [85]. As e-methanol production becomes more sustainable and available at scale, it could emerge as a reliable and promising fuel option [105]. HVO100 or other diesel alternatives were excluded from this comparison, as diesel will no longer be a viable option in the future, rendering it an unnecessary and unrealistic reference.

9.5. Development Energy Modules

In Section 9.1.4, the total energy requirement for the red ships was determined to be 4322.4 kWh for an 8-hour shift. This Section will calculate the dimensions and mass of the energy modules necessary to meet this demand, specifically the space and mass required to sustain 8 hours of continuous operation. The 8-hour period represents the typical maximum operational time without docking, except in rare cases, such as extended firefighting efforts on a crude oil carrier, which could last up to 48 hours. Docking intervals are typically used for refueling and maintenance. For 24-hour operations, the 8-hour module can be scaled by a factor of three, ensuring adequate energy supply for uninterrupted operations.

Table 9.9 provides a comprehensive overview of the key metrics for each fuel type that are used in order to calculate the energy modules.

Table 9.9: Input Values for estimation Fuel Blocks (All values are based on DNV Alternative Marine Fuel [3]

Parameter	Value	Unit
Battery Energy Density	260	Wh/kg
Battery Efficiency	0.90 [77]	-
Motor Efficiency	0.95 [49]	-
Methanol Energy Density	23	MJ/kg
Methanol Density	0.792	kg/L
Methanol Fuel Cell Efficiency	0.50 [150]	-
Hydrogen Energy Density	141.7	MJ/kg
Hydrogen Tank Capacity (Density for 350 bar)	21	kg
Hydrogen Fuel Cell Efficiency	0.60 [169]	-
Battery Swappable Energy Capacity	3920	kWh
Energy Requirement	4322.4	kWh

9.5.1. Boundary Conditions and Variables in Modules

Data from the DNV Alternative Marine Fuel report [3] is utilized to estimate the performance of shore-charged batteries, methanol fuel (excluding carbon capture), and a hydrogen system at 350 bar, including a swappable battery system.

Battery System

The battery energy density is 260 Wh/kg, directly impacting the required mass and volume. The battery efficiency is 90% [77], indicating a 10% energy loss as heat. The motor efficiency is 95% [49] , with a 5% loss attributed to friction and heat dissipation.

The battery system requires an additional 15% mass and volume [157] to house essential auxiliary systems. These include the Battery Management System (BMS) for regulating charge cycles, cooling systems to prevent overheating, fire suppression and thermal runaway safety measures, and inverters to convert DC to AC power for vessel operations.

Methanol Module

The energy density of methanol is 23 MJ/kg, which is used to determine the necessary fuel mass. The density of methanol is 0.792 kg/L, facilitating the calculation of the required volume. The efficiency of the methanol fuel cell is 50% [150], which influences the quantity of methanol needed for electricity generation.

Methanol fuel systems require a 45% overhead [106] for additional infrastructure, including corrosion-resistant fuel containment, complex delivery systems, and, in some cases, methanol reformers to produce hydrogen for fuel cells. Fuel cells or engines also need fuel injection, cooling, and exhaust systems. Due to methanol's flammability and toxicity, extensive safety measures are required, including containment and leak prevention systems.

Hydrogen Module

Hydrogen has an energy density of 141.7 MJ/kg, which is critical for calculating the fuel mass. The hydrogen tank capacity is 21 kg at 350 bar pressure, which determines the number of tanks required. The efficiency of the hydrogen fuel cell is 60% [169], affecting the amount of hydrogen needed.

Hydrogen systems require significant additional mass and volume of 162% [154] due to the need for high-pressure or cryogenic storage tanks, which must be heavily reinforced. Fuel cells are required to convert hydrogen into electricity, adding complexity. Given hydrogen's flammability and leak risks, robust safety measures are essential, including leak detection, venting, and fire suppression. Overall, the infrastructure is larger and more complex than other fuels, increasing system overhead.

Battery Swapping System

The battery swapping system has a total energy capacity of 3920 kWh, distributed across four battery packs, based on a current Battery Swapping System method. The energy requirement is 4322.4 kWh, which is used to calculate the mass and volume of each fuel type.

Battery Swapping Systems require 20% more mass and volume [127] due to the infrastructure for interchangeability, including battery racks, modular containers, and quick-connect vessel interfaces. Safety systems ensure secure handling and transport during the swap process. These systems improve efficiency by reducing port downtime through rapid battery exchanges.

9.6. Analyse Energy Modules

The energy modules were modeled in a Python script. The script sets constants for energy densities, efficiencies, and capacities for the battery, methanol, hydrogen, and battery swapping systems. Using these inputs, it calculates each energy carrier's required mass and volume, accounting for energy density, fuel cell efficiency (for methanol and hydrogen), and battery efficiency. Additional overhead for auxiliary systems, storage, cooling, and safety is factored into the calculations, assumed by the percentages from Section 9.5. This facilitates a clear comparison of the spatial footprint and performance and is shown in Figure 9.8 and Figure 9.9.

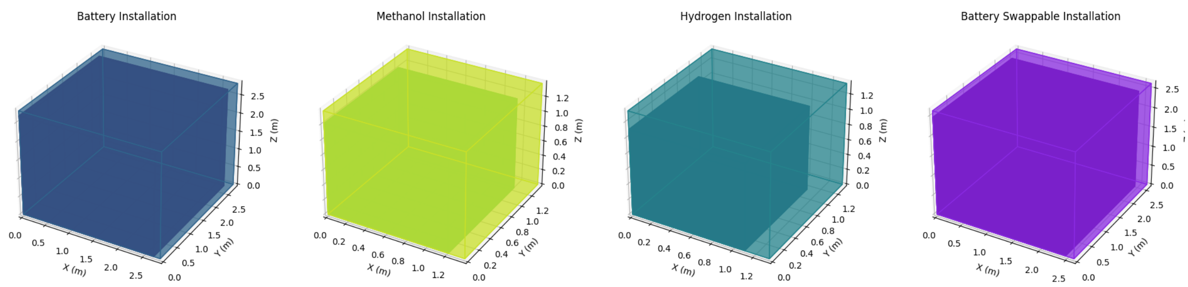


Figure 9.6: Installation space comparison for different energy carriers. *Created by the author*

Centers of mass and side lengths for cubic representations of each fuel system are computed and visualized as 3D wireframe cubes, allowing for a direct comparison of spatial requirements. The dark color per box in Figure 9.6 is the space occupied by the fuel, and the lighter color is the systems. It is assumed that all secondary systems, including storage space, are situated in the light areas. These areas also accommodate fuel cells, peak load batteries, system components, and energy loss management equipment. In Part III of the Concept Development, additional space is allocated in the engine room to allow for the installation of potential supplementary systems if the fuel modules prove insufficient and to address future spatial requirements.

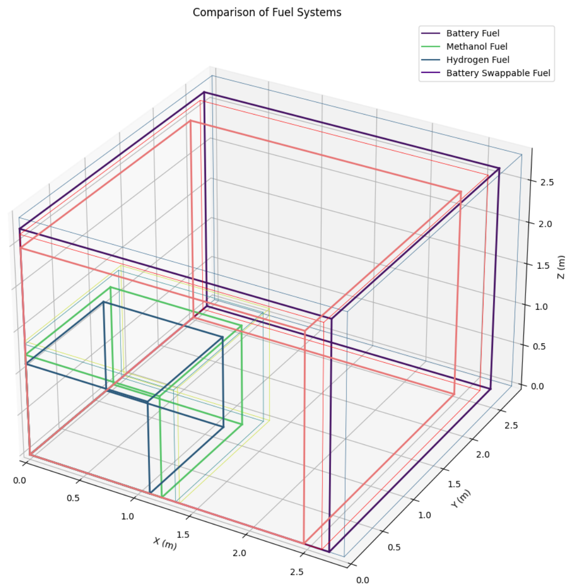


Figure 9.7: Installation space comparison for different energy carriers including dimensions. *Created by the author*

Further analysis includes bar graphs comparing energy densities (kWh/kg) and system efficiencies, integrating fuel cell or battery performance with motor efficiency. Clear labels and legends improve readability.

The battery system exhibits high efficiency but lower energy density, making it appropriate for compact spaces, though less optimal for long-range applications. Methanol, with a higher energy density than batteries, is better suited for extended energy storage but demands more space. Hydrogen, offering the highest energy density, provides superior performance but requires the largest storage volume. Refer to Figure 9.8 for the densities of different fuel types and Figure 9.9 for the overall efficiency and the motor efficiency per different fuel type.

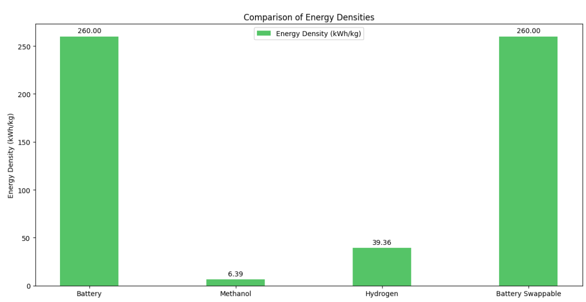


Figure 9.8: Comparison of Energy Densities Fuel Types. *Created by the author*

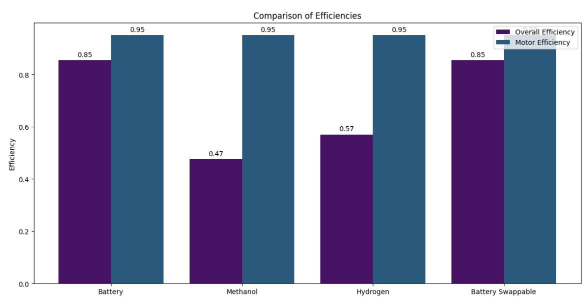


Figure 9.9: Comparison overall efficiency and Motor efficiency per fuel type. *Created by the author*

Figures 9.10 and 9.11 provide further insight into the installation space required for each energy carrier. Figure 9.10 highlights the space and volume requirements of the fuel modules, while Figure 9.11 is crucial for assessing ship stability, as it illustrates the fuel mass and total system mass. The battery system has compact footprint makes it advantageous for space-constrained environments. The methanol system requires more space but offers a balance between storage capacity and energy density. The hydrogen system occupies the most space yet provides the highest energy density for high-power applications.

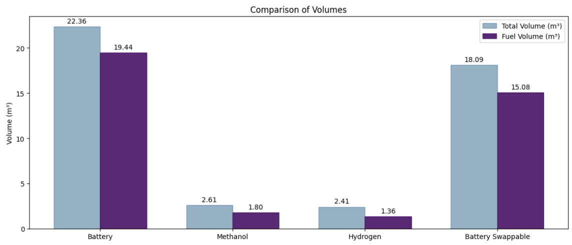


Figure 9.10: Copmarison of Fuel Volumes and Total (including system) Volumes per Fuel type. *Created by the author*

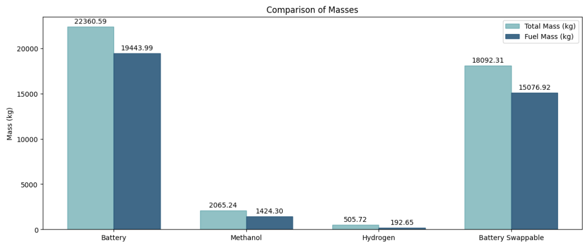


Figure 9.11: Compmarison of Fuel Mass and Total (including system) Mass per Fuel type. *Created by the author*

This comparison provides insights into the trade-offs between space utilization and performance, aiding in selecting the most appropriate energy carrier for specific applications, mainly where space and energy efficiency are critical in the new design of the concept ships of the PoR. These building blocks of the energy modules will form the base for the new design.

9.7. Conclusion Energy Modules Development

The configurations depicted in Figure 9.6 form the basis for the designs explored in this thesis. Using the estimated energy requirements, the necessary onboard energy and spatial and mass considerations have been calculated for four energy systems: Electric, Electric Swappable, Hydrogen, and Methanol. These estimates, combined with the results from the MFD model, offer critical insights into the equipment layout for the proposed concept ships.

Table 9.10: Comparison of Fuel Types Including Box Dimensions

Metric	Battery	Methanol	Hydrogen	Battery Swappable
Energy Requirement (kWh)	4322.4	4322.4	4322.4	3920
Battery Efficiency	0.90	-	-	0.90
Fuel Cell Efficiency	-	0.50	0.60	-
Motor Efficiency	0.95	0.95	0.95	0.95
Overall Efficiency	0.855	0.475	0.57	0.855
Energy Density (Wh/kg)	260	6388.89	39495.56	260
Total Volume (m³)	22.03	4.11	4.37	18.14
Fuel Volume (m³)	19.14	2.84	2.66	16.00
Total Mass (kg)	22025.83	3255.73	1042.65	18137.00
Fuel Mass (kg)	19140.00	2253.59	721.96	16000.00
Center of Mass (m)	(1.33, 1.33, 1.33)	(0.80, 0.80, 0.80)	(0.75, 0.75, 0.75)	(1.27, 1.27, 1.27)
Box Dimensions (m) (L x W x H)	2.66 x 2.66 x 2.66	1.60 x 1.60 x 1.60	1.50 x 1.50 x 1.50	2.54 x 2.54 x 2.54
Storage	Below Deck	Above Deck	Above Deck	Above Deck

The summary table 9.10 consolidates key data on energy requirements, efficiencies, densities, volumes, and masses for each system. Since detailed specifications for tanks, engines, or fuel cells have not yet been developed in this thesis, the energy containers are modeled as square modules. Although this assumption may be refined in future work, it is maintained for the scope of this research. While standardizing these modules may not fully reflect the practical integration of tanks and fuel cells into a single unit, this simplification is valuable for generating initial estimates and facilitating the early design process.

The analysis underscores the strategic advantage of modularity, allowing for rapid reconfiguration based on evolving mission needs and technological advancements. This capability is critical given the IRV's role in diverse operational contexts within the Port of Rotterdam. Additionally, assessing potential modules against drivers such as commonality, mission flexibility, and adaptability confirms that a well-executed modular strategy can enhance operational efficiency and lifecycle sustainability.

Transitioning into Chapter 10, the focus will shift from individual module characteristics to the holistic integration of these modules within the IRV's overall architecture. Chapter 10 will explore the strategic implications of these modular design choices, detailing how they align with the Port of Rotterdam's sustainability goals. By synthesizing the modular evaluations with system-wide performance criteria, Chapter 10 aims to comprehensively understand how the modular IRV concept supports immediate operational demands and long-term environmental objectives.

Chapter 10 discusses the MFD model, in which all foundational elements have been gathered, including the energy modules that define the various energy carriers. These energy carriers serve as the basis for different designs, around which the MFD model will analyze various onboard systems, examining their inter dependencies and correlations to form functional clusters. The following Chapter 10, will present the key results of the MFD analysis, establishing a foundation for the conceptual designs.

10 Modular Function Deployment Model

This chapter discusses the modular function deployment model and its elaboration and results. Chapter 10 consists of 6 sections that all contribute to answering the fifth sub-question of this research:

- *How can Modular Function Deployment (MFD) be applied to optimize the design of a modular, zero-emission IRV for the Port of Rotterdam?*

Modular Function Deployment (MFD) is a strategic tool for creating modular products that align with customer needs and technical requirements. In this chapter, the MFD process is applied to design zero-emission Incident Response Vessels for the Port of Rotterdam. The chapter uses MFD to clarify customer needs, identify key functions, and break them into manageable modules. This approach will help optimize the vessel design, ensuring it is modular and adaptable to future technological changes.

In this chapter, the MFD analysis for the conceptual design of an incident response vessel for the Port of Rotterdam (PoR) is presented. This analysis aims to develop an emission-free vessel with an optimal layout designed for maximum efficiency while fulfilling all predefined operational tasks. Utilizing an MFD model allows for systematically identifying the vessel's functional requirements, which are then translated into a modular layout that ensures optimal performance and flexibility [112]. By employing iterative improvements, complex problems can be addressed through step-by-step solutions. This chapter will cover the analysis of the Quality Function Deployment (QFD) matrix, the Design Parameter Matrix (DPM), the Module Interface Matrix (MIM), and the Interface Matrix. These combined matrixes are named the product Management Map (PMM) and are shown in Figure 10.1. Additionally, the potential modules and technological solutions will be discussed.

The primary aim of this chapter is to discuss the results of the comprehensive MFD model. This model is dynamic and can be continuously adapted based on new insights or changes. Currently, the model is designed specifically for Red Ships. The output is presented as clusters and modularity scores, which form the foundation for the concept development in Part III, using the building blocks derived from the MFD model. The various fuel modules serve as the central framework around which the systems are organized. The chosen building blocks and clusters may be subject to change in future research and modifications.

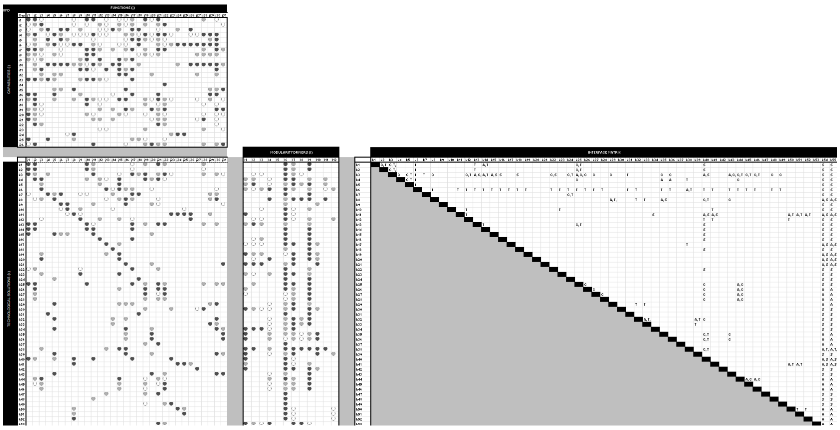


Figure 10.1: Results of MFD matrices Product Management Map. *Created by the author*

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

Figure 10.2: Value an impact score of QFD, DPM and MIM [130]

10.1. MFD Methodology

This section provides a brief overview of the model development process and the steps taken in its implementation. The details of the reasoning and decision-making process for the QFD and the DPM rationale is in the model. In contrast to Appendix G that contains the MIM matrix reasoning. The MFD methodology is reviewed step-by-step in this section to clarify the model's construction.

1. Step-by-Step explanation: introduce the 5-step process of MFD, highlights its modularization principles from [138] and [140].
   (a) Step 1: Clarification of customer needs and key functions.
   (b) Step 2: Functional decomposition and identification of modules.
   (c) Step 3: Identifying key drivers for modularity.
   (d) Step 4: Generation of module concepts.
   (e) Step 5: The most suitable modular structure is evaluated and selected.
2. Stakeholder Involvement: Discuss the role of the different Voices (Market, AM, User, Business). in the MFD process.

10.2. Voices in PoR for MFD Design

In Chapter 3 of the literature study discusses the various "Voices" within the MFD model. The Voices have been defined, refined, and analyzed for this research. These four Voices, outlined in Table 10.1, represent the perspectives, interests, and concerns of all stakeholders involved in the fleet renewal program.

These voices collectively represent the diverse stakeholder perspectives essential to the MFD process. The Voice of the Business (VoB) addresses strategic and financial objectives, ensuring alignment with company goals. The Voice of the User (VoU) focuses on the practical and operational needs of end-users. The Voice of the Asset Managers (VoA) emphasizes sustainability and cost-effectiveness throughout the vessel's lifecycle. Lastly, the Voice of the Engineer/Market (VoE) considers technical feasibility and market readiness. Integrating these voices ensures a balanced design that meets immediate operational requirements, aligns with long-term strategic objectives, and remains technically viable and future-proof.

Table 10.1: Different Voices (Source: From Research)

Voice	Personas	Interests	Role
Voice of the Business (VoB)	Policy makers, program managers, strategic planners, financial managers, and executives	Cost control, return on investment, regulatory compliance, short-term and long-term sustainability	Setting strategic goals, ensuring ship designs align with company objectives and budget constraints
Voice of the User (VoU)	End-users of the vessels, such as captains, crew members, and operational staff	Usability, safety, comfort, efficiency, functionality, performance, and reliability	Providing feedback on operational performance of vessels, suggesting areas for improvement
Voice of the Asset Managers (VoA)	Asset managers, maintenance managers, and logistics coordinators	Efficient maintenance, extending vessel lifespan, optimizing operational availability, fuel and lubricant procurement, long-term cost control	Planning and executing maintenance, ensuring operational performance and availability, providing input on design for maintenance-friendly and cost-effective solutions
Voice of the Engineer/Market (VoE)	Designers, engineers, technicians, and partially, maintenance personnel	Technical aspects such as buildability, ease of maintenance, technical feasibility, current and future market offerings, system integration	Translating customer requirements into technical specifications, ensuring implementation in design and construction

In order to fill in the MFD appropriately, each iteration and corresponding score in the matrices must carefully consider all stakeholder Voices. This ensures that a balanced compromise is reached, incorporating perspectives from all parties. While this process may generate discussion, it ultimately leads to a consensus on the final score.

10.2.1. Capabilities and Functions:

The requirements derived from the analyses, as presented in Table 8.2 and Table 8.3, have informed the specifications for the new fleet. The capabilities were developed based on these requirements, and the functions were defined by the port authority and through a decomposition of the tasks performed by the current fleet. These capabilities and functions serve as inputs for the QFD matrix and the remainder of the MFD matrix.

The capabilities and functions are listed here.
the defined capabilities and functions create a foundation that feeds into the MFD model, as outlined

Table 10.2: Capabilities

I	Id.	Capabilities
I_1	1	Advanced Navigation
I_2	2	Efficient Propulsion
I_3	3	Environmental Monitoring
I_4	4	Incident Response and Firefighting
I_5	5	Pollution Control
I_6	6	Crew Comfort and Safety
I_7	7	Autonomous Operations
I_8	8	Robust Communication
I_9	9	Maintenance and Upgradeability
I_{10}	10	Compliance with Regulations
I_{11}	11	Energy Efficiency and Sustainability
I_{12}	12	Modular Design for Flexibility
I_{13}	13	Integrated Data Management
I_{14}	14	Icebreaking capability
I_{15}	15	Enhanced storage and handling
I_{16}	16	Advanced safety systems
I_{17}	17	Operational flexibility
I_{18}	18	Twin-screw propulsion
I_{19}	19	Reaction force management
I_{20}	20	Shallow water operations
I_{21}	21	Sea state operations
I_{22}	22	Disengageable propellers
I_{23}	23	Fendering
I_{24}	24	Eat and drink
I_{25}	25	Surveying
I_{26}	26	Supportive operations

Table 10.3: Functions

J	Id.	Functions
J_1	1	Provide GPS and Radar Integration
J_2	2	Provide Dynamic Positioning System
J_3	3	Operate Hybrid Propulsion System
J_4	4	Monitor Air and Water Quality
J_5	5	Detect and Suppress Fire
J_6	6	Contain Oil Spill
J_7	7	Treat Waste
J_8	8	Accommodate Crew
J_9	9	Provide HVAC Systems
J_{10}	10	Enable Autonomous Navigation Algorithms
J_{11}	11	Communicate
J_{12}	12	Schedule Maintenance
J_{13}	13	Connect to Shore Power
J_{14}	14	Monitor Compliance
J_{15}	15	Integrate Renewable Energy
J_{16}	16	Provide Modular Payload Systems
J_{17}	17	Analyse Real-Time Data
J_{18}	18	Integrate E-nose
J_{19}	19	Maneuver sideways
J_{20}	20	Lift operation 10-20 tonnes
J_{21}	21	Maintain in a required position
J_{22}	22	To steer the ship
J_{23}	23	Facilitate working space
J_{24}	24	Provide fresh water
J_{25}	25	Provide eating facilities
J_{26}	26	Provide clean air
J_{27}	27	Provide an alternative way to abandon the ship
J_{28}	28	Rescue people in the seas
J_{29}	29	Extinguish fire onboard
J_{30}	30	Extinguish fires
J_{31}	31	(Un)load and secure cargo

in Figure 10.1. Here, each capability and function is linked with specific technological solutions, aiding in the prioritization and feasibility assessment of the vessel's modular components. The detailed alignment between capabilities and MFD outputs ensures a comprehensive integration into the IRV's design, balancing functional performance with sustainability and modular flexibility.

All information required for the concept design, module divisions, and ESSD design is derived from the defined capabilities i_n and functions j_n. These encompass all relevant data for the process. In the future, with more extensive research, the capabilities and functions can be further specified in greater detail. These capabilities and functions will ultimately inform the technological solutions discussed in Table 10.4. With the foundation for the model now established, the results are discussed in Section 10.3.

10.3. Results of the MFD Application

The application of MFD to the IRV design produced a structured and highly modular architecture. The entire model was developed in an integrated Excel file, encompassing all requirements, functions, capabilities, and results. This approach offered clear insights into how the vessel's functionality could be divided into interchangeable modules, satisfying customer requirements and technical constraints. This was achieved through iterative and incremental steps, where various matrices were systematically developed and refined. The QFD matrix is provided in Appendix D, and the DPM matrix can be found in Appendix B. The following sections discuss and examine the MIM matrix and the Interface matrix, including an analysis of the results.

Table 10.4: Technical Solutions (K1-K55)

Code	Technical Solution	Code	Technical Solution
K_1	GPS Module	K_{29}	Firefighting Monitors
K_2	Radar System	K_{30}	Rescue Boarding Platform
K_3	Integrated Bridge System	K_{31}	Gas Detection System
K_4	Electric Motors	K_{32}	Foam-Forming System
K_5	Hydrogen Fuel Cells	K_{33}	Powder Extinguishers
K_6	Battery Packs	K_{34}	Modular Firefighting Storage
K_7	Environmental Sensors	K_{35}	Advanced Crane 1
K_8	Fire Pumps and Extinguishers	K_{36}	Crane 2
K_9	Oil Booms and Skimmers	K_{37}	Fendering
K_{10}	Waste Treatment Units	K_{38}	Battery Swapping System
K_{11}	Crew Cabins and Mess Areas	K_{39}	Module Foam Tank 12m³
K_{12}	HVAC Units	K_{40}	Cabin (Communication Suite)
K_{13}	AI Navigation System	K_{41}	Restaurant
K_{14}	Satellite Communication System	K_{42}	Rescue Boat
K_{15}	VHF Radio	K_{43}	Remote Controls
K_{16}	CMMS	K_{44}	Propulsion System
K_{17}	Shore Power Connectors	K_{45}	Azipod Propeller
K_{18}	Compliance Reporting Software	K_{46}	Waterjet
K_{19}	Solar Panels	K_{47}	Mooring Lines and Anchors
K_{20}	Wind Turbines	K_{48}	Deck and Navigation Lighting
K_{21}	Modular Cargo Holds	K_{49}	Work Lighting
K_{22}	Real-Time Data Processing Units	K_{50}	Drinking Water Tank
K_{23}	Energy Recovery Systems	K_{51}	Grey Water Tank
K_{24}	E-nose	K_{52}	Black Water Tank
K_{25}	DPS	K_{53}	Hydrofoil
K_{26}	Bow Thruster	K_{54}	Monohull
K_{27}	Spade Rudders	K_{55}	Double hull
K_{28}	Disengageable Propellers		

10.3.1. Module Indication Matrix (MIM)

The Module Interface Matrix (MIM) evaluates the interactions between modules within the incident response vessel, ensuring seamless integration and effective operation. It maps interfaces between components like propulsion, navigation, and safety systems, identifying potential integration challenges early. The MIM is shown in Figure 10.3, with ranking criteria detailed in Appendix G. To visualize the ranking between technical solutions (k_n) and the modularity drivers (l_n), the symbols that imply the impact are shown in table 10.5.

Table 10.5: Description of Relationships and Impacts

Description MIM	Score	Symbol
High impact	9	●
Medium impact	3	● (grey)
Low impact	1	❍
No impact	0	

For a detailed description of the QFD, see Paragraph 3.5.1.

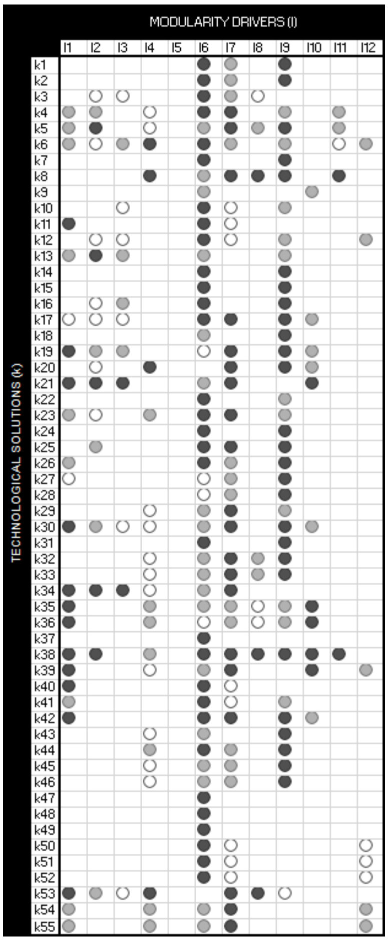


Figure 10.3: Results of MIM matrix. *Created by the author*

10.3.2. Modularity Drivers in the MIM Matrix

The modularity drivers utilized in the MFD model are designed to steer the development towards an efficient and flexible product architecture. Key focus areas include operational excellence, product leadership, and customer intimacy. Additional details on these modularity drivers and the questionnaire used in the model can be found in Appendix B.

Table 10.6: Overview of Strategies and Focus Areas

code l_n	Strategy	Focus Area
l_1	Carry Over	*Operational Excellence*
l_2	Technology Push	*Product Leadership*
l_3	Planned Design Changes (Product Plan)	*Product Leadership*
l_4	Technical Specification	*Product Leadership*
l_5	Styling	*Product Leadership*
l_6	Common Unit	*Operational Excellence*
l_7	Process/Organization	*Operational Excellence*
l_8	Separate Testing	*Operational Excellence*
l_9	Purchase	*Operational Excellence*
l_{10}	Service/Maintenance	*Customer Intimacy*
l_{11}	Upgrading	*Customer Intimacy*
l_{12}	Recycling	*Operational Excellence*

The various modularity drivers determine the degree to which solutions can be modular. Evaluating each technical solution against these drivers makes it clear whether modularity is applicable in each specific case. The justification and rationale for the scoring are detailed in Appendix G.

10.3.3. Interface Matrix

In Modular Function Deployment, the Interface Matrix is essential for mapping module relationships. Interfaces are categorized as Attachment (A), Transfer (T), Command and Control (C), and Spatial (S), which organize interactions systematically. Attachment interfaces ensure physical connections and load distribution; Transfer interfaces manage the exchange of energy, resources, or information; Command and Control interfaces coordinate operations and communication; and Spatial interfaces address the alignment and spatial arrangement of modules.

The Interface Matrix results, shown in Figure 10.4, compare technical solutions, marking relationships with A, T, C, S, or combinations. Table 10.7 classifies the connections of the interactions as: Attachment, Transfer, and Command & Control Spatial.

Denotation	Interaction taxonomy
A	Attachment
T	Transfer
S	Spatial
C	Command & control

Table 10.7: Denotation and Interaction Taxonomy

In Section 10.3.2, the degree of modularity for all technological solutions is assessed using the MIM Matrix. The interface matrix now critically evaluates the dependencies and interactions between the various technological solutions. It identifies how each solution connects with others, whether they rely on data exchanges, electrical power, or other forms of integration. This matrix provides a detailed overview of how systems are interconnected and interdependent, indicating the flow of information and resources necessary for the operation.

The interface matrix illustrates the connections between modules. A white box indicates no connection or dependency on a specific system, allowing that system to be incorporated independently into the ship design. Connections that require power or command interfaces between systems are labeled

INTERFACE MATRIX

	k1	k2	k3	k4	k5	k6	k7	k8	k9	k10	k11	k12	k13	k14	k15	k16	k17	k18	k19	k20	k21	k22	k23	k24	k25	k26	k27	k28
k1		C,T	C,T,:			T							T	A,T											C,T			
k2			C,T,:			T							T												C,T			
k3				C	C,T	T	T	C				C,T	A,C,T	A,T	A,S	S		S				C,S		C,T	A,C,T	C	C	
k4					C,T	T																			C			
k5						T																						
k6								T			T	T	T	T	T	T	T	T	T			T	T	T	T	T	T	T
k7																								C,T				
k8																												
k9																												
k10												T											T					
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	k29	k30	k31	k32	k33	k34	k35	k36	k37	k38	k39	k40	k41	k42	k43	k44	k45	k46	k47	k48	k49	k50	k51	k52	k53	k54	k55
k1												S														S	S
k2												S														S	S
k3	C		T				C	C				A,S			A,C,T	C,T	C,T	C,T		C	C					S	S
k4							A	A		T						C										S	S
k5																										S	S
k6			T	T			T	T		A,T		T	T		T	T	T	T		T	T					S	S
k7																										S	S
k8	A,T,:			T	T		A,S					C,T			C											A,S	A,S
k9																										S	S
k10													T													S	S
k11						S						A,S	A,S									A,T	A,T	A,T		A,S	A,S
k12												T	T									T				S	S
k13												S														S	S
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k15												S														S	S
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k24																										S	S
k25												C				A,C										S	S
k26												C				A,C										A	A
k27												C				A,C										A	A
k28												C				A,C										A	A
k29				T	T																					A	A
k30																										S	S
k31																										S	S
k32					A,T,S						A,T	C														S	S
k33											T															S	S
k34																										S	S
k35												C,T			C											A	A
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k37																										A	A
k38												C,T														A,T,S	A,T,S
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k48																										S	S
k49																										S	S
k50																							T	T		A	A
k51																										A	A
k52																										A	A
k53																										A	A
k54																											
k55																											

Figure 10.4: Results of Interface Matrix. *Created by the author*

with ”T” (for power transmission) or ”C” (for command). Spatially integrated systems within the hull are marked with ”S” to denote the physical arrangement within the hull structure. Components directly attached to propulsion systems, such as propellers, are marked with ”A” to indicate attachment.

10.4. Analysis of the MFD Results

The analysis of the MFD results is conducted by examining the MIM matrix and the outcomes of the Interface matrix. The MIM matrix indicates the degree of modularity and the interdependence of onboard systems. System interactions and dependencies are further detailed in the Interface matrix, which assesses how systems collaborate or rely on one another.

10.4.1. Analysis MIM Matrix

The relative weight in modular design measures the proportional importance of each technical solution based on its modularity drivers, calculated as its percentage contribution to the total modularity score. It helps prioritize design efforts, ensuring that high-weight components, which significantly impact the system’s modularity, receive more attention. This metric helps with resource allocation and indicates where time and budget should be spent for optimal integration, maintenance, and scalability. Relative weight influences decisions on modularization vs. integration, highlights key modules for standardization, and supports lifecycle considerations like upgradeability and flexibility. By focusing on high-weight components, designers can make strategic decisions that maximize the benefits of modularity, leading to more efficient and scalable systems.

The eigenvalue method was used to calculate the weights of different criteria from pairwise comparison matrices, ensuring mathematical consistency and reducing subjective biases. This method allowed for a structured decision-making process by assigning relative importance to various design factors and is simplified in Formula 10.1. By using the eigenvalue-derived weights, this research optimized the selection of technical solutions and modular configurations, aligning the design and modularity.

$$\text{Formula eigenvalue relative weight : } a_{ij} = \frac{w_i}{w_j} \tag{10.1}$$

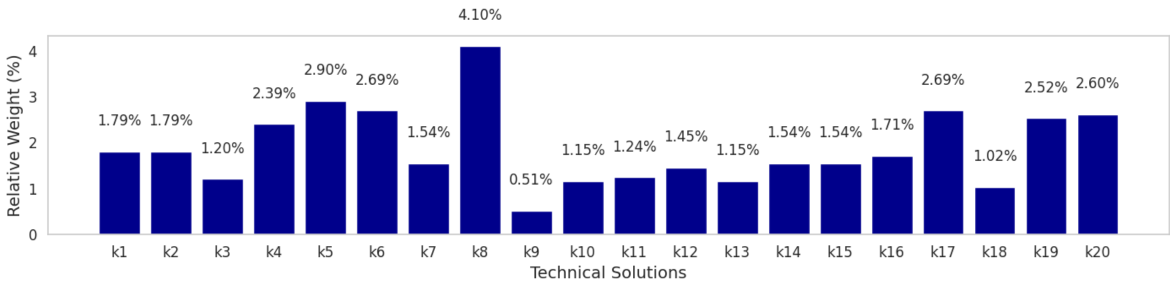


Figure 10.5: Relative weight of Modularity Drivers per Technical Solution [k1 - k20]. *Created by the author*

The bar chart highlights the relative weights of modularity drivers for various technical solutions in your modular IRV, revealing the contribution to the overall system modularity. High-impact components, such as Battery Swapping System (5.64%), Fire Pumps and Extinguishers (4.10%), and Hydrogen Fuel Cells (2.90%), should be prioritized for modularity, as they play critical roles in vessel operations and zero-emission goals.

Moderate-weight components, like Electric Motors (2.39%) and DPS (2.43%), should support flexibility and interchangeability. In contrast, low-impact components, such as Mooring Lines (0.77%) and Compliance Reporting Software (1.02%), can focus on standardization and simplicity to minimize design complexity.

