

Model-Based Systems Engineering with Integrated Decision Support for Early-Stage Offshore Vessel Design

Configuring and Evaluating Vessel Systems Architectures
in Capella Using a Cooling Water System Case Study



Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design

Model-Based Systems Engineering with Integrated Decision-Support for Early-Stage Offshore Vessel Design

*Configuring and Evaluating Vessel Systems Architectures in Capella
Using a Cooling Water System Case Study*

Author

Jamie Hanselaar

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Supervisors

Dr. A.A. Kana
Delft University of Technology

Z.P. Oikonomou
Delft University of Technology

Ir. B. Daman
Ulstein Design & Solutions B.V.

Author Details

Student number: 5491347

Thesis Examination Committee

Chair: Dr. A.A. Kana
Member: Z.P. Oikonomou Member:
Dr.Ir. P. de Vos Company Member:
Ir. B. Daman



Abstract

With the design of an offshore vessel, a naval architect must address a highly complex problem and constantly rely on expert knowledge to make decisions. During the Early-Stage Ship Design (ESSD) phase, most of these decisions occur while developing the main aspects of the vessel systems architecture, which comprises the mission, thruster, power generation, and auxiliary systems. Due to the complexity and numerous interdependencies of these systems, errors are not uncommon and can lead to costly setbacks. Model-Based Systems Engineering (MBSE), combined with a Decision Support System (DSS), could provide the missing framework during the ESSD decision-making process by offering traceability, centralised data, and configuration suggestion capabilities.

This study first analyses the complexity of offshore vessel systems architecture by identifying its main complexity drivers, system interdependencies, and design constraints. The current design approach is evaluated together with the opportunities and challenges of applying MBSE. Based on this analysis, the MBSE framework Capella is selected and combined with a DSS to support early-stage cooling system architecture design.

An MBSE-DSS methodology is subsequently developed consisting of four stages: MBSE system modelling, automated data extraction, design space generation, and multi-objective evaluation based on risk and cost. The methodology is demonstrated using two offshore vessel case studies, generating and evaluating approximately 8.8 million and 23.9 million feasible cooling system configurations, respectively.

The results show that the proposed framework systematically explores design alternatives that would be infeasible to evaluate manually while producing solutions that closely align with engineering practice. Comparison with a cooling system design developed by Ulstein demonstrates that the DSS identifies similar architectural design choices while providing quantitative insight into the trade-offs between cost, cluster risk, and pump room risk. Furthermore, cross-case analysis shows consistent design trends across vessels of different size and complexity, indicating that the proposed methodology is robust beyond a single case study.

Overall, the developed MBSE-DSS improves the transparency, consistency, and traceability of early-stage cooling system design by replacing experience-driven exploration with a structured evaluation of design alternatives and data-driven decision-making. Although the framework remains dependent on the availability of accurate cost and reliability data and is currently limited by computational effort, it provides a promising foundation for future MBSE-based decision support in offshore vessel systems architecture design.

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I look back with great appreciation on this project and hope that the results presented in this thesis contribute, even if only modestly, to the further application of Model-Based Systems Engineering in offshore vessel systems architecture design.

AI Statement

During the preparation of this work, I utilised OpenAI. ChatGPT (August, 2026 version) [Large Language Model]. <https://chat.openai.com/chat> to obtain inspiration for the overall structure of the report and assist in reviewing and improving grammar, spelling, and expression. Following the use of this tool, I carefully reviewed and edited the content as necessary and assume full responsibility for the final content of this publication.

Jamie Hanselaar
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Nomenclature

Abbreviations

Abbreviation	Definition
AI	Artificial Intelligence
BESS	Battery Energy Storage System
DBSE	Document-Based Systems Engineering
DP	Dynamic Positioning
DSS	Decision Support System
E-KOL	Electrical Key-One-Line
ESSD	Early-Stage Ship Design
FW	Fresh Water
GUI	Graphical User Interface
INCOSE	International Council on Systems Engineering
KS	Knowledge System
LA	Logical Architecture
LAB	Logical Architecture Blank
MBSE	Model-Based Systems Engineering
MCDA	Multi-Criteria Decision Analysis
MTBF	Mean Time Between Failures
OA	Operational Architecture
OAB	Operational Architecture Blank
PAC	Pyhton4Capella
PA	Physical Architecture
PAB	Physical Architecture Blank
PHE	Plate Heat Exchanger
PPS	Problem-Processing System
SA	System Architecture
SAB	System Architecture Blank
SE	Systems Engineering
SoI	System of Interest
SW	Sea Water
SWB	Switchboard

Glossary

Complexity

A measure of how difficult it is to understand how a system will behave or to predict the consequences of changing it. It occurs when there is no simple relationship between what an individual element does and what the system as a whole will do, and when the system includes some element of adaptation or problem solving to achieve its goals in different situations [1].

Complex System

A system in which there are non-trivial relationships between cause and effect: each effect may be due to multiple causes; each cause may contribute to multiple effects; causes and effects may be related as feedback loops, both positive and negative; and cause-effect chains are cyclic and highly entangled rather than linear and separable [2].

Cluster

A subsystem consisting of cooling system components connected in series that together provide cooling for one or more vessel loads. Within this research, clusters represent the lowest level at which redundancy, reliability, and Dynamic Positioning performance are evaluated.

Cluster Risk

The expected annual loss of Dynamic Positioning capability caused by failures of cooling system components within individual clusters. Cluster risk represents single-failure scenarios and is closely related to DP2 redundancy requirements.

Decision Support Systems (DSS)

An interactive computer-based system or subsystem intended to help decision makers use communications technologies, data, documents, knowledge, and/or models to identify and solve problems, complete decision process tasks, and make decisions. Decision support system is a general term for any computer application that enhances a person or group's ability to make decisions [3].

Early-Stage Ship Design (ESSD)

Represents the initial phase of the ship design process, encompassing both the concept design and basic design stages. During the concept design stage, key requirements are established, design freedom is high, and initial concepts are generated. Cost estimations are also developed at this point. Through multiple iterations, the design is refined into the basic design, which serves as the foundation for the subsequent design phases. In this stage, the main constraints and parameters that will guide the vessel's further development are defined.

Electrical Key-One-Line (E-KOL)

A high-level representation of the vessel electrical architecture showing power generation, switchboards, power distribution, and electrical consumers. The E-KOL serves as the primary architecture input for the developed decision-support methodology [4].

Logical Architecture (LA)

A simplified representation of a system that illustrates its components and their interconnections using single lines and standard symbols to provide a given service or function, without necessarily depicting their actual physical locations [5].

Model-Based Systems Engineering (MBSE)

The formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases [2].

MBSE Framework

The combination of the three pillars: languages, methodologies and tools [6, 7, 8].

MBSE Pillar 1: Languages

Serves as the foundation for the MBSE framework. It defines the standard methodology, consisting of syntax, grammar and notation, by which stakeholders communicate system requirements, design, and behaviour. This communication can be visual, textual, or a combination of both, ensuring that each stakeholder can clearly understand the perspectives of different disciplines.

MBSE Pillar 2: Methodologies

Define the MBSE process and provide a framework for the involved tools and stakeholders. So the methodology shows how the systems architecture can be build.

MBSE Pillar 3: Tools

Facilitates the systems architecture with the use of the rules and guidelines from the used language(s). A MBSE tool is different from the tools the naval architects use. A MBSE tool ensures that the elements of the system are stored and connected with each other.

Operational Architecture (OA)

Represents the spatial and physical characteristics of the system and of its environment [5].

Physical Architecture (PA)

Describes temporal behaviour of a system, including human-system interactions to some extent [5].

Pump Room

A physical compartment containing cooling system equipment and one or more cooling clusters. Pump rooms form the spatial level at which compartment-failure scenarios are analysed.

Pump Room Risk

The expected annual loss of Dynamic Positioning capability resulting from complete compartment failures, such as flooding or fire. Pump room risk represents DP3-related failure scenarios.

Stakeholder

Any group or individual who can effect or is affected by the achievement of the firm's objective [9].

System

The combination of elements that function together to produce the capability required to meet a need [10].

Systems Architecture (SA)

The system architecture design defines system behaviour and structure characteristics in accordance with derived requirements. The architecture ensures that the system elements operate together in the applicable operating environment to satisfy stakeholder needs [11].

Systems Engineering (SE)

The transdisciplinary and integrative approach to enable the successful realisation, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods [12].

Vessel Systems Architecture

Represents the vessel as an integrated system by defining its physical, logical, and operational architectures [5].

Introduction

1.1. Context and Motivation

Traditionally, the early stages of vessel design have relied on the Design Spiral and the expertise of naval architects. This conventional approach makes the initial design process both time-consuming and error-prone, as engineers must manually navigate extensive sets of requirement documents [13, 14]. Moreover, because many low-level system interconnections remain unnoticed, design flaws are sometimes only detected in later development phases, which can lead to costly revisions and project delays [15].

This problem has also been identified by Ulstein, a naval architecture company specialised in the design of complex offshore vessels [16]. One potential solution is the use of Model-Based Systems Engineering (MBSE). MBSE employs languages, methodologies, and tools to provide a framework to integrate data from different programs [17, 18]. During the Early-Stage Ship Design (ESSD) phase of a vessel, requirements can be entered into an MBSE tool and accessed more easily. More importantly, the system can automatically identify and flag unmet requirements, thereby preventing costly mistakes early in the process [19]. Since in MBSE the system architecture is linked to its elements and requirements, multiple stakeholders can work in parallel while the data and requirements lists are continuously updated in the MBSE environment, ensuring that everyone operates with the most recent information [20].