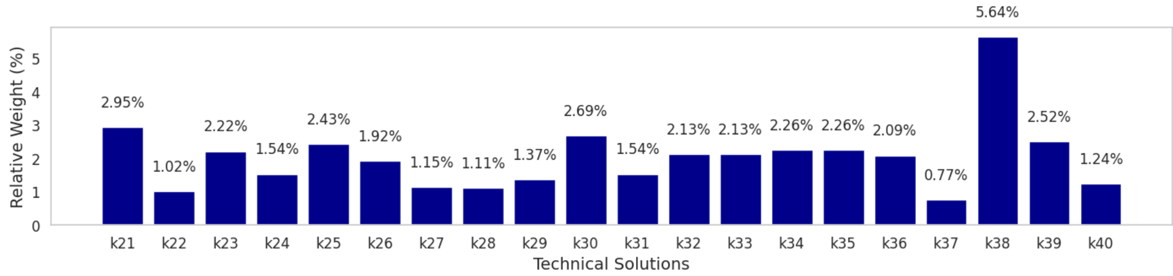


Figure 10.6: Relative weight of Modularity Drivers per Technical Solution [k21 - k40]. *Created by the author*

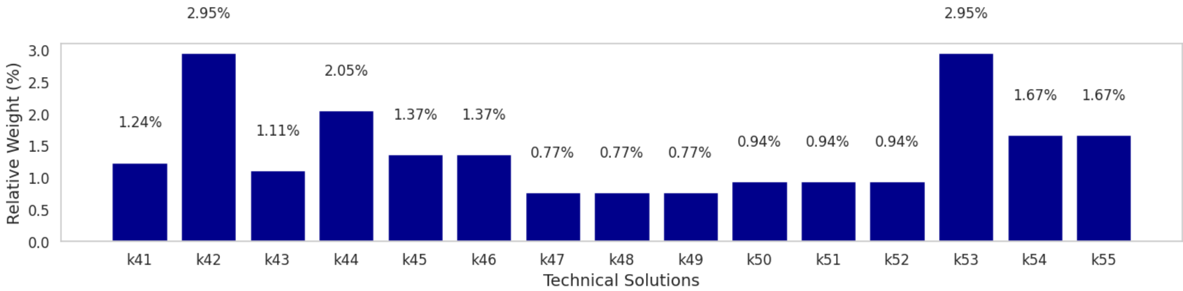


Figure 10.7: Relative weight of Modularity Drivers per Technical Solution [k41 - k55]. *Created by the author*

This analysis supports resource allocation to high-impact modules, ensuring lifecycle flexibility and optimal layout. The scores of the various technical solutions offer valuable insights into the design process because in evaluating the degree of modularity and the potential for standardization.

10.4.2. Technical Solutions

To make clear which technical solutions scored the highest, the sum of the numerical values for the top ten technical solutions with the highest total modulairty score is listed in Table 10.8, where all 12 modularity drivers were added together. A high modularity score reflects that each module in the system performs specific, independent functions with minimal overlap or dependency on other modules. This means that individual components or subsystems can be modified, replaced, or upgraded without significantly affecting the rest of the system. The 12 modularity drivers cover all aspects of flexibility, efficiency, innovation, integration, and customization. Overall, modularity drivers aim to create a well-balanced product architecture that meets strategic objectives and requirements.

Table 10.8: Top 10 Technical Solutions based on scores

Ranking	k_number	Technical Solutions	Total Modularity Score
1	k_{38}	Battery Swapping System	75
2	k_8	Fire Pumps and Extinguishers	48
3	k_{21}	Modular Cargo Holds	48
4	k_{53}	Hydrofoil	41
5	k_5	Hydrogen Fuel Cells	40
6	k_{34}	Modular Firefighting storage	40
7	k_{42}	Rescue boat	39
8	k_{30}	Rescue boarding platform	38
9	k_{19}	Solar Panels	37
10	k_6	Battery Packs	35

The Battery Swapping System is a technological solution included as both a product and a technical solution. Although it conflicts with the option of swappable batteries as an energy carrier on board, it represents an interesting innovation that the port authority is considering. The MFD data was valuable for this and other applications. Additionally, the Battery Swapping System scores well and could function effectively as a module.

Fire pumps and extinguishers should be separate modules, operating independently. The modular cargo on the ship provides flexibility and is considered a good module. Although a hydrofoil was examined for data purposes, it will not be used in this design and should be a separate module. A hydrogen fuel cell, like the Battery Swapping System, is a standalone fuel source and was included for data analysis.

The modular firefighting storage is important to have on board as a separate module, offering flexibility and meeting strategic objectives and requirements. A rescue boat should be flexible and independent, scoring high in modularity. A rescue boarding platform, having little correlation with other systems, scores relatively high but would need to be integrated into the hull and would only be flexible if it is a mechanical system. Solar panels and battery packs, providing the electrical power supply, score high for modularity and flexibility.

10.4.3. Modularity Drivers

By examining the modularity drivers, it is possible to identify which have received the highest scores. This insight helps to determine the most critical aspects of the various technical solutions.

- L_6 **Common unit:** Many solutions score high on this driver, this indicates that common units are important for modular construction.
- L_7 **Process/Organization:** There are also high scores, meaning that organizational processes and structures are crucial.
- L_9 **Purchase:** This is another driver with high scores, indicating that purchasing decisions play a significant role.

Figure 10.8 illustrates the modularity drivers by the relative weight, highlighting that the Common Unit, Process/Organization, and Purchase have the highest scores, which is indicated by the average line above which these three modularity drivers sit well above. Figure 10.9 presents a Radar chart depicting the shift among the modularity drivers for the top 10 technical solutions across all Modularity Drivers. It is important to note that styling and recycling rank significantly lower in priority among the top 10 technical solutions. This trend is consistent across the remaining technical solutions as well.

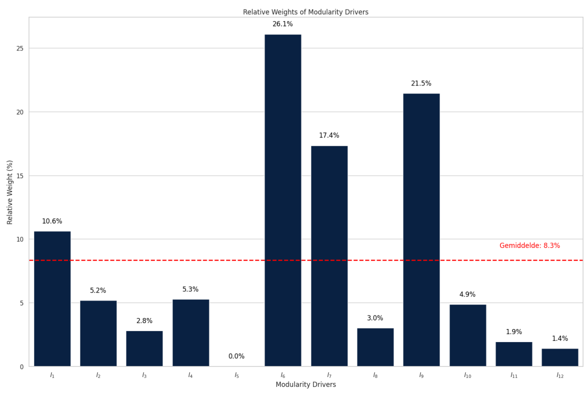


Figure 10.8: Relative Weight MIM matrix - With average relative Weights. *Created by the author*

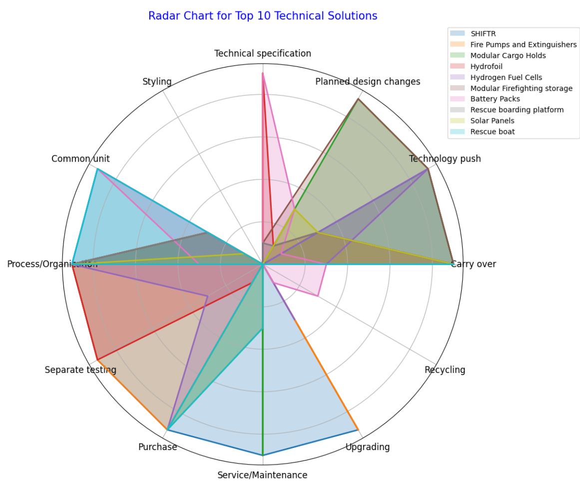


Figure 10.9: Radar Chart top 10 Technical Solutions data MIM. *Created by the author*

The concept of a common unit is a critical modularity driver in the design of new IRV(s). It assesses whether certain systems onboard can share a standardized physical form across different product variants. This strategy is crucial for the Port of Rotterdam (PoR) to enable rapid part replacement across the entire fleet. Ensuring that technical solutions, including core platform components and discrete elements like taps and water cannons, maintain a consistent physical form enhances operational efficiency and simplifies maintenance.

In the design of the ships, the modularity drivers highlighted process/organization as a key factor. Several onboard systems and technical solutions were identified as requiring independent modularization. Efficient processes like modular design can reduce delivery times by simplifying tasks like part replacement. For example, consolidating similar operations within a single team area can enhance automation and streamline assembly.

The MFD model identifies purchasing as a high-scoring modularity driver. This indicates strong justification for creating separate modules that specialists can deliver as fully integrated ”black boxes.” In some cases, separating a technical solution into a distinct module, such as water cannons, can reduce logistical costs. By having a specialist or vendor supply the entire technical solution as a standardized module rather than individual components, operational efficiency is enhanced. The analysis of the MFD model highlights this approach as particularly advantageous for the PoR.

10.4.4. Concluding Remark Interface Matrix

This analysis focuses on the technical solutions grouped into clusters based on functional dependencies. Certain systems must work together for the vessel's operation, such as a propeller and its drive or an energy source. Other clusters consist of systems required for specific functions, like firefighting, where components such as an engine, pump, monitors, water cannon, and foam installation must be integrated. While cluster formation often involves physical connections, dependencies can also exist through data and control systems, where components need not be physically adjacent. For example, the bow thruster, located at the front of the vessel, is part of the propulsion cluster despite its physical separation from other propulsion elements.

10.5. Output of Clusters and Groups of Modules

Figure 10.4 illustrates the interface analysis, developed by populating the Modular Function Deployment (MFD) model and evaluating all interfaces from the perspectives of the various stakeholder Voices to reach a consensus. In this study, all technical solutions with interfacing relationships were grouped, leading to clusters' automatic formation. These clusters consist of systems that are either physically connected or linked through operational dependencies. The section titles specify the tasks associated with each cluster, distinguishing between Green Task, which encompasses general tasks, and Red Task, focused on incident response. The clusters are organized according to all four types of interfaces, meaning that the systems within a cluster do not necessarily need to be spatially connected but can also be linked through command and control interfaces. Each cluster is categorized accordingly. The identified clusters are outlined in Table 10.9.

Cluster 1: Navigation and Positioning - Green Task & Red Task

All these technical solutions are related to navigation or positioning and facilitate crew communication. These systems will form a comprehensive and integrated bridge system. In the concept design and during the ship's construction, it is crucial to include all these systems. These systems will form one module and will be housed within a cabin communication suite featuring an integrated bridge system.

Cluster 2: Propulsion and Positioning - Green Task & Red Task

The ship's propulsion and steering systems are interdependent. For zero-emission ships, a battery pack is important. The rudders and bow thrusters play a significant role in maneuverability. Combined with a Dynamic Positioning System (DPS), these elements form a critical link in the onboard systems. While this module is not a single unit, it comprises a group of technical solutions that are always integrated into a ship's design.

Cluster 3: Firefighting - Red Task
Firefighting equipment is a distinctive feature of modern ships. To maintain this capability in the future, organizing these systems as a group of modules is essential.

Cluster 4: Foam Modules - Red Task
Foam-forming systems will remain crucial for future firefighting. To ensure the effectiveness, it is important to organize them as a group of modules. This will create a connecting module that integrates with the firefighting cluster 3.

Cluster 5: Crew Comfort and Safety - Green Task
The onboard systems that ensure the crew can live comfortably, eat, and have access to fresh or warm air, including waste and energy recovery systems, are interdependent to maintain a good climate for the crew. These systems will be partially integrated within the crew cabin. The systems will be partly spatial in a Crew cabin.

Cluster 6: Sensor Systems - Green Task
To facilitate observations, various sensors are installed on board. Different types of sensors are required and can be grouped and clustered together. These sensors will be physically connected and can be positioned on top of the ship or the wheelhouse.

Highlighting each cluster clarifies whether it is associated with green or red tasks. Specific clusters are categorized according to the corresponding task color. For instance, a blue ship can be created by assigning predominantly green tasks to a red ship. This flexibility in task assignment can be leveraged during concept design to optimize fleet composition.

Table 10.9: Clusters of Technical Solutions with Explanations

Cluster	Technical Solutions and Explanation
Cluster 1:	**Navigation and Positioning Green Task & Red Task** • **GPS Module** (k_1) - Provides precise location data for navigation. • **Radar System** (k_2) - Detects objects around the vessel for safe navigation. • **Integrated Bridge System** (k_3) - Centralizes control of systems. • **AI Navigation System** (k_{13}) - Enhances navigation with AI. • **Satellite Communication System** (k_{14}) - Ensures communication with shore. • **VHF Radio** (k$_{15}$) - Short-range communication. • **DPS (Dynamic Positioning System)** (k_{25}) - Maintains vessel's position. • **Cabin Communication Suite** (k_{40}) - Houses integrated bridge systems. • **Remote Controls** (k_{43}) - Wireless system management.
Cluster 2:	**Propulsion and Positioning Green Task & Red Task** • **Electric Motors** (k_4) - Converts electrical energy into propulsion. • **Battery Packs** (k_6) - Provides power for zero-emission ships. • **DPS (Dynamic Positioning System)** (k_{25}) - Maintains vessel's position. • **Bow Thruster** (k_{26}) - Enhances maneuverability at the bow. • **Spade Rudders** (k_{27}) - Efficient steering devices.
Cluster 3:	**Firefighting Red Task** • **Fire Pumps and Extinguishers** (k_8) - Firefighting equipment. • **Fire Monitors** (k_{29}) - Remotely controlled firefighting nozzles.
Cluster 4:	**Foam Modules Red Task** • **Foam Generation System** (k_{32}) - Creates firefighting foam. • **Powder Extinguishers** (k_{33}) - Versatile firefighting tools. • **Module Foam Tank** (k_{39}) - Stores firefighting foam concentrate.
Cluster 5:	**Crew Comfort and Safety Green Task** • **HVAC Units** (k_{12}) - Regulates climate for crew comfort. • **Crew Cabins and Mess Areas** (k_{11}) - Living and dining spaces for crew. • **Energy Recovery Systems** (k_{23}) - Converts waste energy into usable power. • **Waste Treatment Units** (k_{10}) - Processes sewage and greywater.
Cluster 6:	**Sensor Systems Green Task** • **Environmental Sensors** (k_7) - Monitors environmental conditions. • **E-nose** (k_{24}) - Detects and identifies odors. • **Gas Detection System** (k_{31}) - Monitors air for hazardous gases.

10.6. Concluding Remark MFD

The MFD analysis in Chapter 10 has demonstrated the versatility and strategic value of modularity for the IRV concept. This chapter has articulated a framework for modular integration through the systematic application of MFD techniques, such as the QFD matrix, DPM matrix, and the MIM matrix. By aligning each module with specific functional requirements and operational objectives, the IRV can achieve high adaptability, allowing it to address diverse mission profiles effectively.

This chapter has also highlighted the significance of crucial modularity drivers, which balance operational flexibility with technical feasibility. The emphasis on standardization across interfaces further strengthens the IRV's capacity for efficient reconfiguration and streamlined maintenance. This modular design approach not only supports the Port of Rotterdam's zero-emission goals but also ensures the vessel can evolve in response to technological advancements, maintaining relevance over its lifecycle.

Looking ahead to Chapter 11, the focus will shift from the conceptual and structural aspects of modular design to the practical implementation of specific modules and building blocks. Chapter 11 will explore how these modules can be effectively integrated into the IRV's architecture, detailing the technical specifications, spatial configurations, and operational roles of each component. This transition from modular theory to practical application will underscore the feasibility of the modular IRV concept, advancing the discussion toward prototype development and real-world deployment strategies.

Part III

Concept Development

11 Modules and Building Blocks

This chapter discusses the modules and building blocks that emerged from the MFD model and are set up in this chapter for the basis of the designs. Chapter 11 consists of five sections that all contribute to answering the sixth sub-question of this research:

- *What modular systems and energy modules can be integrated into the concept design of the new zero-emission IRV fleet?*

This chapter presents the concept development phase of the research, focusing on the integration of modular systems and energy modules into the design of the new zero-emission IRV fleet. It explores the different modules identified through the MFD process and evaluates how the systems and modules can be applied in practice. The chapter aims to develop a cohesive design concept that not only meets the operational needs of the Port of Rotterdam but also adheres to zero-emission goals and future adaptability.

11.1. Input Modules for the Concept Designs

In the concept design for the fleet composition, various input modules are utilized, categorized into three distinct types. The first category includes modules formed from the clusters identified through the MFD model. The second comprises separate technical solutions that interface with the vessel or must be independently integrated into the new design. Lastly, the third category consists of energy modules, as outlined in Chapter 9, which focus on both propulsion and the operation of the firefighting systems.

11.1.1. Modules based on clusters from MFD Model

Technological solutions within each cluster are combined into modules, both to simplify the design and because of the interrelated functions, as identified through the Interface Matrix.

- **Cluster 1: Navigation and Positioning**: *GPS Module, Radar System, Integrated Bridge System, AI Navigation, Satellite Communication, VHF Radio, Dynamic Positioning System (DPS), Cabin Communication, Remote Controls.*
- **Cluster 2: Propulsion and Positioning**: *Electric Motors, Battery Packs (peak shaving), DPS, Bow Thruster, Spade Rudders.*
- **Cluster 3: Firefighting**: *Fire Pumps, Extinguishers, Fire Monitors.*
- **Cluster 4: Foam Modules**: *Foam Generation System, Powder Extinguishers, Module Foam Tank.*
- **Cluster 5: Crew Comfort and Safety**: *HVAC Units, Crew Cabins, Energy Recovery Systems, Waste Treatment Units.*

- **Cluster 6: Sensor Systems**: *Environmental Sensors, E-nose, Gas Detection System.*

Some modules are functionally clustered via the matrix but are not physically connected, such as propulsion and positioning systems. For instance, the bow thruster is located at the forward section of the vessel, while the rudders are positioned aft. Although these elements are physically separated in the concept design, they form part of a cohesive module that is essential for the vessel's operation and must be included in every ship.

11.1.2. Individual Modules from MFD Model

Technical solutions that are part of the design but not integrated into a specific cluster are also considered. Examples include the water tanks and mooring lines, which function as independent modules within the system architecture. These functions are itemized here.

- **Rudders SB and PS**
- **Bow Thruster**
- **Drinking Water Tank**
- **Grey Water Tank**
- **Black Water Tank**
- **Engine Room**
- **Crane**
- **Water Cannons**
- **Mooring Lines and Anchors**
- **Oil Boom and Skimmers**
- **Firefighting Equipment Room**
- **Modular Unit**

11.1.3. Energy Modules

The next step involves integrating the various energy modules onboard the vessel. Standardized containers are utilized to house the different energy carriers selected during this research. The energy containers are depicted in Figure 11.1.

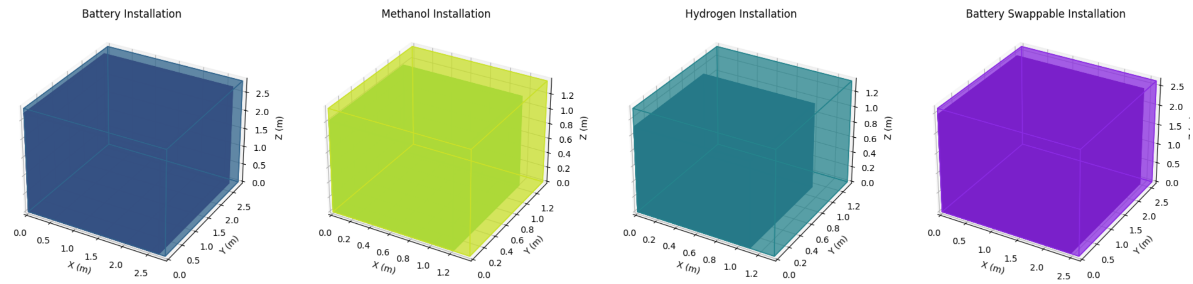


Figure 11.1: Fuel Moduels for different energy carriers. *Created by the author*

The total energy available onboard from the various fuel types is presented in Table 11.1, along with the corresponding volume and mass of the different fuels.

Table 11.1: Fuel Types Comparison with Tank Volume, Mass, and Energy Requirements

Fuel Type	Total Volume (m^3)	Total Mass (kg)	Description	Energy Requirement (kWh)
Battery	22.03	22025.83	A zero-emission solution using electric motors powered by battery packs.	4322.4
Methanol	4.11	3255.73	Methanol-powered vessels using fuel cells.	4322.4
Hydrogen	4.37	1042.65	Hydrogen fuel cell with storage for compressed hydrogen gas.	4322.4
Battery Swappable	18.14	18137.00	Modular battery units designed to be swapped.	3920

11.2. Fuel for Firefighting Systems

The results of the MFD indicate that the fire extinguishing system is critical for fulfilling the operational tasks of the red vessels. This system also requires a significant amount of energy, which had not been previously accounted for in the sailing profile under auxiliary conditions. Firefighting operations are highly energy-intensive. To estimate the energy requirements, an assumption was made that the vessel could perform up to 8 continuous hours of firefighting. Therefore, in this research, the energy capacity onboard is designed to accommodate the maximum energy demand for an 8-hour firefighting shift. The corresponding calculations are presented in Appendix E.

The calculation and estimation of the energy requirements for the firefighting system, based on a flow rate of 45 cubic meters per minute (m^3/min) at a pressure of 12 bar, the following value is determined:

- **Total Energy Firefighting** 1 Hour Operation: Approximately **1,068.5 kWh**

Table 11.1 presents the energy capacity per block of energy containers for each fuel type. To assess the fuel requirements for onboard storage, Figure 11.1 illustrates the progression of energy containers and the respective fuel coverage. Notably, all energy containers align precisely with the required energy levels, except for the swappable container. This discrepancy is expected, as the swappable container follows a standard size, whereas the containers for methanol, hydrogen, and integrated batteries are specifically designed to meet the exact energy requirements.

The energy profile indicating the number of energy containers required to support firefighting operations is illustrated in Figure 11.2. A minor discrepancy is observed in the swappable energy container, where a shortfall of 18.1% is identified. This arises because the swappable container is based on real data from Norled, and adding an entire additional battery would be inefficient. The shortfall is compensated by adjustments in the sailing profile during firefighting operations, where minimal energy is required for Dynamic Positioning (DP) or minor location adjustments. The reduction in energy consumption for sailing offsets the deficit in firefighting capacity.

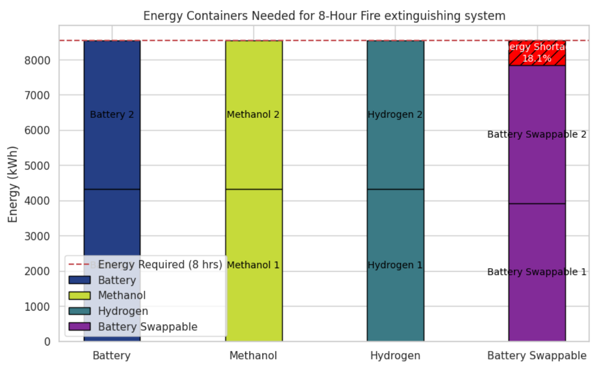


Figure 11.2: Required number of energy containers for 8 hours fire extinguishing per fuel type. *Created by the author*

Figure 11.3 illustrates the energy progression with three energy containers onboard for each fuel option. A separate grey container is designated specifically for propulsion fuel. Additionally, colored boxes in the figure indicate the available energy for 8 hours of operation, including firefighting activities. A minor energy deficit of 8.6% is observed in the swappable container.

Given that not all design concepts can accommodate three energy containers, the energy flow was also analyzed for configurations with only two containers onboard. This is depicted in Figure 11.4. A minor energy shortfall is observed in the swappable container, resulting in an 8.8% deficit. This discrepancy arises because the swappable container is based on real data from Norled; however, adding an entire additional battery for such a small shortfall would be inefficient.

11.2.1. Estimations Based on Current Ship

To accurately integrate the 11.1.1 and 11.1.2 systems into the model, a space estimation is required. This was performed through two approaches: referencing relevant literature and examining the cur-

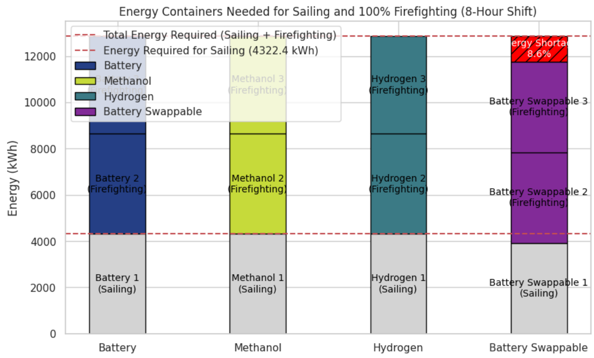


Figure 11.3: Energy containers for fully operation of 8 hours per fuel type (100% fire extinguishing and sailing). *Created by the author*

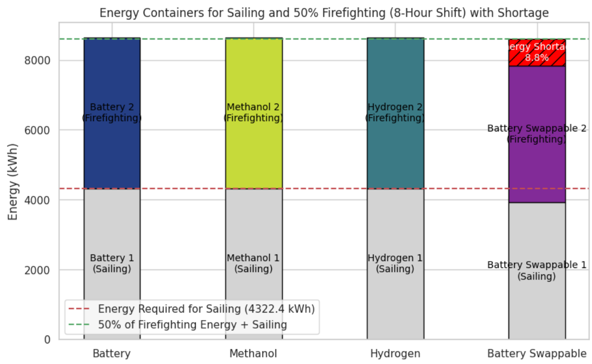


Figure 11.4: Energy containers for fully operation of 8 hours per fuel type (50% fire extinguishing and sailing). *Created by the author*

rent vessel configuration. Assessing the current situation is particularly crucial for components like the wheelhouse, ensuring accurate measurements that align with operational requirements.

The dimensions, including surface area and volume, were analyzed based on the drawings of the current vessel, RPA12.

11.3. Ratio's Length, Beam, Depth

The primary input for the length-to-beam (L/B) ratio was derived from the current fleet, which has an L/B ratio of 3.50 and a beam-to-depth (B/D) ratio of 2.16. Additional reference was made to Watson's data, though these sources are relatively outdated and pertain primarily to larger vessels. Given the preliminary stage of the design process, the L/B ratio of 3.50 and B/D ratio of 2.10 provide a solid foundation for the initial design phase. However, more stringent analysis will be required during the detailed design phase as the design is further refined.

Figure 11.5 shows the length beam ratio from Watson Pratical Ship Design [164] that have given guidance for many years. The proportions of the ship's dimensions of the new concept design are based on current ships and the guidance from the Watson ratios.

11.4. Table of Inputs Modules

Table 11.2 presents all the systems, including the clusters and individual components, along with the calculated volumes and masses. This data is essential for ensuring the modules fit within an optimal layout, while the mass values are required for stability calculations.

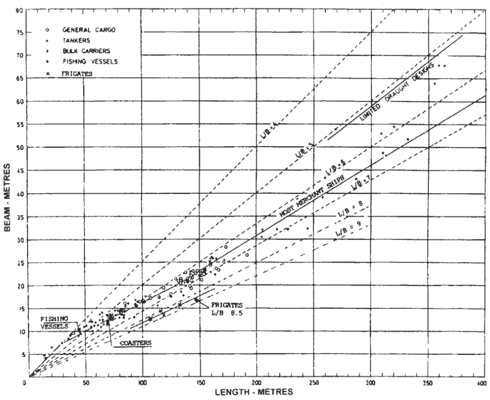


Figure 11.5: Length Beam Ratio [164]

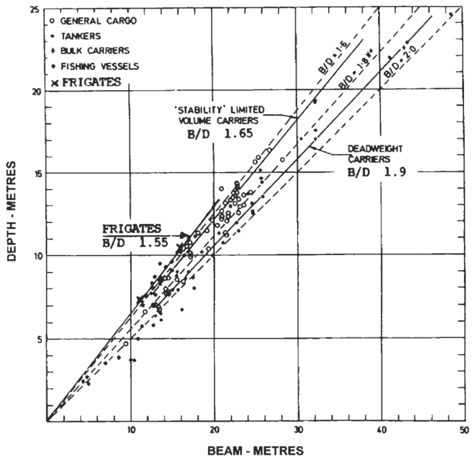


Figure 11.6: Beam Depth Ratio [164]

11.4.1. Estimations Based on Research

Table 11.2: Component Capacities and Dimensions

Component/Cluster	Volume (m³)	Mass (kg)	Description
Drinking Water Tank	3.6	5,400	Drinking water and tank for 2-3 days [91]
Grey Water Tank	2	3,000	Total grey water and tank [68]
Black Water Tank	2	3,000	Total black water and tank [68]
Navigation and Positioning	35 - 90	2,500	Wheelhouse volume, changes with beam and lenght [56] [89] [164]
Propulsion and Positioning	22.5 - 27.5	17,300 - 22,300	Additional space for propulsion systems, battery packs, DP [86] [89]
Engine Room	40-50	20,000	Resevered space for engines/fuelcells [86] [56]
Rudders	4	300	2 Rudders and propellers [86] [89]
Bow Thruster	1.5	400	Space allocation in front of ship for installation and thruster [86] [164]
Firefighting	4	1,600	Firefighting equipment, pipes, waterpump, monitors [158]
Foam Modules	4.3 - 7.75	3,650 - 6,875	Mimimum tank capacity and foam generation systems [69]
Crew Comfort and Safety	34.5 - 54	4,050 - 13,100	Crew mess area, eating facilities, HVAC, waste treatment [164] [86] [100]
Sensor Systems	1.2 - 2.5	120 - 400	Enviromental sensors, E-Nose, gas detection [66] [149]
Oil booms and skimmers	6	900	Space for Oilbooms [113]
Solar Panels	2.4	180	Total volume, mass in description [145]
Modular Cargo holds	Contigent	Contigent	Variable to ship dimensions and free allocation space
Crane	4	20,000	Total volume and mass of crane [120] [57] [43]
Fenderering	Contigent	Contigent	Variable to ship dimensions and design, estimation in hull
Mooring lines and anchor	2	550	Total volume and mass of mooring lines and anchor
Deck and navigation lighting	1	24	Including navigation lighting [31]
Work lighting	1	24	Total volume and mass of work lighting [31]
Water Cannons Front SB	2.25	600	Estimations based on current systems
Water Cannons Front PS	2.25	600	Estimations based on current systems
Water Cannons Aft	2.25	600	Estimations based on current systems

These are the results that will serve as input for the ship designs in Chapter 12. An important consideration in the Rhino design is that variations in the ship's length-to-beam ratio, resulting from longer or shorter vessel configurations, can influence overall dimensions, including those of secondary components. Consequently, elements such as the wheelhouse or Cluster 5 (Crew Comfort and Safety) may be reduced in size if the vessel's beam is narrower. While the values provided in the table are ensured, they may serve as guidelines in instances where design constraints necessitate adjustments. These dimensional changes can affect both the center of gravity and displacement of the conceptual vessels.

The design of the IRV is based on a modular approach to enhance operational efficiency, flexibility, and compliance with zero-emission standards. Each functional system is divided into distinct clusters, with modules optimized for space and weight to meet the vessel's specific operational requirements. This modular architecture ensures efficient use of space, facilitating both maintenance and future scalability. The independent yet fully integrated clusters enable seamless operations, supporting the vessel's environmental objectives. Furthermore, this modularity extends the vessel's operational lifespan by allowing for the easy incorporation of future technological advancements.

11.5. Concluding Remark on Module Integration and Systems

Chapter 11 has explored the intricate process of integrating modular systems and building blocks within the IRV, emphasizing the critical role of coherent system architecture. By incorporating the various modules identified through the MFD process, this chapter has laid the foundation for a highly adaptable and future-proof vessel design. Each module, from propulsion and energy storage to navigation and emergency response, was examined for its technical compatibility and capacity to support the IRV's mission-specific requirements.

The integration strategy presented here focuses on standardizing interfaces across modules, thereby simplifying the process of component replacement and future upgrades. This approach ensures that the IRV can leverage advancements in sustainable energy and maritime technology and optimize a design with emissie free operations. The modular architecture not only enhances operational flexibility but also minimizes downtime by enabling swift reconfiguration of mission-critical systems.

Transitioning into Chapter 12, the focus will expand from technical integration to performance evaluation and validation of the IRV's modular design. Chapter 12 will examine the vessel's performance in simulated operational scenarios, testing the functionality and resilience of the integrated modules under real-world conditions. This transition from design to validation is essential to confirm that the modular IRV concept meets its operational, environmental, and safety objectives, ensuring that the vessel is equipped to handle the dynamic and demanding tasks expected in incident response scenarios within the PoR.

12

Fleet Composition and Concepts

This chapter discusses the fleet composition and concepts of the different designs with different fuel types. Chapter 12 consists of nine sections that all contribute to answering the seventh sub-question of this research:

- *How does the fleet composition and modular design can assist in future decision making for the Port of Rotterdam IRV fleet?*

Effective fleet composition and modular design are crucial for the Port of Rotterdam to make informed, future-oriented decisions regarding its Incident Response Vessels. This chapter discusses the modular concepts developed for the future fleet of the Port of Rotterdam, focusing on zero-emission IRVs. Four key energy solutions have been identified: integrated battery packs, swappable battery systems, methanol energy modules, and hydrogen energy containers. Each subsection elaborates on the design, energy capacity, system layout, and potential fleet configurations for vessels utilizing these technologies. The results and modules of the MFD are explained and substantiated in the concept development. With the various modules and within the demarcations and space that will be discussed in modeling, in this chapter, a visualization of the various models based on the four sustainable energy solutions is made in the 3D CAD program Rhino.

12.1. Concepts

Four concepts have been drawn up in the literature review that are options for energy containers. Chapter 9 analyses the amount of energy required on board. For each fuel, a module is drawn up in the model for these energy carriers that will be included in the design. This study focuses on fleet compositions based on a single fuel type rather than exploring concepts integrating multiple fuel types. This approach was chosen to avoid introducing unnecessary complexity for the Voice of the Asset Manager. The conclusion will address whether future research should consider a different approach. Concepts will be created for the following four fuels:

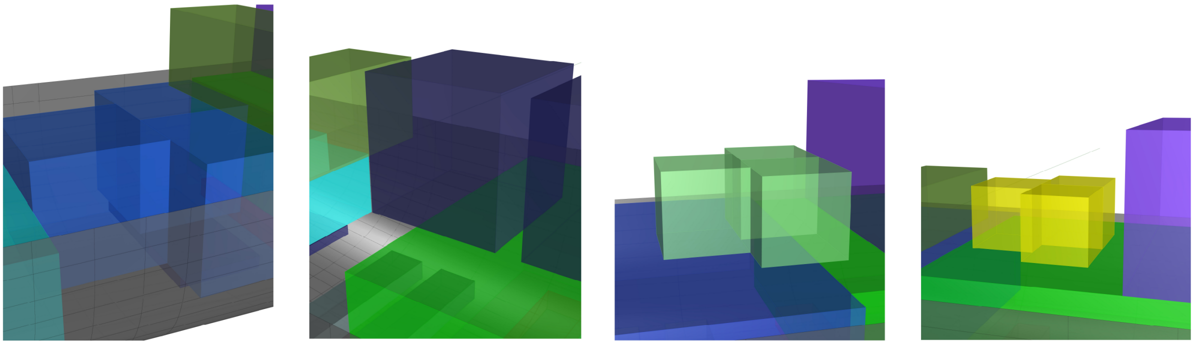
1. **Fully Integrated Battery**
2. **Battery Swapping System**
3. **Methanol Energy Module**
4. **Hydrogen Energy Module**

By incorporating various fuel types into the design concepts, multiple configurations can be developed using the modules, clusters, and dependencies outlined in Chapter 11 of the Modular Function Deployment model. The fuel type is the foundation, with the modules and technological solutions integrated around it to form the complete design.

12.1.1. System Layouts and Modules

The layout of the vessels is largely dictated by the type of energy storage system used, which impacts space allocation, stability, and operational performance. All designs share core systems: energy storage, propulsion, firefighting equipment, and crew support but differ significantly in how these are integrated.

Energy storage is the primary driver of design differences. Vessels with integrated batteries house heavy, bulky battery packs below the deck, which improves stability but consumes valuable space. For instance, the largest vessel carries three battery packs, which weigh 66 tonnes in total, impacting both weight distribution and available room for other systems. Swappable battery systems, while faster to replace, are placed on the upper deck, raising the center of gravity and affecting stability, though the battery swapping system reduces downtime. In contrast, significantly lighter and more compact methanol and hydrogen modules are stored on the upper deck for safety, freeing up space below the deck but introducing handling challenges due to the explosive potential. Figure 12.1 depicts all the energy modules.



(a) 1. Fully Integrated Battery (blue boxes)

(b) 4. Battery Swapping System (purple boxes)

(c) 2. Methanol Energy Module (green boxes)

(d) 3. Hydrogen Energy Module (yellow boxes)

Figure 12.1: The four different energy module building blocks in Rhino. *Created by the author*

Propulsion systems remain consistent across designs, with azimuth thrusters at the aft and a bow thruster at the front, offering good maneuverability. This setup for propulsion systems, which includes secondary propulsion components such as the engine room, propeller shaft, and similar elements unrelated to the energy carrier, does not significantly differ in spatial requirements across vessel types.

Firefighting equipment varies based on the vessel's energy capacity. Larger vessels with batteries or swappable systems can carry more firefighting gear, such as three water cannons and larger foam tanks. Smaller vessels or those powered by methanol and hydrogen have reduced firefighting capacity, requiring additional vessels to meet full firefighting output. The space saved by lighter energy systems allows for more below-deck equipment storage in these designs.

Crew comfort and safety systems are consistently placed midship below deck in all designs. These include HVAC, waste treatment, and mess areas for easy access and operational efficiency. Smaller vessels offer more limited space for crew accommodations, but the essential systems remain similar.

Upper deck systems generally house navigation and sensor modules alongside cranes with varying capacities. However, the upper deck must also accommodate energy storage systems in vessels using swappable batteries, methanol, or hydrogen, limiting space for other equipment. This is more pronounced in smaller vessels where deck space is already constrained. Each system is represented by a distinct color, as illustrated in Figure 12.2.