Furthermore, MBSE is particularly advantageous because vessel systems are often highly intertwined. While the main system connections are relatively easy to identify, the interdependencies at the lower levels of the system hierarchy are nearly impossible for a human to fully grasp [21]. An example is the cooling pump system, where possible system architectures may include varying numbers of pumps, different redundancy concepts, and differing impacts on structural layout, power demand, and space requirements. These subtle interconnections can nevertheless have a significant effect on the overall effectiveness and performance of the vessel [15].

To make use of the potential benefits of MBSE, Ulstein has expressed interest in exploring how decision-support functions could be integrated into a future MBSE framework. Such functions would leverage system interdependencies to indicate how design choices affect various subsystems and to provide guidance in evaluating alternative configurations. For example, when determining which Dynamic Positioning (DP) class the vessel should comply with, the framework could propose multiple options along with their respective advantages and disadvantages [18], ultimately leading to corresponding requirements for the thrusters and propulsion units.

This type of guidance not only reduces design errors but also supports naval architects in exploring a wider range of viable solutions [13].

By applying MBSE, the time required for the initial design phases may be significantly reduced, while also improving the overall quality and robustness of offshore vessel designs [14].

1.2. Problem Definition

The early stages of offshore vessel design currently lack a dedicated framework that enables designers to identify system interdependencies, compare design alternatives, and trace how early decisions propagate through the ship's systems. Although there is considerable potential for MBSE, it is unclear how it should be applied to ESSD, which modelling approaches are suitable for such a workflow, and what effects it may have on the design process. This absence of a defined MBSE framework prevents naval architects from exploiting the benefits of MBSE for configuration exploration and error reduction in ESSD.

1.3. Research Objective

The objective of this thesis is to develop an MBSE-based Decision Support System (DSS) to assist in the early concept design of offshore vessels, focusing on the configuration and evaluation of the vessel systems architecture. The proposed MBSE-DSS will integrate decision-support functionality to help naval architects evaluate multiple design configurations, such as the number of propulsion units, arrangement of engine rooms, degree of redundancy, and auxiliary system sizing. By systematically comparing the advantages and disadvantages of each configuration, the tool will enable informed design decisions, improve traceability of system interdependencies, and reduce the likelihood of errors in the early design phase.

1.3.1. Research Questions

Main research question:

To what extent can a model-based systems engineering tool with integrated decision-support functionality assist in the configuration and evaluation of the vessel systems architecture during the early design phase of offshore vessels?

To reach the objective and answer the main research question, five sub-questions have been defined:

- RQ1:** Which system interdependencies and technical factors contribute to the complexity of offshore vessel systems architecture?
- RQ2:** Which benefits and challenges are associated with adopting MBSE for the early design phase in the maritime sector?
- RQ3:** Which MBSE frameworks are most suitable for developing an MBSE decision-support tool that can model system architecture and compare system configurations?
- RQ4:** How can the MBSE-DSS facilitate the identification of system interdependencies and support the evaluation of design trade-offs across different vessel configurations?
- RQ5:** To what extent can the use of an MBSE-DSS improve the decision-making process, reduce design errors, and support early estimation of cost, layout, and system performance, compared to the approach Ulstein uses?

1.3.2. Research Scope

This thesis focuses on the early design phase of offshore vessels, specifically the concept and basic design stages. The research is limited to the main onboard systems within the vessel systems architecture, including mission, thruster, power generation, and auxiliary systems. These systems form the basis of the logical architecture, which is represented by the electrical key one-line diagram used in Ulstein's ESSD process. The scope places emphasis on system-level configuration and the interactions between the main onboard systems.

The scope includes the identification and modelling of system interdependencies, the generation and evaluation of alternative system configurations, and the development of an MBSE-based decision-support approach to support early-stage design decisions. The proposed approach will be demonstrated through a representative case study and evaluated using measurable indicators related to the design decision-making process. Detailed engineering design, component sizing, control system implementation, and analyses beyond the concept and basic design stages are outside the scope of this research.

Offshore Vessel Systems Complexity

Offshore vessels do not represent a single vessel type, but rather a broad category encompassing vessels that support activities in the offshore wind and offshore oil and gas industries. Because offshore projects are highly complex, the vessels that support them are likewise specialised and sophisticated.

As Ulstein primarily focuses on complex offshore vessels, this study considers the following vessel types: wind farm installation vessels, heavy lift crane vessels, pipelay vessels, rock installation vessels, shallow draught construction support vessels, and drill vessels [16].

Each vessel type has specific operational requirements and onboard systems, resulting in different system interdependencies. Understanding these interdependencies is essential before developing a decision support system. This chapter addresses **RQ1** by first introducing the factors contributing to vessel complexity in Section 2.1, followed by the different types of interdependencies in Section 2.2. Section 2.3 discusses the regulatory and operational constraints, while Section 2.4 presents the ESSD systems, their interdependencies, and their impact on offshore vessels.

2.1. Complexity Drivers

Ship design is an inherently complex process, with vessels considered among the most complex massive, and expensive engineering products in existence today [22]. This complexity results from multiple factors such as vessel size, hull form [23], the number and diversity of onboard systems, and the interactions between these systems [24, 25]. Furthermore, ship design is a specific customer-oriented and customer-dominated process [24], making each offshore vessel effectively a unique, one-off design. On top of that, vessels increasingly resemble open, highly interconnected systems with fewer rigid subsystem boundaries, further amplifying their complexity [26].

Before examining the systems of offshore vessels in detail, it is essential to define and structure the relevant complexity types. As this study focuses on the ESSD phase, a subset of complexity types is selected from the framework proposed by Ebrahimi et al. [24]. The full framework includes structural, temporal, behavioural, spatial, contextual, perceptual, decision-making, directional, and technological complexity. However, not all of these are equally relevant within the scope of this study. Complexity types related to temporal, behavioural, contextual, perceptual, and technological complexity are not explicitly considered, as the DSS is applied at a fixed design stage with predefined system behaviour and established technology assumptions.

The following complexity types are therefore selected as most relevant for ESSD offshore vessel system architecture design:

- CT1: Structural complexity**, referring to the number and variety of systems and components, including their interdependencies and interfaces.
- CT2: Decision-making complexity**, referring to the number, diversity, and influence of decisions and decision makers involved in the design process.
- CT3: Spatial complexity**, referring to the physical placement and interactions of systems and components within the available space.

These complexity types are selected because they directly relate to the ESSD phase, where naval architects define system architectures, evaluate alternative configurations, and allocate systems and subsystems. The other complexity types, proposed by Ebrahimi et al. [24], were excluded because they fall outside the scope of the present study. The next section builds on these complexity drivers by examining the specific offshore vessel systems and their contribution to overall vessel complexity.

2.2. System Interdependencies

This section examines the internal interdependencies between offshore vessel systems, describing how they interact and influence one another within the vessel. For the purpose of this study, these interdependencies are categorised into three groups: direct, indirect, and spatial interdependencies. This classification is adapted from the interdependency framework proposed by Rinaldi, Peerenboom, and Kelly [27], who distinguish between physical, geographic, cyber, and logical interdependencies. To better reflect the interactions encountered during offshore vessel design, these categories are translated into direct, indirect, and spatial interdependencies. This terminology also avoids ambiguity with the functional, logical, and physical architecture layers used later on in Capella. External interdependencies, referring to dependencies between the vessel and its operational environment, are acknowledged but fall outside the scope of this study. The specific systems that depend on one another are discussed in Section 2.4, while this section focuses on the nature of the interdependencies themselves.

2.2.1. Direct Interdependencies

Direct interdependencies occur when the operation of one system directly depends on another system. In other words, one system cannot perform its intended function without the support of another. A typical example is the cooling system of a diesel generator: without sufficient cooling, the generator overheats and can no longer operate. Identifying these direct interdependencies is therefore essential for developing a functional vessel systems architecture. They primarily contribute to structural complexity (CT1), as they determine the interfaces and connections required between systems.

2.2.2. Indirect Interdependencies

Indirect interdependencies arise when one system influences another without being directly required for its operation. Instead, the interaction occurs through operational constraints or dependencies elsewhere in the vessel. For example, a failure of the DP system prevents a heavy-lift crane from performing lifting operations safely, even though the crane itself remains fully operational. Because these relationships are less explicit than direct interdependencies, they are more easily overlooked during the design process. Indirect interdependencies mainly increase decision-making complexity (CT2), as they require designers to consider secondary effects across multiple systems.

2.2.3. Spatial Interdependencies

Spatial interdependencies arise from the physical arrangement of systems within the vessel. They include constraints related to machinery spaces, compartment layouts, cable and piping routes, accessibility, and maintenance requirements. Since many systems compete for limited space, their placement directly influences the feasible arrangement of other systems. Consequently, naval architects must balance operational, safety, and accessibility requirements to achieve an efficient vessel layout [4]. These interdependencies primarily contribute to spatial complexity (CT3), as they determine how systems can be integrated within the available space.

2.3. System Regulatory and Operational Constraints

In addition to complexity arising from interdependencies between systems, regulatory and operational constraints further increase overall complexity. System regulatory and operational constraints affect mainly the decision-making complexity (CT2).

This means that an offshore vessel must, first and foremost, comply with national and international regulations [28]. Every system has its own requirements that must be met to ensure that the vessel can be operated safely and does not harm the environment [29].

In addition, the vessel must meet the requirements set by the customer. Customer requirements also cause an increase in complexity [24]. For example, the type of missions the vessel has to perform influences the overall systems architecture. This may require a specific DP class, which in turn affects the regulatory redundancy requirements and thereby increases the overall system complexity. Similarly, the required number of operational hours before refuelling influences the amount of fuel and provisions that must be stored on board.

The main complexity driver of the vessel systems architecture in terms of regulatory and operational constraints is the DP class. DP refers to offshore operations that require high positioning precision, for which maintaining a stable and stationary platform and a safe operating environment is essential. The DP class defines the required level of redundancy and fault tolerance of the vessel systems. Offshore vessels can be equipped with one of three DP classes, namely DP1, DP2, or DP3, each with increasing redundancy and reliability requirements [29, 30, 31].

- DP1:** is the most basic class, providing automated position and heading control without manual intervention. It has no redundancy, meaning that a failure in any critical system can result in total loss of positioning capability. DP1 is typically suitable only for operations in low-risk environments. Due to the heavy equipment and harsh conditions encountered in offshore operations, DP1 is generally not relevant for such vessels.
- DP2:** offers automated positioning and heading control, combined with sufficient redundancy to tolerate the failure of any single component without losing positioning capability. For instance, if one engine fails, the vessel can continue full operation. DP2 is generally applied in medium-risk operations, such as offshore construction.
- DP3:** provides the highest level of redundancy. In contrast to DP2, a DP3 system remains fully operational even after the loss of an entire compartment, such as a complete engine room, without compromising positioning capability. This level is used for high-risk operations requiring precise coordination, where failure could have severe or catastrophic consequences, for example on drilling vessels.

Relevant requirements which correspond to the DP classes are listed in Appendix A.

2.4. Offshore Vessel Systems

An offshore vessel comprises multiple complex systems, each contributing to the overall design complexity. For vessels, the mission determines the main functions the systems must be able to perform [28]. In the ESSD phase of offshore vessel design, the main onboard systems of the vessel systems architecture form the starting point of this phase, shown in Figure 2.1, only these systems are considered to be within the scope of this study.

The ESSD specific logical architecture used, defined as the electrical key-one-line (E-KOL) diagram, illustrates the overall architecture of the electrical system. In this configuration, four engines drive generators that produce electrical power. This power is distributed through two main switchboards, which supply power to several consumers: frequency converters feeding electric propulsion motors, and transformers that step down voltage levels for low-voltage systems and auxiliary equipment.

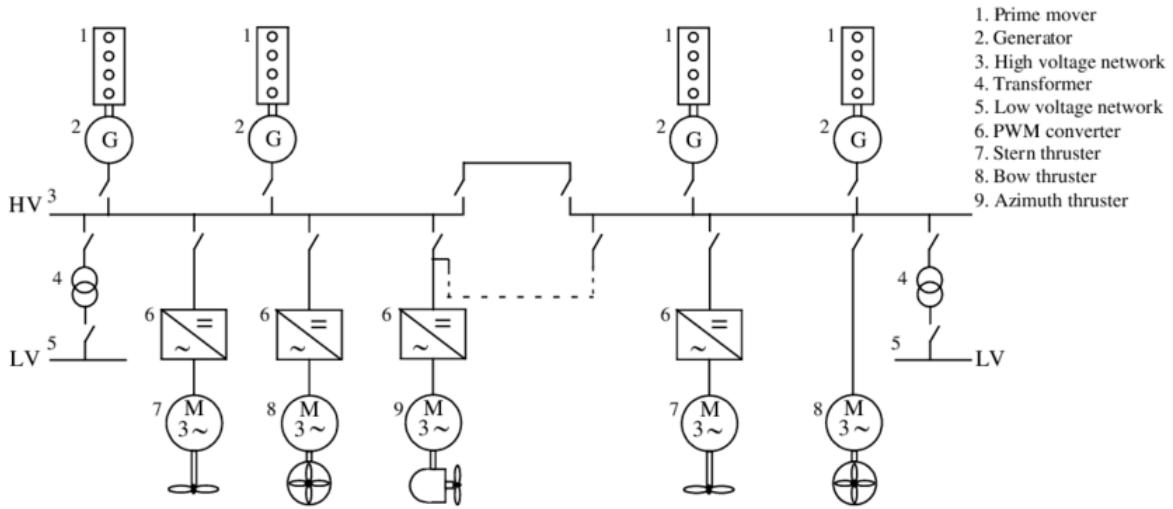


Figure 2.1: Key-One-Line Diagram of an Offshore Vessel [32]

These systems can be grouped into the following categories based on Ulstein's Ship Functional Identification (SFI) document [33] and [34]: mission, thruster, power generation and auxiliary systems. During the ESSD process based on the defined requirements, the mission systems and the corresponding thruster systems are selected first [4]. Based on these selections, the power generation systems are subsequently determined. Finally, the auxiliary systems are chosen, as they primarily support the operation of the other systems. These high-level systems are highly interconnected and can be further divided into subsystems, which themselves exhibit interdependencies. Consequently, understanding the behaviour and interactions of these systems is a critical component of the ESSD phase. An overview of the high-level interdependencies between these systems is provided in Section 2.5.

Other systems not mentioned here fall outside the scope of this study but must still be considered in later stages of the ship design process, as they may contribute to overall complexity.

2.4.1. Mission Systems

Mission systems enable the vessel to perform its intended offshore operations. Depending on the vessel type, these systems include equipment such as cranes, drilling equipment, cable-laying equipment, and rock installation systems [35].

Mission systems exhibit both direct and spatial interdependencies. Large mission equipment requires electrical power, auxiliary services, structural support, and sufficient deck space. For example, heavy lifting operations require substantial electrical power, affecting both the power generation and auxiliary systems, while also relying on the DP system to maintain vessel position. In addition, the large physical footprint of mission equipment places significant constraints on the vessel layout. Simply increasing the vessel size is often not economically feasible and may introduce operational limitations, such as restrictions on port depth, beam, or air draft.

Consequently, mission systems exhibit high structural and spatial complexity. Decision-making complexity is considered medium, as the overall mission equipment is largely determined by customer requirements, while naval architects primarily optimise its integration within the vessel [4].

2.4.2. Thruster Systems

Thruster systems comprise all systems responsible for propelling and manoeuvring the offshore vessel, including propellers, azimuth thrusters, tunnel thrusters, and shafting arrangements [34]. As shown in Figure 2.1, the example vessel employs stern thrusters, bow thrusters, and azimuth thrusters.

The primary function of these systems is to generate the forces required for propulsion and DP [36]. Thruster systems exhibit strong direct interdependencies with both the electrical power system and the DP control system. The DP controller depends on the available thrusters to execute positioning commands, while the thrusters rely on the electrical power system for operation. To satisfy DP redundancy requirements, these direct dependencies are partially decoupled through redundant power distribution, reducing the impact of single failures while increasing overall system complexity [4].

As a result, thruster systems exhibit high structural complexity due to their numerous direct interdependencies, while decision-making and spatial complexity remain moderate because their configuration and physical arrangement are relatively well defined.

2.4.3. Power Generation Systems

The power generation system is responsible for generating and distributing electrical energy to all onboard consumers [34]. The vessel's operational profile strongly influences the required installed power. Offshore operations typically involve highly variable electrical loads, requiring a flexible power generation architecture rather than a constant power output [36]. Flexibility is commonly achieved by installing multiple generator sets that can be operated according to demand, while battery energy storage systems can further improve operational flexibility by supplying reserve capacity and absorbing load peaks.

Because virtually every onboard system depends on electrical power, the power generation system forms the backbone of the vessel systems architecture and therefore exhibits numerous direct interdependencies [4]. In addition, indirect interdependencies arise through regulatory requirements such as the selected DP class, which influences redundancy arrangements, engine room configuration, and overall system architecture. The physical separation required for higher DP classes also introduces spatial interdependencies.

Consequently, the power generation system exhibits very high decision-making complexity, high structural complexity, and medium spatial complexity.

2.4.4. Auxiliary Systems

Auxiliary systems support the operation of the vessel's primary systems and ensure safe and reliable operation. These systems include cooling systems, pumps, piping, lubrication systems, HVAC, fresh water production, waste handling, and heat exchangers [34]. Together, they provide essential services to the mission, thruster, and power generation systems [28, 37].

Auxiliary systems exhibit all three types of interdependencies. Direct interdependencies arise because engines and other major equipment require cooling, lubrication, and other auxiliary services to operate. Indirect interdependencies occur because design decisions elsewhere in the vessel architecture, such as increasing the number of engines, affect the required cooling capacity, pump sizing, and auxiliary equipment, even though these relationships are not immediately visible in the high-level system architecture. Finally, spatial interdependencies arise because pumps, piping, and heat exchangers must be integrated within the limited machinery spaces while satisfying accessibility, redundancy, and routing constraints [4].

Due to this combination of direct, indirect, and spatial interdependencies, auxiliary systems are considered the most complex system group. They exhibit very high structural and decision-making complexity and high spatial complexity.

2.5. System Complexity Overview

Table 2.1 provides an overview of the complexity scores for each system group defined in this chapter. As shown, the auxiliary and power generation systems are the most complex systems during the ESSD phase. Additionally, the mission and thruster systems also have high scores, making them important to consider in the naval architect's decision-making process when iterating between different designs.