In summary, integrated batteries require significant below-deck space and add weight, while swappable batteries improve operational flexibility but impact stability. Methanol and hydrogen modules are lighter and more space-efficient but require stringent safety measures and have lower energy capacities, ne-

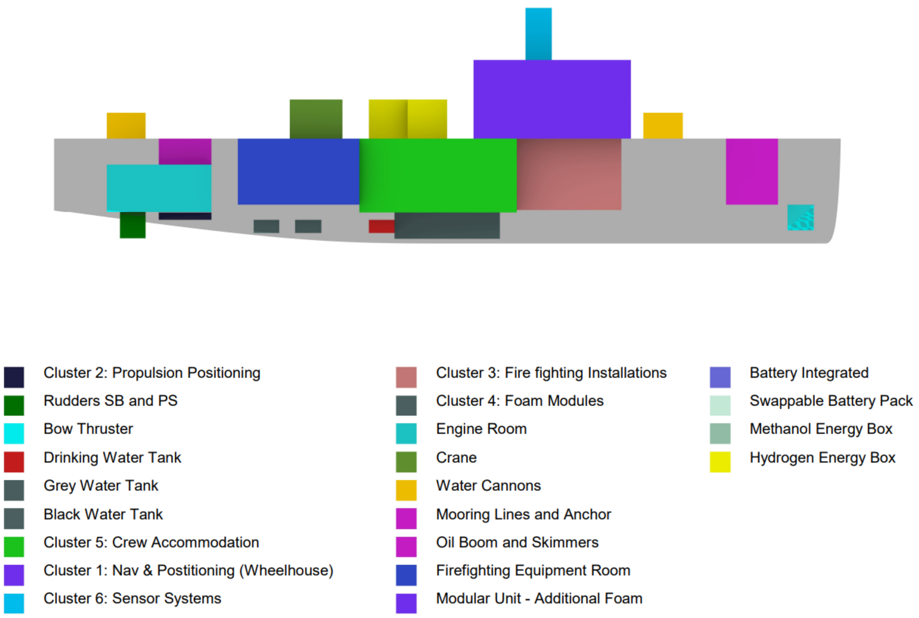


Figure 12.2: Legend in 3D Cad Program Rhino Design Modules. *Created by the author*

cessitating additional vessels for full firefighting capability. These energy storage differences dictate each vessel's layout, performance, and operational capacity.

To ensure future-proofing, the choice of integrated batteries limits the flexibility to switch fuels easily. In contrast, opting for a battery-swapping system, methanol, or hydrogen allows for such adaptability. Therefore, selecting integrated batteries impacts the vessel's long-term resilience and flexibility regarding future fuel options.

12.1.2. Operational and Design Requirements for Concept Development

In the concept development phase, various requirements that the vessel must meet are assessed. Each vessel is evaluated against these requirements, or the standardized fleet is scaled accordingly, adjusting the number of vessels as needed to fulfill the criteria. The design requirements are outlined below:

- *Ability to operate 24/7*
- *Integration of alternative fuel systems and onboard energy sources*
- *Firefighting capacity of 90 cubic meters per minute per zone (2 zones in total)*
- *Maximum vessel length of 35 meters*
- *Compliance with all clusters and modules on board of the ship*
- *Compliance with stability requirements (Based on Rhino Calculations)*

All standardized and modularly designed vessels meet the requirements outlined above. The number of operational vessels, reserve vessels, and recharging vessels within the fleet composition is determined based on these criteria. The configuration and length of each vessel are further influenced by stability calculations conducted in Rhino. In total, nine different designs have been developed: three with integrated electric systems, two with battery-swapping systems, two with methanol-based systems, and two with hydrogen-based systems. These designs establish the foundation of a standardized fleet, with identical vessels assigned to each type. An exception is vessel 3C, which can serve as an assisting vessel for 1A, as 1A does not fully comply with all clusters and modules required onboard. The various new designs are presented in the following sections:

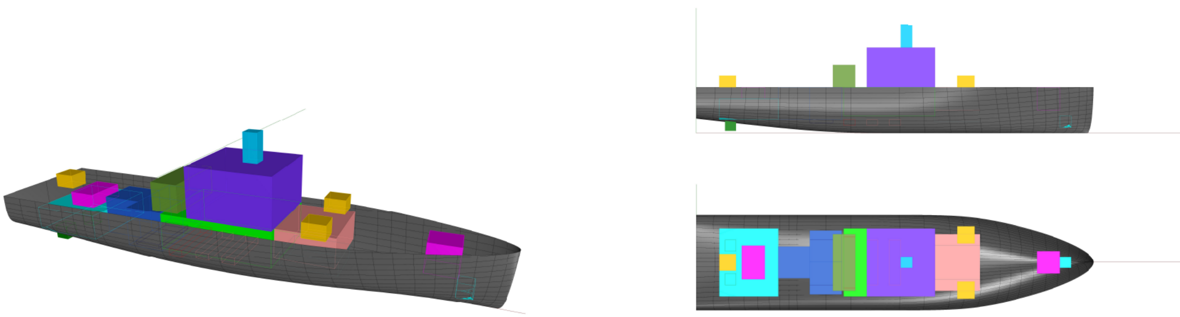
12.2. Integrated Battery Pack Systems Concepts

In this piece, the concepts of battery-integrated systems are presented. In this section, three concepts are elaborated. A large one with three energy modules, a small one with two energy modules, and an assisting vessel which can serve as a blue vessel.

12.2.1. Electric Ship - Design 1A

Table 12.1: Specifications Design: 1A

Parameter	Value	Unit
LOA	35	m
Beam	8.4	m
Depth	4	m
Draft	1.160	m
Displ.	134.932	t
GM	1.964	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.3: Two views of the ship design - 1A Electric Integrated. *Created by the author*

This concept utilizes a fully integrated battery system with three battery packs installed permanently within the vessel. Each pack can deliver enough energy for an 8-hour operational shift, including firefighting and propulsion. Based on calculations, 8,000 kWh is required for operations, with 1,000 kWh specifically allocated for firefighting systems delivering 45 m³/min of water.

Challenges and Considerations

Each battery pack weighs approximately 22 tonnes, contributing 66 tonnes to the ship's load, impacting stability and design. Furthermore, the discharge rate necessary for firefighting poses significant challenges for the battery's C-rate, potentially influencing the choice of battery technology and thermal management systems. Integrated battery cooling is essential to manage the high load during operations.

System Layout

The battery packs are located in the lower hull, offering stability benefits. Below deck, the ship is divided into operational clusters:

- **Cluster 2**: Propulsion and positioning, including azimuth thrusters and a bow thruster.
- **Cluster 3 & 4**: Firefighting systems and foam storage, including fire pumps and water distribution systems.
- **Cluster 5**: Crew comfort systems, such as the mess area, HVAC, and waste treatment units.

The upper deck houses **Cluster 1** (navigation and control systems) and **Cluster 6** (sensor systems), ensuring full situational awareness.

Fleet Composition

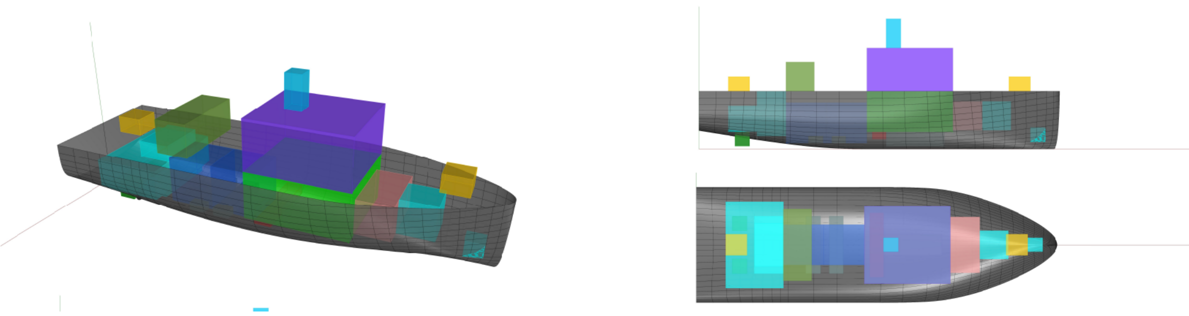
- 4 operational vessels (2 per zone) for continuous shifts.
- 4 recharging vessels, ready after an 8-hour shift.
- 3 reserve vessels to maintain operational readiness.

For continuous operations, 11 vessels would be required, making this option the largest and most costly fleet configuration, in alignment with the operational and design requirements for concept development.

12.2.2. Electric Ship - Design 2B

Table 12.2: Specifications Design: 2B

Parameter	Value	Unit
LOA	25	m
Beam	8.0	m
Depth	4	m
Draft	1.330	m
Displ.	114.925	t
GM	2.497	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.4: Two views of the ship design - 2B Electric Intergrated. *Created by the author*

This smaller vessel features two battery packs, limiting firefighting capability to 22.5 m³/min, requiring four ships to meet the same firefighting capacity as the larger design. The smaller design sacrifices space and weight distribution, resulting in fewer firefighting capabilities and a limited ability to store additional equipment.

Fleet Composition

- 8 operational vessels for firefighting, spread across two zones.
- 8 recharging vessels ready after shifts.
- 3 reserve vessels for redundancy.

This design requires 19 ships, increasing fleet size and cost.

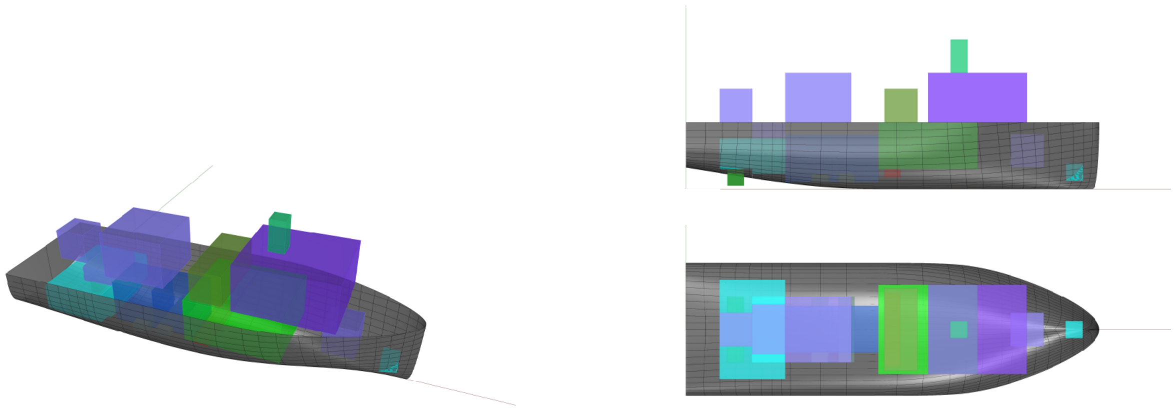
12.2.3. Electric Ship - Design 3C

The ship 3C is based on the design of 2B but with several key differences. It lacks firefighting systems, including the two water cannons, foam tank, and Cluster 3 firefighting installations (water pump and engine). Instead, 3C is equipped with a larger crane capable of lifting 20 tonnes, compared to the 10-tonne crane on 2B. Additionally, 3C has two battery modules, allowing it to operate for two 8-hour shifts (16 hours) without recharging.

3C can transfer energy to other vessels, promoting continuous firefighting operations. It also carries extra firefighting equipment, such as additional suits and foam, to support red vessels in emergencies.

Table 12.3: Specifications Design: 3C

Parameter	Value	Unit
LOA	25	m
Beam	8.0	m
Depth	3.5	m
Draft	1.167	m
Displ.	92.639	t
GM	2.334	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.5: Two views of the ship design - 3C Electric Intergrated assisting vessel. *Created by the author*

While primarily a blue vessel for regular operations, 3C can assist in red operations during emergencies. However, this dual-purpose role means that the blue vessel is out of regular service during a calamity.

Although 3C can assist with modular firefighting equipment, the critical firefighting systems must remain on 2B for immediate response. 3C provides extra equipment, energy, and support but could function solely as a blue vessel or as a red vessel, although reserving it only for emergencies would result in underutilization.

Fleet Composition

- 1 operational vessels per area. Total is 2.
- 1 reserve vessels for redundancy.

This setup results in a fleet of 4 battery-powered vessels, covering all blue tasks for a full day, though it would be an expensive and extensive fleet. Blue Vessels can assist with extra foam and modular material.

12.2.4. Integrated Battery Pack System Fleet

The various designs are systematically compared in this subsection and the results are shown. For each design, a fleet is configured based on specific requirements, comprising operational vessels that actively perform tasks, electric vessels for loading, and reserve vessels stationed at the quay. It is assumed that three vessels are necessary as backup vessels, though this number could be reduced. Figure 12.6 illustrates Design 1A, the large electric variant; Design 2B, a smaller electric variant requiring a larger fleet; and Design 3C, which primarily functions as a blue vessel but can assist the red vessels as needed.

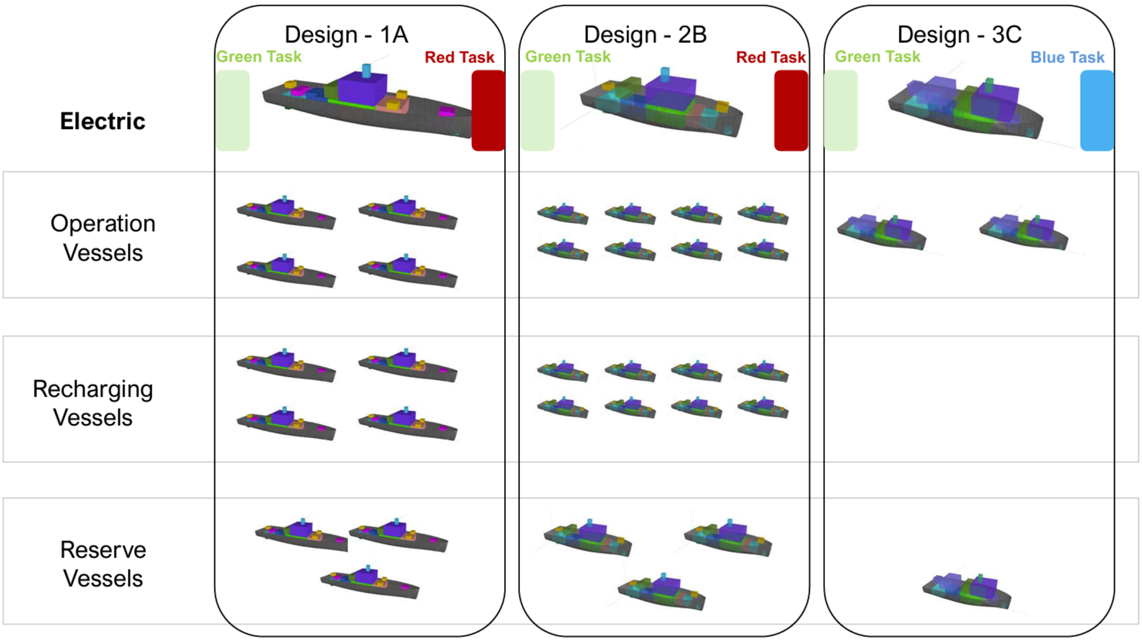


Figure 12.6: Potential options fleet: Integrated Battery Pack: Design 1A, 2B and 3B. *Created by the author*

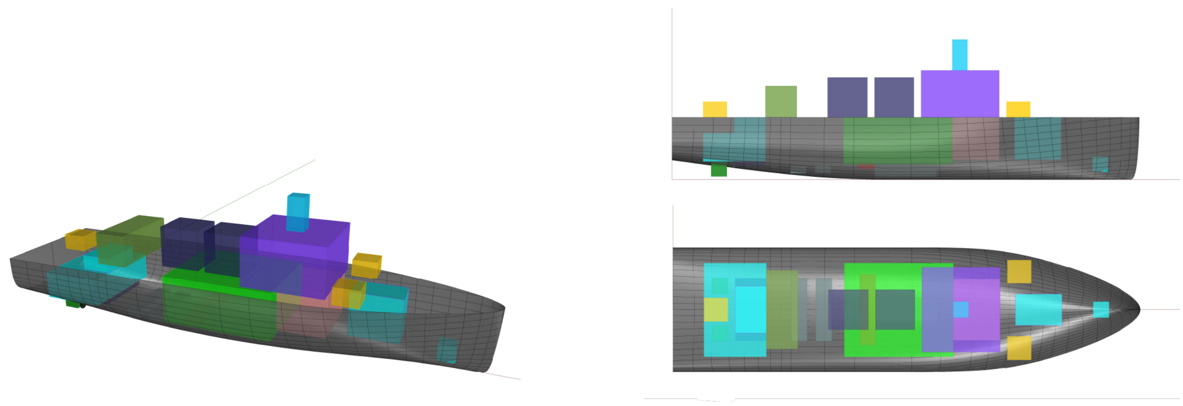
12.3. Battery Swapping Systems Concepts

This section discusses the battery swapping method, where the batteries are swapped. These concepts differ greatly from those of the battery integrated systems. This section elaborates on two types of models: a small and a large variant.

12.3.1. Electric Swapping Ship - Design 4A

Table 12.4: Specifications Design: 4A

Parameter	Value	Unit
LOA	30	m
Beam	8.4	m
Depth	4	m
Draft	1.167	m
Displ.	111.166	t
GM	1.370	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.7: Two views of the ship design - 4A Battery Swapping Design. *Created by the author*

This design employs swappable battery packs, reducing downtime for recharging by allowing quick swaps at port. The vessel can carry three battery packs weighing approximately 18 tonnes each. This system provides flexibility, but the weight distribution and higher center of gravity affect ship stability. Two battery packs are allocated for firefighting, with one reserved for propulsion.

System Layout

The swappable battery packs are located on the upper deck to facilitate easy access during swapping. The below deck remains dedicated to propulsion, firefighting systems, and crew comfort, following a similar layout to the integrated battery design.

Fleet Composition

- 4 operational vessels across two zones, no additional recharging vessels required.
- 3 reserve vessels for fleet redundancy.

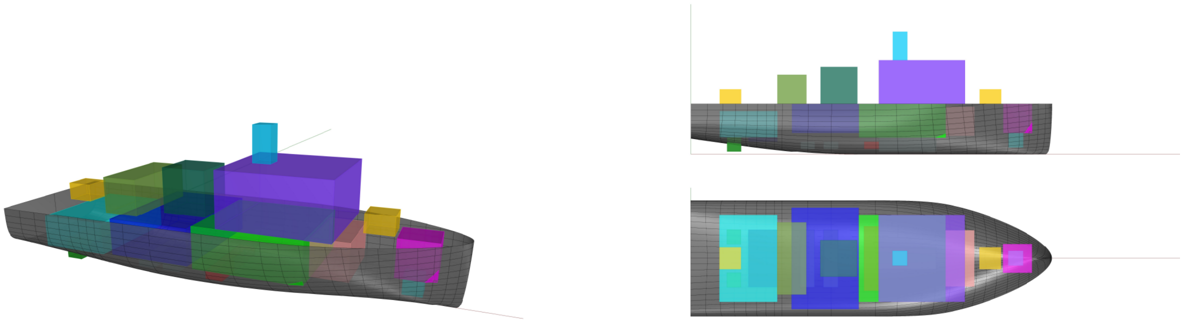
This configuration requires 7 ships, reducing the total fleet size due to the rapid swapping mechanism, in alignment with the operational and design requirements for concept development.

12.3.2. Electric Swapping Ship - Design 5B

This smaller vessel design operates with two swappable battery packs, halving firefighting capabilities to 22.5 m^3/min. As a result, two vessels are required to meet the firefighting capacity of one larger vessel.

Table 12.5: Specifications Design: 5B

Parameter	Value	Unit
LOA	25	m
Beam	8.0	m
Depth	3.5	m
Draft	1.111	m
Displ.	92.929	t
GM	2.414	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.8: Two views of the ship design - 5B Battery Swapping Design. *Created by the author*

Fleet Composition

- 8 operational vessels per zone.
- 3 reserve vessels, maintaining the same modular approach for repairs and upgrades.

A total of 11 ships are needed for continuous operation in alignment with the operational and design requirements for concept development.

12.3.3. Battery Swapping Systems Fleet

The various designs are compared in this subsection, and the results are presented. A fleet configuration is developed for each design based on specified requirements, comprising operational vessels that perform tasks and reserve vessels stationed at the quay. It is assumed that three vessels are needed as reserve ships, although this number could be reduced. Figure 12.9 illustrates Design 4A, the large battery-swapping electric variant, and Design 5B, the smaller battery-swapping electric variant, necessitating a more extensive fleet.

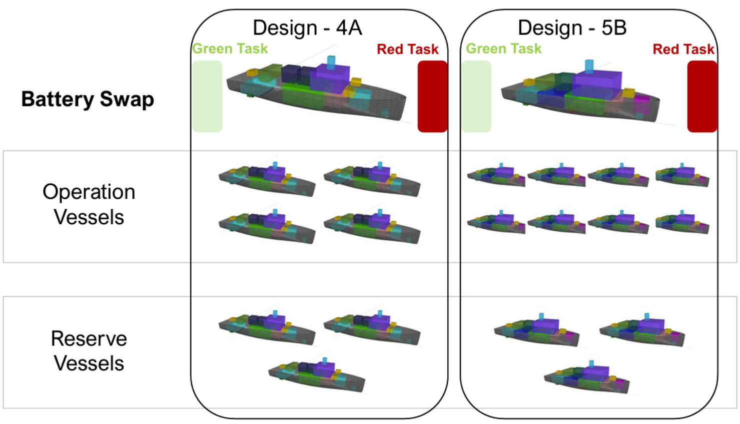


Figure 12.9: Potential options fleet: Battery Swapping Systems: Design 4A and Design 5B. *Created by the author*

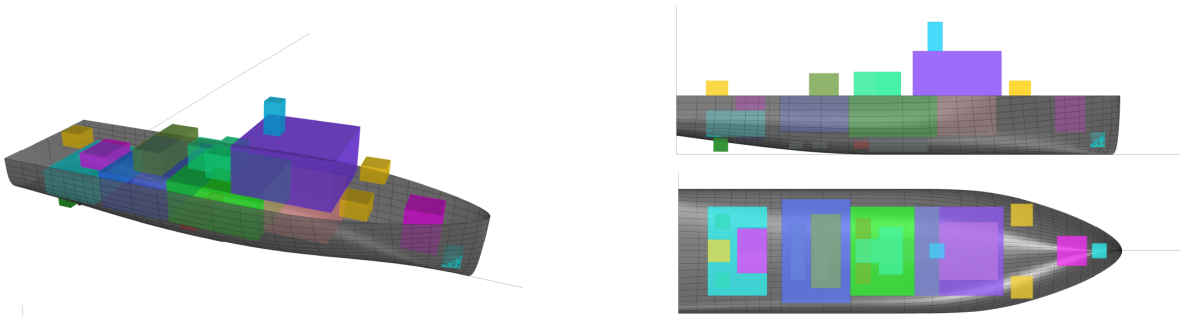
12.4. Methanol Energy Modules Concepts

Methanol energy modules are split into a large and a small variant. The results and clusters are shown.

12.4.1. Methanol Ship - Design 7A

Table 12.6: Specifications Design: 7A

Parameter	Value	Unit
LOA	30	m
Beam	8.4	m
Depth	4	m
Draft	1.167	m
Displ.	116.724	t
GM	1.550	m



(a) Layout: Side View **(b)** Layout: Top View

Figure 12.10: Two views of the ship design - 7A Methanol Design. *Created by the author*

This vessel design features methanol energy containers, which are lighter and more compact than battery systems. Each methanol module weighs approximately 3 tonnes and provides 8,000 kWh for firefighting and 4,000 kWh for propulsion. Methanol storage, however, must be placed on the deck due to safety considerations.

System Layout

The below deck layout remains similar to previous designs, with clusters for firefighting, crew safety, and propulsion. The methanol modules are safely positioned on the upper deck to minimize the risk of explosion or leakage.

Fleet Composition

- 4 operational vessels per zone.
- 3 reserve vessels.

This design requires 7 ships, offering a compact energy solution with fewer safety and space constraints in alignment with the operational and design requirements for concept development.

12.4.2. Methanol Ship - Design 8B

The smaller methanol vessel offers half the firefighting capacity (22.5 m^3/min) and requires two ships to meet complete firefighting demands. The design leverages the same lightweight and compact methanol energy modules.

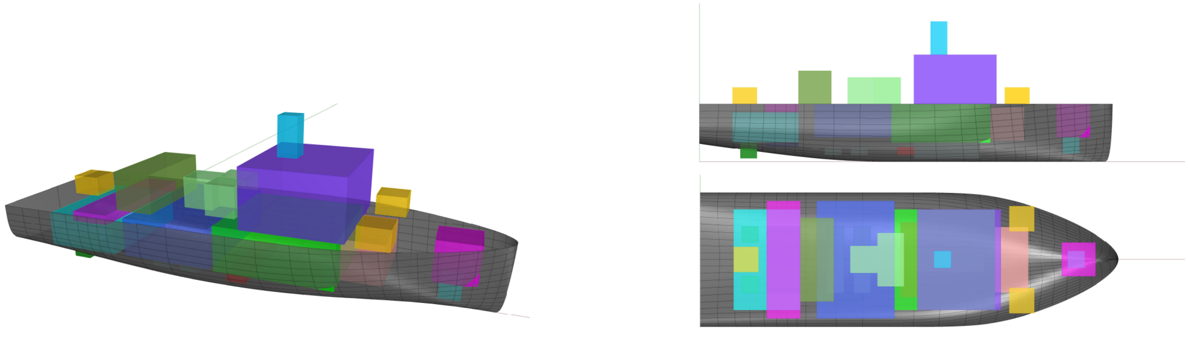
Fleet Composition

- 8 operational vessels per zone.
- 3 reserve vessels.

A total of 11 ships are required, offering a lower cost and weight alternative to battery systems.

Table 12.7: Specifications Design: 8B

Parameter	Value	Unit
LOA	25	m
Beam	8.0	m
Depth	3.5	m
Draft	1.000	m
Displ.	78.420	t
GM	2.839	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.11: Two views of the ship design - 8B Methanol Design. *Created by the author*

12.4.3. Methanol Energy Module Fleet

The various designs are compared in this subsection, and the results are presented. For each design, a fleet configuration is developed based on specific requirements. The fleet consists of operational vessels performing duties and reserve vessels stationed at the quay. The assumption remains that three reserve vessels are necessary, though this number could be reduced. Figure 12.12 illustrates Design 7A, the large methanol variant, and Design 8B, the smaller methanol variant, necessitating a more extensive fleet.

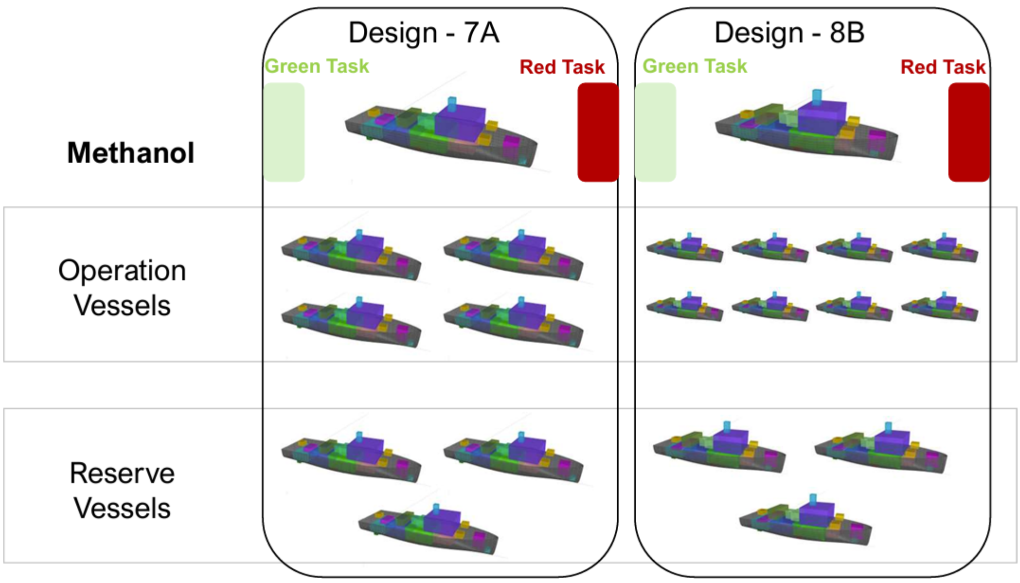


Figure 12.12: Potential options fleet: Methanol Energy Modules: Design 7A and Design 8B. *Created by the author*

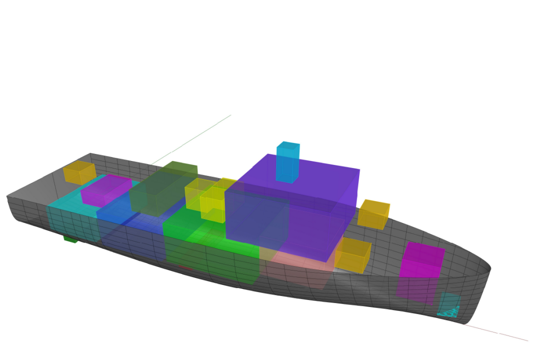
12.5. Hydrogen Energy Modules Concepts

Hydrogen energy modules are split into large and small variants. The results and clusters are shown.

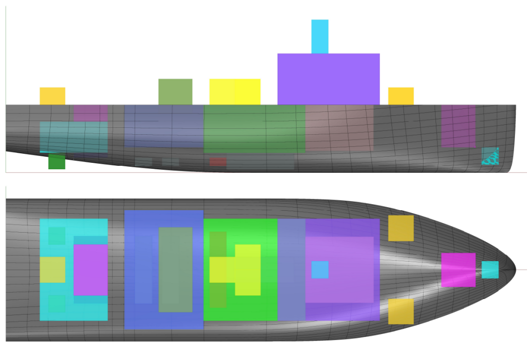
12.5.1. Hydrogen Ship - Design 9A

Table 12.8: Specifications Design: 9A

Parameter	Value	Unit
LOA	30	m
Beam	8.4	m
Depth	4	m
Draft	1.167	m
Displ.	116.724	t
GM	2.549	m



(a) Layout: Side View



(b) Layout: Top View

Figure 12.13: Two views of the ship design - 9A Hydrogen Design. *Created by the author*

Hydrogen offers the lightest energy solution, with each module weighing just 1 tonne. This ship can carry three hydrogen containers, providing 8,000 kWh for firefighting and 4,000 kWh for propulsion. Hydrogen storage must be placed on the upper deck for safety reasons like methanol.

System Layout

Hydrogen modules are integrated on the upper deck, while the layout below mirrors the modular design used in other vessel concepts. Hydrogen provides ample energy capacity while reducing the overall ship weight.

Fleet Composition

- 4 operational vessels per zone.
- 3 reserve vessels.

In total 7 ships are required, and hydrogen is the most energy-efficient solution in terms of weight and space. The number of ships was determined in alignment with the operational and design requirements for concept development.

12.5.2. Hydrogen Ship - Design 10B

This smaller version reduces firefighting capacity to 22.5 m^3/min, necessitating two ships to meet complete firefighting requirements. Hydrogen remains the most compact and lightweight energy solution available.

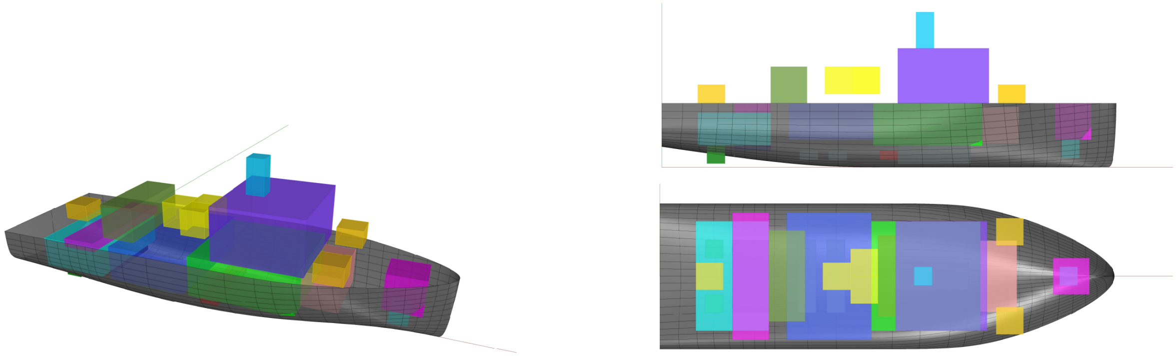
Fleet Composition

- 8 operational vessels per zone.
- 3 reserve vessels.

This design requires 11 vessels, balancing efficiency with fleet size.

Table 12.9: Specifications Design: 10B

Parameter	Value	Unit
LOA	25	m
Beam	8.0	m
Depth	3.5	m
Draft	1.167	m
Displ.	100.559	t
GM	2.265	m



(a) Layout: Side View

(b) Layout: Top View

Figure 12.14: Two views of the ship design - 10B Hydrogen Design. *Created by the author*

12.5.3. Hydrogen Energy Module Fleet

n this subsection, the various designs are compared, and the results are presented. A fleet configuration is developed for each design based on the specified requirements, comprising operational vessels responsible for task execution and reserve vessels stationed at the quay. It is currently assumed that three reserve vessels are necessary, although this number may potentially be reduced. Figure 12.15 illustrates Design 9A, the large hydrogen variant, and Design 10B, the smaller hydrogen variant, which requires a more extensive fleet.

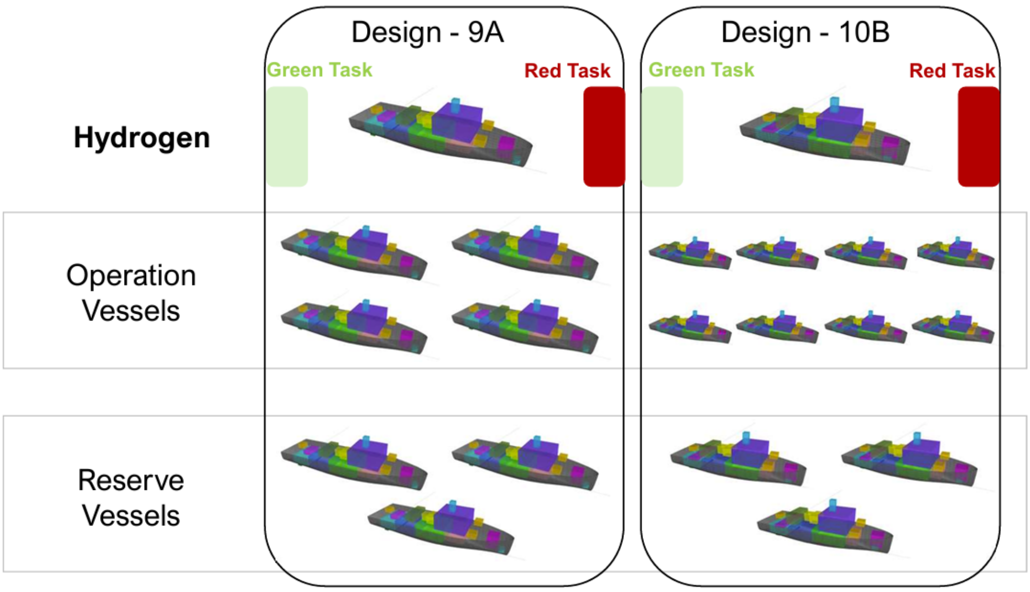


Figure 12.15: Potential options fleet: Hydrogen Energy Modules: Design 9A and Design 10B. *Created by the author*

12.6. Concluding Remark

Each energy solution presents trade-offs in terms of vessel size, operational capacity, and fleet composition. Integrated battery systems offer simplicity but require a larger fleet due to recharging times, while swappable batteries and methanol offer greater flexibility at the cost of higher system complexity. Hydrogen provides the most compact and lightweight solution, making it a promising option for future-proofing the fleet.

Considering fleet composition, operational flexibility, and the number of vessels required, the swappable battery systems, with the highest energy readiness, represent the most viable option. These systems and corresponding ship designs demonstrate the most excellent feasibility. Based on the scope of this study, swappable battery systems are recommended as the optimal choice for the Port of Rotterdam.

12.7. Stability Assessment and Design Criteria for Incident Response Vessels

The layout and design of the ships are fixed. The design tool automatically calculates some calculations for the concept designs. This includes the Draft (T), the Displacement, the Center of Buoyancy (CoB), and the GM. The goal of the preliminary design is to surpass certain design criteria, looking for initial stability. A design is considered stable if the metacentric height is positive, so GM > 0.

Ship stability refers to a vessel's ability to remain upright and return to its original position after tilting due to external forces like wind or waves. The primary measure of stability is the metacentric height (GM), calculated as [30]:

$$GM = KB + BM - KG \tag{12.1}$$

where:

- KB is the vertical distance from the keel to the center of buoyancy (CoB), representing the centroid of the submerged hull,
- BM is the metacentric radius, the distance between the CoB and the metacenter (M), and can be calculated by dividing the transverse moment of inertia of the waterplane by the ship's volume displacement,
- KG is the distance from the keel to the center of gravity (CoG), influenced by the vessel's weight distribution.

A positive GM indicates stability, meaning the ship will return to an upright position after tilting, while a negative GM signals instability, increasing the risk of capsizing. GM is a key indicator of ship stability, where a higher GM implies greater stability but quicker rolling motions, while a lower GM provides smoother motion but a higher risk of instability.