Table 2.1: Dominant Complexity Types per System Group in ESSD

System group	CT1: Structural	CT2: Decision-making	CT3: Spatial
Auxiliary Systems	Very High	Very High	High
Power Generation Systems	Very High	High	Medium
Mission Systems	High	Medium	High
Thruster Systems	High	Medium	Medium

Figure 2.2 shows an overview of the interdependencies between the high-level systems of an offshore vessel. Note that these interdependencies can vary depending on the type of offshore vessel. For instance, the mission systems of heavy lift crane vessels have a much greater influence on the other systems due to their very large lifting capacities, compared to, for example, an offshore support vessel. The core idea remains unchanged: the auxiliary and power generation systems are the primary complexity drivers and should be addressed first during the ESSD phase.

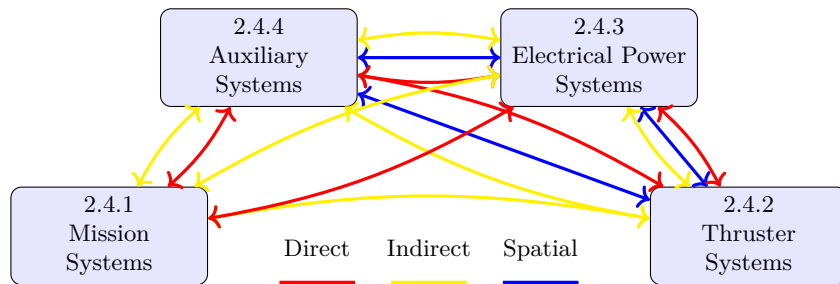


Figure 2.2: Offshore Vessel Systems Interdependencies Overview

Benefits and Challenges of Adopting MBSE

This chapter addresses **RQ2**, examining the key benefits and challenges of applying MBSE in the ESSD phase. First, Section 3.1 and Section 3.2 outline the principles of systems engineering and the current ship design practices, as well as their limitations. Next, Section 3.3 explores the advantages of adopting MBSE in ESSD compared to the traditional Design Spiral and DBSE. Finally, Section 3.4 discusses the main challenges involved in implementing MBSE. An overview of these benefits and challenges is presented in Section 3.5.

3.1. Systems Engineering

Before exploring the current systems engineering approach and potential future MBSE methods, it is important to understand the fundamentals of Systems Engineering (SE).

As engineering projects such as shipbuilding became increasingly complex [6], collaboration between multiple stakeholders became necessary, with each stakeholder aiming to optimise their own interests. In such complex projects, optimising individual components does not necessarily result in an optimal overall design [38]. This is largely due to interdependencies between system components, where even small changes can produce significant effects on the overall system. Consequently, the ideal solution is often not known in advance [39, 40].

A more structured approach was needed to manage the complexity of ship design projects involving numerous components. This need gave rise to Systems Engineering. SE is a process-oriented methodology that focuses on balancing the interests of all stakeholders. Instead of optimising individual components, SE aims to achieve a design that satisfies all stakeholders requirements by providing guidance throughout the design process. This improves stakeholders understanding of the project and clarifies the ultimate goal, which is delivering a vessel that meets the defined requirements, performance objectives, and operational needs [40, 41].

Stakeholders in SE include all groups with direct influence on or interest in the project. These typically include customers, who define requirements and request the end-product that fulfils all stakeholder requirements, engineers, who optimise their specialised components, regulatory bodies, who are responsible for verifying that the vessel complies with applicable standards, and management, who ensure the project remains economically feasible and on schedule.

SE plays a leading role in early project stages by defining system boundaries, defining and allocating requirements, evaluating design trade-offs, reducing risks associated with identifying interdependencies, and providing a structured approach to verification and validation [10]. While SE introduces additional effort, it is crucial for complex ship design projects because errors made later are more costly to fix than the upfront investment in systems engineering [6]. Figure 3.1 illustrates the typical life-cycle costs in a design project. Early-phase decisions determine a significant proportion of total project costs, and revisiting earlier phases later can lead to substantial rework [10]. Therefore, SE emphasises cost-effective decision-making by ensuring necessary information is available and selecting safe options that meet requirements, minimise cost and schedule impact, and reduce risk.

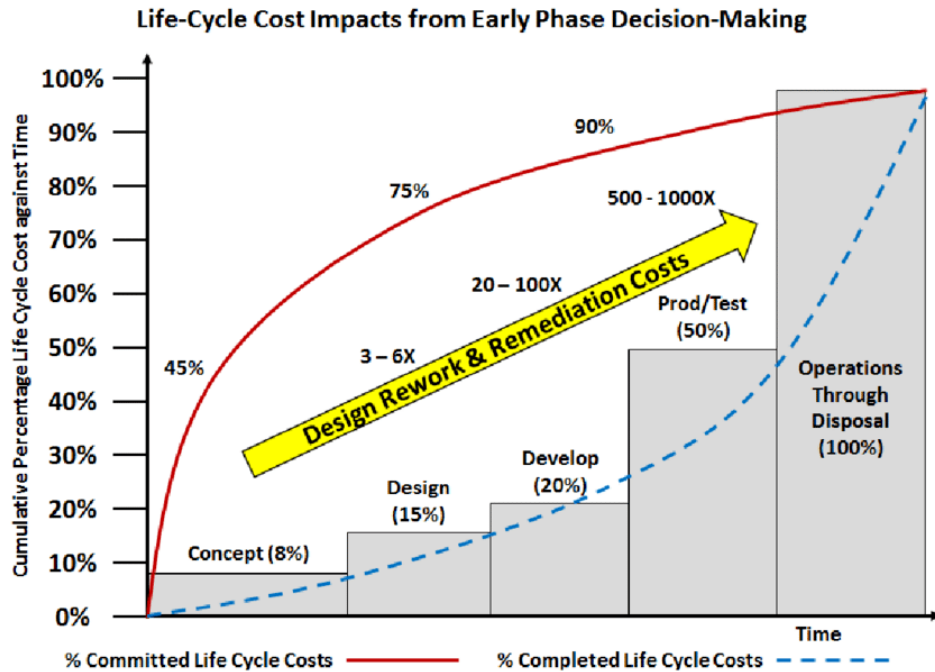


Figure 3.1: Life-Cycle Cost Impacts of Early Phase Decision-Making [42]

3.1.1. V-Model

The SE process can be represented using the V-Model, shown in Figure 3.2. This model combines a top-down and bottom-up approach. The primary purpose of the V-Model is to establish a clear understanding of the end goal and to verify and validate the design throughout the development process. Verification ensures that the requirements are satisfied, while validation confirms that the design effectively meets stakeholder requirements in the intended operational environment.

The process starts at the top-left by defining the vessel's purpose as determined by the customer. Next, the vessel's functions and requirements are specified, which are then decomposed into sub-requirements. During the concept phase, iterative exploration of design options occurs, as it is the most cost-effective time for evaluating alternatives [43]. Moving down the left side of the V-Model, the design transitions from high-level system definitions to lower-level subsystems. This allows engineers to handle complexity and focus on their expertise while maintaining alignment with the overall system [26].

The right side of the V-Model addresses integration and testing. Subsystems are verified against

requirements and, if necessary, redesigned. As subsystems are integrated, interdependencies are assessed and tested. This process continues until the complete system meets stakeholder expectations and satisfies all requirements [10].

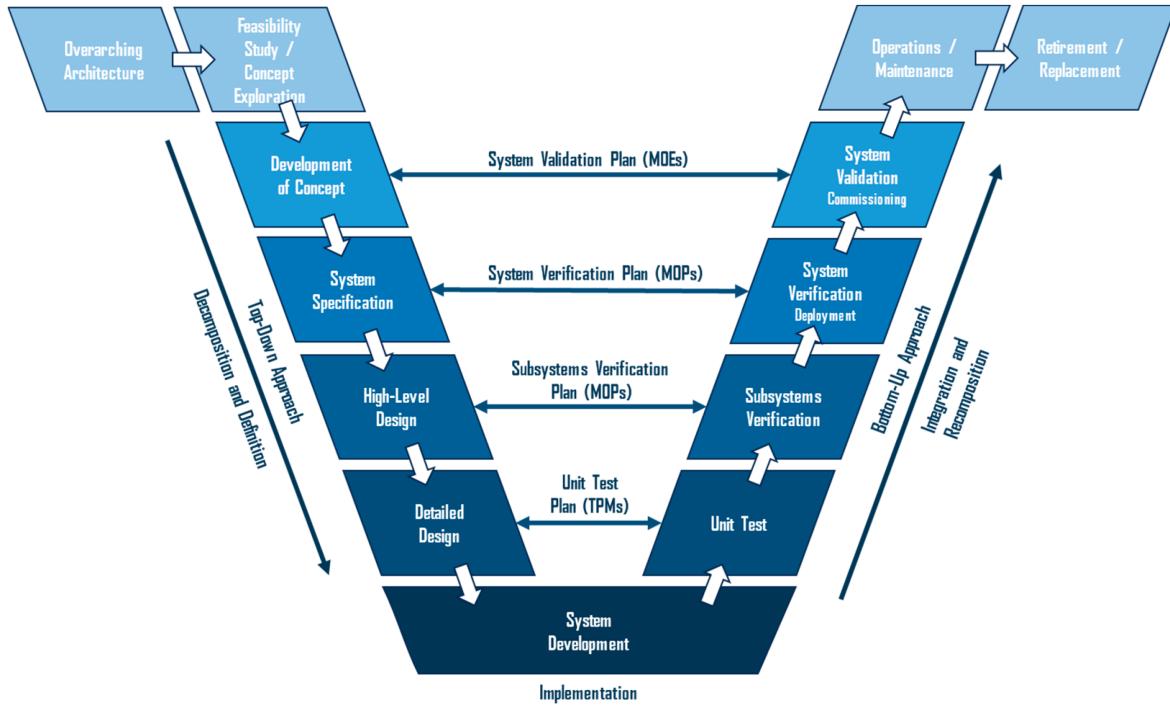


Figure 3.2: V-Model Representation of Systems Engineering [44]

3.2. Current Design Practice

As mentioned earlier in Section 1.1, the Design Spiral, which is a document-centric approach, is traditionally used in the ESSD phase. In addition, traditional systems engineering relies on Document-Based Systems Engineering (DBSE) [6]. The main difference is that the Design Spiral focuses more on iteratively developing the vessel concept by progressively refining the design, whereas DBSE focuses on capturing, dividing, and subsequently integrating the systems architecture. In a typical ship design project, multiple stakeholders collaborate simultaneously. Each stakeholder contributes their own expertise while working in parallel with others. Throughout the design phase, information is exchanged through documents, spreadsheets, and other files. These files not only facilitate communication but also represent the evolving state of the design and serve as input for subsequent engineering phases. A design process is considered document-based when every activity ultimately results in the creation of new documents.

Because these files are static [45], they capture only one specific moment in the design process. This characteristic causes problems and limits flexibility during design iterations. The limitations and errors are described in Subsection 3.2.1, which are adapted from [46].

3.2.1. Limitations and Errors

Communication

A key challenge of document-centric approaches is that communication between stakeholders relies heavily on document publication, as illustrated in Figure 3.3. Stakeholders frequently have to wait for updated information from others, which slows down the design cycle. Additional visualisations or presentations are typically created only upon request. Since information is spread across multiple documents, it becomes difficult to locate relevant data [46, 47]. This problem is increased by the complexity of a vessel's systems architecture, which is not easily represented in static formats. When errors occur in these documents, the time needed to correct, redistribute, and revalidate information increases even further.

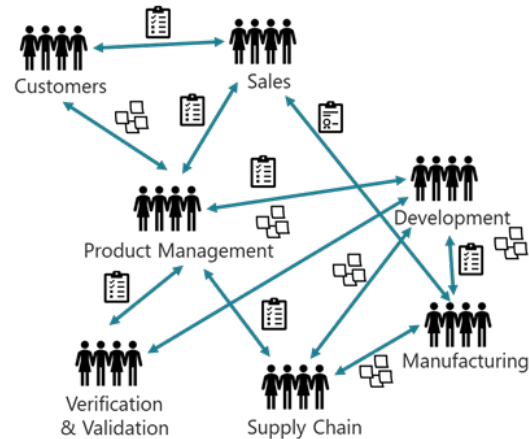


Figure 3.3: DBSE Data-distribution [48]

Interpretation

Each document produced during the project contains a different aspect of the design. Some information is difficult to capture in text or tables, which can lead to misinterpretations or ambiguity [46]. Moreover, converting diverse inputs into a uniform notation often increases documentation time. If mistakes or inconsistencies arise, additional time is required to identify, clarify, and correct them.

Traceability

With information scattered across numerous documents, identifying interdependencies between the vessel's systems becomes challenging. A modification to one part of the design can have significant consequences elsewhere. Even if these relationships are known, stakeholders must still wait for updated document releases before they can proceed. If a stakeholder updates something that affects system requirements, other documents may become outdated immediately [46]. When such inconsistencies or errors appear, resolving them requires extra effort and extends the overall design timeline.

3.3. Benefits of MBSE

MBSE provides numerous advantages across the entire design and development lifecycle. By integrating system information, promoting consistent communication, and supporting automated analyses, MBSE enhances both the quality and efficiency of engineering activities. The International Council on Systems Engineering (INCOSSE) likewise identified these benefits, noting that MBSE was intended to address the shortcomings of traditional DBSE methods [2, 49].

Centralised Data

Instead of exchanging documents between stakeholders, MBSE stores all system data in one central repository, as illustrated in Figure 3.4. This ensures that every stakeholder works with the most up-to-date information, reducing inconsistency errors and preventing the use of outdated data. Because everyone contributes to and retrieves information from the same location, the project maintains a single source of truth [15, 50]. This centralisation also enables stakeholders to work in parallel without waiting for each other to release revised documents, thereby improving overall workflow efficiency [51]. This is especially relevant in ESSD, where core elements such as the hull design and the E-KOL are developed simultaneously.

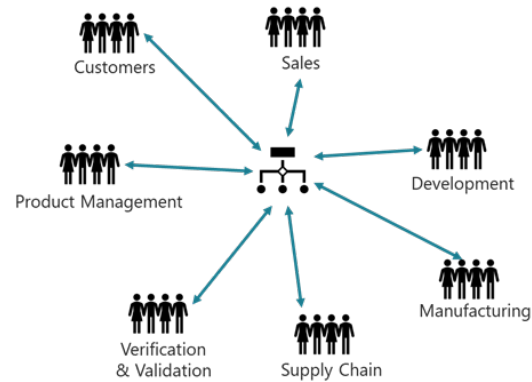


Figure 3.4: MBSE Data-distribution [48]

Standardised Modelling

MBSE uses standardised modelling languages, ensuring that all stakeholders employ consistent notations and terminology [52]. This uniformity improves the clarity, accuracy, and integration of system information. It also simplifies collaboration and reporting because all contributors rely on the same structure, data types, and metrics. Different stakeholders are able to understand each other's work even if they are not in the same discipline, as they can interpret the standardised notation, such as a systems diagram. As a result, communication becomes more transparent and misunderstandings are reduced [45, 50].

Automated Documentation

A major advantage of MBSE is the ability to automatically generate documentation directly from the model [15]. This eliminates the need to manually create static documents [45], freeing up time that can instead be used to explore alternative solutions or refine the design. Because the underlying model is centralised, any design modification becomes immediately visible to all stakeholders, enabling faster reviews and more efficient iteration cycles [52]. This is particularly important in the ESSD phase, where multiple design concepts must be evaluated in quick succession and changes in the key parameters such as length, width, and draught are automatically updated and analysed.

Integrated Requirements

In MBSE, requirements are embedded directly into the central system model. This integration allows automatic checking of whether requirements are satisfied. When a requirement is violated, warnings or error messages identify the source of the issue, greatly improving traceability [15, 50]. For example, when a DP3 redundancy level is required, the MBSE tool, with requirements linked to the relevant systems, checks whether each system meets them. If a system does not satisfy these requirements, the corresponding requirement will trigger a warning. As the vessel's system complexity increases, the model captures and documents these changes consistently across the entire project. This reduces the risk of oversight and supports more reliable decision-making.

Improved Decision-Making

Because requirements, constraints, and interdependencies are integrated into the model, MBSE supports more informed and efficient decision-making. Engineers can easily visualise how changes in one component affect others and can analyse system behaviour dynamically. This enables exploration of a wider range of design options and facilitates selection of a more optimal final solution. Additionally, MBSE supports the development of Decision Support Systems (DSS), further enhancing accuracy, robustness, flexibility, and time efficiency [52].

Reusability

MBSE tools and models are not limited to a single project. Once the modelling environment and structure are established, they could be reused for future projects [6, 52]. Only specific elements such as requirements or constraints may need updating. Because changes propagate automatically throughout the model, updates become more efficient and consistent for all stakeholders. Despite the initial setup effort, as seen in Figure 3.5, MBSE leads to long-term efficiency gains across multiple design cycles.

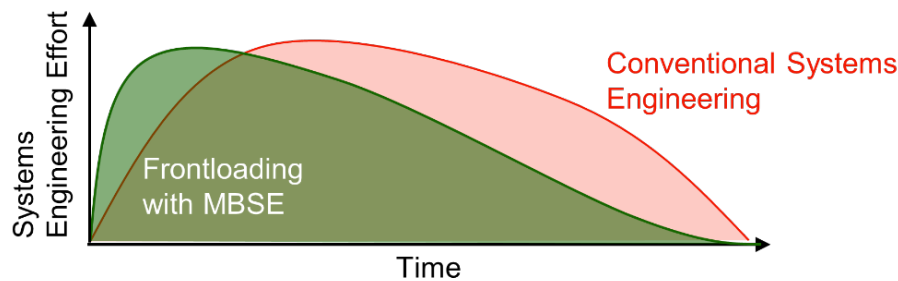


Figure 3.5: Change of Work Hours Division [53]

3.4. Challenges of MBSE

MBSE holds significant potential to revolutionise ship design, but it is not a silver bullet. Several challenges need to be addressed before MBSE can be fully leveraged. These challenges span technical, cultural, and research aspects, as outlined below.

Limited Empirical Evidence

A major challenge of MBSE is that much of its perceived value is based on expectations rather than empirical evidence. Studies suggest that up to two-thirds of the claimed benefits are derived from perceived advantages rather than documented practical results [6]. This creates uncertainty and could potentially lead to an "MBSE bubble", where expectations exceed actual performance.

Transition to MBSE

Before implementing MBSE in the ESSD phase, a careful transition from traditional DBSE is required. DBSE relies heavily on previous successful designs and is deeply ingrained in the ship design culture [15, 51]. This cultural shift can lead to scepticism and resistance among experienced naval architects, who may be reluctant to fully adopt a new methodology. Additionally, MBSE may sometimes suggest solutions that contradict an architect's intuition, either due to the inherent complexity of system interdependencies or errors in MBSE setup, which can result in trust issues [15]. Furthermore, a lack of knowledge about MBSE and SE within the maritime sector can cause confusion and mistakes during adoption [6, 52].