Table 12.10: Stability Judgement for Ships

Ship Name	LOA [m]	B [m]	D [m]	T [m]	Displ. [t]	GM [m]	CoB (xyz) [m]	Stability
1A Electric	35	8.4	4	1.160	134.932	1.964	[17.549, 0.0, 0.709]	+
2B Electric	25	8.0	4	1.330	114.925	2.497	[12.217, 0.0, 0.817]	++
3C Electric	25	8.0	3.5	1.167	92.639	2.334	[12.522, 0.0, 0.712]	++
4A BatSwap	30	8.4	4	1.167	111.166	1.370	[15.026, 0.0, 0.713]	+
5B BatSwap	25	8.0	3.5	1.111	92.929	2.414	[12.332, 0.0, 0.681]	++
7A Methanol	30	8.4	4	1.167	116.724	1.550	[15.026, 0.0, 0.713]	+
8B Methanol	25	8.0	3.5	1.000	78.420	2.839	[12.566, 0.0, 0.611]	++
9A Hydrogen	30	8.4	4	1.167	116.724	2.549	[15.025, 0.0, 0.713]	++
10B Hydrogen	25	8.0	3.5	1.167	100.559	2.265	[12.217, 0.0, 0.715]	++

The Stability judgement for Ships table outlines critical parameters for evaluating the stability of various ship designs, including dimensions (length, beam, depth, draft), displacement, metacentric height (GM), and the center of buoyancy (CoB). The GM value is a key indicator of stability, with higher values denoting greater initial stability. All ships in the table have positive GM values ranging from 1.37 m to 2.839 m, confirming stability under the given conditions. The highest GM, 2.839 m, is found in the 8B Methanol Design, which has a smaller displacement and narrower beam, contributing to a larger metacentric radius (BM).

These variations in GM are driven by differences in ship geometry, particularly beam width, which affects the waterplane area and second moment of inertia. Ships with higher GM values, while more stable, may experience more abrupt rolling motions. In contrast, ships with lower GM values, such as the 4A Battery Swapping Method Design (GM of 1.37 m), offer smoother motion but slightly reduced initial stability. Overall, the table demonstrates that all vessels meet fundamental stability requirements, with each design appropriately balancing stability and motion characteristics. Further optimization will fine-tune performance for specific operational conditions, but all ships are well within acceptable stability ranges.

12.8. Fleet Composition per Different Fuel Type

Two designs have been created for each fuel type, and for the battery-integrated version, three designs have been developed. These vessels meet the design requirements for deployability, operational tasks, and fit within the boundaries of maximum dimensions, as well as fulfill the design requirements derived from the MFD model and outlined in this thesis. A standardized version has been created for each fuel type and design, ensuring a sufficient number of vessels can be deployed per zone to meet operational demands. Various modules and clusters serve as the foundational building blocks of these vessels.

Based on the methodology and assumptions in Section 9.3, theoretically only the energy carrier module would need to be replaced to switch to a different energy source. However, in the integrated battery systems, the battery is placed in the hold to meet stability requirements, rendering it unsuitable for replacement. The swappable battery container, methanol, and hydrogen designs, however, could accommodate an alternative energy carrier. Table 12.11 presents the total number of vessels, along with the operational, charging, and reserve vessels, while Figure 12.16 illustrates the total number of ships per design. The different fleet configurations are explained as follows:

Table 12.11: Fleet Composition for Different Concepts

Concept	Total Vessels	Operational Vessels	Charging	Reserve Vessels
1A Electric	11	4	4	3
2B Electric	19	8	8	3
3C Electric	3	2	0	1
4A BatSwap	7	4	0	3
5B BatSwap	11	8	0	3
7A Methanol	7	4	0	3
8B Methanol	11	8	0	3
9A Hydrogen	7	4	0	3
10B Hydrogen	11	8	0	3

The Electric Ship 1A and Electric Ship 2B concepts require the most significant number of vessels, mainly due to continuous recharging. While these vessels offer simplicity in design, relying entirely on integrated battery systems, the downside lies in the operational inefficiency caused by the recharging process, and for the 1A ship, all the systems are integrated onboard the ship. With four operational vessels and an equal number of vessels near shore for recharging, the fleet must be significant to maintain uninterrupted operations. The Electric Ship (Smaller) design further amplifies this inefficiency by requiring more vessels (19 in total) due to the lower energy capacity and firefighting capabilities, leading to higher fleet size and operational costs. This results in increased downtime and reduced flexibility compared to other solutions.

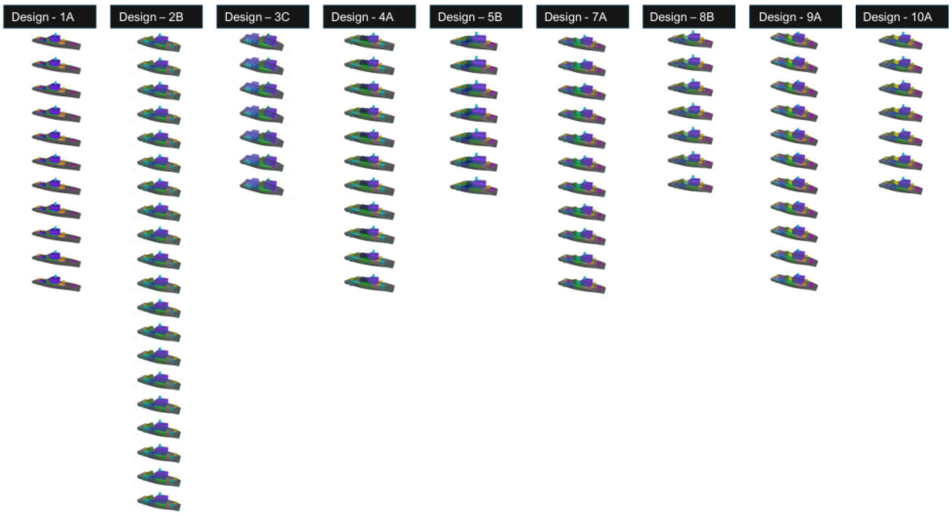


Figure 12.16: Potential Fleet Composition and Number of Vessels per Fuel Type. *Created by the author*

The Swappable Battery System addresses many of these shortcomings by eliminating the need for recharging vessels. With battery swaps at port, the vessels can resume operations without long recharging periods, significantly reducing fleet size. The Large Swap System operates with only seven vessels, and the Smaller Swap System has 11, making them highly efficient in fleet size and turnaround time. This system also enhances operational flexibility, as long charging intervals do not limit vessels and can continue service after quick battery swaps, making it ideal for high-intensity operations.

Methanol and Hydrogen energy systems offer similar benefits to the Swappable Battery System, particularly in minimizing fleet size and enhancing flexibility. Large Methanol and Large Hydrogen configurations require only 7 vessels, while the smaller versions require 11, mirroring the fleet requirements of the Swappable Battery System. These concepts benefit from the compact and energy-dense nature of methanol and hydrogen, allowing vessels to operate for longer periods without needing large, heavy battery systems. Furthermore, the reduced weight of these energy solutions contributes to better ship performance and lower operational costs. Methanol and hydrogen systems also have faster refueling processes than recharging large battery systems, improving overall fleet efficiency.

In terms of operational advantage, Swappable Battery, Methanol, and Hydrogen systems outperform Electric Ship configurations due to the reduced fleet sizes, faster turnaround times, and greater flexibility. The Swappable Battery System allows quick energy replenishment, while Methanol and Hydrogen systems offer longer operational durations and faster refueling. These benefits make them more suited for operations requiring continuous availability and quick recovery.

In contrast, the Electric Ship configurations, especially the Smaller variant, are less efficient due to the reliance on recharging, which increases downtime and fleet size, thereby driving up operational costs. The need for a significant portion of the fleet to remain near shore for recharging further limits these vessels' operational range and flexibility.

Table F.3 presents all systems and clusters incorporated into the design concepts, offering a clear overview of each concept's completeness. This allows for a systematic comparison of how thoroughly each ship design integrates the necessary components and specifies which design includes which elements. Currently, this is an output table, subject to change if layouts are modified in the future. It provides an organized view of which model meets specific system and module requirements.

12.9. Concluding Remark on Fleet Composition

Chapter 12 presented an extensive performance evaluation of the IRV, focusing on validating the modular design within simulated operational scenarios. This analysis included four distinct energy carrier, Battery Integrated, Battery Swapping System, Methanol, and Hydrogen—based on energy modules developed in Chapter 9 for the conceptual designs.

In Chapter 10, all requirements, tasks, functions, and capabilities were integrated into the MFD model. This model was systematically linked to systems and technical solutions, resulting in a comprehensive framework where all tasks are supported by corresponding systems. Clustering and system organization were used to form modules that constitute the building blocks for vessel construction.

The energy modules serve as the core components of the design, around which additional systems are integrated into the vessels. The primary goal was to maximize system integration while maintaining stability and optimal geometry, as calculated using the Rhino Design Tool. The fleet composition is structured around the operational tasks and functions of the vessels, based on the Design Requirements outlined in Section 12.1.2.

Transitioning into the conclusions of this research, the focus will shift toward synthesizing the findings from the entire thesis, drawing together insights from the IRV's design, modularity, energy solutions, and performance validation. Chapter 13 will conclude the lessons learned and propose recommendations for implementation while also reflecting on the broader implications of this modular IRV concept for maritime sustainability and emergency response capabilities. This synthesis will provide a conclusive assessment of the IRV's potential to set a new standard in modular, zero-emission maritime design for the PoR.

Part IV

Conclusions

13
Conclusion, Discussion and Recommendations

This chapter serves as the final section of the research and concludes the thesis. Section 13.1 provides the conclusions, addressing the research questions and summarizing key findings. The discussion, presented in Section 13.2, outlines the limitations of this study and proposes potential future directions. Recommendations related to the research are presented in Section 13.3.

13.1. Conclusion

This study aimed to investigate *How a zero-emission, modularized, and standardized Incident Response Vessel (IRV) can be designed to serve as a scalable decision-making concept for a fleet, optimizing layout and functionality to meet operational requirements*. The study employed Modular Function Deployment and developed concept designs to form a flexible and sustainable IRV fleet.

This thesis explores the optimal approach for the PoR to tackle early-stage ship design, focusing on a conceptual design to standardize the IRV fleet. The primary aim is to support critical decision-making regarding the transition to an emission-free fleet by developing design concepts and establishing a framework using the MFD approach. This study represents the first application of MFD to IRV vessels, demonstrating its effectiveness in managing the complexities of PoR's fleet renewal and ensuring all tasks and operational profiles are met by an adaptable, emission-free fleet. The "no-regret" vessel concept allows for future energy flexibility, minimizing the risk of premature commitment to a specific fuel source. This research addresses key questions essential to achieving PoR's sustainable fleet goals. The key conclusions from the sub-research questions are summarized below.

Sub-Question 1:

- *What are the most effective modular design principles for ensuring flexibility in ship energy systems and future-proofing the design?*

The research identified modular design principles such as **functional modularity** and **standardization**. Initially, ship design methods were examined, followed by an analysis of various modular design approaches. These principles form the foundation for flexibility and future-proofing in ship energy systems and designs. By dividing ship systems into independent modules (e.g., energy storage and propulsion), the design facilitates future technological upgrades without requiring a complete redesign. Consequently, traditional baseline designs are not viable options.

These modular design principles ensure that components can easily be replaced or upgraded, integrating emerging energy systems such as hydrogen, methanol, or advanced batteries. Moreover, **redundancy** in design enhances operational reliability by enabling module replacement without interrupting vessel operations.

Practical Applications: This research examines various modular design principles suitable for IRVs. Although the MFD method has been applied to other vessel types, such as marine and Offshore Support Vessels, it is used here for the first time with IRVs. MFD is implemented to ensure comprehensive coverage of the operational tasks required by both the vessels and the PoR's fleet. This approach can be applied at both the vessel and fleet levels, providing design flexibility that supports future-proofing while enabling continuous innovation and improvement throughout the design process.

Sub-Question 2:

- *Which alternative fuels provide the most viable solution for reducing emissions in the Port of Rotterdam's IRV future fleet?*

The evaluation examined three fuel types: electric, hydrogen, and methanol. The electric option was further divided into two approaches: onboard integrated electric systems and battery swapping methods. Hydrogen and methanol were also considered alternative fuels, with hydrogen offering zero emissions and methanol approaching low emissions only if combined with carbon capture, a factor not included in this study. Although ammonia is referenced in the literature, it was excluded from consideration for Port of Rotterdam vessels due to its low technological readiness and higher toxicity compared to other options, making it less feasible.

Despite the high volume and mass associated with electric systems, electric power is preferred in this research, because it is currently the most reliable energy source, within the port due to its technological maturity and feasibility for powering both vessel propulsion and onboard systems. Methanol and hydrogen, when used in fuel cells, introduce an additional conversion step to the onboard electrical network, resulting in efficiency losses. Gravimetric and volumetric energy densities are critical considerations for determining the suitability of each fuel type, as fuels with higher energy densities often require larger storage volumes. For comparative purposes and potential future flexibility, all four energy methods were included in this analysis to facilitate an objective assessment.

The study evaluated **methanol**, **hydrogen**, and **battery-electric systems** as the most viable alternative fuels for reducing emissions. Each fuel has unique advantages:

- Methanol offers high energy density and compatibility with existing engines but needs carbon capture systems (to reduce emissions).
- Hydrogen enables zero-emission operations but faces challenges with storage and infrastructure.
- Battery-electric systems are ideal for short-range tasks but are limited by energy density, recharge times, and weight. A battery can be swapped easily.

Practical Applications: The integration of emission-free fuels is a strict requirement set by the port authority; however, identifying a viable alternative proves challenging due to the unique operational profile of these vessels and the niche market they occupy. The need for 24/7 operation, high peak energy demands, specific vessel types, and limited space led to the evaluation of three energy carriers. Given current technology readiness, electric power is concluded to be the most feasible option. Within this choice, adopting a swappable battery system is crucial, as it allows potential future scalability to methanol or hydrogen power.

Sub-Question 3:

- *How can the existing design of the Port of Rotterdam's Incident Response Vessels be optimized for modularity and zero-emission technology?*

The research highlighted that modularity enables the rapid integration of new energy systems, such as batteries, methanol, and hydrogen while preserving operational efficiency and optimizing vessel layout. Understanding which components are essential, which can be excluded, and what is already onboard is crucial. The ship's systems (e.g., propulsion, firefighting) can be modularly deconstructed and redesigned, facilitating straightforward maintenance and future upgrades.

Key improvements include:

- **Space Optimization:** Efficient space allocation for energy storage and systems.
- **Scalability:** Energy systems can be scaled based on mission requirements and onboard systems.
- **Integration of Zero-Emission Technology:** The vessel layout supports the use of alternative propulsion systems in combination with the extra space requirement of alternative fuels and additional systems.

Practical Applications: The foundational information on the vessels can be extracted directly from the ships themselves, with systems readily identifiable. However, defining and identifying specific tasks for this vessel type is more complex, as these often arise from concessions among various stakeholders within the safety region. Consequently, ships frequently carry excessive equipment, much of which may be unnecessary. Modular storage or systems could address this issue effectively. Currently, two cranes are onboard to ensure operational continuity in case one requires extended maintenance, a redundancy that may be unnecessary with optimized onboard systems and reduced cargo. Additionally, specialized firefighting foams could enhance future response capabilities for handling chemical fires.

Sub-Question 4:

- *What is the energy demand profile of the IRV fleet, and how can alternative energy modules meet these demands while ensuring operational efficiency in the future?*

In this study, the sailing profiles of the red vessels were analyzed based on estimates derived from prior data. While operational conditions vary daily, it is possible to determine the minimum onboard energy requirements to ensure specific voyages and systems can operate effectively. To adopt a comprehensive approach, four different methods were employed to verify the alignment of this study's calculations with other sources. These comparisons confirmed that the estimated values in this research were above the average, supporting the robustness of the energy estimation approach.

Energy consumption profiles were calculated based on 8-hour operational shifts, during which vessels use approximately 4,322.4 kWh per shift, totaling an energy consumption of 15.56 GJ. Profiles for patrolling, cruising, and firefighting activities were assessed using data from existing vessels and leading maritime research institutions. This analysis guided the selection of energy systems capable of meeting the operational requirements of the IRV fleet, ensuring that energy carriers such as methanol, hydrogen, and battery systems provide adequate power for diverse missions. Only the battery-swapping system operates with a slightly lower capacity of 3,920 kWh, as it is based on the initial maritime battery-swapping systems. Given that 4,322.4 kWh represents a high estimate, the capacity of the battery-swapping system is considered sufficient, but it is essential to consider that the capacity of storage methods continues to grow, but at the same time, the energy demand may also increase in the future, due to more electrification.

Practical Applications: In the current ESSD phase, the energy demand estimate is a reasonable value for each vessel type, provided that the maximum dimensions of 35 meters are adhered to. This ensures that, in principle, sufficient energy is always available onboard. However, future advancements, new systems, increased digitalization, and more electric, autonomous, or automated systems could lead to higher energy consumption. Consequently, the energy demand estimate should be recalibrated and refined as system requirements become clearer and vessel specifications are finalized. Given the current lack of a clear consensus on energy consumption from various scientific and industry stakeholders, this estimation serves as a sound initial assumption.

Sub-Question 5:

- *How can Modular Function Deployment (MFD) be applied to optimize the design of a modular, zero-emission IRV for the Port of Rotterdam?*

MFD provides a systematic approach to modular design well-suited to these types of vessels, ensuring that the ship's key operational functions are addressed. By conducting small iterations, all aspects of functions, tasks, and capabilities are controlled and matched to technical solutions. The modules and clusters formed through the system result from breaking down the vessel's functions into independent modules. This allows the design to remain adaptable to future technological changes, such as new propulsion or energy systems.

MFD was selected as the most suitable methodology for modular design in this project due to its structured approach to balancing technological needs, customer requirements, and strategic considerations. By systematically incorporating the voices of customers, engineers, asset managers, and business stakeholders, MFD offers a framework in this research for designing modular vessels that meet current operational needs while remaining adaptable to future energy advancements and covering the product lifecycle, in this case, the vessels.

Practical Applications: MFD is an optimization method that ensures all tasks are covered by onboard systems, supporting both vessel-level and fleet-level configurations. It ensures that the fleet is operationally efficient and future-proof for evolving energy systems. Given the reduced onboard space due to emission-free fuel systems, such an optimization method is essential for layout planning. MFD enables the distribution of functions across multiple vessels or clusters, enhancing flexibility as requirements evolve. Additionally, the methodology facilitates easier maintenance, reduces downtime, and offers cost-effective lifecycle management.

Sub-Question 6:

- *What modular systems and energy modules can be integrated into the concept design of the new zero-emission IRV fleet?*

The research identified various modular systems: propulsion, energy storage, firefighting, and auxiliary systems that can be independently replaced or upgraded. Methanol and hydrogen energy modules and battery systems are proposed as energy modules serving different mission profiles. These form the building blocks for different ship concepts, shaping the fleet according to energy sources.

The Port of Rotterdam categorizes vessel operations into three main themes: red (incident response), blue (patrol), and green (basic). These themes were instrumental in defining the functional and system requirements for the new IRV designs. The functional breakdowns of the vessels, derived from these task themes, ensured that the modular systems, such as firefighting equipment and propulsion, were optimized for current and future operational scenarios.

Practical Applications: These modular systems provide scalability and adaptability. While tasks are now distinctly allocated per vessel, there may be functional overlap in certain areas, allowing for operational flexibility. Integrating alternative energy sources supports the Port of Rotterdam in achieving zero-emission targets while maintaining adaptability for future missions. The research indicated that some tasks overlap and are not delineated; refining task assignments in the future could further optimize vessel operations by enhancing task-specific efficiency.

Sub-Question 7:

- *How do the fleet composition and modular design assist in future decision-making for the Port of Rotterdam IRV fleet?*

Modular designs and optimized configurations enhance fleet flexibility, allowing vessels to adapt to evolving operational requirements. This approach reduces the need for specialized vessels and optimizes fleet composition by enabling multifunctional ships through modular configurations. Rather than developing each vessel individually, entire batches can be produced based on a standardized modular framework. Additionally, insights gained from fleet composition provide valuable guidance for future decision-making, underscoring the importance of developing conceptual sketches to convey explicit visual representations.

Practical Applications: A modular fleet composition reduces total costs, improves maintenance efficiency, and facilitates strategic decision-making regarding future upgrades or vessel acquisitions. A more extensive fleet of uniform vessels optimizes spare parts inventory and streamlines knowledge transfer related to maintenance. Standardized spare parts, such as cranes and modules, can be quickly replaced, and the current reserve fleet of three vessels could be reduced to two or even one. This reduction would significantly lower both CAPEX and OPEX due to the smaller fleet size.

13.1.1. Answer to the Research Question

This study demonstrates that an emission-free, modular, and highly standardized IRV fleet can be designed for the Port of Rotterdam, incorporating modularity to integrate all operational processes seamlessly. Through the implementation of new zero-emission energy carriers, a novel vessel layout was developed using MFD, allowing the conceptual design process to take full advantage of modular flexibility. The balance between zero-emission energy carriers and MFD proves to be a significant success in this study. Although focused solely on red vessels to assess the feasibility of meeting operational tasks, the findings suggest that while certain requirements may be challenging to meet, a standardized fleet can be designed for each vessel type.

The choice of a swappable battery system aligns with the specific scope and objectives of this study, emphasizing flexibility, future-proofing, and long-term cost savings. However, a comprehensive market analysis and a realistic assessment of the Commercial Readiness Level (CRL) are essential. This system offers a robust solution that can be scaled and adapted to future technological developments without requiring substantial modifications to vessel designs.

While external factors, such as extensive fleet renewal infrastructure, remain relevant, this choice meets the immediate feasibility and requirements for an emission-free, modular IRV design. It represents a critical step toward a more sustainable and efficient maritime sector. The key findings are as follows:

1. **Energy Supply and Operational Limitations:** The modular energy systems in this research can support a maximum of 8-hour shifts with onboard energy, allowing for normal operations and shifts, but require recharging or swapping after 8 hours. The space required by alternative energy sources constrains onboard capacity and introduces trade-offs in task fulfillment. Looking at the current requirements of the current fleet, there is a need for a 48-hour energy supply at 50% power, which is no longer feasible by only sailing on emission-free fuels.
2. **Design Optimization and System Integration:** Clustering and optimizing systems will enhance layout efficiency and enable seamless integration of alternative fuels while maintaining stability in a monohull design. Hydrofoil configurations are not yet proven to be feasible for red vessels, though a double-hull option may warrant further exploration. Modular design offers advantages, facilitating redesign and accommodating future technological advancements.
3. **Considerations for Speed and Fleet Composition:** Operational speeds of up to 31 km/h are unrealistic for extended shifts, given current energy constraints. Speed requirements must be carefully evaluated, and energy distribution optimized. This approach also requires an organizational shift in crew roles and responsibilities. Additionally, modular fleet composition can reduce total costs, minimize downtime, and optimize both the number and types of vessels deployed.
4. **Alternative Fuel Assessment:** The analysis included four energy systems: integrated electric, electric with battery swapping, methanol, and hydrogen. Integrated electric systems are feasible but spatially limiting, with designs nearly exceeding size constraints and lacking adequate storage for firefighting equipment. However, Swappable battery systems demonstrate strong potential, with larger designs (4A) requiring only seven vessels and smaller designs (5B) requiring eleven. These systems offer sufficient energy for 8-hour shifts and accommodate all necessary functionalities.
5. **MFD Layout Optimization:** The MFD framework enables modular optimization, allowing configuration changes as puzzle-like elements for flexible system development. This adaptability supports efficient fleet system distribution across vessels and aligns with modular fleet objectives, ensuring that the system layout can evolve with future requirements. It is a comprehensive system that covers tasks and functions at both the fleet and vessel levels, provides clear oversight, and is essential for integration within the Port of Rotterdam.

In summary, the swappable battery system offers the most practical and feasible option, particularly for immediate implementation, with flexibility for future integration of advanced energy sources. This approach optimizes the IRV fleet for the Port of Rotterdam, meeting operational requirements and allowing for future scalability and technological advancements. The application of the MFD method to this IRV fleet lays a strong foundation for a sustainable, emission-free future for the Port of Rotterdam.

13.2. Recommendations

This section outlines the recommendations arising from this thesis. The research concludes that developing an emission-free fleet is feasible. The ESSD phase has been examined, and the fleet's configuration can be optimized by utilizing the MFD framework. However, several recommendations are made for the implementation phase and future studies.

Technological Readiness and Future Research: The Port of Rotterdam should prioritize developing energy infrastructure, particularly for electricity to avoid grid congestion and for methanol and hydrogen production, as these technologies are expected to increase use. Ongoing research into emerging battery technologies and green fuel storage methods is essential for long-term sustainability. Initial pilot programs should be employed to integrate electricity onboard and gather operational data. This process has already begun, with the upcoming refit and electrification of the RPA8 and the lease of a hydrofoil electric patrol vessel. Concurrently, prompt decision-making will be critical to achieving sustainability targets. It is also interesting not to dismiss hydrogen and methanol entirely, as both hold potential for future applications.

Investment in Renewable Infrastructure: The Port of Rotterdam should invest in renewable energy infrastructure, such as shore power and rapid charging stations for electric and hybrid vessels. Currently, PoR leads this transition in the Netherlands, serving as both a user and a facilitator of maritime energy infrastructure. This dual role provides PoR with a unique position to support the IRV fleet's sustainability goals while encouraging visiting vessels to adopt clean energy solutions. Additionally, the Port could explore options to integrate renewable energy sources, such as wind and solar, into its operational network, thereby reducing the carbon footprint of port activities.

Modular Design: This research primarily focused on the red vessels, with occasional reference to tasks of the green and blue vessels. However, by examining the potential for increased interchangeability among all vessels, the entire fleet, not just the red fleet, could be optimized. The application of MFD across the fleet must balance comprehensive modular integration with operational clarity. The Excel model developed in this study demonstrates the extent and complexity that modularization can introduce. To maintain clarity, systems and components can be divided into separate modules, which can then be individually analyzed as building blocks for various designs. From these modular elements, a cohesive fleet composition can be established.

MFD can serve as a foundational approach for other processes and projects within the port. The principles of MFD enhance flexibility for future system upgrades, allowing vessels to adapt to new technologies as they emerge. This adaptability reduces the risk of obsolescence and improves cost-efficiency through standardization across the fleet, an approach that will also benefit projects related to quay infrastructure, port management, and future port operations.

Evaluation of Requirements: Some elements identified in this study arise from tasks that are not yet well-defined or have traditionally been carried out in a particular manner. Additionally, agreements with regional safety authorities sometimes led to ambiguity in task delineation, creating significant grey areas. Although the current design elements are provisionally accepted, the opportunity to redesign the entire fleet warrants a critical examination of these requirements. It is essential to question the necessity and future applicability of certain specifications. Are they genuinely required, and how should these obligations be addressed moving forward? Could they be approached differently?

Phased Implementation A phased approach to fleet renewal is recommended, beginning with hybrid energy systems that utilize batteries alongside fuels such as methanol. Hydrogen integration can follow as infrastructure and storage technologies advance, though it is not the immediate priority and will require further investigation. Decommissioning the current fleet should only proceed once the new vessels have demonstrated operational reliability. This gradual transition to zero-emission IRV vessels will ensure continuous operational performance while allowing for technological progress and evaluation of implementation. A phased approach also minimizes operational risks and facilitates the incorporation of lessons learned from earlier vessels as the fleet expands.

Integrating Sustainable Practices into Vessel Lifecycle Management The Port of Rotterdam should incorporate sustainability measures throughout the entire lifecycle of its vessels, from design and construction through operation and eventual disposal. Life Cycle Assessment (LCA) should be employed to evaluate the environmental impacts of vessels at each stage, ensuring that materials, energy sources, and systems are selected with long-term sustainability in mind. Additionally, the PoR is responsible for managing its vessels' end-of-life phase responsibly. Upon fleet replacement, consideration should be given to repurposing these ships for other applications within the port or sustainably dismantling them to minimize environmental impact.

13.2.1. Requirements and Influence Green Fuels

In summary, an overview of requirements most affected by zero-emission fuel integration has been compiled from this research and is presented in Table 8.2 and Table 8.3. Recommendations are provided for these requirements, highlighting potential future design challenges that should be addressed. Specific requirements, for instance, should be re-evaluated to ensure alignment with the vessel's tasks and operational needs. Table 13.1 outlines the selected requirements, accompanied by explanations of the recommendations and the specific impacts. Requirements with lower impact are marked in orange, while those with higher impact are indicated in red.

Table 13.1: Recommendations - Selected Requirements: Future Difficulty's in New Incident Response Vessel

Nr.	Requirement Component	Requirement Statement
1	Dimensions and Hull Specifications	
1.1	Length	The vessels cannot exceed the maximum length of 35 meters.
	Suggestion: To make all systems fit in the ship, the length will change with the increased space for fuels and systems. To remain operational, it may not exceed 35 m. The length will become an issue in determining the fleet and integrating all systems on board.	
2	Performance Requirements	
2.1	Speed	The vessel must achieve a maximum 31 km/h (16.75 knots).
	Suggestion: High speeds cost too much energy with electric drives. The speed will be achievable but for short intervals. Speed requirements need to be reconsidered.	
2.2	Range	The vessel must be capable of continuous operation for one 8-hour shift without refueling and maintain operational readiness for a minimum of 8 hours at 100% fuel capacity.
	Suggestion: The range will change due to green fuels and has already been scaled down to 8 hours instead of continuous operation for one week without refueling and maintaining operational readiness for a minimum of 48 hours at 50% fuel capacity. This has an impact on bunkering, planning, and berthing locations.	
3	Power and Propulsion	
3.1	Main Propulsion System	The vessel must have a net zero emissions propulsion system.
	Suggestion: Despite the complexity, sailing on green fuels is possible in the future. This requires adaptive power and new designs with modular construction.	
3.2	Auxiliary Power Systems	The vessel must have a UPS for critical systems with a minimum capacity of 500 kWh.
	Suggestion: Running all auxiliary power on green fuels will be a challenge. Especially extinguishing systems make that difficult and for this a hybrid system with methanol will be an option.	
4	Safety and Incident Response Systems	
4.1	Firefighting Equipment	The vessel must have two large fire pumps (45 m³/min at 12 bar), one small fire pump (2 m³/min at 8 bar), and multiple monitors (4 small, 1 large, 1 on firefighting arm).
	Suggestion: The amount of extinguishing affects the power supply and becomes a tricky part. The tasks must be made clear in order to design and have in the fleet ships that can meet this in the future.	
4.2	Pollution Control	The vessel must have oil booms for water pollution containment.
	Suggestion: Discuss whether this should be a task for red ships only or also blue ships.	
4.3	Search and Rescue	The vessel must have a rescue boarding platform (drenkelingen instap) at the rear or side.
	Suggestion: Discuss whether this should be a task for red ships only or also blue ships.	
4.4	Surveying	The operators shall be able to survey the port.
	Suggestion: Consider the necessity of this task, restructure and consider integration of this task among blue ships.	
4.5	Storage	The vessel must be able to store firefighting equipment, with a floor area of approximately 10 m², ensuring efficient use of the available height.
	Suggestion: Storage of equipment may become a bigger issue in the new ships, consider whether all equipment is needed on each ship.	
4.6	Foam System	The vessel must have a foam-forming system with a storage capacity of 9000 liters of foam. That must be able to deliver foam at full capacity (5,000 l/min) with a mixing ratio of 3%, requiring a foam supply for at least 20 minutes, resulting in a necessary storage capacity of 3,000 liters.
	Suggestion: Space constraints and new foam requirements must be carefully considered to ensure the correct amount of foam is carried on board.	
7	Deck and Cargo Handling	
7.1	Cranes	The vessel must have a deck crane with a minimum reach of 18 meters and a lifting capacity of 1.5 tons.
	Suggestion: Crane you want to have on board modularly and see if it can be installed in such a way that 2 are not needed.	
9	Crew Support and Accommodation	
9.1	Accommodation	The vessel must accommodate a minimum crew of 3 and a maximum of 5, with a day room for 9 people and multifunctional spaces including a pantry and meeting area.
	Suggestion: The office space on board the ship, including the living space, now takes up a large area. Consider moving this to the quay for space optimization.	

13.3. Discussion and Limitations

This study outlines a framework for a modular, zero-emission IRV fleet for the Port of Rotterdam, yet it also reveals several limitations and considerations for further investigation. The technological readiness of battery systems for large-scale maritime use remains uncertain, with hydrogen and methanol fuel cells adding even greater complexity. Infrastructure costs, especially for hydrogen, may also restrict the short-term feasibility of these systems. Currently, only electric systems, including battery-swapping technology, offer proven, market-ready solutions based on applications in the automotive industry.

Energy provision is a critical challenge. Space is limited, weight is increasing, safety regulations are evolving, and systems are becoming increasingly complex. Designing a fleet that meets these constraints requires balancing energy supply with operational needs, particularly as smaller vessels often fulfill only partial requirements. Distributing capabilities across multiple vessels could offer a solution, but it adds operational complexity.

Certain design specifications need re-evaluation. The 35-meter length constraint, for instance, may limit design flexibility, and a 31 km/h top speed could quickly drain battery power beyond sustainable limits. Foam systems and other ”nice-to-have” features should also be reassessed for necessity, with some potentially excluded to maintain a more adaptable design.

Further research is needed to validate these findings in real-world settings, especially concerning hybrid energy systems and the durability of modular components. The modular design’s long-term success will hinge on ongoing technological advancements and regulatory changes, highlighting the importance of continued collaboration with industry stakeholders.

Additionally, the Port of Rotterdam itself must adopt a flexible approach to infrastructure, ensuring sufficient charging capacity, managing grid congestion, and preparing for future uncertainties. This adaptability will be crucial for responding to industry shifts as the port advances toward a sustainable maritime future.

Modularity enhances fleet flexibility and enables standardization, reducing construction and maintenance costs. Modularity supports the Port of Rotterdam’s strategy of avoiding reliance on a single energy solution and facilitating future upgrades by allowing components such as propulsion systems and energy storage to be easily replaced without a complete rebuild. However, this approach requires careful coordination of module interfaces and higher initial engineering costs to ensure compatibility. Furthermore, only a few shipyards can construct modular vessels with the required interface compatibility for such complex systems.

Alternative Propulsion and Fuel Technologies

This research explored zero-emission energy systems, including electric propulsion, hydrogen fuel cells, and methanol engines. Each energy carrier presents unique advantages and limitations that influence its suitability for the operational requirements of the Port of Rotterdam. However, technical maturity and costs still need to be evaluated.

- **Electric Propulsion:** Electric propulsion is likely the most mature of the three options, with a well-developed charging infrastructure. Battery technology is particularly suited for port operations, where vessels are not required to cover long distances, and is ideal for short-duration, reliable missions such as incident response. However, current battery technology still suffers from limited energy density, necessitating frequent recharging and thereby limiting the operational availability of the vessels. The battery-swapping solution explored in this thesis offers an innovative approach but requires significant investment in specialized port infrastructure.
- **Hydrogen:** Hydrogen holds promising potential as a zero-emission fuel due to its high energy density and capability to support long-range operations. However, the storage requirements, such as cryogenic or high-pressure tanks, impose considerable space and weight constraints. Moreover, the hydrogen refueling infrastructure remains underdeveloped, both in the Port of Rotterdam and globally, raising concerns about its practical applicability in the short term.

- **Methanol:** Methanol is another viable option, mainly because it can be produced from renewable sources. Methanol provides higher energy density than batteries and is easier to store than hydrogen. Its liquid form also simplifies bunkering compared to gaseous fuels like hydrogen. However, while cleaner than traditional marine fuels, methanol combustion still produces emissions, making full decarbonization challenging unless paired with carbon capture technologies.

In summary, while each energy source offers distinct benefits, a phased approach that includes further validation of the technological maturity and cost implications of these options will be essential for informed decision-making. Furthermore, the technical feasibility of a fuel switch, including the associated costs, remains debatable and requires further investigation. Integrating fuel systems, whether combustion-based, fuel cell, or transfer systems, may present significant challenges in the future.

The last essential aspect to consider is the future trajectory of the industry. Currently, the swappable system appears to be the solution for the fleet's operation, design, and layout. However, an in-depth industry analysis has not been conducted. Additionally, this study does not provide a cost comparison between options, such as establishing a complete swapping infrastructure versus commissioning an additional vessel. The Commercial Readiness Level (CRL) should not be underestimated and warrants further investigation in future research.

Bibliography

[1] Yoji Akao. *Quality Function Deployment: Integrating Customer Requirements into Product Design*. G.H. Mazur (trans.) Cambridge, MA: Productivity Press, 1990.

[2] Moreno Alexander and Johannes Francis. *Feasibility Study of a Fast Electric Passenger Ferry*. Tech. rep. Delft: TU Delft Marine Technology, Aug. 2019. URL: http://repository.tudelft.nl/..

[3] Jon Anders. "Comparison of Alternative Marine Fuels SEA\LNG Ltd". In: (2019). ISSN: 2019-0567. URL: www.dnvgl.com.

[4] D Andrews. "The Sophistication of Early Stage Design for Complex Vessels". In: *International Journal of Maritime Engineering* Vol 160.SE 18 (2018). DOI: 10.3940/rina.ijme.2018.se.472.

[5] David Andrews. *100 Things a Ship Designer Needs To Know*. Tech. rep. Vancouver, Canada: 14th International Marine Design Conference, June 2022. DOI: https://doi.org/10.5957/IMDC-2022-230. URL: www.rina.org.uk.

[6] David Andrews. *CHOOSING THE STYLE OF A NEW DESIGN-THE KEY SHIP DESIGN DECISION*. Tech. rep.

[7] by BS Antonius Roi S-tvawau-i. *The Challenge of Standardization for Shipyards in Developing Countries Chairman. Departmental Committee on Graduate Students IBM 3a*. Tech. rep. 1993.

[8] V. Arrichiello and P. Gualeni. "Systems Engineering and Digital Twin: A Vision for the Future of Cruise Ships Design, Production and Operations". In: *International Journal on Interactive Design and Manufacturing (IJIDeM)* 14 (2020). DOI: 10.1007/s12008-019-00621-3.

[9] *ASD Tugs - Azimuth Stern Drive vessels — damen.com*. https://www.damen.com/vessels/tugs/. [Accessed 10-02-2024]. 2024.

[10] R. G. Askin and J. B. Goldberg. *Design and Analysis of Lean Production Systems*. Wiley, 2002.

[11] P. G. Balakrishnan, R. Ramesh, and T. P. Kumar. "Safety Mechanisms in Lithium-Ion Batteries". In: *Journal of Power Sources* 155.2 (2006), pp. 401–414. DOI: 10.1016/j.jpowsour.2005.09.001. URL: https://doi.org/10.1016/j.jpowsour.2005.09.001.

[12] C. Y. Baldwin and K. B. Clark. "Managing in an Age of Modularity". In: *Harvard Business Review* 75.5 (Sept. 1997), pp. 84–93.

[13] Carliss Y. Baldwin and Kim B. Clark. *Design Rules, Volume 1, The Power of Modularity*. Cambridge, MA: MIT Press, 2000.

[14] Benjamin S. Blanchard. *System Engineering Management*. John Wiley & Sons, 2004.

[15] Elena C. Blanco et al. "Methanol and ammonia as emerging green fuels: Evaluation of a new power generation paradigm". In: *Renewable and Sustainable Energy Reviews* 175 (Apr. 2023). ISSN: 18790690. DOI: 10.1016/j.rser.2023.113195.

[16] Ties Bruinessen et al. "Towards a Different View on Ship Design: The Development of Ships Observed Through a Social-Technological Perspective". In: *Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE)*. Vol. 1. June 2013. DOI: 10.1115/OMAE2013-11585.

[17] Stefano Brusoni et al. "The power of modularity today: 20 years of "Design Rules"". In: (2023). DOI: 10.1093/icc/dtac054/6972656. URL: https://academic.oup.com/icc/advance-article/doi/10.1093/icc/dtac054/6972656.

[18] V. Bucci et al. "Evolution in Design Methodology for Complex Electric Ships". In: *Journal of Ship Production and Design* 37 (2021), pp. 1–13. DOI: 10.5957/JSPD.08190045.

[19] Allard Castelein. *Building a Sustainable Port*. Tech. rep. 2019.

[20] Peter Cebon, Oscar Hauptman, and Chander Shekhar. “Product modularity and the product life cycle: New dynamics in the interactions of product and process technologies”. In: *International Journal of Technology Management* 42.4 (2008), pp. 365–386. ISSN: 02675730. DOI: 10.1504/IJTM.2008.019381.

[21] J. Chalfant. “Early-stage Design for Electric Ship”. In: *Proceedings of the IEEE* 103.12 (2015), pp. 2252–2266. DOI: 10.1109/JPROC.2015.2459672.

[22] Connie Chang Assistant Professor, Sally Dibb Professor of Marketing, and openacuk -. *Reviewing and Conceptualising Customer-Perceived Value*. Tech. rep. 2012.

[23] N. D. Charisi, A. Kana, and J. J. Hopman. “Early-stage design of novel vessels: How can we take a step forward?” In: *SNAME 14th International Marine Design Conference, IMDC 2022*. Society of Naval Architects and Marine Engineers, 2022. DOI: 10.5957/IMDC-2022-239.

[24] Kim B Clark and Steven C Wheelwright. “Product Development Challenge: Competing Through Speed, Quality, and Creativity (Hardcover)”. In: *Harvard Business School Press Books* (1995). ISSN: 19300166.

[25] Bjorn Cole et al. “Model Based Systems Engineering: Application and Lessons from a Technology Maturation Project”. In: *Proceedings of the 17th Annual Conference on Systems Engineering Research (CSER)* (2019).

[26] Damen. *RSD Tug 2513 Electric | Damen — damen.com*. https://www.damen.com/vessels/tugs/electric-tugs/rsd-tug-2513-electric. [Accessed 18-12-2023]. 2022.

[27] M. Danilovic and T. R. Browning. “Managing Complex Product Development Projects with Design Structure Matrices and Domain Mapping Matrices”. In: *International Journal of Project Management* 25.3 (2007), pp. 300–314.

[28] Steven J. Davis et al. *Net-zero emissions energy systems*. June 2018. DOI: 10.1126/science.aas9793.

[29] Us Department of Energy. *U.S. Department of Energy Hydrogen Program 2021 Annual Merit Review and Peer Evaluation Report*. Tech. rep. 2021.

[30] D. R. Derrett and C. B. Barrass. *Ship Stability for Masters and Mates*. 7th ed. Elsevier, 2012. ISBN: 978-0080970936.

[31] DHR Marine. *Navigation Lights*. Accessed: [Insert date of access here]. 2023. URL: https://www.dhr.nl/dhr-marine/products/navigation-lights.

[32] Distance.to. *Distance Calculation Tool*. Accessed: [24-08-2024]. 2023. URL: https://nl.distance.to/.

[33] DNV. *Maritime Forecast To 2050*. Tech. rep. DNV, July 2024.

[34] Andrea Dobberfuhl and Mark W. Lange. “Interfaces per module is there an ideal number?” In: *Proceedings of the ASME Design Engineering Technical Conference*. Vol. 2. PARTS A AND B. 2009. DOI: 10.1115/DETC2009-86872.

[35] N. Doerry et al. *Using Set-Based Design in Concept Exploration*. Presented/Published at [Insert Conference or Organization here if applicable]. Arlington, VA, USA, 2014.

[36] E. A. E. Duchateau. “Interactive Evolutionary Concept Exploration in Preliminary Ship Design”. Available at TU Delft Library. Doctoral thesis. Delft University of Technology, 2016. URL: https://doi.org/10.4233/uuid:27ff1635-2626-4958-bcdb8aee282865c8.

[37] Etienne Duchateau. “Interactive evolutionary concept exploration in preliminary ship design”. In: (2014). DOI: 10.4233/uuid:27ff1635-2626-4958-bcdb-8aee282865c8. URL: https://doi.org/10.4233/uuid:27ff1635-2626-4958-bcdb-.

[38] D. R. Elvekrok. “Concurrent Engineering in Ship Design”. In: *Journal of Ship Production* 13.4 (1997), pp. 258–269. DOI: 10.5957/JSP.1997.13.4.258. URL: https://doi.org/10.5957/JSP.1997.13.4.258.

[39] Stein Erikstad et al. “System Based Design of Offshore Support Vessels”. In: *Proceedings of [Insert Conference Name Here]*. Please update the conference name and any other missing details. Jan. 2012.

[40] European Environment Agency. *Ammonia (NH3) Emissions*. Accessed: [Insert date of access here]. 2010. URL: https://www.eea.europa.eu/data-and-maps/indicators/eea-32-ammonia-nh3-emissions-1.

[41] J. H. Evans. "Basic Design Concepts". In: *Journal of the American Society for Naval Engineers* 71.4 (1959), pp. 671–678. DOI: 10.1111/j.1559-3584.1959.tb01836.x. URL: https://onlinelibrary.wiley.com/doi/abs/10.1111/j.1559-3584.1959.tb01836.x.

[42] M. A. Fahim, T. A. Alsahhaf, and A. Elkilani. "Chapter 12 - Clean Fuels". In: *Fundamentals of Petroleum Refining*. Ed. by M. A. Fahim et al. Amsterdam: Elsevier, 2010, pp. 303–324. ISBN: 978-0-444-52785-1. DOI: 10.1016/B978-0-444-52785-1.00012-7. URL: https://www.sciencedirect.com/science/article/pii/B9780444527851000127.

[43] Fassi. *F660RA He-Dynamic Loader Crane*. Accessed: [Insert date of access here]. 2023. URL: https://www.fassi.com/fassi-loader-crane/heavy-duty/f660ra-he-dynamic.html.

[44] M. E. Fitzgerald and A. M. Ross. "Artificial Intelligence Analytics with Multi-Attribute Tradespace Exploration and Set-Based Design". In: *17th Annual Conference on Systems Engineering Research (CSER)*. Vol. 153. 2019, pp. 27–36. DOI: 10.1016/j.procs.2019.05.037. URL: https://www.sciencedirect.com/science/article/pii/S1877050919307112.

[45] Sebastian K. Fixson. "Modularity and commonality research: Past developments and future opportunities". In: *Concurrent Engineering Research and Applications* 15.2 (2007). ISSN: 1063293X. DOI: 10.1177/1063293X07078935.

[46] Christoph Fuchs and Franziska J Golenhofen. *Management for Professionals Mastering Disruption and Innovation in Product Management Connecting the Dots*. Tech. rep. 2018. DOI: https://doi.org/10.1007/978-3-319-93512-6. URL: http://www.springer.com/series/10101.

[47] Christoph Fuchs and Franziska J Golenhofen. *Management for Professionals Mastering Disruption and Innovation in Product Management Connecting the Dots*. Tech. rep. URL: http://www.springer.com/series/10101.

[48] H. M. Gaspar et al. "Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach". In: *Journal of Ship Production and Design* 28.4 (2012), pp. 145–159. DOI: 10.5957/JSPD.28.4.120015.

[49] R. D. Geertsma et al. *Design and control of hybrid power and propulsion systems for smart ships: A review of developments*. 2017. DOI: 10.1016/j.apenergy.2017.02.060.

[50] K. Gericke and L. T. Blessing. "Comparisons of Design Methodologies and Process Models Across Disciplines: A Literature Review". In: *Design Studies* 32.2 (2011), pp. 227–265.

[51] Kilian Gericke, Lucienne Blessing, and Luciënne Blessing. *Comparisons of design methodologies and process models across disciplines: A literature review INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11 COMPARISONS OF DESIGN METHODOLOGIES AND PROCESS MODELS ACROSS DISCIPLINES: A LITERATURE REVIEW*. Tech. rep. 2011. URL: https://www.researchgate.net/publication/237049562.

[52] Taylor Dean Goodrum et al. "Understanding Initial Design Spaces: Set-Based Design Using Networks and Information Theory". In: *Advances in Human Factors and Ergonomics*. Ed. by Gavriel Salvendy. CRC Press, 2019. Chap. 33, pp. 421–435. URL: https://www.taylorfrancis.com/.

[53] P Gu and S Sosale. *Product modularization for life cycle engineering*. Tech. rep. 1999, pp. 387–401.

[54] P. Gu, M. Hashemian, and A. Y. C. Nee. "Adaptable Design". In: *CIRP Annals* 53.2 (2004), pp. 539–557.

[55] Gunnar Erixon. "Modular Function Deployment (MFD), Support for Good Product Structure Creation". In: *Centre for Industrial Engineering at Dalarna University and KTH* (1998).

[56] Roy L Harrington. *Marine Engineering*. Jersey City, NJ, USA: Society of Naval Architects and Marine Engineers, 1992. ISBN: 978-0-939773-10-7. URL: https://app.knovel.com/hotlink/khtml/id:kt010R58J5/marine-engineering/historical-perspective.

[57] Heila Cranes. *Fully Foldable Telescopic Crane*. Accessed: [Insert date of access here]. 2023. URL: https://heila.com/fully-foldable-telescopic-crane/.

[58] M. J. Henshaw et al. “Systems of Systems, Systems Engineering, and Test and Evaluation”. In: *International Test and Evaluation Association Journal* 32.1 (2011), pp. 3–8.

[59] J J M Hermans. *Retrofit modeling for green ships A data-driven design approach for emission reduction using bunker delivery notes*. Tech. rep. Delft: TUDelft, Mar. 2024. URL: http://repository.tudelft.nl/..

[60] Cornelius Herstatt and Birgit Verworn. “The ‘Fuzzy Front End’ of Innovation”. In: *Bringing Technology and Innovation into the Boardroom*. Palgrave Macmillan UK, 2004, pp. 347–372. DOI: 10.1057/9780230512771{_}16.

[61] Julie Hirtz et al. “A functional basis for engineering design: Reconciling and evolving previous efforts”. In: *Research in Engineering Design - Theory, Applications, and Concurrent Engineering* 13.2 (2002), pp. 65–82. ISSN: 09349839. DOI: 10.1007/s00163-001-0008-3.

[62] A. S. Hornby and Joanna Turnbull. *Oxford Advanced Learner’s Dictionary of Current English*. 8th ed. Managing editor: Joanna Turnbull. Oxford: Oxford University Press, 2010.

[63] C. C. Huang. “Overview of modular product development”. In: *Proceedings of the National Science Council, Republic of China, Part A: Physical Science and Engineering* 24.3 (2000). ISSN: 02556588.

[64] D. Huang. *Speciality English for Fundamentals and Concepts in Shipbuilding Engineering*. Beijing: National Defense Industry Press, 2013.

[65] IMO. *IMO Strategy on Reduction of GHG Emissions from Ships*. 2023. URL: https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx?trk=article-ssr-frontend-pulse_little-text-block.

[66] Instrument Solutions. *E-Nose Technology for Organoleptic Analysis*. Accessed: [03-09-2024]. 2023. URL: https://www.instrument-solutions.com/technologie/organoleptische-analyse/e-nose.

[67] International Maritime Organization. *Alternative Fuels: Technology and Commercial Readiness*. Accessed: [Insert date of access here]. 2023. URL: https://futurefuels.imo.org/home/future-insight/alternative-fuels/technology-and-commercial-readiness/.

[68] International Maritime Organization. *MEPC 295 71*. Tech. rep. July 2017. URL: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/MEPC.295(71).pdf.

[69] Interstate Technology Regulatory Council (ITRC). *Firefighting Foams*. Accessed: [26-08-2024]. 2023. URL: https://pfas-1.itrcweb.org/3-firefighting-foams/.

[70] IRENA and Methanol Institute. *Innovation Outlook: Renewable Methanol*. Accessed: [Insert date of access here]. 2021. URL: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2021/Jan/IRENA_Innovation_Renewable_Methanol_2021.pdf.

[71] A. C. Habben Jansen. “A Markov-Based Vulnerability Assessment of Distributed Ship Systems in the Early Design Stage”. Doctoral dissertation. Delft University of Technology, 2020. DOI: 10.4233/UUID:F636539F-64A5-4985-B77F-4A0B8C3990F4.

[72] A. C. Habben Jansen et al. “A Framework for Vulnerability Reduction in Early Stage Design of Naval Ship Systems”. In: *Naval Engineers Journal* 132-2 (2020).

[73] Daniel I Janson et al. *The Development of a Green Shipyard Concept*. Tech. rep. 2016.

[74] Serope Kalpakjian and Steven R. Schmid. *Manufacturing Processes for Engineering Materials*. 6th ed. Pearson Education, 2017. ISBN: 978-0-13-429055-3.

[75] Zahid A S M Kawser. *A Modular Design Methodology for OSV Accommodation Areas*. Tech. rep. Trondheim: Norwegian University of Science and Technology, June 2012.

[76] Corey Kerns. “Naval Ship Design and Synthesis Model Architecture Using a Model-Based Systems Engineering Approach”. Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Ocean Engineering. Alan J. Brown, Chairman. Master’s thesis. Blacksburg, Virginia: Virginia Polytechnic Institute and State University, 2011.

[77] Matthew Keyser et al. “Enabling fast charging – Battery thermal considerations”. In: *Journal of Power Sources* 367 (Nov. 2017), pp. 228–236. ISSN: 03787753. DOI: 10.1016/j.jpowsour.2017.07.009.

[78] A Khoryanton et al. “Participatory rural appraisal strategy in realizing the standardization of ship components”. In: *IOP Conference Series: Materials Science and Engineering* 1108.1 (2021). ISSN: 1757-8981. DOI: 10.1088/1757-899x/1108/1/012048.

[79] T. Klein. *Methanol: A Future-Proof Fuel*. Accessed: [Insert date of access here]. 2020. URL: https://www.methanol.org/wp-content/uploads/2020/03/Future-Fuel-Strategies-Methanol-Automotive-Fuel-Primer.pdf.

[80] Claudia Koch and Knut Blind. “Towards Agile Standardization: Testbeds in Support of Standardization for the IIoT”. In: *IEEE Transactions on Engineering Management* 68.1 (2021). ISSN: 15580040. DOI: 10.1109/TEM.2020.2979697.

[81] Markus Kohl, Michael Roth, and Udo Lindemann. *Safety-oriented Modular Function Deployment*. Tech. rep. 2016.

[82] Aleksander A. Kondratenko, Pentti Kujala, and Spyros E. Hirdaris. “Holistic and Sustainable Design Optimization of Arctic Ships”. In: *Ocean Engineering* (2023). Received 13 September 2022; Revised 25 November 2022; Accepted 2 March 2023, p. 114095. DOI: 10.1016/j.oceaneng.2023.114095.

[83] Toyohiro Kono and Leonard Lynn. *Strategic new product development for the global economy*. 2007. DOI: 10.1057/9780230599383.

[84] Jerry Krasner. *How Product Development Organizations Can Achieve Long-Term Cost Savings Using Model-Based Systems Engineering (MBSE)*. How financial managers can achieve lower costs of development, faster deployment of new products, and lower ongoing maintenance costs. Oct. 2015.

[85] Kroes Marine. *Rapport Onderzoek Emissieloze Vaartuigen Havenbedrijf Rotterdam*. Tech. rep. 2022.

[86] Thomas. Lamb. *Ship design and construction*. Society of Naval Architects and Marine Engineers, 20032004. ISBN: 0939773406.

[87] Jesús F. Lampón and Elena Rivo-López. “Modular product architecture implementation and decisions on production network structure and strategic plant roles”. In: *Production Planning and Control* 33.15 (2022), pp. 1449–1464. ISSN: 13665871. DOI: 10.1080/09537287.2021.1877367.

[88] F. Larsson et al. “Toxic Fluoride Gas Emissions from Lithium-Ion Battery Fires”. In: *Scientific Reports* 7 (2017), p. 10018. DOI: 10.1038/s41598-017-09784-z. URL: https://doi.org/10.1038/s41598-017-09784-z.

[89] Lars Larsson and Rolf Eliasson. *Principles of Yacht Design*. 3rd ed. London, UK: Adlard Coles Nautical, 2000.

[90] C. Lautenberger, J. Torero, and C. Fernandez-Pello. “Understanding Materials Flammability”. In: *Flammability Testing of Materials Used in Construction, Transport and Mining*. Ed. by V. B. Apte. Woodhead Publishing, 2006, pp. 1–21. ISBN: 978-1-85573-935-2. DOI: 10.1533/9781845691042.1. URL: https://www.sciencedirect.com/science/article/pii/B9781855739352500016.

[91] Edward V. Lewis. *Principles of Naval Architecture, Volume 1*. 2nd ed. Society of Naval Architects and Marine Engineers (SNAME), 1988.

[92] W. Li. “Application of Digital Twins in the Design of New Green Transport Vessels”. Available at TU Delft Library. Master’s thesis. Delft University of Technology, 2023. URL: http://resolver.tudelft.nl/uuid:728e8857-1c6d-444d-a1af-06c710095056.

[93] D. Linden and T. B. Reddy. *Handbook of Batteries*. 3rd ed. McGraw-Hill, 2002.

[94] Lloyd Registers. *Engine Retrofit Report 2023: Applying alternative fuels to existing ships*. English. Tech. rep. LloydRegister, 2023. URL: www.lr.org/fuelforthought.

[95] Lloyd's Register. *Maritime Decarbonisation Hub: Zero-Carbon Fuel Monitor*. Accessed: [Insert date of access here]. 2023. URL: https://www.lr.org/en/expertise/maritime-energy-transition/maritime-decarbonisation-hub/zcfm/.

[96] P. Machiele. *Summary of the Fire Safety Impacts of Methanol as a Transportation Fuel*. Tech. rep. Technical report. SAE International, 1990. URL: https://saemobilus.sae.org/content/901113/.

[97] Azad M. Madni and Michael Sievers. "Model-Based Systems Engineering: Motivation, Current Status, and Research Opportunities". In: *Systems Engineering* (2018). First published: 08 May 2018, Citations: 213. DOI: 10.1002/sys.21438.

[98] A. Manthiram. "A Reflection on Lithium-Ion Battery Cathode Chemistry". In: *Nature Communications* 8.1 (2017), p. 14522. DOI: 10.1038/ncomms14522. URL: https://doi.org/10.1038/ncomms14522.

[99] MARIN. *MARIN Official Website*. Accessed: [24-08-2024]. 2023. URL: https://www.marin.nl/nl.

[100] Marine HVAC Design. *Marine HVAC Design Official Website*. Accessed: [01-09-2024]. 2023. URL: https://marinehvacdesign.com/.

[101] F. Mauro and A. Kana. "Digital Twin for Ship Life-Cycle: A Critical Systematic Review". In: *Ocean Engineering* 269 (2023), p. 113479. DOI: 10.1016/j.oceaneng.2022.113479. URL: https://doi.org/10.1016/j.oceaneng.2022.113479.

[102] Dimitri N Mavris and Daniel Delaurentis. *Methodology for Examining the Simultaneous Impact of Requirements, Vehicle Characteristics, and Technologies on Military Aircraft Design*. Tech. rep. 2000. URL: http://www.asdl..

[103] K. Mazloomi and C. Gomes. "Hydrogen as an Energy Carrier: Prospects and Challenges". In: *Renewable and Sustainable Energy Reviews* 16 (2012), pp. 3024–3033. DOI: 10.1016/j.rser.2012.02.028.

[104] Thomas McKenney. "An Early-Stage Set-Based Design Reduction Decision Support Framework Utilizing Design Space Mapping and a Graph Theoretic Markov Decision Process Formulation". Available at: University of Michigan Library. Doctoral thesis. University of Michigan, 2013. URL: https://hdl.handle.net/2027.42/102464.

[105] Methanol Institute. *Methanol Safe Handling Manual*. Accessed: [Insert date of access here]. 2017. URL: https://www.methanol.org/wp-content/uploads/2020/03/Safe-Handling-Manual_5th-Edition_Final.pdf.

[106] Liu Ming Main Author et al. *Methanol as a Marine Fuel-Availability and Sea Trial Considerations Alternative Fuels for International Shipping A Study on the Future Energy Options of Singapore Harbour Craft Electrification of Singapore Harbour Craft-Shore and Vessel Power System Considerations Executive Summary*. Tech. rep. 2020.

[107] S. P. Mitrofanov. *Scientific Principles of Group Technology*. Moscow, Russia: Partizdat, 1966.

[108] E. Mosedale. *Is the Ship Design Spiral Holding You Back?* Accessed: [Insert date of access here]. July 2020. URL: https://blogs.sw.siemens.com/simcenter/ship-design-spiral-simcenter/.

[109] S. Mouzakitis et al. "Enabling Maritime Digitalization by Extreme-Scale Analytics, AI, and Digital Twins: The VesselAI Architecture". In: *Proceedings of [Insert Conference Name Here]*. Please update with conference details if applicable. Sept. 2023. DOI: 10.1007/978-3-031-16075-2_16.

[110] B. Ni and L. Zeng. *Ship Design Process*. Ed. by W. Cui, S. Fu, and Z. Hu. Springer Singapore, 2019, pp. 1–8. DOI: 10.1007/978-981-10-6963-5_36-1. URL: https://doi.org/10.1007/978-981-10-6963-5_36-1.

[111] Lampros Nikolopoulos and Evangelos Boulougouris. "A Novel Method for the Holistic, Simulation Driven Ship Design Optimization Under Uncertainty in the Big Data Era". In: *Ocean Engineering* (2020). School of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde in Glasgow, UK, p. 107634. DOI: 10.1016/j.oceaneng.2020.107634.

[112] Per Nilsson and Gwmar Erixon. *The Chart of Modular Function Deployment*. Tech. rep. Delft, The Netherlands: Delft University of Technology, Oct. 1998.

[113] NOAA Office of Response and Restoration. *Spill Containment Methods*. Accessed: [03-09-2024]. 2023. URL: https://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/spill-containment-methods.html.

[114] Norled. *Norled Official Website*. Accessed: [22-08-2024]. 2023. URL: https://www.norled.no/en/.

[115] H. Nowacki. "Five Decades of Computer-Aided Ship Design". In: *Computer-Aided Design* 42.11 (2010). Computer Aided Ship Design: Some Recent Results and Steps Ahead in Theory, Methodology and Practice, pp. 956–969. DOI: 10.1016/j.cad.2009.12.002. URL: https://www.sciencedirect.com/science/article/pii/S0010448509001985.

[116] George A. Olah. "Beyond oil and gas: The methanol economy". In: *Angewandte Chemie - International Edition* 44.18 (Apr. 2005), pp. 2636–2639. ISSN: 14337851. DOI: 10.1002/anie.200462121.

[117] OSHA European Agency for Safety and Health at Work. *Directive 2000/39/EC - Indicative Occupational Exposure Limit Values*. Accessed: [Insert date of access here]. 2000. URL: https://osha.europa.eu/en/legislation/directives/directive-2000-39-ec-indicative-occupational-exposure-limit-values.

[118] OSHA European Agency for Safety and Health at Work. *Directive 2006/15/EC - Indicative Occupational Exposure Limit Values*. Accessed: [Insert date of access here]. 2006. URL: https://osha.europa.eu/en/legislation/directives/commission-directive-2006-15-ec.

[119] Gerhard Pahl and Wolfgang Beitz. *Engineering Design: A Systematic Approach*. 3rd ed. Library of Congress Control Number: 2006938893. London, UK: Springer, 1996. ISBN: 978-1-84628-318-5.

[120] Palfinger. *FL Range Truck-Mounted Forklifts*. Accessed: [Insert date of access here]. 2023. URL: https://www.palfinger.com/en/products/truck-mounted-forklifts/fl-range?gad_source=1&gclid=Cj0KCQjwu-63BhC9ARIsAMMTLXSvZi0pUBd73UxvVlyuT_HsNQMTdFxB-2Qj4A8YcAZNR7W1GZVZDggaAupBEALw_wcB.

[121] A. Papanikolaou. "Developments and Potential of Advanced Marine Vehicles Concepts". In: *Bulletin of the KANSAI Society of Naval Architects, Japan* 55 (2002), pp. 50–54.

[122] Apostolos D. Papanikolaou. "Holistic Approach to Ship Design". In: *Journal of Marine Science and Engineering* 10.11 (Nov. 2022). ISSN: 20771312. DOI: 10.3390/jmse10111717.

[123] Paul Pearce and Sanford Friedenthal. "A Practical Approach for Modelling Submarine Subsystem Architecture in SysML". In: *Proceedings of [Insert Conference Name Here]*. ASC Pty. Ltd. and SAF Consulting. Osborne, South Australia and Fairfax, Virginia, USA, 2020.

[124] Thomas U. Pimmler and Steven D. Eppinger. "Integration Analysis of Product Decompositions". In: *Proceedings of the ASME 1994 Design Engineering Technical Conferences* (1994). Paper No: DETC1994-0034, pp. 343–351. DOI: 10.1115/DETC1994-0034. URL: https://doi.org/10.1115/DETC1994-0034 (visited on 03/12/2021).

[125] J. J. le Poole et al. "On-The-Fly Design Rationale to Support Real-Time Collaborative Naval Ship Layout Design". In: *Proceedings of the SNAME 14th International Marine Design Conference, IMDC 2022* (June 26–30, 2022). Published at SNAME 14th International Marine Design Conference, IMDC 2022, Vancouver, Canada. Vancouver, Canada, 2022, pp. 1–16.

[126] Ioannis Poulis. "Application of Model Based System Engineering (MBSE) with Ship Design Arrangement Tool of Advanced Zero Emissions Power, Propulsion and Energy Systems in Maritime Technology". Available at TU Delft Library. Master's thesis. Delft University of Technology, 2022. URL: http://resolver.tudelft.nl/uuid:7faf4cc0-c493-4efb-ad3b-5046ca208288.

[127] Rohan Pradhan et al. "Battery Swapping System for the Electric Vehicles". In: *3rd IEEE 2022 International Conference on Computing, Communication, and Intelligent Systems, ICCCIS 2022*. Institute of Electrical and Electronics Engineers Inc., 2022, pp. 919–924. ISBN: 9781665462006. DOI: 10.1109/ICCCIS56430.2022.10037225.

[128] Bimal Prasad and Nepal Dissertation. *AN INTEGRATED FRAMEWORK FOR MODULAR PRODUCT ARCHITECTURE*. Tech. rep. 2005.

[129] S. Pugh. *Total Design: Integrated Methods for Successful Product Engineering*. Addison-Wesley, 1991.

[130] R.J.Smit. "Modular Platform Towards a Product Family for a Series of Navy Support Vessels". In: 1 (2019), pp. 1–160.

[131] J. B. ReVelle, J. W. Moran, and C. A. Cox. *The QFD Handbook*. Wiley, 1998.

[132] Evelien Scheffers. *An improved approach for on-board distribution system robustness estimation in early-stage ship design*. Tech. rep. 2021. URL: `http://repository.tudelft.nl/..`

[133] Melissa A. Schilling. "Toward a general modular systems theory and its application to interfirm product modularity". In: *Academy of Management Review* 25.2 (2000). ISSN: 03637425. DOI: `10.5465/AMR.2000.3312918`.

[134] N. Shevchenko. *An Introduction to Model-Based Systems Engineering (MBSE)*. Retrieved September 18, 2024. Dec. 2020. URL: `https://insights.sei.cmu.edu/blog/introduction-model-based-systems-engineering-mbse/`.

[135] W. Shi et al. "Evolution of Green Shipping Research: Themes and Methods". In: *Maritime Policy & Management* 45.7 (2018), pp. 863–876. DOI: `10.1080/03088839.2018.1505057`.

[136] Vasileios Sideris. *Advancing Model-Based Systems Engineering (MBSE) in the Development of Systems Architecture Exploring the Value of MBSE during Early-Stage Naval Vessel Design*. Tech. rep. Delft: TUDelft, July 2024. URL: `http://repository.tudelft.nl/..`

[137] Timothy W Simpson Jianxin Jiao Zahed Siddique Katja Hölttä-Otto Editors. *Advances in Product Family and Product Platform Design*. Tech. rep. 2014. DOI: `10.1007/978-1-4614-7937-6`.

[138] Timothy W Simpson Jianxin Jiao Zahed Siddique Katja Hölttä-Otto Editors. *Advances in Product Family and Product Platform Design*. Tech. rep.

[139] David Singer et al. "What Is Set-Based Design?" In: *Naval Engineers Journal* 121 (Oct. 2009), pp. 31–43. DOI: `10.1111/j.1559-3584.2009.00226.x`.

[140] R J Smit. *Modular Platform Towards a Product Family for a Series of Navy Support Vessels*. Tech. rep.

[141] J. Brock Smith and Mark Colgate. "Customer value creation: A practical framework". In: *Journal of Marketing Theory and Practice* 15.1 (Dec. 2007), pp. 7–23. ISSN: 10696679. DOI: `10.2753/MTP1069-6679150101`.

[142] D. K. Sobek. "Principles that Shape Product Development Systems: A Toyota-Chrysler Comparison". Available at: University of Michigan Library. Doctoral thesis. University of Michigan, 1997. URL: `https://hdl.handle.net/2027.42/130365`.

[143] Manuel E. Sosa, Steven D. Eppinger, and Craig M. Rowles. "Identifying Modular and Integrative Systems and Their Impact on Design Team Interactions". In: *Journal of Mechanical Design* 125.2 (2003). Published Online: June 11, 2003, pp. 240–252. DOI: `10.1115/1.1564074`. URL: `https://doi.org/10.1115/1.1564074` (visited on 06/11/2003).

[144] Ctibor Stadler and Stanislav Hosnedl. "Development and application of Modular Function Deployment". In: Dubrovnik: International Design Conference - Design 2002, May 2002.

[145] Sungold Solar. *Flexible Solar Panel*. Accessed: [Insert date of access here]. 2023. URL: `https://www.sungoldsolar.com/flexible-solar-panel/?gad_source=1&gclid=Cj0KCQjwu-63BhC9ARIsAMMTLXQfxlqvCpD3wyvjP0xtLCmooyWj4thkwZ_f_X4FBS1mmG5qfwnh3OEaAuOKEALw_wcB`.

[146] R. Taggart. "Ship Design and Construction". In: *Coating* (1980).

[147] Nadia Tepper. "Exploring the Use of Model-Based Systems Engineering (MBSE) to Develop Systems Architectures in Naval Ship Design". Available at MIT Libraries. Master's thesis. Massachusetts Institute of Technology, 2010. URL: `http://hdl.handle.net/1721.1/61910`.

[148] Tom Soik. *Ship Production Symposium Proceedings Paper No. 9B-1: Standardized Designs Within a Shipyard-Basing Decisions on Costs Versus Returns*. Tech. rep. 1992. URL: https://apps.dtic.mil/sti/tr/pdf/ADA458243.pdf.

[149] Trelleborg Marine and Infrastructure. *Environmental Monitoring for Docking and Mooring*. Accessed: [03-09-2024]. 2023. URL: https://www.trelleborg.com/en/marine-and-infrastructure/products-solutions-and-services/marine/docking-and-mooring/environmental-monitoring.

[150] U.S. Department of Energy. *Fuel Cell Handbook (Seventh Edition)*. Tech. rep. 2004.

[151] K. T. Ulrich and S. D. Eppinger. *Product Design and Development*. 6th ed. McGraw-Hill, 2016.

[152] A. Valera-Medina et al. “Ammonia for Power”. In: *Progress in Energy and Combustion Science* 69 (2018), pp. 63–102. ISSN: 0360-1285. DOI: 10.1016/j.pecs.2018.07.001. URL: https://www.sciencedirect.com/science/article/pii/S0360128517302320.

[153] T ; Van Essen et al. *Optimizing inventory strategy for modular shipbuilding*. Tech. rep. 2019, pp. 165–172. URL: https://www.openaccess.nl/en/you-share-we-take-care.

[154] Laurens Van Hoecke et al. “Challenges in the use of hydrogen for maritime applications”. In: *Energy & Environmental Science* 14.2 (2021), pp. 815–843. ISSN: 1754-5692. DOI: 10.1039/D0EE01545H.

[155] Bart Van Oers et al. “Warship Concept Exploration and Definition at The Netherlands Defence Materiel Organisation”. In: *Naval Engineers Journal* 130 (June 2018), p. 61.

[156] Stephen L. Vargo, Paul P. Maglio, and Melissa Archpru Akaka. “On value and value co-creation: A service systems and service logic perspective”. In: *European Management Journal* 26.3 (June 2008), pp. 145–152. ISSN: 02632373. DOI: 10.1016/j.emj.2008.04.003.

[157] Jaya Verma and Deepak Kumar. *Recent developments in energy storage systems for marine environment*. Nov. 2021. DOI: 10.1039/d1ma00746g.

[158] Charles H. Vervalin. *Fire Protection Manual for Hydrocarbon Processing Plants, Volume 2*. Gulf Publishing Company, 1981. ISBN: 978-0872012882.

[159] VesselFinder. *RPA10*. 2023. URL: https://www.vesselfinder.com/nl/vessels/details/9239563 (visited on 11/24/2023).

[160] Øyvind Vestbøstad. “System Based Ship Design for Offshore Vessels”. Available at NTNU Open. Master’s thesis. Norwegian University of Science and Technology (NTNU), 2011. URL: http://hdl.handle.net/11250/265905.

[161] K. M. Wallace and L. T. M. Blessing. “A Structured Approach to Functional Breakdown”. In: *Design Studies* 21.5 (2000), pp. 453–470.

[162] Yifan Wang and Laurence A. Wright. “A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation”. In: *World* 2.4 (Oct. 2021), pp. 456–481. DOI: 10.3390/world2040029.

[163] A. C. Ward et al. “The Second Toyota Paradox: How Delaying Decisions Can Make Better Cars Faster”. In: *Sloan Management Review* 36.2 (1995), pp. 43–61.

[164] D G M Watson. *ELSEVIER OCEAN ENGINEERING BOOK SERIES VOLUME 1 PRACTICAL SHIP DESIGN*. Tech. rep. 2002.

[165] WebsiteNI. *Artemis Technologies - Maritime Technology — artemistechnologies.co.uk*. https://www.artemistechnologies.co.uk/. [Accessed 10-04-2024]. 2024.

[166] Frank M. White. *Fluid Mechanics*. 8th ed. McGraw-Hill, 2016. ISBN: 978-0077422417.

[167] K. Wilcox. “Fusing Models and Data to Achieve Efficient Design, Optimization, and Uncertainty Quantification”. In: (Sept. 2018).

[168] Yuqing Yang et al. *Battery energy storage system size determination in renewable energy systems: A review*. Aug. 2018. DOI: 10.1016/j.rser.2018.03.047.

[169] Meiling Yue et al. *Hydrogen energy systems: A critical review of technologies, applications, trends and challenges*. Aug. 2021. DOI: 10.1016/j.rser.2021.111180.

A

Appendix: Current fleet of AM Port of Rotterdam

A.1. Red Ships

In figure A.1 all the red vessels are shown:

(a) RPA10 (building year 2002)

(b) RPA 11 (building year 2002)

(c) RPA 12 (building year 2002)

(d) RPA 13 (building year 2002)

(e) RPA 14 (building year 1985)

(f) RPA 15 (building year 1985)

(g) RPA 16 (building year 2002)

Figure A.1: Incident Response Vessels of PoR: Red Ships

A.2. Blue Vessels

A.2.1. Blue Vessels

In figure A.2 all the blue vessels are shown:

(a) RPA 1 (building year 2002)

(b) RPA 2 (building year 2002)

(c) RPA 5 (building year 2019)

(d) RPA 6 (building year 2005)

(e) RPA 7 (building year 2005)

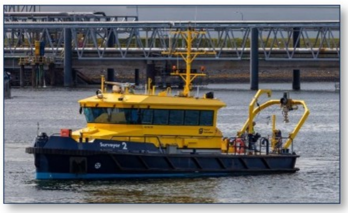
(f) RPA 8 (building year 2018)

Figure A.2: Patrol vessels of PoR: Blue Ships

A.2.2. Alternative Vessels

In figure A.3 the Surveyors and Nieuwe Maze are shown:

(a) Surveyor 1 (building year 2007)



(b) Surveyor 2 (building year 2007)

(c) Nieuwe Maze (building year 1994)

Figure A.3: Three Ships

B

Appendix: Discussion Questions for MIM Matrix

B.1. Exemplary Questionnaire Modulairty Drivers:

Source: Mastering Disruption and Innovation in Product Management - Christoph Fuchs, Franziska J. Golenhofen (2019) [46]

In MFD and tho quantify the impact of the modulaity drivers to the technical solutions or the functions there is some support. Various types of questions have been compiled to provide guidance and help complete the MIM matrix. Initially, it's essential to perform a functional decomposition to identify the core functions of a system. Subsequent to defining the functions and modularity drivers, they are entered into a tabular format. This format, as detailed in Figure B.2, prompts an examination of each function in isolation, assessing it against the relevant modularity driver. The outcomes of these evaluations are systematically recorded within a matrix. Within this framework, the modularity drivers are then mapped and evaluated for each function, employing a rating system that ranges from 0 to 9, as is shown in Figure B.1.