Complexity

Ship design is inherently multi-disciplinary, and meeting the expectations of all stakeholders requires significant time, resources, and intensive communication. Setting up an MBSE framework that integrates all interdependencies is particularly challenging due to the highly complex and intertwined nature of vessels [52].

Platform Limitations

Current MBSE platforms have limitations because they have not yet been widely implemented in the maritime sector [6]. Companies adopting MBSE early face higher risks due to the lack of empirical feedback for improvement of the platforms. As a result, quantifying the return on investment is challenging, and actual benefits may fall short of expectations [51].

Conservatism in the Maritime Sector

The maritime sector is generally conservative in adopting new methodologies, primarily due to high capital costs and complex design regulations. This conservative culture can slow MBSE adoption, as stakeholders are cautious about changing well-established design practices without clear and proven benefits [6].

Methodological Issues

Integrating MBSE with traditional ship design is challenging due to the differences in methodology [6]. MBSE employs a different terminology and approach compared to naval architecture, which can lead to communication difficulties, increase the likelihood of errors, and slow down adoption [15].

3.5. Summary

Table 3.1 below summarises the benefits from Section 3.3 and the challenges from Section 3.4. As shown, MBSE has significant potential with numerous benefits. It could transform the way naval architects approach a ship design problem by providing a more structured methodology while allowing greater design flexibility. However, MBSE also presents several challenges that counterbalance these benefits, with the limited empirical evidence being the most significant concern. Without sufficient proof, the advantages may remain theoretical. This further emphasises the need for a thorough study of the effects MBSE has on the ESSD phase.

Table 3.1: Overview of MBSE Benefits and Challenges

Benefits of MBSE	Challenges of MBSE
• Centralised Data - Single source of truth, fewer inconsistencies, parallel workflows. • Standardised Modelling - Common notation, clearer communication, fewer misunderstandings. • Automated Documentation - Model-driven documentation, faster updates, quicker iteration. • Integrated Requirements - Automatic requirement checks, strong traceability. • Improved Decision-Making - Insight into system dependencies, supports DSS. • Reusability - Models and structures reusable across projects.	• Limited Empirical Evidence - Many benefits perceived rather than proven. • Transition to MBSE - Cultural resistance, trust issues, lack of awareness. • Complexity - High integration effort, multidisciplinary nature. • Platform Limitations - Limited maritime-specific maturity, unclear ROI. • Conservatism - Risk-averse industry, slow adoption of new methods. • Methodology Gap - Different terminology, communication challenges.

MBSE Framework Evaluation

This chapter evaluates the available MBSE frameworks for developing a decision-support tool, in order to address **RQ3**. First, the trade-off framework is introduced in Section 4.1, where the criteria for assessing the MBSE frameworks are defined, the scoring scheme is established, and the threshold limits are presented. Section 4.2 discusses the available MBSE frameworks. Subsequently, each MBSE framework is evaluated against these criteria. The results are presented in Section 4.3.

4.1. MBSE Framework Selection

To determine which MBSE framework is best suited for the ESSD phase and can support the integration of a decision support system, it is first necessary to establish the framework selection criteria. As a prerequisite, the framework should be accessible without restrictive commercial licensing. This enables the development of a practical proof of concept from which meaningful conclusions can be drawn.

Furthermore, preference is given to open-source frameworks, as they reduce vendor lock-in, minimise dependency on commercial software, enable customisation to the specific requirements of the ESSD phase, and facilitate faster implementation of new features and improvements. In addition, the absence of licensing costs makes open-source frameworks particularly attractive for research and prototype development [54].

4.1.1. Criteria

Based on the defined interdependencies in Chapter 2 and the current limitations in Chapter 3, the criteria are defined and grouped into two main categories: Decision Support Capabilities and Workflow Integration. These categories reflect the essential aspects required to support informed decision-making and efficient design workflows in the ESSD phase.

Decision Support Capabilities Criteria

As the main goal of implementing the MBSE tool is to support naval architects in making quicker, well-substantiated decisions, having a tool with strong decision support capabilities is crucial. Criteria in this category assess how effectively the tool enhances insight, comparability, and analytical depth during the ESSD decision-making process.

D1: Visualisation: The extent to which the tool enables clear visualisation of system architectures, relationships, performance indicators, and trade-off impacts.

D2: Traceability: The ability to automatically trace system interdependencies, propagate changes across the model, and provide warnings when functional, logical, or physical conflicts arise.

Workflow Integration Criteria

In addition to supporting the decision-making process in the ESSD phase, it is important that implementing the MBSE framework does not negatively affect the current design process. The adoption threshold should be low, avoiding additional complexity or radical changes to established working methods. Criteria in this category assess how well the tool supports efficient workflow integration, collaboration, and the iterative work typical of the ESSD phase.

W1: Usability: How easily naval architects without MBSE expertise can learn and apply the tool during iterative ESSD cycles.

W2: Applicability: The range of design stages (e.g., ESSD) for which the tool offers relevant support.

W3: Interoperability: The extent to which the tool integrates with other design, simulation, or documentation environments relevant for the ESSD workflow.

W4: Reusability: How easily existing models can be updated, adapted, and reused for new design projects.

4.1.2. Scoring Scheme

The score for each criterion is calculated as $N_i = w_i \cdot A_i$, where N_i is the weighted score, w_i is the weight of the criterion, and A_i is the absolute score assigned to the MBSE framework for that criterion. These weighted scores are then summed, after which the MBSE frameworks are ranked in descending order. The MBSE framework with the highest total score is identified as the most suitable option for the MBSE decision-support tool.

$$\text{Total Score} = \sum N_i = (0.4 \cdot A_{DS} + 0.6 \cdot A_{WI})$$

where A_{DS} , A_{WI} are the absolute scores for decision support capabilities and workflow integration, respectively, for each MBSE framework. The weights of the sub-criteria are shown in Table 4.1. The weighting of the criteria reflects the primary objective of this study, which is to improve the quality of decision-making during the ESSD phase. Consequently, greater emphasis is placed on decision support capabilities than on workflow integration.

The decision support capabilities criteria have each assigned an equal weight of 0.20, resulting in a total weight of 0.40. These sub-criteria directly relate to the ability of an MBSE framework to support design decisions, which is considered the core functionality of the proposed decision-support tool. Workflow integration criteria have each assigned a weight of 0.15, resulting in a total weight of 0.60. Although workflow integration is important for ensuring practical applicability and usability, it is considered secondary to decision support capabilities. The underlying assumption is that improvements in decision quality should not come at the expense of the efficiency of the workflow.

Table 4.1: Trade-off Criteria with Associated Weights

Criteria	Weight
Decision Support Capabilities	[0.40]
D1: Visualisation	0.2
D2: Traceability	0.2
Workflow Integration	[0.60]
W1: Usability	0.15
W2: Applicability	0.15
W3: Interoperability	0.15
W4: Reusability	0.15

Each MBSE framework is scored on a scale from 1 to 5 for each criterion, with 1 representing the least desirable outcome and 5 the most favourable.

The scoring for the decision support capabilities criteria was defined as follows:

1. Minimal visualisation, no traceability.
2. Limited visualisation, limited manual traceability.
3. Basic visualisation, partial automatic traceability.
4. Good visualisation, largely automatic traceability, with conflicts often detected.
5. Interactive visualisation, fully integrated automatic traceability with conflict warnings.

The scoring for the workflow integration criteria was defined as follows:

1. Very steep learning curve, not applicable to the ESSD phase, no integration with other tools, no reusability.
2. Steep learning curve, limited applicability to the ESSD phase, limited integration with other tools, partly reusable.
3. Moderate learning curve, applicable to the ESSD phase, integration with other tools possible, reusable with minor adaptations.
4. Small learning curve, excels in the ESSD phase, integrated with other tools, easily modified and reused.
5. Very user-friendly, excels in the ESSD phase and subsequent phases, fully integrated with other workflows, flexible modelling, and fully reusable.

4.1.3. Threshold Limits

If any MBSE framework scores 1 in one or more criteria, it is excluded from further consideration, as it does not meet the minimum requirements in that category. For example, a score of 1 in decision support capabilities indicates that the MBSE framework cannot support even basic decision-making compared to DBSE, thereby reducing its decision support effectiveness.

Similarly, a score of 1 in workflow integration suggests that the work environment for stakeholders would be significantly impacted, potentially increasing the time and cost of the ESSD phase and making the framework less feasible than DBSE.

4.2. MBSE Framework Candidates

With these criteria established, it is possible to evaluate the available MBSE frameworks. As visualised by the OMG [55] and the MBSE4U platform [56], a wide range of MBSE frameworks are available. Table 4.2 presents the MBSE frameworks that are open-source.

Table 4.2: Overview of Open-Source MBSE Frameworks

Languages	Methodologies	Tool
Arcadia Language	Arcadia	Capella
LML, SysML v1	LML Lifecycle Methodology	Innoslate
ECSS-E-TM-10-25	ECSS Concurrent Engineering	COMET
SysML v2	MagicGrid, OOSEM	SysON
POOSL	POOSL	POOSL
SysML v1	MagicGrid, OOSEM, Harmony SE	Eclipse Papyrus
SysML v1, BPMN	MagicGrid, OOSEM	Modelio
SysML v2	MagicGrid, OOSEM	SysIDE

These frameworks are built on three fundamental pillars: languages, methodologies, and tools [6, 7, 8].