Rating	Description
9	High impact
3	Medium impact
1	Low impact
0	No impact

Figure B.1: Rating and Description for Module Drivers [137]

Design and Development	**Carry over**		
	Are there	[ ] Strong [ ] Medium [ ] Any	Reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations?
	Technology push		
	Is it	[ ] A great risk [ ] A medium risk [ ] Some risk	That this part will go through a technology shift during the product lifecycle?
	Planned design changes (Product plan)		
	Are there	[ ] Strong [ ] Medium [ ] Some	Reasons why this part should be a separate module since it is the carrier of attributes that will be changed according a product plan?
Variance	**Technical specification**		
	Is this part	[ ] Strongly [ ] Fairly [ ] To some extent	Influenced by varying requirements?
	Styling		
	Is this part	[ ] Strong [ ] Medium [ ] Some	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?
Manufacturing	**Common unit**		
	Can this function have the same physical form in	[ ] All [ ] The most [ ] Some	Of the product variants?
	Process/Organization		
	Are there	[ ] Strong [ ] Medium [ ] Some	Reasons why this part should be a separate module because • A specific or specialized process is needed? • It has a suitable work content for a group? • A pedagogical assembly can be formed? • The lead time will differ extraordinary?
Quality	**Separate testing**		
	Are there	[ ] Strong [ ] Medium [ ] Some	Reasons why this part should be a separate module because its function can be tested separately?
Purchase	**Purchase**		
	Are there	[ ] Strong [ ] Medium [ ] Some	Reasons that this part should be a separate module because • There are specialists that can deliver the as black box? • The logistics cost can be reduced? • The manufacturing and development capacity can be balanced?
After sales	**Service/maintenance**		
	Is it possible that	[ ] All [ ] Most [ ] Some	Of the service repair will be easier if this part is easy detachable?
	Upgrading		
	Can	[ ] All [ ] Most [ ] Some	Of the future upgrading by simplified if this part is easy to change?
	Recycling		
	Is it possible to keep	[ ] All [ ] Most [ ] Some	Of the highly polluting material or easy recyclable material in this part (material purity)?

Figure B.2: Value disciplines shown with the aligned Module Driver [137]

C

Appendix: Systematic Deconstruction of the Red Ship's Systems

This study employs a systematic deconstruction of the ship's systems, categorizing them into distinct subgroups: hull structure (RPA 12 Casco), electrical installation, auxiliary and accessory equipment, hydraulic installation, incident response systems, navigation and communication systems, propulsion system, and exhaust gas after-treatment installation. This systematic peeling of systems allows for a detailed analysis of each component, providing a comprehensive understanding of the vessel's operational capabilities.

C.1. RPA 12

The main systems are divided in 12 sub systems. Figure C.1 shows these 12 different sub systems.

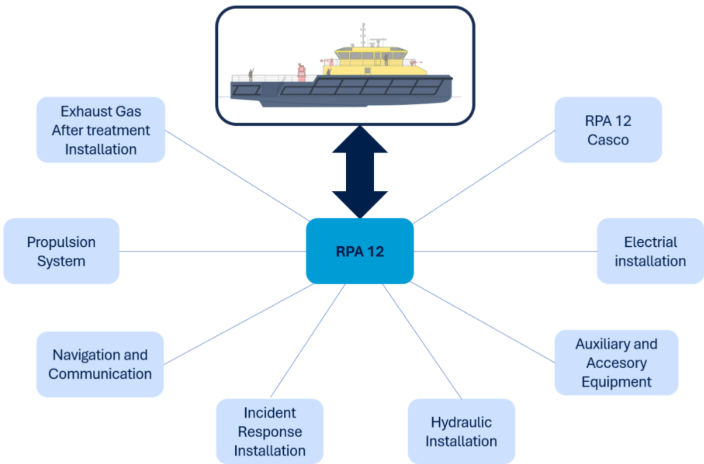


Figure C.1: Function Descriptions - Casco. *Created by the author*

C.1.1. Casco Construction

Figure C.2 illustrates the casco of the RPA 12, highlighting the division of the vessel's structure into two primary sections: the above-water and below-water components. The above-water section includes deck covers, an out-of-service dinghy, liferafts, safety equipment provided by DHMR, and rescue and aid equipment. The fendering system is a critical feature that needs to be integrated into the new design. Additionally, a comprehensive maintenance protocol has been established, and the approval

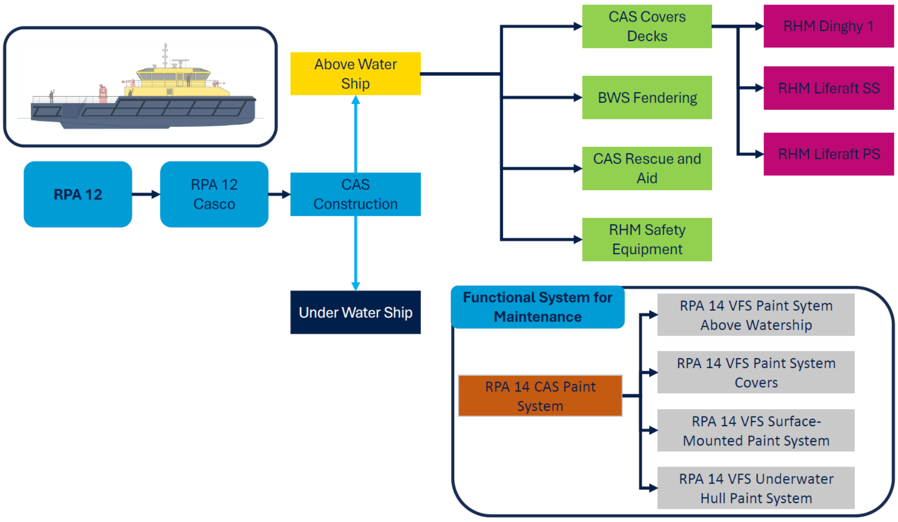


Figure C.2: Function Descriptions - Casco Construction. *Created by the author*

processes for painting various components have been codified within the functional descriptions.

C.1.2. Electrical Installation

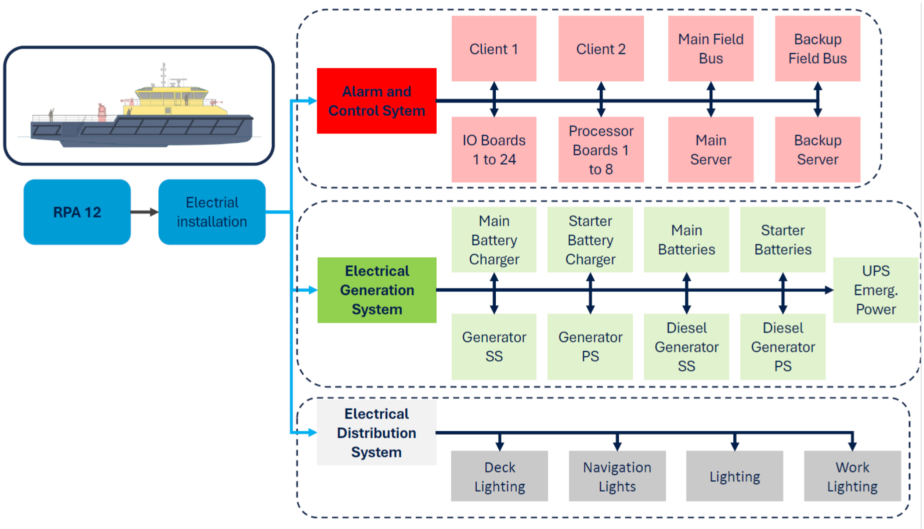


Figure C.3: Function Descriptions - Electrical Installation. *Created by the author*

Figure C.3 illustrates the electrical installations comprising the alarm and control system, the power generation system, and the electrical distribution network. Currently, power is supplied by two onboard generators, one on the starboard side and the other on the port side, providing electricity to various systems, including alarm systems and deck lighting. In the future, the electrical installation will function as the ship's central nervous system, adhering to the KISS principle [47]. With the integration of an electric drive, all systems will be interconnected through a unified transfer mechanism.

C.1.3. Auxiliary and Accessory Equipment

Figure C.4 presents the auxiliary and accessory equipment subsystem, which comprises a range of distinct systems categorized under this group. These include cranes, anchor winches, ballast tanks, and HVAC systems. The current configuration also includes fuel and waste oil systems. However, these

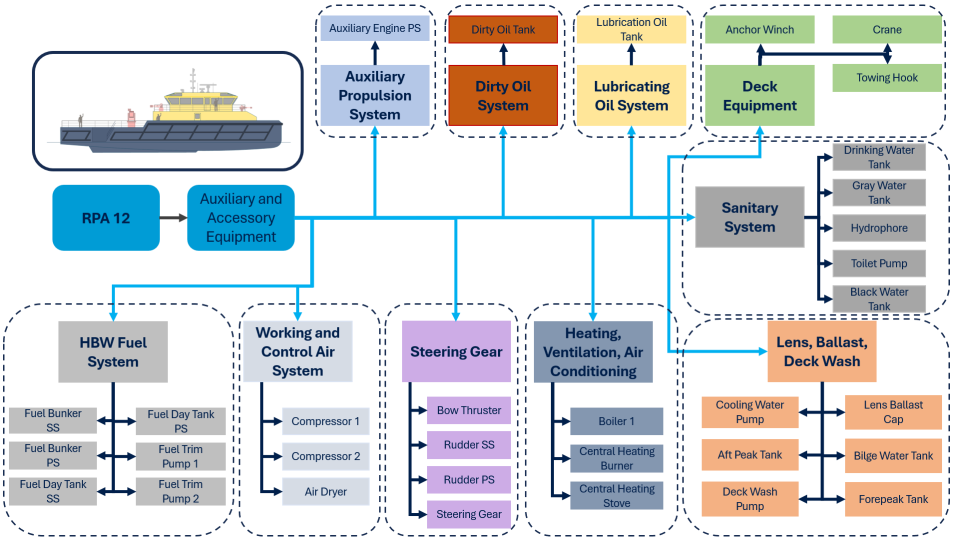


Figure C.4: Function Descriptions - Auxiliary and Accessory Equipment. *Created by the author*

components will be replaced by advanced software and control systems to align with emission-free operational standards in the new zero-emission vessels.

C.1.4. Hydraulic Installation

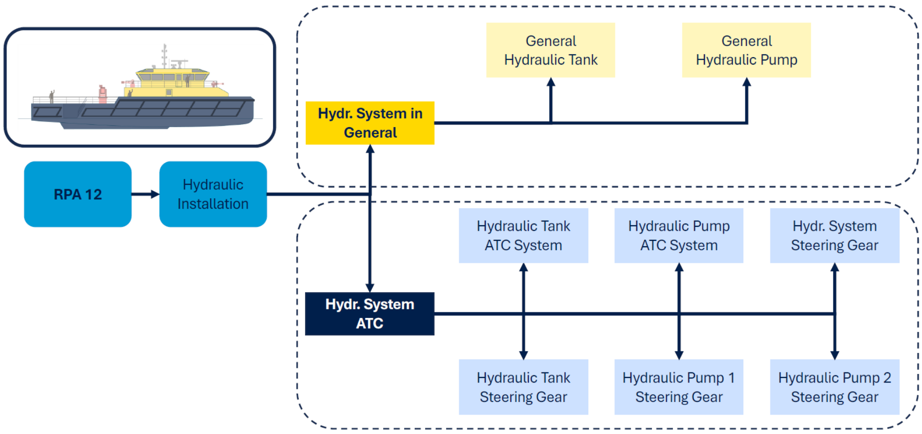


Figure C.5: Function Descriptions - Hydraulic Installation. *Created by the author*

The current RPA 12 is equipped with a hydraulic system consisting of a general hydraulic installation, which includes a central hydraulic tank and pump. Additionally, the hydraulic system's Automated Transfer Control (ATC) is illustrated, showing the locations of the pumps and tanks, as depicted in Figure C.5. Hydraulics are essential for lifting and hoisting operations and, in some cases, such as with the RPA 16, can be utilized for the bow thruster. The decision between hydraulic and electric systems is critical in future design phases.

C.1.5. Incident Response Installation

Figure C.6 illustrates one of the most critical systems and functional elements: the incident response installation. This system enables the vessel to operate as an incident response ship, addressing all

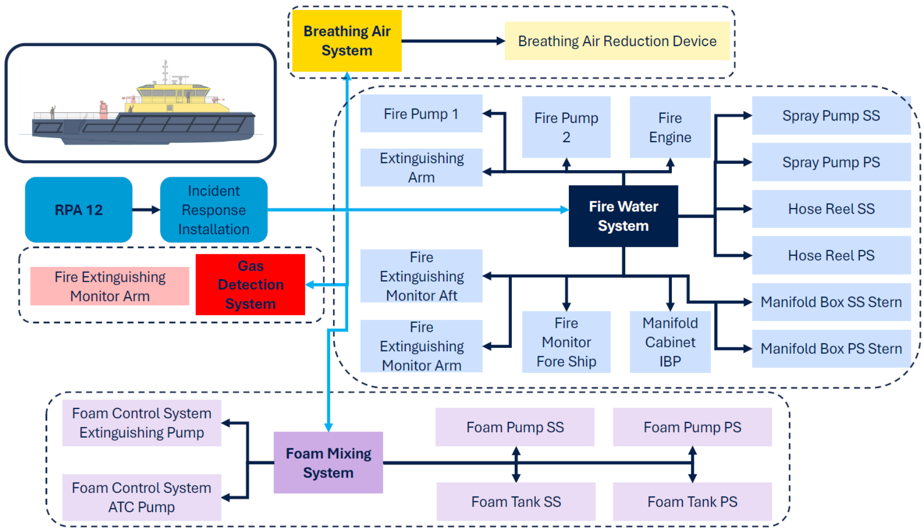


Figure C.6: Function Descriptions - Incident Response Installation. *Created by the author*

necessary tasks related to incident management. The primary component of this installation is the fire water system, consisting of multiple pumps connected to a fire engine, along with spray pumps, hose reels, and manifold boxes. The RPA 12 is also equipped with an elevated extinguishing arm for fire-fighting from raised positions.

Port fires, often involving hazardous materials such as chemicals or oil, require the ability to extinguish fires using foam. To accommodate this, foam mixing systems are integrated onboard. Given the Port of Rotterdam's expected handling of heavy crude oil carriers over the next 30 to 40 years [19], foam-based firefighting capabilities remain essential. Thus, fire pumps, engines, and foam systems are key considerations in the vessel's design

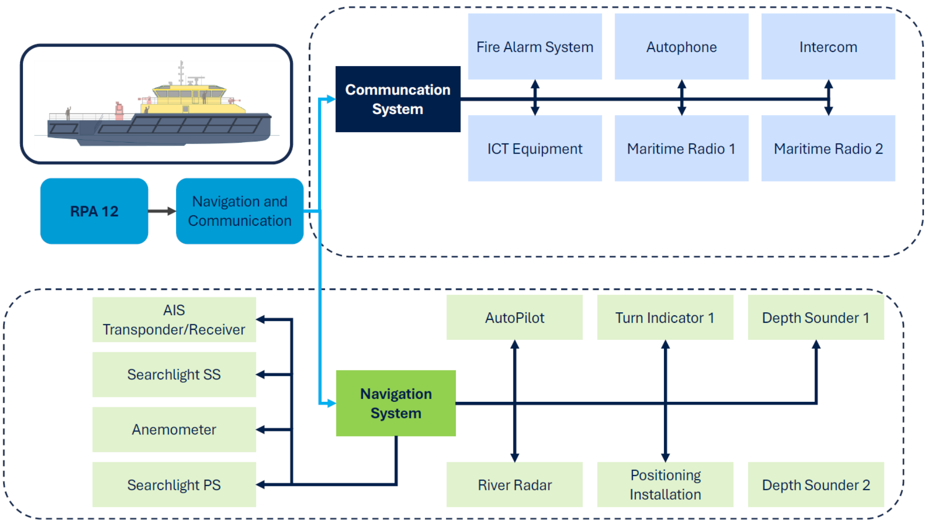


Figure C.7: Function Descriptions - Navigation and Communication. *Created by the author*

C.1.6. Navigation and Communication

Figure C.7 illustrates the navigation and communication systems. The various systems on board are categorized into distinct major components. These essential systems are crucial for the ship's operations and will remain unchanged. Notably, the RPA 12 lacks a DP system, which is desired for the future fleet. Aside from this, there will be minimal changes, and most systems will adhere to standard requirements applicable to all ship types.

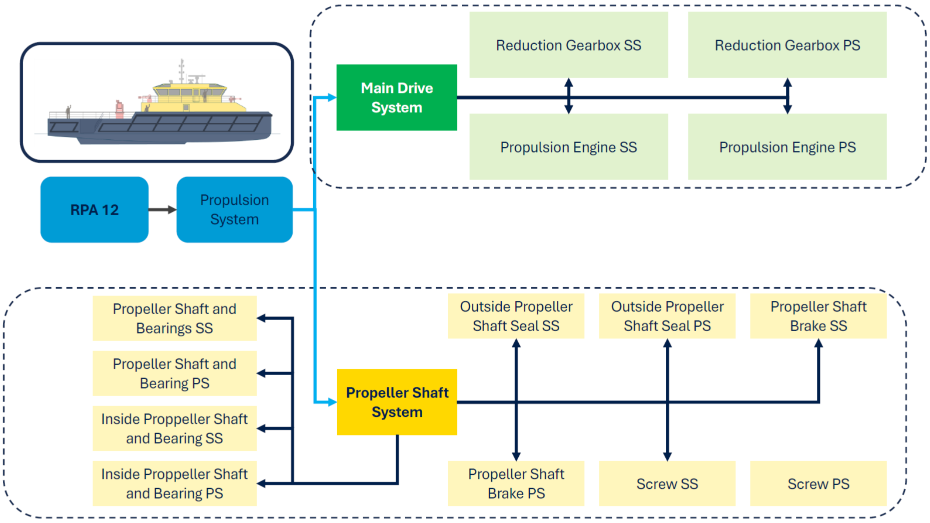


Figure C.8: Function Descriptions - Propulsion System. *Created by the author*

C.1.7. Propulsion System

The RPA12 has a very extensive description of the function of the propulsion system. The propulsion system is divided into a main drive system and a propeller shaft system and is shown in Figure C.8. The main drive system shows the gearbox and the engine on both sides. The current RPA12 has two separately operating engines to drive the ship. Each has its own system. They are both connected to the propeller shaft system. These are complex propulsion systems with many gearboxes and shaft brakes because of the diesel engines. In the future, this can be replaced by electrical systems and drives.

C.1.8. Exhaust Gas and Aftertreatment Installation

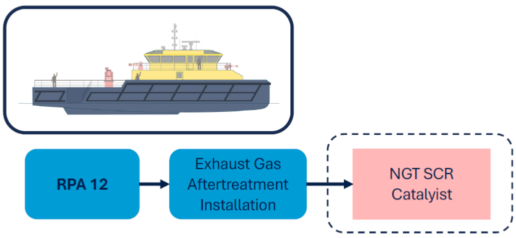


Figure C.9: Function Descriptions - Exhaust Gas Aftertreatment Installation. *Created by the author*

The current ships have been upgraded in 2020 with an exhaust gas aftertreatment installation to filter exhaust gases. This system includes a catalyst to reduce the harmfulness of the exhaust gases. If the new fleet operates emission-free, such a system will no longer be required. Figure B provides a brief overview of the system.

C.2. System Components

Table C.1: Overview of Systems and Components

#	System	Components	System Group
1	**Electrical Installation**	- Control system - Electrical generation system - Main batteries pack - Main Battery Charger - Navigation and deck lighting - Work Lighting	*Power Systems* *Lightning*
2	**Auxiliary and Accessory Equipment**	- Anchor Winch - Crane module - BWS Fendering	*Auxiliary Systems*
3	**Sanitary System**	- Drinking water tank - Grey water tank - Black water tank	*Water Systems*
4	**HVAC (Heating, Ventilation, and Air Conditioning)**	- Heating Ventilation Air Conditioning (HVAC)	*Quality Systems*
5	**Steering Gear**	- Bow Thruster - Rudder starboard - Rudder portside - Steering Gear	*Auxiliary Systems*
6	**Working and Control Air System**	- Working and Control Air System	*Quality Systems*
7	**Incident Response Installation**	- Fire water system - Fire pump + Fire engine - Extinguishing arm - Foam mixing system - Pump and tank - Gas Detection System - Fire Pump 1 - Foam Pump SS	*Fire Fighting systems*
8	**Navigation System**	- All the needed navigation systems and communication systems - Navigation Lights - Communication System - Navigation System	*Navigation and communication* *Lightning*
9	**Propulsion System**	- Main Drive System	*Propulsion Systems*

C.3. System Deconstruction

This section of the appendix presents the results of the analysis on various breakdowns: requirements, functions, and systems. These breakdowns are based on the future program of requirements and have been systematically examined and organized in this study.

C.3.1. Requirements Breakdown

In designing the new fleet, particularly the Red vessels, a detailed assessment was conducted to determine the operational capabilities these ships must possess. Below is a brief overview of the key findings. The primary considerations include the vessel's ability to perform incident response, support logistical operations, provide adequate workspace for the crew, and meet emission reduction targets. Figure C.10 summarizes these requirements, organized into thematic categories.

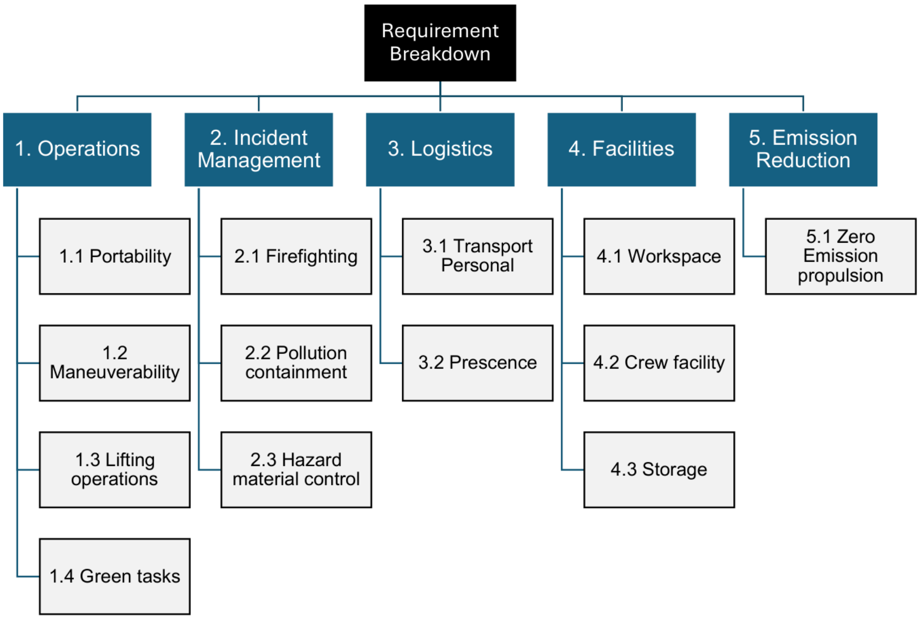


Figure C.10: Requirement Breakdown Diagram. *Created by the author*

In the breakdown of the requirements, the operational aspects were analyzed. A key focus was on incident management, which was identified as the primary function of the Red Ships. Additionally, logistics and facilities were examined, particularly emphasizing the role of crew components. Another critical requirement is the reduction of emissions, specifically the transition to zero-emission propulsion systems.

C.3.2. Functional Breakdown

The various requirements and program requirements identify key functions that must be integrated into the ship's design. These functions are categorized into command and control, power and propulsion, safety and incident response, environmental monitoring, operational support, maintenance, repair, and autonomous and remote operations. A comprehensive diagram illustrating the analysis of these functions is presented in Figure C.11, which also details the onboard systems necessary to ensure optimal vessel performance.

The functional breakdown examines the various functions onboard the red ships. Command and control functions are associated with communication and control interfaces. Power and propulsion functions are integral to safety and incident response capabilities. Additionally, environmental monitoring is a key function of these vessels. Operational support, including maintenance and repair, is also critical. A notable future function is autonomous and remote operation, which is expected to gain increasing importance.

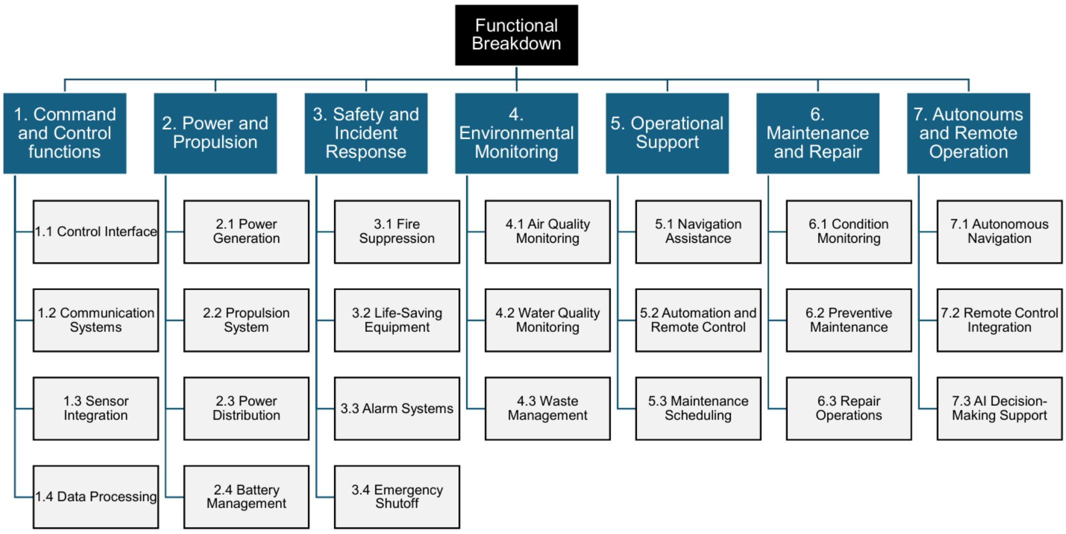


Figure C.11: Function Breakdown Diagram. *Created by the author*

C.3.3. System Breakdown

With the completion of the requirements and functional breakdowns, a system breakdown can now be developed based on these analyses. To address the identified requirements and functions, the necessary onboard systems have been determined. This assessment draws on the program of requirements, discussions with the fleet renewal team, current onboard systems, and future systems that have been requested but are not yet implemented. The resulting system breakdown is presented in the diagram shown in Figure C.12.

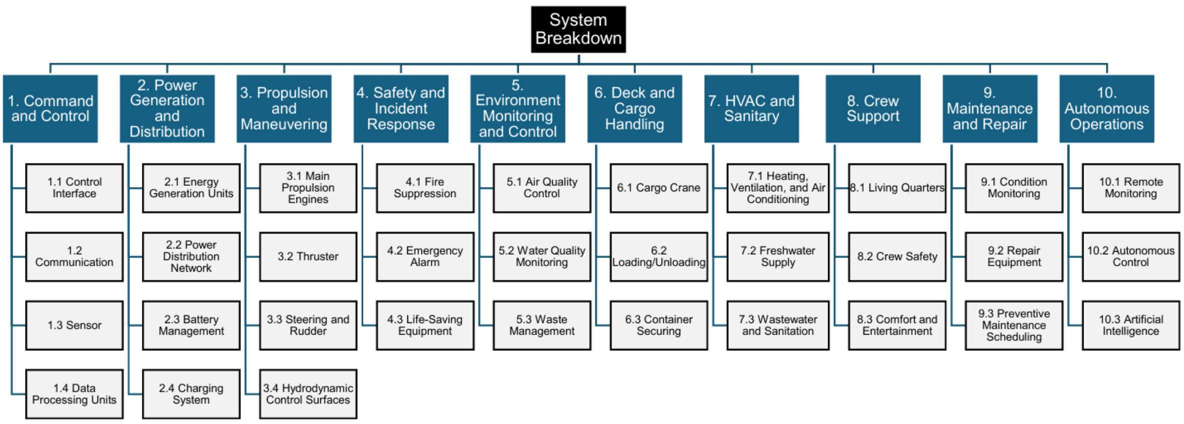


Figure C.12: System Breakdown Diagram. *Created by the author*

The final breakdown encompasses the various systems that could be integrated into the new red ships. These include command and control systems, power generation and distribution, and propulsion and maneuvering systems. Critical red ship functions are represented through safety, incident response, and environmental monitoring and control systems. Deck and cargo handling systems form a distinct subgroup, while HVAC, sanitary systems, and crew support ensure onboard livability. The breakdown includes maintenance and repair systems and future systems designed for autonomous operations.

D

Appendix: Results MFD

D.1. QFD Matrix

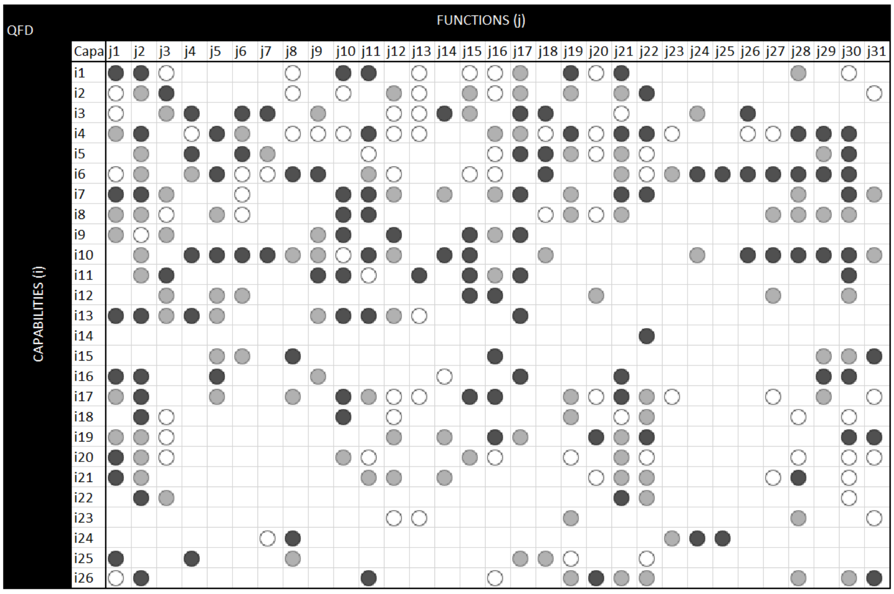


Figure D.1: Results of QFD matrix. *Created by the author*

D.2. DPM Matrix

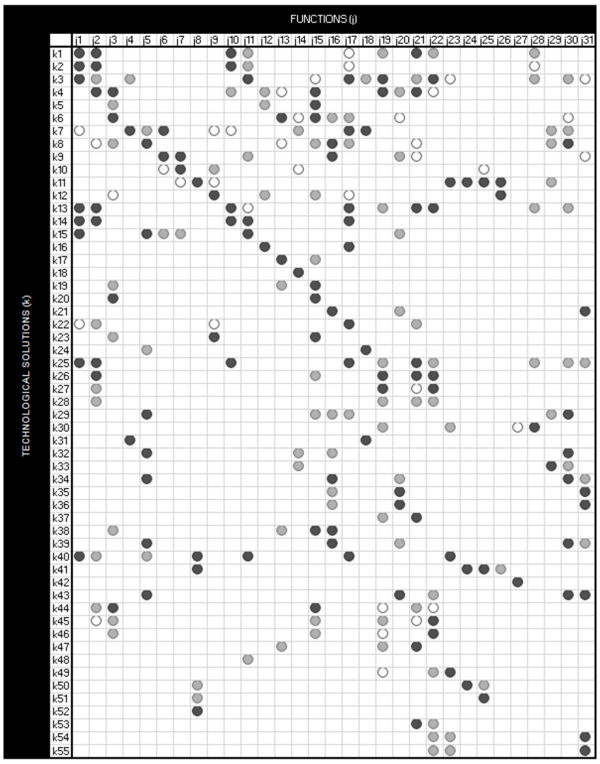


Figure D.2: Results of DPM matrix. *Created by the author*

E

Appendix: Calculations Firefighting

To calculate and estimate the energy requirements for the firefighting system, based on a flow rate of 45 cubic meters per minute (m³/min) at a pressure of 12 bar, the following values were determined:

- **Total Power Required for Fire Pumps**: Approximately **1,053.5 kW**
- **Total Energy Consumption for 1 Hour Operation**: Approximately **1,068.5 kWh**

These values represent the energy capacity, in kilowatt-hours (kWh), required for one hour of firefighting operations. A standard operational shift is calculated as 8 hours, necessitating additional energy modules to meet the demand, particularly for extended firefighting operations that span an entire shift or longer. This also requires additional space allocation for the extra energy modules. In addition to the energy and space requirements for the firefighting operations, additional energy is consumed by foam generation, fire monitors, and auxiliary systems that support the extinguishing process. The estimated energy consumption for these systems is presented in Table E.1 [158].

Component	Energy Consumption (kWh)	Energy Estimated (kWh)
Foam Generation System	5-10	**7.5**
Fire Monitors (2 units)	4	**4**
Auxiliary Systems	2-5	**3.5**

Table E.1: Energy consumption of additional firefighting system components. Source = [158]

The energy requirements are based on a flow rate of 45 cubic meters per minute at a pressure of 12 bar, with an assumed system efficiency of 70% (0.7) [158]. The calculations of this estimation are shown here [166]:

1.
$$\text{Flow Rate} = Q = 45\,\text{m}^3\text{/min} \times 60\,\text{min/h} = 2,700\,\text{m}^3\text{/h} \tag{E.1}$$

2.
$$\text{Power (kW)} = \frac{Q \times P}{\eta} \tag{E.2}$$

3.
$$\text{Power (kW)} = \frac{2,700 \times 12 \times 9.81}{0.7 \times 36} \approx 1,053.5\,\text{kW} \tag{E.3}$$

4.
$$\text{Energy (kWh)} = \text{Power (kW)} \times \text{Operating Time (hours)} \tag{E.4}$$

5.
$$\text{Energy} = 1,053.5\,\text{kWh} \tag{E.5}$$

6.
$$\text{Total Energy} = P_{total} = P_{pumps} + P_{foamsystem} + P_{monitors} \tag{E.6}$$

7.
$$\text{Total Energy} = P_{total} = 1,053.5 + 7.5 + 4 + 3.5 =\approx 1,068.5 \, \text{kWh} \tag{E.7}$$

With the energy requirements for the foam generation system and related auxiliary systems now calculated, the total energy necessary to support an 8-hour firefighting shift is determined.

F

Appendix: Results Concept Development

Table F.1: Technical Solutions and Explanations part 1

Code	Technical Solution	Explanation
K_1	GPS Module	*Provides precise location data for safe and efficient navigation, crucial for coordinating the vessel's position during emergency response operations.*
K_2	Radar System	*Detects and measures objects around the vessel, enhancing collision avoidance and navigation in poor visibility conditions.*
K_3	Integrated Bridge System	*Centralizes control of navigational, communication, and safety systems, improving operational efficiency and situational awareness.*
K_4	Electric Motors	*Convert electrical energy into propulsion, offering a flexible and efficient power source for the vessel's movement.*
K_5	Hydrogen Fuel Cells	*Generate electricity through a clean chemical process, reducing the vessel's reliance on fossil fuels.*
K_6	Battery Packs	*Store electrical energy, providing backup power during peak demands or when primary sources are unavailable.*
K_7	Environmental Sensors	*Monitor environmental conditions, ensuring safe operations and compliance with regulations.*
K_8	Fire Pumps and Extinguishers	*Essential for onboard fire safety, providing water and chemical suppression capabilities.*
K_9	Oil Booms and Skimmers	*Contain and remove oil spills, minimizing environmental damage during incidents.*
K_{10}	Waste Treatment Units	*Process sewage and greywater to meet environmental standards, ensuring sustainable operations.*
K_{11}	Crew Cabins and Mess Areas	*Provide living and dining spaces for crew, supporting their well-being during extended missions.*
K_{12}	HVAC Units	*Regulate indoor climate, maintaining comfort and safety for the crew in all weather conditions.*
K_{13}	AI Navigation System	*Uses AI for real-time decision-making, enhancing navigation in complex or hazardous environments or mooring.*
K_{14}	Satellite Communication System	*Ensures reliable communication with shore and other vessels, even in remote areas.*
K_{15}	VHF Radio	*Provides essential short-range communication, critical for operations in crowded or coastal waters.*
K_{16}	CMMS	*Tracks and manages maintenance schedules, keeping the vessel's systems in optimal condition.*
K_{17}	Shore Power Connectors	*Allow the vessel to use shore-based power when docked, reducing fuel consumption and emissions.*
K_{18}	Compliance Reporting Software	*Automates tracking and reporting of environmental and safety compliance, simplifying adherence to regulations.*
K_{19}	Solar Panels	*Convert sunlight into electricity, contributing to the vessel's energy efficiency and sustainability.*
K_{20}	Wind Turbines	*Generate electricity from wind, offering a renewable energy source that complements other systems.*
K_{21}	Modular Cargo Holds	*Customizable storage spaces, enhancing the vessel's flexibility in transporting various cargo types.*
K_{22}	Real-Time Data Processing Units	*Enable quick analysis of incoming data, supporting informed decision-making during operations.*
K_{23}	Energy Recovery Systems	*Capture waste energy and convert it into usable power, improving overall energy efficiency.*
K_{24}	E-nose	*Detects and identifies odors, useful for monitoring air quality or detecting hazardous leaks.*
K_{25}	DPS	*Automatically maintains the vessel's position and heading, crucial for operations requiring precise station-keeping.*
K_{26}	Bow Thruster	*Enhances maneuverability during docking and undocking by providing lateral thrust at the bow.*
K_{27}	Spade Rudders	*Efficient steering devices that improve maneuverability with minimal drag, ideal for navigating tight spaces.*
K_{28}	Disengageable Propellers	*Can be decoupled when not in use, reducing drag and improving fuel efficiency.*

Table F.2: Technical Solutions and Explanations part 2

Code	Technical Solution	Explanation
K_{29}	Firefighting Monitors	*Remotely controlled nozzles for precise fire suppression, enhancing the vessel's emergency response capabilities.*
K_{30}	Rescue Boarding Platform	*Facilitates safe boarding during rescue operations, essential for transferring individuals from the water.*
K_{31}	Gas Detection System	*Monitors air for hazardous gases, triggering alarms if dangerous levels are detected, crucial for safety in enclosed spaces.*
K_{32}	Foam-Forming System	*Generates firefighting foam, effective at suppressing fires by smothering flames and cooling the area.*
K_{33}	Powder Extinguishers	*Versatile firefighting tools, effective on various types of fires, interrupting the chemical reactions that sustain a fire.*
K_{34}	Modular Firefighting Storage	*Customizable storage for firefighting equipment, ensuring accessibility and organization during emergencies.*
K_{35}	Advanced Crane 1	*Sophisticated lifting device for heavy cargo, crucial for safe and efficient cargo handling operations.*
K_{36}	Crane 2	*Another lifting device, likely with different specifications, used for handling cargo or equipment.*
K_{37}	Fendering	*Protects the vessel from impact during docking, safeguarding against damage from collisions.*
K_{38}	SHIFTR	*Likely involves systems for optimizing cargo movement or handling, though details are sparse.*
K_{39}	Module Foam Tank 12m³	*Stores firefighting foam concentrate, ensuring an adequate supply for fire response readiness.*
K_{40}	Cabin (Communication Suite)	*Equipped with advanced communication tools, essential for maintaining continuous contact during operations.*
K_{41}	Restaurant	*Provides dining services for the crew, ensuring their well-being during extended missions.*
K_{42}	Rescue Boat	*A small, agile boat for emergency rescue operations, essential for transferring individuals from the water.*
K_{43}	Remote Controls	*Enable wireless operation of onboard systems, enhancing safety and flexibility in vessel management.*
K_{44}	Propulsion System	*Drives the vessel forward, encompassing engines, propellers, or waterjets, each offering specific operational benefits.*
K_{45}	Azipod Propeller	*Provides 360-degree rotation for exceptional maneuverability, ideal for complex navigation tasks.*
K_{46}	Waterjet	*Propels the vessel using high-speed jets of water, offering superior maneuverability in shallow waters.*
K_{47}	Mooring Lines and Anchors	*Secure the vessel when docked or stationary, ensuring stability in adverse conditions.*
K_{48}	Deck and Navigation Lighting	*Provide safe operations, signaling the vessel's position and status.*
K_{49}	Work Lighting	*Illuminates work areas, ensuring tasks can be performed safely at any time.*
K_{50}	Drinking Water Tank	*Stores drinkable and usable water.*
K_{51}	Grey Water Tank	*Stores wastewater for treatment or disposal, maintaining environmental compliance.*
K_{52}	Black Water Tank	*Stores sewage, ensuring safe handling and discharge in accordance with environmental compliance.*
K_{52}	Black Water Tank	*Stores sewage, ensuring safe handling and discharge in accordance with environmental compliance.*
K_{53}	Hydrofoil	*Lifts the vessel's hull above water at speed, reducing drag and increasing efficiency.*
K_{54}	Monohull	*A traditional single-hull design, offering buoyancy and stability across various sea conditions.*
K_{55}	Doublehull	*Features two hull layers for added protection, reducing risks of spills or breaches. Less loading capacity in the hull.*

Table F.3: Technical Systems and Clusters for Concept Designs

		Concept Design								
Index	**Technical System**	**1-Elect A**	**2-Elect B**	**3-Elect C**	**4-Swap A**	**5-Swap B**	**7-Met A**	**8-Met B**	**9-Hyd A**	**10-Hyd B**
1	Battery Integrated	3	2	2	0	0	0	0	0	0
2	Battery Swapping Method	0	0	0	2	1	0	0	0	0
3	Methanol Energy Box	0	0	0	0	0	3	3	0	0
4	Hydrogen Energy Box	0	0	0	0	0	0	0	3	3
5	Cluster 2: Propulsion Positioning	1	1	1	1	1	1	1	1	1
6	Rudder SB	1	1	1	1	1	1	1	1	1
7	Rudder PS	1	1	1	1	1	1	1	1	1
8	Bow Thruster	1	1	1	1	1	1	1	1	1
9	Drinking Water Tank	1	1	1	1	1	1	1	1	1
10	Grey Water Tank	1	1	1	1	1	1	1	1	1
11	Black Water Tank	1	1	1	1	1	1	1	1	1
12	Cluster 5: Crew Accommodation	1	1	1	1	1	1	1	1	1
13	Cluster 1: Nav Post (Wheelhouse)	1	1	1	1	1	1	1	1	1
14	Cluster 6: Sensor System	1	1	1	1	1	1	1	1	1
15	Cluster 3: Fire Fighting Installations	1	1	0	1	1	1	1	1	1
16	Cluster 4: Foam Modules	1	1	0	1	1	1	1	1	1
17	Engine Room	1	1	1	1	1	1	1	1	1
18	Crane 10 tonnes	0	1	1	0	1	0	1	0	1
19	Crane 20 tonnes	1	0	0	1	0	1	0	1	0
20	Water Cannon Front SB	1	0	0	1	0	1	0	1	0
21	Water Cannon Front PS	1	0	0	1	0	1	0	1	0
22	Water Cannon Front Central	0	1	0	0	1	0	1	0	1
23	Water Cannon Aft	1	1	0	1	1	1	1	1	1
24	Mooring Lines and Anchor	1	1	1	1	1	1	1	1	1
25	Oil Booms and Skimmers	1	1	1	1	1	1	1	1	1
26	Firefighting Equipment Storage	0	0	1	1	1	1	1	1	1
27	Additional Foam Module	0	0	1	0	0	0	0	0	0
28	Modular Cargo Unit	0	0	1	0	0	0	0	0	0

G

Appendix: MFD MIM Matrix Reasoning and Explantion

G.1. MFD decision and reasoning of the MIM Matrix

k1: GPS Module function (k_1)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Every new ship will be installed with a navigation function system in order to navigate. The equipment on board of current ships are very reliable and working systems. So that is the reason that there will be no groundbreaking new technologies on the GPS module and this module will not be expected to change or to develop. This technology will be expected to be carried over in the next lifespan of the fleet.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The current GPS module functions are very accurate and have been operating for a long time via the same system. There are technological developments, but they will not cause a huge technological push for the ship in the product lifecycle.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A GPS Module function will process and provide GPS and location data for its entire life. It is not possible to adjust this system, and therefore no design changes will follow in the life of this system.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
GPS module function on board of the ship is common for every type of ship. Also within the product groups and will not be influenced by varying requirements or different requirements per product.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A GPS module function forms part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinary.*

The installation and maintenance of a GPS module can be carried out by a specialized team, but the volume of work may not be large enough to keep a full team busy at all times.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
The GPS module is ready-made and tested at the factory. It is not necessary to place it in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
GPS repairs are often in the software, and if it is hardware, they are fairly easy to replace. The systems are also not too big.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k2: Radar System (k_2)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Every new ship will be equipped with a navigation system to ensure guidance, where a radar system is also being installed. The current ships' equipment is highly reliable and fully operational. Therefore, there will be no significant advancements in the radar system, and it is not anticipated to undergo any changes or developments. This technology is expected to be carried forward into the next generation of the fleet.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Also, the current radar systems are very accurate and have been operating on the same system for a long time. The conservative systems will have minimal technological developments that are not likely to be integrated into the ship. This will not cause a technological push in the product lifecycle.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A radar system is good for providing radar data and images. In such a system that is equivalent to a GPS system, it will not undergo product design changes during its life.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Radar systems on board of the ship are common for every type of ship. Also within the product groups and will not be influenced by varying requirements or different requirements per product.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A Radar module function forms part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
The installation and maintenance of a radar can be carried out by a specialized team, but the volume of work may not be large enough to keep a full team busy at all times.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
The radar is ready-made and tested at the factory. It is not necessary to place it in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
Radar system repairs are often in the software, and if it is the hardware, they are fairly easy to replace. The systems such as radar are often already outside and on top of the ship or roof.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k3: Integrated Bridge System (k_3)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
An integrated bridge system is present on board where all necessary components for a total system are integrated. The current bridge systems are of a high readiness and will not differ in the future. Therefore this will be carried over.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
An integrated bridge system is often designed for the entire life cycle of the system. However, with the modular installations and future potential adjustments, there is some risk that the integrated bridge will undergo a technology shift during the product life cycle of the vessel.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
The integrated bridge system is built for the specific ship and therefore for the product in its life. However, there is a chance that a retrofit or major interim maintenance will take place where some things will be changed. Then the strategy can change and new products can be added to the integrated bridge and the system.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Integrated bridge systems on board of the ship are common for every type of ship. Also within the product groups and will not be influenced by varying requirements or different requirements per product.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
An integrated bridge system module function forms part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
The installation and maintenance of an integrated bridge system can be carried out by a specialized team, but the volume of work may not be large enough to keep a full team busy at all times.

l_8 ***Seperate testing:*** *There are SOME reasons why this part should be a separate module because its function can be tested separately.*
The integrated bridge system consists of certain off-the-shelf products and can be tested in advance to control if all systems are working correctly. The main concern here is whether all systems work well together and interface.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
The integrated bridge system is extremely complex and consists of various components. Many different systems come together on board and they do not come from the same manufacturers or suppliers. It is not wise to purchase this module as black box modules.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
An integrated bridge system is a very complicated system within the wheelhouse and cannot simply be placed in an easier to replace location.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k4: Electric Motors (k_4)

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
With the current developments on electrical motors, there is still a lot to improve and that is the reason that there are medium reasons for the electrical motors to be carried over. The design should be modular in order to be future proof, that is why it is important to keep the new technological improvements in mind. There is a potential that new electrical motors are needed and that these motors cannot be carried over.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
The electric motors are reasonably well developed and there is still room for improvement in efficiency. But there will be no extreme technological shifts that will have a big impact on the ships.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Electric motors will not have planned design changes during the product life cycle, because the function of these motors will not change. An electric motor does not change its functionality and will not be tinkered with.

l_4 ***Technical specification:*** *This part is TO SOME EXTEND influenced by varying requirements.*
Electrical motors will be integrated on every ship of the product family but will diverge for every type of ship. The ambition is to standardize the entire fleet and then the ships with the view of propulsion will need the same electric motors. But there can still be a difference in secondary systems. Therefore the electric motors are to some extent influenced by the technical requirements and specifications.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Electrical motors form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Installing and maintaining electric motors requires specialized knowledge and processes, such as electrical wiring, calibration and integration with other systems. The delivery time for electric motors can vary depending on specifications and suppliers, which requires some flexibility in planning.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
The electric motors are ready-made and tested at the factory. It is not necessary to place it in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
It would be advantageous to design it as a black box module, because the technical solution consists of sophisticated components and due to the standardization these systems can be ordered for the entire product group, which can reduce the complex costs.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
The electric motors are located midship due to their weight and need to stay dry and would not be easy to replace. However, current ships now work with hatches that can be unscrewed to lift out current engine blocks. This does involve moving a lot of parts but would be easier with electric motors.

l_{11} ***Upgrading:*** *MOST of the future upgrading can be simplified if this part is easy to change.*
This technological solution can be upgraded in the future if it is easy to change. It involves strategies aimed at extending the product's lifespan or enhancing its performance. It provides customers with the option to modify the product in the future, especially with improvements in the electric motors.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k5: Hydrogen Fuel Cells (k_5)

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
As well as the electrical motors, there is still a lot of process when looking at fuel cells. This means that there is a possibility that the fuel cell cannot be carried over.

l_2 ***Technology push:*** *It is A GREAT risk that this part will go through a technology shift during the product lifecycle.*
Hydrogen fuel cells do exist but are still largely in design and test phases. The membrane in a fuel cell is still fragile and experiments are being conducted to improve and optimize hydrogen fuel cells. In addition to the fuel cell itself, there is also a lot of technological push within the storage of hydrogen.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Because a hydrogen fuel cell is an energy supplier for on board a potential ship, the function will always remain the same. Reducing costs or adjusting components will not play a role for a fuel cell.

l_4 ***Technical specification:*** *This part is TO SOME EXTEND influenced by varying requirements.*
The hydrogen fuel cells can be installed on the ships and the fleet when integrated. The developments of the fuel cells are currently such that the power generated by the fuel cell is increased by installing them in parallel. So more power required means more fuel cells required. Depending on the technical specifications and requirements, there is therefore an influence on the number of fuel cells.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Installing and maintaining hydrogen fuel cells requires specialized knowledge and processes, such as safe storage and handling of hydrogen, as well as integration with other energy and propulsion systems. Maintenance by a dedicated team is also required.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because its function can be tested separately.*
A fuel cell is still a new product that continues to innovate. This is not standard on board ships and should definitely be tested to see if it functions properly. Doing this at an earlier stage promotes the speed of the construction process.

l_8 ***Seperate testing:*** *There are MEDIUM reasons why this part should be a separate module because its function can be tested separately.*
A hydrogen fuel cell is a very new and still developing concept, testing the system can be cost reducing.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Hydrogen fuel cells involve advanced technology that requires specialized knowledge to design and manufacture. By outsourcing this as a black box module, companies can leverage the expertise of specialists or vendors who have the necessary technical know-how.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
Fuel cells do have a sensitive lifespan, especially the membranes. Some parts would therefore be easier to replace, but these are already detachable.

l_{11} ***Upgrading:*** *MOST of the future upgrading can be simplified if this part is easy to change.*
This technological solution can be upgraded in the future if it is easy to change. It involves strategies aimed at extending the product's lifespan or enhancing its performance. It provides customers with the option to modify the product in the future. This mainly has to do with hydrogen fuel cells that are improving and further developed.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k6: Battery Packs (k_6)

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The batteries are almost at their maximum capacity but there is still some progress in the development of new batteries. These new technologies will increase the energy capacity in batteries and this causes the potential of not being able to re-use the technology but a possible new integration of new batteries. So it is not possible to carry it over.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
The battery packs are reasonably at their maximum capacity as previously indicated. The technological push will therefore also be very absent or very mild. The biggest changes will be in efficiency in the transition and possibly the use of other raw materials.

l_3 ***Planned design changes (product plan):*** *There are MEDIUM 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.*
A battery pack can be changed during its life cycle and will probably be updated when possible to incorporate new technology, or a higher energy density or changing safety features. This can also have to do with changing energy needs from the ship. There is therefore a reasonable chance for planned design changes.

l_4 ***Technical specification:*** *This part is STRONGLY influenced by varying requirements.*
Battery packs on board of the ship have some dependency on the total required amount of energy. So to some extent the battery packs are influenced by the requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Battery packs form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
The installation and maintenance of a battery pack system can be carried out by a specialized team, but the volume of work may not be large enough to keep a full team busy at all times.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
Battery packs are ready-made and tested at the factory. It is not necessary to place it in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*

Integrating pre-assembled battery packs into products can streamline the manufacturing process, reducing assembly time and complexity.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
Batteries are connected in parallel to simplify battery replacement. This makes charging and discharging of batteries more efficient. There is no need to build a special detachable in this module.

l_{11} ***Upgrading:*** *SOME of the future upgrading can be simplified if this part is easy to change.*
This technological solution can be upgraded in the future if it is easy to change. It involves strategies aimed at extending the product's lifespan or enhancing its performance. It provides customers with the option to modify the product in the future. Battery packs will see a small efficiency improvement in the future.

l_{12} ***Recyling:*** *It is possible to keep some of the highly polluting material or easy recyclable material in this part (material purity).*
Recycling some of these materials is possible. Batteries contain substances that are toxic and must be captured, but can also be used for other purposes. It involves strategies that facilitate the proper disposal of hazardous and uniform materials. This approach can limit the variety of materials used and ensure that environmentally harmful materials are contained within the same module.

k7: Environmental Sensors (k_7)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
There is no reason to think that the environmental sensor cannot be able to be carried over. These sensors are very well developed and are currently very market conform. There will be no technological sprint with regard to new developments that will get in the way of the carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Environmental sensors are conservative devices that will not get much better or worse. The shelf life of these systems is long and there will be no major technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Environmental sensors have a clear task and that is to sense everything from the environment. This is also a fixed task of the Port Authority. There is no room for leeway in this task and the functionality of these sensors and therefore there is no reason for planned design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Because these environmental sensors are installed on each type of ship of the product group because these are secondary systems to properly observe the port. This does not differ per type of ship and is therefore not influenced by technical specifications.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Environmental sensors form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A sensor requires no specific maintenance or pedagogical assembly and can be easily installed.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*

Environmental sensors are ready-made and tested at the factory. It is not necessary to place it in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
This installation cannot be placed in a place that is easier to replace.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k8: Fire Pumps and Extinguishers (k_8)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Fire pumps and extinguishers have been the same for the past decades and for this reason they will be carried over very well. In the systems on board, there will be no new type of pump or extinguisher installed. There are currently new developments but these would concern completely different extinguishing systems where, for example, a jet is used. That is not applicable in this situation.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Fire pumps and extinguishers, the fire cannons, are very robust and conservative systems. There is no technological progress to be made here, and that will not happen in the life cycle of the product or the product group.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Fire pumps and extinguishers are on board for the reason of being able to extinguish. This function will continue to exist on board the ship and for the port authority. A change or planned design changes does not apply to the fire pumps and extinguishers.

l_4 ***Technical specification:*** *This part is STRONGLY influenced by varying requirements.*
The fire pumps and extinguishers are necessary to be able to extinguish fires. When choices are made for the entire product group where extinguishing is carried out by half of the ships in the fleet, this determines by means of varying requirements whether or not fire pumps and extinguishers are on board the ships.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*

Fire pumps and extinguishers are not common for all types of ships that can form from the product group. It will not always be standard integrated on all ships.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Seperate testing:*** *There are STRONG reasons why this part should be a separate module because its function can be tested separately.*
Fire pumps and extinguishers are among the important core elements of a fire ship. These are large installations that definitely need to be tested.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Fire pumps and extinguishers are complex systems and important for the proper operation of the ship. For this, it would save complexity, errors, and maintenance if this module could be delivered as a black box.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
The fire pumps and extinguishers are large and complex systems that cannot be replaced as a whole in one go.

l_{11} ***Upgrading:*** *ALL of the future upgrading can be simplified if this part is easy to change.*
With an uncertain future and much future innovation, it is not yet entirely certain how extinguishing will or can be done. Will this be climate neutral or completely emission-free? For this, we need to look at how the fire pumps and extinguishers can be upgraded, and therefore be accessible.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k9: Oil Booms and Skimmers (k_9)

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
When the oil booms and skimmers are installed on board the ship, they will always be carried over. It is possible that they are replaced after use, but the systems remain exactly the same.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Oil booms and skimmers are very easy and simple systems. These systems will not experience a technology push during the lifespan.

l_3 ***Planned design changes (product plan):*** *There are 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.*
The oil booms and skimmers are on board the ships to be able to collect and discharge any damage, leakage, or other substances that have come into the water from the port. This function is very clear and will not change. Therefore, there will also be no planned design changes for these technological solutions.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Having oil booms and skimmers on board is essential for the functionality to be able to collect and discharge oil and other substances. These systems take up little space on board the ships and are now stored on all types. However, if the requirements are drawn up or change, the oil booms and skimmers will not be on board every ship.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user

or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Oil booms and skimmers are not common for all types of ships that can form from the product group. They will not always be standardly integrated on all ships.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
An oil boom and skimmers are available for purchase and easy to install on board a ship. Standard components are required and do not need to be split into separate components, so there is no reason to make this a separate module.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
Oil booms and skimmers are ready-made and tested at the factory. It is not necessary to place them in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Oil booms and skimmers are not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is possible that MOST of the service repair will be easier if this part is easy detachable.*
Because oil booms and skimmers must be in an accessible place for use but also for maintenance or inspection.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k10: Waste Treatment Units (k_{10})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The waste treatment units onboard ships are standard and standardized. These can be carried over very easily and will not be fixed specifically for the ships.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Waste treatment units are installations on board the ship that do not have special or complex parts or functions. This makes the chance that there will be a huge technology push zero.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
A waste treatment unit has a possible chance to change when regulations regarding drinking water, grey water, black water, etc., and the further handling will change. When that is the case, a changing strategy will also have to come from the company to adapt the systems.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The waste treatment units will be on board independently of the requirements of each ship type. With a side note: unmanned vessels will, of course, not have waste treatment on board because no human dirty water is created.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Waste treatment units form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A waste treatment unit is a conventional system and does not require a specific or specialized process. It does require a certain type of maintenance, but this is not frequent.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
Waste treatment units are ready-made and tested at the factory. It is not necessary to place them in a separate module, as this does not affect the acceleration of the construction process.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Waste treatment units are desired to be delivered as a black boxed module. This saves logistic costs because the standardized fleet can be equipped with the systems by one supplier.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
Waste treatment installations are on board the ship connected to the entire hull and all systems from which waste comes. This installation cannot be placed in a location that is easier to replace.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k11: Crew Cabins and Mess Areas (k_{11})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The crew cabins and mess areas are under the normal market situation a conservative type of concept. Its construction is straightforward and unlikely to evolve. However, requirements can vary. For instance, the cabins in the potential product family need to be larger than the current ones. Despite this, future technology or concepts for the next generation of ships will experience minimal to no changes.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
This is due to the fact that crew cabins and mess areas will develop in a way that there will be a large technology push. These cabins and areas are simple locations where the crew can work or enjoy a break.

l_3 ***Planned design changes (product plan):*** *There are 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.*

Crew cabins and mess areas also have a very clear function and will not change in the future. The company strategy will not change with regard to these simple functions on board the ship.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The crew cabins and mess areas will be present on every ship type and will not differ per ship. This reusable space is therefore not influenced by technical specifications within the fleet.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Crew cabins and the mess area form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
In building and realizing a crew cabin it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
A cabin is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
A crew cabin cannot be supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
A crew cabin is fixed into the hull of the ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k12: HVAC Units (k_{12})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
HVAC Units are currently available at a current level where there will be no large improvements to the systems. These conservative systems are operating very well and are able to be carried over.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
HVAC units are, as said before, very well-functioning systems. Also, the HVAC units are not complex or complicated systems that would require solutions. This makes them not sensitive to a technology push because the push will not happen for HVAC units during the life cycle of the products.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
HVAC Units are there to keep the conditions on board the ship at the right level. There is a small chance that planned design changes would come for possible small improvements in energy efficiency or have to comply with new environmental standards. This will entail high costs, so it is not necessarily a favorable option.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The HVAC units will also be present on each ship type and will not be affected by different technical specifications. The HVAC units will always be present on each ship type to maintain or create the conditions properly.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
HVAC Units form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
An HVAC unit is a conventional system and does not require a specific or specialized process. It does require a certain type of maintenance, but this is not frequent.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship, and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
HVAC units are desired to be delivered as a black-boxed module. This saves logistic costs because the standardized fleet can be equipped with the systems by one supplier.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
HVAC units are on board the ship connected to the entire hull and all systems from which waste comes. This installation cannot be placed in a place that is easier to replace.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is possible to keep some of the highly polluting material or easy recyclable material in this part (material purity).*
Recycling some of these materials is possible. The coolant in this system is currently often polluting and environmentally unfriendly. The chemicals are not all fully reusable but can be used for other purposes. It involves strategies that facilitate the proper disposal of hazardous and uniform materials. This approach can limit the variety of materials used and ensure that environmentally harmful materials are contained within the same module.

k13: AI Navigation System (k_{13})

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*

An AI Navigation system is constantly improving and is still in the development phase. Although the integration is by software, it is not fully able to carry over.

l_2 ***Technology push:*** *It is A GREAT risk that this part will go through a technology shift during the product lifecycle.*
AI navigation systems, despite being a software system, are still fully in development. This ensures that the AI Navigation system will most likely still experience a major technological shift, and this push will ensure that many new developments will come. The integration of AI navigation systems can also increase the dependency on other secondary systems.

l_3 ***Planned design changes (product plan):*** *There are MEDIUM 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.*
Because AI Navigation systems can be affected a lot by new innovation, upgrades, developments, and regulations. The idea and strategy of the PoR can change with regard to the use of AI Navigation systems. This is why there is a medium reason why this should be a separate module.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
An AI Navigation system will be able to assist different ship types differently but is seen within the port authority as an option to install on all ship types. The integration separately on a product of the product group would make it less useful because communication between different ships is needed and makes the system work and function better. Hence, this will be added to each type and will not be affected by varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
AI Navigation system is not common for all types of ships that can form from the product group. It will not always be standard integrated on all ships.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
An AI Navigation system is a software package with a computer. This is not split up.

l_8 ***Seperate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship, and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
AI navigation systems are complex systems where a lot of data and software needs to be connected to hardware. If these systems are delivered as a black box module, this would save on complexity and reduce costs.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
An AI navigation system consists mainly of software and is connected to hardware.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recyling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render

some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k14: Satellite Communication System (k_{14})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The satellite communication system is not going to change from its current phase. The status quo is in such a way that this could reduce the change to be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Satellite communication system has been developed so much that these systems will not be affected by new developments. The satellite connections used on the various PoR ships are the most widely used and accepted systems in the maritime world. These are integrated in such a way that there is no risk of a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
The use of satellite communication systems will be used to assist on board the ships with regard to normal operations and calamities. On board, the strategy of using these systems will not change. The only possibilities where this could possibly change are in the control rooms on the quay of the port authority.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, satellite communication systems can be applied to any kind of ship type within the product group. This helps the communication within the ships.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Satellite communication systems form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A satellite communication system is a software package with a computer. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship, and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
Satellite communication systems are often accessible through roof-mounted antennas.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k15: VHF Radio (k_{15})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The VHF system hasn't changed as a system on board since the last decennia and it won't change in a way that it won't be able to carry it over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The VHF Radio is also very widely accepted and used in the operational area that it will not disappear in the coming product life cycle. This product can also no longer be developed and therefore there will be no technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
VHF Radio has the task of communicating between the ship, the control room, the quay, and other ships. The use of this will not undergo any design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, VHF system can be applied to any kind of ship type within the product group. This helps the communication within the ships and does not make it dependent on varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
VHF radios form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A VHF radio is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship, and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*
VHF radio systems are often accessible with antennas on the roof.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k16: CMMS (Computerized Maintenance Management System) (k_{16})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
A computerized maintenance management system will be integrated into the ship after the design is approved. The chance that there will be an update for this CMMS will only be there after the end of the life of the ship. It can be integrated with all other systems.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
Computerized maintenance management systems are systems that look at the possible maintenance operations on board the ships. This is done with existing software and by the PoR Asset Management teams. These are systems that can receive an update but will not change extremely.

l_3 ***Planned design changes (product plan):*** *There are MEDIUM 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.*
The maintenance and the business strategy of the PoR are now fairly fixed. Certain conditions for the maintenance have been established in this. However, this does not guarantee that the maintenance as it is now planned will remain completely fixed in its current form. The possibility that this will change, including in the computerized maintenance management system, is therefore present.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, CMMS (computerized maintenance management system) can be applied to any kind of ship type within the product group. This helps the communication within the ships and does not make it dependent on varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
CMMS forms part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A CMMS, computerized maintenance management system, is a fixed computer system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship, and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy detachable.*

Software systems can be replaced and maintained via online software updates.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k17: Shore Power Connectors (k_{17})

l_1 ***Carry over:*** *There are ANY reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The shore power connectors are currently following the standard of the three-phase connection. But there is a possibility that the connectors will change after some improvement and then it needs to change.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
The use of the current shore power connectors is reasonably based on the uniform connectors. There are developments underway for systems that can charge faster, also known as superchargers, but the developments there are more in the systems themselves of charging and not in the connection. So there is some risk of a technology push within the product life cycle.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
The connections on board the shore power connectors therefore have a small chance to undergo a product design change during the lifespan of the product because there may be a change in the shore power, the possibility for shore power, or a change in policy in the future. There is also a dependency on the grid and there is a chance of possible grid congestion.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, shore power connectors can be applied to any kind of ship type within the product group. This helps the communication within the ships and does not make it dependent on varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Shore power connectors form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? -*

The manufacturing and development capacity can be balanced?
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is possible that MOST of the service repair will be easier if this part is easily detachable.*
Shore power will be wired or via coupling systems. This is often located on the outside of the ship and will need to be replaced quickly if damaged.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k18: Compliance Reporting Software (k_{18})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The compliance reporting software that the PoR is using renewal by software updates, so it is able to carry over at this moment and in the future.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Compliance reporting software is not sensitive to real big technology push. This is used to check whether everything meets the requirements according to the regulation and this will not change with regard to the current systems.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Compliance reporting software will not change. This is purely software that reports whether the regulations etc. are still being met. This will not change the entire product planning.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, compliance reporting software can be applied to any kind of ship type within the product group. This helps the communication within the ships and does not make it dependent on varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Compliance reporting softwares are not common for all types of ships that can form from the product group. It will not always be standard integrated on all ships.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Compliance reporting software is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*

This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
Software systems can be replaced and maintained via online software updates.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k19: Solar Panels (k_{19})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design cannot be carried over to coming product generations.*
This is due to regulations that make it very difficult to mix this module with other modules. Although it is possible to integrate the system in combination with other electrical systems, it is preferred as a separate module. Also, there are currently no solar panels in use.

l_2 ***Technology push:*** *It is A MEDIUM risk that this part will go through a technology shift during the product lifecycle.*
Solar panels have been on the market for some time, but there are still many technological developments taking place. The chance is greater that a type of solar panels will be chosen that will remain on the ship for the rest of its lifespan, but there is a medium risk that the technological developments will go so far that during the lifespan of the ship, a change would have to be made to the ship due to the technological push.

l_3 ***Planned design changes (product plan):*** *There are MEDIUM 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.*
Solar panels are one of the technical solutions that may be installed on the ship to provide extra energy. These solar panels currently work fine, but there are potential improvements possible. It is also possible that the solar panels will become redundant and are no longer needed on board.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Also, solar panels can be applied to any kind of ship type within the product group. This helps the communication within the ships and makes it independent of varying requirements.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in SOME of the product variants.*
Solar panels can be applied to ships but there must be enough surface area. This will not be self-evident that these will be on every standard ship and do not belong to the common standard base of ship designs.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Creating certain equipment as black box modules would be advantageous due to the need to meet strict regulations and the precise construction. If a specialist could supply these modules, the logistics costs could be reduced.

l_{10} ***Service/maintenance:*** *It is possible that MOST of the service repair will be easier if this part is easily detachable.*
Solar panels are always positioned facing the sun and will be easily accessible for maintenance.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k20: Wind Turbines (k_{20})

l_1 ***Carry over:*** *There are SOME reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The wind turbines have the possibility to be combined in a module, but because of the specific operating profile and capabilities, it is a good idea to separate it in order to make the ship more flexible. Currently, there are no wind turbines being used.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*
Wind turbines have not yet been developed to be available off the shelf on the market. However, this technology is being strongly developed. There is therefore a small chance and some risk that this part and component will undergo a technological shift. But wind turbines on board this type of ship have a very low probability.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Wind turbines did not undergo any further product design changes because wind turbines are a large installation on board the ship. Also, the chance that a wind turbine will be installed on board one of the future products (ships) is not very big.

l_4 ***Technical specification:*** *This part is STRONGLY influenced by varying requirements.*
The need to be able to install a wind power turbine on board is a major intervention in the ship. Installing such a system has a major impact on the rest of the functionalities. The varying requirements strongly influence whether the wind turbines are present or not.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as

long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in NONE of the product variants.* Wind turbines can be applied to the ships, but for this, there must be enough free surface area. This is a large installation that can possibly be tested but on a single ship. For the normal ship types of the current fleet, it would not be an option at all because it does not fit in the operational profile. It will therefore not belong to the common standard base of the ship designs.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.* This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.* This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?* Creating certain equipment as black box modules would be advantageous due to the need to meet strict regulations and the precise construction. If a specialist could supply these modules, the logistics costs could be reduced.

l_{10} ***Service/maintenance:*** *It is possible that MOST of the service repair will be easier if this part is easily detachable.* The wind turbines are powered by the wind and must therefore be exposed to the open air. This makes replacement easy.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.* At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).* When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k21: Modular Cargo Holds (k_{21})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.* The technical solution of a modular cargo hold is a very specific solution on its own. It is difficult to combine this module with others and therefore it is a good idea to create a separate module.

l_2 ***Technology push:*** *It is A GREAT risk that this part will go through a technology shift during the product lifecycle.* Modular cargo holds have a high probability that these types of cargo holds will develop a lot. All the modular functions on board of the ships and especially the parts that are conceived in the future will be very sensitive to technological push. The exchange and being as flexible as possible for all operations, that is what a modular cargo hold will have to deal with throughout the entire product lifecycle.

l_3 ***Planned design changes (product plan):*** *There are STRONG 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.* Modular cargo holds will have a big chance of a possible change and a planned design change because this is a variable factor within the ship. The current function, or the function at delivery, does not have to be the same as the function in 10 years. It is very likely that these technical solutions will undergo a design change.