To support the evaluation, the most relevant MBSE frameworks identified in Section 4.2 are briefly described. Since Capella emerged as the most promising candidate during the evaluation process, it is discussed in detail within this section. The remaining frameworks are described in Appendix C, as they serve primarily as comparison baselines in the trade-off analysis.

4.2.1. Capella

Capella [57] is an open-source MBSE framework that makes use of the ARCADIA (ARChitecture Analysis and Design Integrated Approach) methodology. In contrast to SysML-based frameworks, it places greater emphasis on the functional aspects of a system rather than on requirements [58]. Its primary aim is to make users more aware of the consequences and benefits of design decisions and to facilitate clearer communication of the system architecture.

Capella employs its own language, which is considered easier to understand and more powerful than SysML [59]. This contributes to its applicability across different domains and enables more effective user guidance through the tighter, in-house integration of the MBSE framework. Capella also promotes collaboration throughout the design process [58]. While requirements are not the central focus, they can be incorporated to define constraints, linked to model elements, and used for verification and validation of systems and subsystems, thereby supporting the justification of design decisions and enhancing transparency.

Traceability is strengthened through Capella's four-layer framework, consisting of: (1) what users need to accomplish, (2) what the system needs to accomplish, (3) how the system will operate, and (4) how the system will be realised. This layered structure is illustrated in Figure 4.1. System modelling can be performed using top-down, bottom-up, or iterative frameworks, in line with the V-model, which improves both traceability and flexibility [58, 60]. In addition, the semantic browser enables consistency checks across model elements.

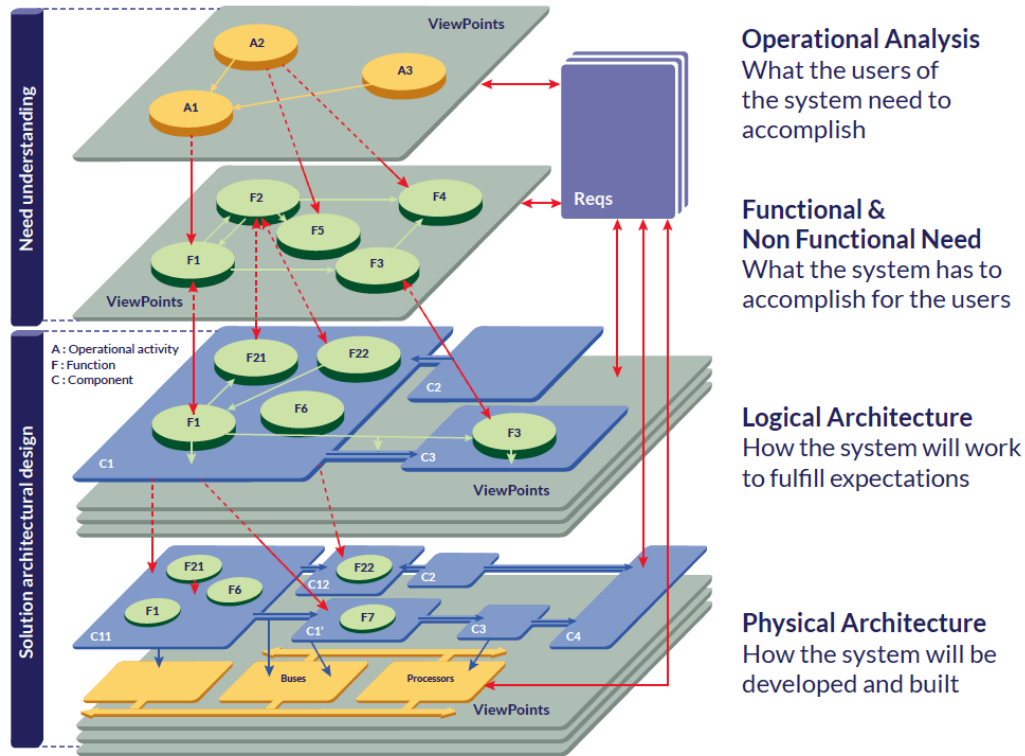


Figure 4.1: Capella Four Layer Framework [57]

Flexibility is further enhanced by the possibility of applying Capella at different levels of a project. However, the predefined methodology tightly coupled to the tool can also reduce flexibility. For example, it is not possible to directly allocate a system function to a physical component without passing through the logical layer. Additionally, the lack of built-in versioning limits flexibility when working iteratively [14, 60].

Capella offers extensive visualisation capabilities that improve comprehensibility for all involved stakeholders, although these require an initial learning effort. The use of homogeneous colour schemes enhances diagram readability and coherence, while filters and chain highlighting support the tracking of subsystems and components. A drawback of these detailed visual diagrams is that restructuring models can be time-consuming [60]. Finally, [14] concludes that Capella performs particularly well in the ESSD phase, making it a suitable candidate for application in this study.

4.3. Trade-off Conclusion

Based on the defined criteria and the framework descriptions provided in this chapter (with additional details in Appendix C), each MBSE framework was evaluated using the scoring scheme introduced in Section 4.1.

After evaluating all MBSE frameworks, Capella was identified as the most suitable framework for supporting the ESSD decision-support tool, achieving the highest overall score across the defined criteria. The results of the trade-off analysis are presented in Section C.8.

Decision Support System

This chapter addresses the integration of a Decision Support System (DSS) within the MBSE framework in the ESSD phase, in order to answer **RQ4**. The DSS is particularly relevant for supporting decisions under conditions of high system interdependencies and regulatory constraints, where design choices in one system affect multiple other systems. First, Section 5.1 briefly explains the general decision-making process. Next, Section 5.2 discusses the different DSS methods. Once the process and methods are clearly defined, Section 5.3 goes over the benefits and Section 5.4 elaborates on the tool requirements, the capabilities, and the overall architecture that could support the naval architect. Finally, Section 5.5 concludes the key findings and design considerations presented in this chapter.

5.1. Decision-Making Process

Before discussing DSS, it is first necessary to understand the general decision-making process of a naval architect. Figure 5.1 illustrates the three main stages of decision-making [61]. First, the problem that needs to be solved is identified and formulated, and possible alternatives are generated. The potential solutions are evaluated based on these alternatives. As the ESSD phase involves multiple conflicting criteria, the use of a Multi-Criteria Decision-Making (MCDM) approach within the DSS is common during this phase [62]. Finally, from the perspective of the naval architect, the most suitable solution or the one with the lowest perceived risk or negative impact is selected. The DSS fits primarily within the evaluation step of the decision-making process and, depending on its capabilities, partly within the framing step. In this role, the DSS supports the decision-making process, rather than altering the underlying process itself.

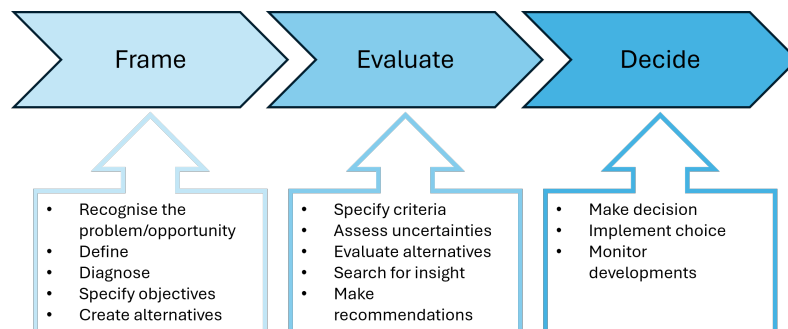


Figure 5.1: Decision-Making Process [61]

Decisions can generally be divided into two categories, namely programmed and non-programmed decisions [61]. Programmed decisions are automated decisions that follow predefined rules and principles and do not require human intervention. In this case, the decision-making process is fully executed by the computer. These decisions are most commonly applied at the lower system levels. Non-programmed decisions are unique decisions that rely on the expertise, experience, and judgement of the naval architect. These decisions typically occur at the higher system levels [61].

For naval architects, it would be beneficial to have a DSS that supports decision-making across hierarchical system levels, while enabling automated decisions at the component level. For example, the required diameter of cooling water pipes could be automatically determined based on the selected pumps and the system that requires cooling.

5.2. Decision Support Methods

In addition to understanding the general decision-making process of a naval architect, it is also necessary to identify which methods can be applied within a DSS. Figure 5.2 presents the different DSS methods as defined by [63]. As shown, these methods can be grouped into three main classes, namely model-focussed, data-focussed, and knowledge-focussed decision support systems.

Model-focussed relies on mathematical models and algorithms to support the analysis of available data. These models provide insight into possible design options and help evaluate different scenarios. This approach often includes simulations and analytical tools that test variables, explore scenarios, and identify optimised outcomes [64, 65, 66]. For example, naval architects can adjust input parameters and evaluate the impact on the performance outputs. This approach allows rapid scenario testing and informed decision-making based on quantitative data.

Data-focussed is suited to projects that produce large data sets. This approach helps naval architects by storing data in a structured format and enabling thorough analysis. The processed data can be used in reporting and visualisation, for example through graphs or other analytical outputs [64, 65, 66]. For example, a DSS can collect and analyse current data from operational vessels to identify performance trends, inefficiencies, or areas for improvement, providing naval architects with a clear overview of potential shortcomings and supporting data-driven decisions.