- l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
  The modular cargo holds on board the ship are important to integrate, and these cargo holds will differ per requirement. This relates to the types of modular holds and the applicability. The integration of a modular cargo hold will be the same on each ship and will not be influenced by varying requirements.
- l_5 ***Styling:*** *This part is 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.*
  The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.
- l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
  Modular cargo holds are not common for all types of ships that can form from the product group. It will not always be standard integrated on all ships.
- l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
  This system is a suitable work content for a group.
- l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
  This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.
- l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
  Modular cargo holds are not supplied according to the black box principle.
- l_{10} ***Service/maintenance:*** *It is possible that ALL of the service repair will be easier if this part is easily detachable.*
  Modular cargo holds will be used as a modular system to store cargo. Because the cargo is exchanged modularly, the cargo hold is also easier to access during replacement or maintenance.
- l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
  At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.
- l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
  When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k22: Real-Time Data Processing Units (k_{22})

- l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
  Because real-time data processing units have the possibility to combine these units with other units. In this way, the base of the ship can be built up by standardized software units.
- l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
  Real-time data processing units will not have a risk because these data processors only actively analyze but do not control anything on board the ship. It therefore has no clear function, which means that a technological push of this technological solution will have no effect. The real-time data processing units that will be installed when building the ship will remain in the ship for its entire life cycle.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Because real-time data processing units have a function, this is fixed. In the future, data will be processed, and this will not change. So there will be no design changes during the life of the ships.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Real-time data processing units will not be influenced by varying requirements because on board this type of ships there are none. In the designs, there will be no varying requirements that will influence the systems for the real-time data processors.

l_5 ***Styling:*** *This part is 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.*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Real-time data processing units form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A real-time data processing unit is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
Software systems can be replaced and maintained via online software updates.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k23: Energy Recovery Systems (k_{23})

l_1 ***Carry over:*** *There are SOME reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
An energy recovery system has the possibility to be carried over but for this specific fleet renewal program, there is a need for very specific energy systems. Therefore, there are some reasons that this should be a separate module.

l_2 ***Technology push:*** *It is SOME risk that this part will go through a technology shift during the product lifecycle.*

Energy recovery systems are currently reasonably efficient and are almost at their maximum. Any development that can still take place will be a minimal improvement in efficiency. When conventional diesel generators disappear from ships, there will be even less residual heat.

l_3 ***Planned design changes (product plan):*** *There are 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 system will ensure that some energy is recovered and has determined its function. It will not be necessary to make a separate module around this technical solution because it is a carrier of characteristics that are changed.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
For energy recovery systems, the size and size will be influenced by the amount of energy that is consumed and needed. The requirements per product and ship design will influence this consumption and therefore also the influence on the entire product group and the individual products.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Energy recovery systems form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Energy recovery systems are desired to be delivered as a black-boxed module. This saves logistic costs because the standardized fleet can be equipped with the systems by one supplier.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k24: E-nose (k_{24})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Because an E-nose is a quite simple system that is easy accessible and interchangeable. This technology is not likely to change. The E-nose technology will be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
E-nose systems are conservative systems that will not change in the future and will not develop technologically. During the life cycle of the products that will be developed for the PoR, an E-nose system will not experience a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Because an E-nose is such a conservative system that it is not needed and there are no intentions to modify or enhance parts of the product.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The Port of Rotterdam will try to create as large a measuring area as possible in order to measure toxic substances as accurately as possible. For this reason, each ship will be equipped with an E-nose and the requirements have no further influence. A second possibility could be that there is an integrated sensor system in the entire port, so that none of the ships would have an E-nose.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
E-nose systems form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
An E-nose requires no specific maintenance or pedagogical assembly and can be easily installed.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technological solution can be easily reached for maintenance.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k25: DPS (Dynamic Positioning System) (k_{25})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*

DPS is a well-developed system and is also not likely to change. It operates from the energy system and by screws. If there is a need for a separate module, this would make the ship very complex.

l_2 ***Technology push:*** *It is MEDIUM risk that this part will go through a technology shift during the product lifecycle.*
DP systems are still being developed at the moment. Just as there was a development of DP3 after DP2, work is still being done on dynamic positions. The technological changes will not be huge, which means there is a medium risk.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A DP system is installed and does not carry any parts or attributes that have a possibility to change in the future. A DP system contributes to the progressive vision of the company and will not be modified.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The use of ships with a DP system will not depend on the requirements of the ships, because the need is to have standardized ships with a similarity in the basic systems. The technical specifications and a variation in them will not ensure that the DP system on board is influenced by the different products.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
DP systems form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k26: Bow Thruster (k_{26})

l_1 ***Carry over:*** *There are SOME reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Given that bow thruster technology is expected to remain relatively unchanged, its existing capabilities might not always meet the performance needs of all ship types. This discrepancy could reduce its adoption across various vessels.

l_2 ***Technology push:*** *It is no risk that this part will go through a technology shift during the product lifecycle.*
The bow thruster is used for mooring and positioning the ship. These have been developed in the right way for the functionalities that will be present for the ships of the PoR and will not be replaced due to a technological push during the lifespan.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A bow thruster is a system that is designed and installed around the ship. Its function speaks for itself and will not change.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The bow thruster is also a simple but important component on board the ships. With this system, standardization is also preferred, and therefore it will not be dependent on different requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Bow thrusters form part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Aangezien alle schepen gelijktijdig functionele componenten, kan de productie fabrikant worden door deze componenten tot op zekere hoogte te modulariseren. Hierdoor kan het gebruik van systematiek in de productie kostenbesparend zijn en bovendien dit systeem effectieve werkinhoud voor een team bieden.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*

When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k27: Spade Rudders (k_{27})

l_1 ***Carry over:*** *There are ANY reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The existing technology is expected to remain unchanged. Nevertheless, any future ship that is built must have an equivalent displacement and similar maneuvering capabilities to be eligible for this module.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Spade rudders are one of the options that can be present on board the product family ships and can be chosen for steering and maneuvering the ships. These rudders will be designed from a standardized vision for the ships. This means that they will be based on a standard model from a shipbuilder or specially matched to the designed model. When the rudders are attached under the ship, these rudders will never be replaced again due to a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
When this control system is chosen, the spade rudders will be designed for the ship or ships themselves. These will then be installed and attached to the ship itself. There will be no changes in this product plan or parts need to be adjusted, because then the ship can no longer function on its own.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The rudders will also be standardized on board and will not change. The functionality must be present on the ship and this will not change due to requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in SOME of the product variants.*
Spade rudders are an option of the possibilities to steer a ship. The choice has not yet been made and can differ per ship type. If the length and functionalities change, the control systems can also change. It will not be part of the common standard design.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Aangezien alle schepen gelijktijdig functionele componenten, kan de productie fabrikant worden door deze componenten tot op zekere hoogte te modulariseren. Hierdoor kan het gebruik van systematiek in de productie kostenbesparend zijn en bovendien dit systeem effectieve werkinhoud voor een team bieden.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k28: Disengageable propellers (k_{28})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Because these disengageable propellers can be reused and be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Disengageable propellers are one of the following methods to propel the ship and to steer it. The same applies to these propellers as to the spade rudders. When these are installed and designed for the ship, they will not be replaced by a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
As also discussed in the planned design changes (product plan) for technological solutions K27, the same applies to the disengageable propeller. This will be matched and designed for the ship itself and does not need to be a separate module.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The disengageable propellers are a choice on their own and differ from other types of propellers. If the choice is made to use disengageable propellers, this will also be applied standardized on the ships.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in SOME of the product variants.*
Disengageable propellers are an option of the possibilities to propel a ship. The choice has not yet been made and can differ per ship type. If the length and functionalities change, the propulsion can also change. It will not belong to the common standard design.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? -*

The manufacturing and development capacity can be balanced?
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k29: Firefighting monitors (k_{29})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The current technology of firefighting monitors will not change, and this will cause no reasons that this technical solution should be a separate module on its own. It is better to combine this module with other firefighting systems. Also, these systems can be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Firefighting monitors are conservative systems that are currently reliable and functioning well. For these systems, there will be no technological push within this product family that comes with new firefighting monitors, which means that these systems will not be replaced by a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Firefighting monitors will belong to the system that deals with extinguishing the fires and does not need to be seen as a separate product where it is necessary to become a separate module. If there would be a planned design change, all systems related to extinguishing must change.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
The firefighting monitors are chosen on the ship and do belong to a certain type of requirements where the ship type is used for firefighting. In this, there is a certain influence of the requirements that are focused on firefighting. There will be influence to some extent.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Firefighting monitors are a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Firefighting monitors are complex systems and important for the proper operation of the ship. For this, it would save complexity, errors, and maintenance if this module could be delivered as a black box. But it should be checked if the systems are available and suitable in the way the systems are needed.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k30: Rescue boarding platform (k_{30})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The technical solution of a rescue boarding platform should be a reliable technology. The construction of this platform will not change or be updated. Therefore, this system will be carried over.

l_2 ***Technology push:*** *It is MEDIUM risk that this part will go through a technology shift during the product lifecycle.*
Rescue boarding platforms are something that is being looked at a lot. Currently, the market has a lot to offer, such as ZIPTS (ADD SOURCE!!!!). After choosing a similar system, that system is initially chosen for the entire lifespan of the ship. If it turns out that a technological push comes with new developments that better fit the operational profile or make operating easier, then this technological shift will be a risk.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
A rescue boarding platform has a minimal possibility to undergo a planned design change when the technology changes or the regulations change.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
The technological solution of a rescue boarding platform is needed for ships that have the functionality to rescue people from the water. If the ships and the requirements differ so much that the functionalities also differ, then it is not always necessary to have a rescue boarding platform on every ship of the product group, and then it is wise to create a separate module.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

- l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
  A rescue boarding platform is a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.
- l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
  This system is a suitable work content for a group.
- l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
  This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.
- l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
  This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module. In this case, there are some current off-the-shelf products.
- l_{10} ***Service/maintenance:*** *It is possible that MOST of the service repair will be easier if this part is easily detachable.*
  A rescue boat will be located at a location where the ship can be quickly evacuated. This makes it easily accessible and simplifies maintenance and service.
- l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
  At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.
- l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
  When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k31: Gas detection system (k_{31})

- l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
  The technical solution of a gas detection system should be a reliable technology. The construction of this platform will not change or be updated. Therefore, this system will be carried over.
- l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
  Gas detection systems are conservative systems on board the ship, and because of their current reliability and functioning, the gas detection systems have no risk of going through a technological shift during the lifespan of the ships.
- l_3 ***Planned design changes (product plan):*** *There are 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.*
  A gas detection system is a conservative and relatively simple system that performs its tasks. There will be no internal company strategies regarding a gas detection system in which this product is changed or replaced. To perform the operations, the crew will also not want or consider other alternatives necessary.
- l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
  A gas detection system is so standard and general that it is installed on every type of ship. Therefore, it does not need to be a separate module as it may or may not be installed depending on varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A gas detection system forms part of the core systems, which will be the same for every vessel in the product group, regardless of the part type.

l_7 ***Process/organization:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
A gas detection system is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But it is necessary for the entire product group and can reduce logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technological solution can be easily reached for maintenance.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k32: Foam-forming system (k_{32})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The system of the foam-forming system should not be a separate system because it is correlated to the other fire fighting systems. There is a correlation. So besides the combination with other systems will be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The foam-forming system will not have a special technological change or possibility to develop. These systems operate conservatively well and reliably, and there is little play in the products. As a result, there is no risk of going through a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
With regard to a foam-forming system, it also applies that this system belongs to the larger overarching component of foam forming. This also includes the tank, etc. This system will not undergo a product change as a foam-forming system for which it is necessary to become a separate module.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
A foam-forming system is needed if there is a fire extinguishing system on board the ship and

extinguishing powder will be used to extinguish fires. There are still some uncertainties in this that cause there to be some influence by varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
A foam-forming system is a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are MEDIUM reasons why this part should be a separate module because its function can be tested separately.*
The foam-forming system is like the fire pumps and extinguishers—one of the important core elements of a fire ship. These are large installations that definitely need to be tested.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Foam-forming systems are complex systems and important for the proper operation of the ship. For this, it would save complexity, errors, and maintenance if this module could be delivered as a black box.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship and is a complex firefighting system.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k33: Powder extinguishers (k_{33})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The powder extinguishers are also currently installed on conventional ships and are very reliable types of technology. The extinguisher will fit well in a module with other firefighting equipment. The systems present on conventional ships are reliable and well-operating systems. Therefore this technology will be carried over.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The same applies to the powder extinguisher as to the foam-forming system. And as mentioned before, the current installation on the current conventional ships has the most up-to-date system, right from the start. So nothing will change and there is no risk of a technological push during the lifespan of the new fleet.

l_3 ***Planned design changes (product plan):*** *There are 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.*
The same applies to the powder extinguishers as to the technological solution of K32, whereby this extinguisher also belongs to the larger overarching module of the foam.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
Just like a foam-forming system, a powder extinguisher is needed when using extinguishing powder to extinguish fires. There are still some uncertainties in this that can cause some influence by varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Powder extinguishers are a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are MEDIUM reasons why this part should be a separate module because its function can be tested separately.*
Powder extinguishers are like the fire pumps and extinguishers—one of the important core elements of a fire ship. These are large installations that definitely need to be tested.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Foam-forming systems are complex systems and important for the proper operation of the ship. For this, it would save complexity, errors, and maintenance if this module could be delivered as a black box.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship and is a complex firefighting system.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k34: Modular firefighting storage (k_{34})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
It is a complex and difficult module to carry modular firefighting storage systems on board. This does not exist on board now and has to be developed specifically for the ships. Therefore it will not be carried over.

l_2 ***Technology push:*** *It is A HIGH risk that this part will go through a technology shift during the product lifecycle.*
Modular firefighting storage systems are still medium-developed and still have to be integrated in a proper way. Especially for ships and incident response vessels. These will undergo major technological development and there is a risk in this when purchasing and building the ships how this will evaluate in the future.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A modular firefighting storage can be filled in many different ways. In the future and with all the uncertainties of the future, it is not yet entirely clear which fires will have to be extinguished in the coming 30 years. The possibilities will still become very diverse and a lot can change. There is a good reason for this that there is a chance of planned design changes for the modular firefighting storage.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
A modular firefighting storage may differ in dimensions and sizes depending on the ship. But the need to standardize and also be able to exchange the module of firefighting storage is great and it retains this. The influence of the requirements will be noticeable to a certain extent.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Modular firefighting storage is a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.

l_7 ***Process/organization:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
A modular firefighting storage is not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship and is a complex firefighting system.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k35: Advanced crane 1 (k_{35})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Since a crane is a system that can be matched reasonably off the shelf to current vessels, but it may still be necessary to have an interchangeable crane for maintenance and flexibility reasons, it is a good idea to make this a separate module.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
A crane will undergo few developments and will be considered a robust fixed value within the ship.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A crane has its clear task as a conventional technological solution. The users of the fleet and the operations imposed by the port authority will not change. Also, reducing costs is not a logical reason to replace the crane during the product life cycle. So there is no reason for a separate module with regard to crane 1.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
The crane on board a ship depends on several factors. A crane must be able to lift a certain capacity, and this depends on the maximum weights that must be lifted. What the maximum weight is that the crane must lift depends on the ship type and thus has an influence on the technical solution.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
The crane does not have to be standard on every ship because not every future design of the product group will necessarily have to have the functionality of lifting.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are SOME reasons why this part should be a separate module because its function can be tested separately.*
Evaluating the crane requires methods that enable individual functions to be tested separately from the overall product. By testing each module independently before the final assembly, significant quality enhancements can be achieved through shorter feedback loops.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Creating the crane as black box modules would be advantageous to be able to deliver with a standardized system for the entire product group. This would reduce the logistic costs.

l_{10} ***Service/maintenance:*** *It is possible that ALL of the service repair will be easier if this part is easily detachable.*
A crane is a large system on board and is important. But when a crane fails or when maintenance is required, the entire ship cannot function. It is important to have easy access and to get the ship sailing again as soon as possible by being able to quickly and easily detach and replace a crane.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications

are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k36: Crane 2 (k_{36})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Since a crane is a system that can be matched reasonably off the shelf to current vessels, but it may still be necessary to have an interchangeable crane for maintenance and flexibility reasons, it is a good idea to make this a separate module. But a second crane is less necessary as a backup if the other crane can be quickly replaced in one go modularly. This way, cranes can be easily exchanged.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
A crane will undergo few developments and will be considered a robust fixed value within the ship.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A crane has its clear task as a conventional technological solution. The users of the fleet and the operations imposed by the port authority will not change. Also, reducing costs is not a logical reason to replace the crane during the product life cycle except for crane 2 that costs can be saved when the crane is not installed initially. So there is no reason for a separate module with regard to crane 2.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
For the same reason as crane 1 is affected by varying requirements, this also applies to the second crane. In the first case, whether a second crane is needed at all, and in addition, how much this crane should be able to lift.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in SOME of the product variants.*
A second crane does not necessarily have to be fitted as standard on every ship next to the first crane, because not every future design of the product group will necessarily have to have the functionality of lifting or lifting from two sides.

l_7 ***Process/organization:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily.*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are SOME reasons why this part should be a separate module because its function can be tested separately.*
Evaluating the crane requires methods that enable individual functions to be tested separately from the overall product. By testing each module independently before the final assembly, significant quality enhancements can be achieved through shorter feedback loops.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Creating the crane as black box modules would be advantageous to be able to deliver with a standardized system for the entire product group. This would reduce the logistic costs.

l_{10} ***Service/maintenance:*** *It is possible that ALL of the service repair will be easier if this part is easily detachable.*
A crane is a large system on board and is important. But when a crane fails or when maintenance is required, the entire ship cannot function. It is important to have easy access and to get the ship sailing again as soon as possible by being able to quickly and easily detach and replace a crane.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k37: Comprehensive Fendering (k_{37})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Today's federation systems are highly standardized and adaptable to any ship. This goes well with the hull and can be easily reused.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The fendering will initially be installed and purchased with the ship. After that, this will remain and will not have to do with technological developments that will pose a risk.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Comprehensive fendering is extremely simplistic and so simple in functionality that there will be no planned design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Comprehensive fendering is so standard and simple that it does not change per ship type in the product group. The length of the fendering must be adapted to the ship length, but in the technological solution, nothing fundamental will change.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Comprehensive fendering forms a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Fendering is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*

This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Fendering is not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k38: ShiftR (k_{38})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The Shift-R is an extremely complex system that is currently (2024) being used for the first time on ships in Norway. The technology readiness is high but they are complex systems. The reusability has not yet been determined and PoR does not yet have the systems.

l_2 ***Technology push:*** *It is A HIGH risk that this part will go through a technology shift during the product lifecycle.*
ShiftR is relatively far in its technological readiness. However, due to the short existence of the company and the new systems, the shiftR will have to deal with technological developments. The fact that the battery systems are modular on top of the ship makes it easy to also go along with a technological shift. This is the reason that there is a high risk for the technological shift for the Shift-R.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A shiftR is seen as an important player and component in the design of the new fleet in this early design stage. This energy carrier that is swappable can offer a huge outcome but there is a big chance of planned design changes. From parts that work less or need to be replaced or adjusted to the policy formation of the company itself to set up the entire fleet, or not, with a shiftR system. The costs can also be reduced with alternative systems or the energy needs of the customers can change enormously, making the shiftR no longer necessary.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
A shiftR system on board will possibly have some changing requirements regarding energy consumption. This will depend on the amount of energy needed on board. Therefore, the requirements can influence the extent to which the technological solution needs to be modular and a stand-alone module.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
SHIFTR energy systems form a part of the core systems which will be the same for every vessel

in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinary?*
This system is suitable work content for a group.

l_8 ***Separate testing:*** *There are STRONG reasons why this part should be a separate module because its function can be tested separately.*
SHIFTR is an innovative idea. Evaluating SHIFTR requires approaches that enable individual functions to be tested separately from the entire product. Testing each module independently before the final assembly can result in notable quality enhancements by shortening feedback times.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
The SHIFTR battery pack must be supplied by the specialist from the company itself. This is a new system that must be supplied as a blackbox module.

l_{10} ***Service/maintenance:*** *It is possible that ALL of the service repairs will be easier if this part is easily detachable.*
A SHIFT-R is a system located at the rear of the ship and has easy access for service and maintenance.

l_{11} ***Upgrading:*** *ALL of the future upgrading can be simplified if this part is easy to change.*
If a SHIFTR is placed well and more easily accessible, which is done because it also has to load and unload, it can also be easily removed. With an uncertain future and much future innovation, it is not yet certain what the best fuel is for an incident response vessel. By maintaining this modularity, you remain flexible in the future.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k39: Module Foam Tank 12m^3 (k_{39})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The foam tank is a separate module that could be taken on the ship. For this, it is important that the module is a separate module. This way, the ship operates just as well without the module as with the module.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The fact that a modular foam tank will be on board the ship gives it little leeway to be sensitive to technological changes.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A module foam tank of 12 cubic meters is a simple system on board and is interchangeable. This makes it possible to bring foam on board. When this system is no longer needed or the policy changes, it can easily be removed from the ship because of the modular system. This makes it unnecessary to have a planned design change for this component.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
The foam tank of 12m^3 is fixed and will be standardized. Because of this, not much will change to this tank. Only if a ship type of the product group will not be used for extinguishing, then a module for foam is unnecessary. Because of this, there is still a certain degree of influence of the requirements.

l_5 ***Styling:*** *This part is 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?*

The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
A modular foam tank is a functionality on board to be able to extinguish fires but will not belong to the common ship. This is a possibility on board but does not necessarily have to be on every type of the product group.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
A modular foam tank is supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is possible that ALL of the service repair will be easier if this part is easily detachable.*
A module foam tank already has easy access and can therefore be quickly replaced and detached.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is possible to keep some of the highly polluting material or easily recyclable material in this part (material purity).*
Recycling some of these materials is possible as the foam is a chemical that can be reused. It involves strategies that facilitate the proper disposal of hazardous and uniform materials. This approach can limit the variety of materials used and ensure that environmentally harmful materials are contained within the same module.

k40: Cabin (communication suite) (k_{40})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Within this market segment, a cabin is a relatively conservative concept. Its construction is not complex and is not expected to change or develop. However, not all requirements are always constant. For example, the desired cabins of the potential product family must be bigger than current installed cabins. Nonetheless, the future technology or concept of the next generation ships will have no to small changes. In the case of the crew space concerning the cabin (communication suite), this is an industrial standard that will change little or will really develop the future. But that does not take away from the fact that in this cabin and communication space, the potential product family should be larger. The changes will be minimal, but the complexity of such a space ensures that a separate module is desired.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The cabin and communication suite of the ships and the product family will be installed on board the ship and will not change. Technological pushes will not bring any change on board.

l_3 ***Planned design changes (product plan):*** *There are 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.*

The cabin and communication suite is a very simple and simply designed module for onboard. The purpose of this cabin will not change during its life cycle.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The cabin and communication suite and the needs of the crew and passengers will be identical on all types of ships of the potential product family. The cabin and cabins can be standardized for the entire product family and will not be affected by varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A cabin and communication suite form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
In building and realizing a cabin and communication suite, it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
A cabin and communication suite cannot be supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k41: Restaurant (k_{41})

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Everything that the restaurant room consists of inside the ship, such as the gas stove, cooling, storage, and seating, are reasonably conservative concepts that will not change much. For this, there will be an installation that is not too complex but, despite the simplistic operation, sensitive to possible changes in the future. This ensures that there are medium reasons to set up a separate module.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The restaurant on board, where the kitchen and the crew can eat, is a space that will be very

simplistic and very functional in a simple way. There is no technological push that will change this layout or this module.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Just like the technological solution K40, the restaurant will serve its function and will not change over the life cycle of the ship.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The restaurant will be identical on all types of ships of the potential product family. For this reason, the restaurants on the different ships will be within the entire product family and will not be affected by varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A restaurant forms a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
In building and realizing a restaurant, it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Separate testing:*** *There are MEDIUM reasons why this part should be a separate module because its function can be tested separately.*
For some (sub)function carriers, it would be advantageous to design them as black box modules because of their relatively complex technology. Examples of this are a gas stove and refrigerators or a dishwasher.

l_9 ***Purchase:*** *There are MEDIUM reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Some parts of the kitchen can be delivered prefabricated.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easily detachable.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k42: Rescue boat (k_{42})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
As for the rescue boat and looking at the current supply in the market, not much will change in the future with regard to developments. The most important thing about the rescue boat is to be

able to offer a way out to the crew when they end up in a calamity and can no longer get on board. Since this is the last resort option and in principle will never happen, this is a separate module that will not be reused.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
A rescue boat is also not affected by technological developments. This is because the functionality of such a rescue boat is simple and must meet certain requirements. A rescue boat still experiences technological developments, but these developments are not for current ships. When a ship is built, a classification society will certify the ship including a rescue boat. This then applies for the rest of the lifespan.

l_3 ***Planned design changes (product plan):*** *There are NO reasons why this part should be a separate module since it is the carrier of attributes that will be changed according a product plan.*
A rescue boat must be able to do what it was initially designed and conceived for. This functionality will not change during the life cycle of the ship and therefore there will be no planned design change for this technological solution.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
The rescue boat is a technical solution that is required on board all types of ships. The function is therefore independent of the varying requirements and is the same and needed on board the ships.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
A rescue boat forms a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Designing a rescue boat as a technical solution as a black box module is a good plan. In a rescue boat, there are different parts and other functions. Delivering this whole as a black box reduces the logistic costs.

l_{10} ***Service/maintenance:*** *It is possible that SOME of the service repair will be easier if this part is easily detachable.*
A rescue boat is already located outside the ship to be able to escape from the ship as quickly as possible, so it has easy access for maintenance and service.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easy recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render

some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k43: Remote controls (k_{43})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Most remote controls are for use with cranes and other standardized systems. These can be carried over very easily.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The most remote controls are designed for the ship and combined to the assisting operations such as a crane or some other fire extinguishing cannon. If these systems do not change, there is also no reason for a risk of a technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Remote controls also have a simple and easy task to be able to remotely control components and other systems, such as a crane. These tasks will not change in the future and therefore there will be no planned design change during the life cycle of this product group.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
The use of remote controls depends on the requirements that influence the use of these controls. A crane or other technological solution may need a remote control, so indirectly the remote controls are influenced by varying requirements. In general, the systems will not vary much.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
Remote controls belong to another technological solution that can control the steering. It will therefore not always be standard in the common design.

l_7 ***Process/organisation:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Remote controls are a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But it is necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k44: Propulsion system (k_{44})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The propulsion system on the ships can be carried over so there is no need for a separate module.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
The propulsion system is built and matched to the ship itself. The propulsion systems themselves will make any technological progress and develop. But the complexity is too high to replace an entire propulsion system of a ship with a new technological development. This would also entail high costs.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A propulsion system is designed for the ship itself, just like the rudders and propellers. Then it has a fixed functionality and this remains the same for the entire life cycle of the ship. This is the reason why there will be no planned product changes for this propulsion system.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
A propulsion system of the ships will be completely adapted to the ship, the shape of the ship, and the functionalities of the ship. If one of these factors changes, then the propulsion changes. Although everything is being looked at to standardize as much as possible, a propulsion system will be sensitive to varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Propulsion systems form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
In a propulsion system there are many different systems that work together and are tuned to each other. Designing a propulsion system as a black box module is therefore a pro because the logistic costs can be reduced and the manufacturing and development capacity can be balanced.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k45: Azipod propeller (k_{45})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
As well as the propulsion system on itself on the ships, the azipod propeller can be carried over so there is no need for a separate module. Although this one is taken into account, in the early design stage, there will not be chosen a type on propeller yet.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Azipod propeller is just like the spade rudder as discussed earlier a part that is installed once. When these are installed and designed for the ship, they will not be replaced from a technological push.

l_3 ***Planned design changes (product plan):*** *There are NO reasons why this part should be a separate module since it is the carrier of attributes that will be changed according a product plan.*
For the azipod propeller, the same applies as for the propulsion system as a whole, technological solution K44.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
A propulsion system like an azipod propeller can be one of the possibilities to serve as a propeller and propulsion. If a certain system is chosen like this, it will be standardized for each ship type. However, the geometry of the ship will possibly have an influence on the size of the propeller.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions in providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
The azipod propeller can be a propulsion system and a control system for the ships at the same time. This depends on the types and can therefore change. The azipod will not belong to the common design.

l_7 ***Process/organisation:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary

for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k46: Waterjet (k_{46})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
As well as the propulsion system on itself on the ships, the waterjet can be carried over so there is no need for a separate module. Although this one is taken into account, in the early design stage, there will not be chosen a type on propeller or waterjet type yet.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
For the waterjet the same applies as for the azipod, because this is also a control system and a propulsion system. When these are installed and designed for the ship, they will not be replaced from a technological push.

l_3 ***Planned design changes (product plan):*** *There are NO reasons why this part should be a separate module since it is the carrier of attributes that will be changed according a product plan.*
For the waterjet, the same applies as for the propulsion system as a whole, technological solution K44.

l_4 ***Technical specification:*** *This part is TO SOME EXTENT influenced by varying requirements.*
A propulsion system such as a waterjet can be one of the possibilities to serve as a propeller and propulsion. If a certain system is chosen as this, it is standardized for each ship type. However, the geometry of the ship will possibly have an influence on the size of the jet and the amount of thrust it must be able to produce.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions in providing high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
The waterjet can be a propulsion system and control system for the ships at the same time. This depends on the types and can therefore change. The jets will not belong to the common design.

l_7 ***Process/organisation:*** *There are MEDIUM reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Since all ships are simultaneously functional components, the production can become a manufacturer by modularizing these components to a certain extent. This can make the use of systematics in production cost-saving and also provide this system with effective work content for a team.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*

This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are STRONG reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
This technological solution is not extremely complex or consisting of different parts. But necessary for the entire product group and can reduce the logistics costs by using the design as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k47: Mooring lines and anchors (k_{47})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Mooring lines and anchors can be reused and be carried over. These are very standardized equipment even for different vessel types.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Mooring lines and anchors are not very complex systems and attributes for onboard. Mooring lines and anchors are essential for being able to perform the work and to be able to operate. However, these are also standardized parts that do not experience an exciting technological push and remain the same for the entire lifespan of the products.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Mooring lines and anchors are again systems on board whose function is fixed and will not change during the life cycle of the ship.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Mooring lines and anchors are not different and can be used very widely on other types of vessels. For the future fleet the requirements will not make a difference.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Mooring lines and anchors form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Mooring lines and anchors are a fixed system on board. This is not split up.

- l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
  This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.
- l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
  Mooring lines and anchors are not supplied according to the black box principle.
- l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
  This technical solution is too integrated into the entire ship. Especially the anchor.
- l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
  At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.
- l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
  When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k48: Deck and navigation lighting (k_{48})

- l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
  Deck and navigation lighting are uniform for all different kinds of ships. These can be reused and be carried over. These are very standardized equipment even for different vessel types.
- l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
  Deck and navigation lighting consist out of a green, red, and white light. Based on international agreements, every ship must comply with these systems on board. There is no chance that this will experience a technological push.
- l_3 ***Planned design changes (product plan):*** *There are 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.*
  Deck and navigation are again systems on board whose function is fixed and will not change during the life cycle of the ship.
- l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
  Also, deck and navigation lighting consisting of simple lights are not different for different ship types. There are no varying requirements within the product family.
- l_5 ***Styling:*** *This part is 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?*
  The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.
- l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
  Deck and navigation lighting form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.
- l_7 ***Process/organisation:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
  Deck and navigation lights are a fixed system on board. This is not split up.
- l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*

This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Deck and navigation lighting are not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k49: Work lighting (k_{49})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
Working lights can be reused and be carried over. These are very standardized equipment even for different vessel types.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
Working lights are large lamps that assist with work. These are often large lamps that provide extra illumination so that everything can be seen clearly in the dark. A lamp and specifically a working lamp will not undergo a special technological push.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Working lighting is another system on board whose function is fixed and will not change during the life of the ship.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Work lights are also standardized and simple systems. These will not differ per varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Work lighting forms a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are NO reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
Working lighting is a fixed system on board. This is not split up.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Work lighting is not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k50: Drinking water tank (k_{50})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
There is no reason to create a separate module for the drinking water tank. This tank can be carried over and be standardized between different models.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
As discussed earlier, a tank will not undergo a technological development.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Drinking water tanks are tanks that provide the function of providing clean water on board the ship. This is a function that will not change and therefore will not undergo any planned design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Drinking water tanks can differ per amount of water that is needed. If the choice is made for standardized ship hull shapes then an average water tank will suffice. This can be chosen the same in the entire product group and will not differ per product group.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Drinking water tanks form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
In creating water tanks it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Drinking water tanks are not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k51: Grey water tank (k_{51})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
There is no reason to create a separate module for the grey water tank. This tank can be carried over and be standardized between different models.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
As discussed earlier, a tank will not undergo a technological development.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Grey water tank will drain the water used in the kitchen, restaurant, etc., and other locations where dirty water is released. This is also a function that will not change and therefore will not undergo any planned design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Grey water tanks can differ per amount of water that is used. If the choice is made for standardized ship hull shapes then an average grey tank will suffice. This can be chosen the same in the entire product group and will not differ per product group.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Grey water tanks form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
In creating water tanks it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Grey water tanks are not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k52: Black water tank (k_{52})

l_1 ***Carry over:*** *There are NO reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
There is no reason to create a separate module for the black water tank. This tank can be carried over and be standardized between different models.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
As discussed earlier, a tank will not undergo a technological development.

l_3 ***Planned design changes (product plan):*** *There are 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.*
Black water tank will drain the water used in the toilets. This is also a function that will not change and therefore will not undergo any planned design changes.

l_4 ***Technical specification:*** *This part is NOT influenced by varying requirements.*
Black water tanks can differ per amount of water that is used. If the choice is made for standardized ship hull shapes then an average black tank will suffice. This can be chosen the same in the entire product group and will not differ per product group.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in ALL of the product variants.*
Black water tanks form a part of the core systems which will be the same for every vessel in the product group regardless of the part type.

l_7 ***Process/organisation:*** *There are SOME reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
In creating water tanks it is not necessary to split it up to speed up the production process enormously. The main reason for this is that the technological solution is simple and easy. The low complexity ensures that splitting is not necessary.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
Black water tanks are not supplied according to the black box principle.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k53: Hydrofoil (draagvleugel) (k_{53})

l_1 ***Carry over:*** *There are STRONG reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The hydrofoils are so enormously engineered to order and specific to a type of ship that they would be better as a separate module. They cannot simply be reused from one ship to another.

l_2 ***Technology push:*** *It is A MEDIUM risk that this part will go through a technology shift during the product lifecycle.*
A hydrofoil will undergo some development during the lifespan of the project. However, the chance that a hydrofoil will be replaced on the ship is less.

l_3 ***Planned design changes (product plan):*** *There are SOME 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.*
A hydrofoil has a small possibility of undergoing a planned design change. The company policy is now to be able to get somewhere with high speed. If it turns out that the functions of the fleet change over the years and during the life of the fleet, then it would be possible that the hydrofoil would be adjusted.

l_4 ***Technical specification:*** *This part is STRONGLY influenced by varying requirements.*
Using a hydrofoil and applying a hydrofoil on board a ship makes a huge difference in the design. The requirements per design can determine whether a hydrofoil is a tactical choice but this varies greatly per ship type. It can have both a positive and negative effect. The hydrofoil will vary greatly per product within the product group and is greatly influenced by varying requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in NONE of the product variants.*
Hydrofoils are complicated systems and require a separate sailing profile and requirements. It will not be part of the common design.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
This system is a suitable work content for a group.

l_8 ***Separate testing:*** *There are STRONG reasons why this part should be a separate module because its function can be tested separately.*

The hydrofoil is a complex system that requires careful implementation. Evaluating the hydrofoil requires methods that allow testing individual functions separately from the overall product. By testing each module separately before final assembly, significant quality improvements can be achieved by reducing feedback times.

l_9 ***Purchase:*** *There are SOME reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
A hydrofoil is a complex system that has a lot of dependency on the rest of the ship's design. If there is the possibility to design the hydrofoil as much as possible as a black box module, that would be beneficial.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
This technical solution is too integrated into the entire ship.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is NOT possible to keep any of the highly polluting material or easily recyclable material in this part (material purity).*
When the system reaches the end of its life, wear, erosion, and other depletion will likely render some of its functionality unreliable. However, the materials can potentially still be reused for other purposes if they are properly separated during dismantling.

k54: Monohull (k_{54})

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The use of a ship hull and its shape are scaled down and coordinated in the design process. In this process, the potential module of the hull, or the potential product family group, can be assembled and reused. Standardizing the ship hull, and in that respect also the shape, is a very good option. Also because the technical systems and installation on board are the same.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
A monohull is fixed for the entire life of the ship.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A monohull is fixed at the design of the ship and at the construction of the ship. This will not undergo a planned design change during the life of the ships.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
The choice of a hull is always important in the ship design process. The requirements must be carefully considered and the hull type and bow shape must be considered to see if they match and fit the requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
In the hull shapes, a choice will most likely be made between a monohull or a double hull. So in most cases, one of these two designs will be chosen and this will belong to the two common designs.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
This system is a suitable work content for a group. For the different types of ships, preference is given to the same hull. This can be built from different same building blocks. By building standardized and modular, the production process can be shorter and more efficient. So for the hull this certainly applies.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
The ship's hull is large and cannot be designed or purchased as a black box module.

l_{10} ***Service/maintenance:*** *It is NOT possible that the service repair will be easier if this part is easy to detach.*
A hull can be engineered so that no maintenance repairs are required during the life of the ship, making detachability unnecessary. In addition, detaching a hull is technically not possible because all other systems are connected.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is possible to keep some of the highly polluting material or easily recyclable material in this part (material purity).*
Recycling some of these materials is possible because the hull is normally made out of pure metal and materials. It involves strategies that facilitate the proper disposal of hazardous and uniform materials. This approach can limit the variety of materials used and ensure that environmentally harmful materials are contained within the same module.

k55: Doublehull (k_{55})

l_1 ***Carry over:*** *There are MEDIUM reasons that this technical solution should be a separate module because the new design can be carried over to coming product generations.*
The use of a ship hull and its shape are scaled down and coordinated in the design process. In this process, the potential module of the hull, or the potential product family group, can be assembled and reused. Standardizing the ship hull, and in that respect also the shape, is a very good option. Also because the technical systems and installation on board are the same.

l_2 ***Technology push:*** *It is NO risk that this part will go through a technology shift during the product lifecycle.*
A double hull is fixed for the entire life of the ship.

l_3 ***Planned design changes (product plan):*** *There are 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.*
A doublehull is fixed at the design of the ship and at the construction of the ship. This will not undergo a planned design change during the life of the ships.

l_4 ***Technical specification:*** *This part is FAIRLY influenced by varying requirements.*
The choice of a hull is always important in the ship design process. The requirements must be carefully considered and the hull type and bow shape must be considered to see if they match and fit the requirements.

l_5 ***Styling:*** *This part is 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?*
The main goal of this system and technical solutions is to provide high functionality for the user or the target. In addition, the costs must remain as low as possible and the age and shelf life as

long as possible. For this, the functional elements will have a uniform and neutral design and are not sensitive to styling, visible elements, shape, or color.

l_6 ***Common unit:*** *This function can have the same physical form in THE MOST of the product variants.*
In the hull shapes, a choice will most likely be made between a monohull or a double hull. So in most cases, one of these two designs will be chosen and this will belong to the two common designs.

l_7 ***Process/organisation:*** *There are STRONG reasons why this part should be a separate module because: - A specific or specialized process is needed? - It has a suitable work content for a group? - A pedagogical assembly can be formed? - The lead time will differ extraordinarily?*
This system is a suitable work content for a group. For the different types of ships, preference is given to the same hull. This can be built from different same building blocks. By building standardized and modular, the production process can be shorter and more efficient. So for the hull this certainly applies.

l_8 ***Separate testing:*** *There are NO reasons why this part should be a separate module because its function can be tested separately.*
This technical solution is a simple concept within the ship and its functionality can be determined without a practical test. It would actually slow down the process to realize a separate test.

l_9 ***Purchase:*** *There are NO reasons that this part should be a separate module because: - There are specialists that can deliver it as a black box? - The logistics cost can be reduced? - The manufacturing and development capacity can be balanced?*
The ship's hull is large and cannot be designed or purchased as a black box module.

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A hull can be engineered so that no maintenance repairs are required during the life of the ship, making detachability unnecessary. In addition, detaching a hull is technically not possible because all other systems are connected.

l_{11} ***Upgrading:*** *NONE of the future upgrading can be simplified if this part is easy to change.*
At this time, upgrades during the life of the ship are unnecessary, but possible future modifications are being considered. However, at this time, the systems are adequate for a future life of the ship and the latest technology is being integrated. Strategies to extend the life of the product or improve performance may exist but entail capital costs.

l_{12} ***Recycling:*** *It is possible to keep some of the highly polluting material or easily recyclable material in this part (material purity).*
Recycling some of these materials is possible because the hull is normally made out of pure metal and materials. It involves strategies that facilitate the proper disposal of hazardous and uniform materials. This approach can limit the variety of materials used and ensure that environmentally harmful materials are contained within the same module.