Knowledge-focussed also known as expert-driven decision-making supports the provision of factual and specialised guidance. This includes established procedures throughout all phases of a project as well as relevant legislation. It also stores findings and recommendations from previous projects, which allows users to benefit from accumulated organisational knowledge [64, 65, 66]. For example, conclusions from previous projects can be stored in the DSS, so could the finding that a vessel with a certain number of engines performs optimally with a specific pump redundancy layout. For future projects, the system can then recommend the most suitable layout by pre-loading proven system configurations, allowing designers to benefit from accumulated organisational knowledge.

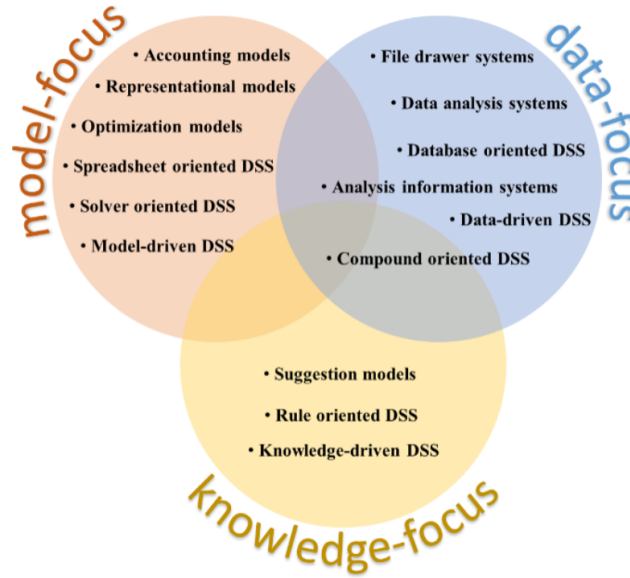


Figure 5.2: Decision Support Systems Classification [63]

Choosing a single DSS classification is not mandatory. To benefit from the strengths of multiple classes, a compound oriented DSS is the most suitable option, as it combines the characteristics of the three DSS types. This combined approach can also be referred to as a model-driven DSS [67] or MBSE-DSS.

5.3. Benefits and Challenges

With the integration of MBSE into ESSD, the potential of integrating a DSS within MBSE becomes particularly relevant. However, before developing a DSS, it is crucial to understand the expected benefits in order to achieve its full potential. Due to the supportive and suggestive nature of a DSS, a lack of understanding of its advantages increases the likelihood that it will be neglected or underutilised [61]. An overview of some important benefits and challenges of DSS are presented in Table 5.1, based on [3, 61, 64, 65, 68]. As seen, the challenges are partly comparable to those of MBSE, as the DSS is intended to operate in conjunction with MBSE and is likewise perceived as a new technology.

Table 5.1: Overview of DSS Benefits and Challenges

Benefits of DSS	Challenges of DSS
• Better Informed Decisions Provides structured and meaningful information and presents multiple perspectives on complex problems. • Faster Problem Solving Enables quicker responses to evolving requirements, reducing time and cost. • Configuration Exploration Allows evaluation of a larger set of design alternatives, trade off analyses, and scenario simulations. • Manage Complexity A DSS helps naval architects to gain a clearer understanding of the complex system resulting from system constraints and interdependencies.	• Reliability Risk that naval architects rely on the DSS as a decision maker instead of a decision-support tool. • Information Overload Information overload due to a large number of configurations. • Transition to DSS Cultural resistance, limited trust, and lack of awareness. • Conservatism Slow adoption of new methods and tools.

5.4. DSS Design Specifications

As stated by [67], identifying an existing decision model for a DSS is extremely rare and, even when a model has already been developed, it generally requires substantial adaptation for a specific implementation. Therefore, in most cases it is necessary to develop a DSS from scratch.

5.4.1. DSS Requirements

When developing the MBSE-DSS it is necessary to satisfy a number of standard requirements in order to provide naval architects with useful and high-quality decision support suggestions. The requirements defined by [67] should be met to achieve this objective. These requirements are known as the 5C-requirements and are listed below.

- **Completeness:** All relevant aspects of the decision are considered, and the information covers all possible inputs or scenarios.
- **Comprehensibility:** The information is presented in a clear and understandable way for the user.
- **Consistency:** The information is logically coherent and free from contradictions in reasoning or preferences.
- **Convenience:** The information is easy to access, provided at the right time, and appropriate for both the task and the user.
- **Correctness:** The information is accurate and valid, and directly supports the decision that needs to be made.

5.4.2. DSS Functionalities

The decision support functionalities listed in Table 5.2 are considered valuable for enhancing the exploration activities of naval architects during the ESSD phase and will be further investigated in the upcoming case study. These functionalities were derived from the complexity factors identified in Chapter 2, the current limitations described in Chapter 3, and consultations with naval architect experts [4]. The main goal of these functionalities is to improve traceability of system interdependencies and design decisions, while effectively managing project constraints.

Table 5.2: Classification of decision support functionalities developed for this study in collaboration with Ulstein Design & Solutions B.V., tailored to the ESSD phase.

DSS Type	Decision Support Functionalities
Model	What-if scenarios simulation Visual representation of design conflicts and constraint violations Detection of constraint violations Visualisation of design choices Support for risk analysis using models Support for multi-criteria decision analysis (MCDA)
Knowledge	Automated checking of requirements Integration of regulatory and class requirements Traceability of design choices Support for suggesting system layouts Support for risk assessment guidelines Support for collaborative decision-making
Data + Model	Visual representation of system architectures

DSS Type	Decision Support Functionalities
	Visual representation of interdependencies between systems Automated comparison of configurations
Data + Knowledge	Pre-loading of standard configurations Pre-loading of standard equipment

5.4.3. DSS Architecture

Lastly, for the development of the MBSE-DSS, the general architecture needs to be clearly defined. Figure 5.3 presents the main components of a generic DSS architecture [69]. In this figure, the DSS is visualised by the light-grey box and consists of the Graphical User Interface (GUI), the Problem-Processing System (PPS), and the Knowledge System (KS).

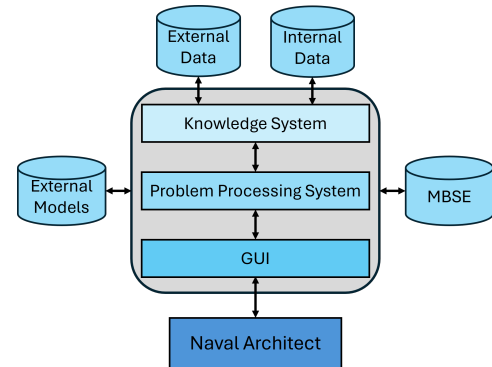


Figure 5.3: DSS Components adapted from [69]

Graphical User Interface

The Graphical User Interface (GUI) is the component of the DSS that enables interaction between the naval architect and the tool. This interaction is realised through visualisations such as diagrams, as well as through buttons, windows, and menus. The primary objective of the GUI is to provide a user-friendly and intuitive interaction environment, rather than requiring users to interact directly through code [62, 70]. Each DSS has a GUI tailored to the needs of the intended stakeholders. For an MBSE-DSS in the ESSD phase, the GUI should specifically support decision-making related to the main systems of the vessel systems architecture.

Problem-Processing System

The Problem-Processing System (PPS) functions as the intermediary between the GUI and the KS. Its main role is to transform raw data into meaningful and usable information without overwhelming the naval architect [62]. Within this component, MBSE models, external models, and the previously defined decision-support functionalities are implemented. The PPS is therefore responsible for analysing information, executing models, and generating suggestions that support the decision-making process during ESSD.

Knowledge System

The Knowledge System (KS) manages both internal and external knowledge on which the DSS relies to support decisions [62]. In the context of an MBSE-DSS, the KS consists of a combination of data modelling and expert modelling. Data modelling involves analysing past projects and decisions to identify patterns or regularities, which can then be used to suggest possible system configurations. Expert modelling captures the experience and knowledge of naval architects and embeds this expertise within the DSS. This knowledge is typically represented using models such as decision trees, multi-criteria decision models, Bayesian networks, and similar techniques [67].

5.5. Conclusion

The analysis presented in this chapter indicates that an MBSE-based DSS could enhance the ability of naval architects to identify system interdependencies and evaluate design trade-offs across vessel configurations. By integrating model-focussed, data-focussed, and knowledge-focussed functionalities, such a DSS enables both automated analysis of lower level decisions and informed guidance at higher system levels.

With the considered DSS functionalities, focusing on what-if scenario simulations, visualisation of design conflicts and interdependencies, and requirements checking, directly facilitate the recognition of how changes in one system affect others. Combined with a structured architecture, the DSS could provide a transparent and interactive environment for exploring multiple design alternatives while respecting project constraints and regulatory requirements.

Overall, the findings suggest that an MBSE-DSS could serve as a tool for supporting complex design decisions in the ESSD phase, improving both efficiency and the quality of outcomes through systematic consideration of interdependencies and informed trade-off analyses.

Methodology

To set up the MBSE-DSS and answer **RQ5**, a processing pipeline was developed based on the proposed methodology, consisting of four main stages. First, the cooling system is modelled in Capella, as described in Section 6.1. Based on this model, data is extracted from Capella to obtain the required system representation, which is detailed in Section 6.2. Subsequently, a design space is generated in which pump room configurations are systematically constructed, including different pump and room arrangements, as explained in Section 6.3. Finally, each configuration is evaluated and ranked using the scoring model introduced in Section 6.4, enabling comparison of alternative designs within the generated design space.

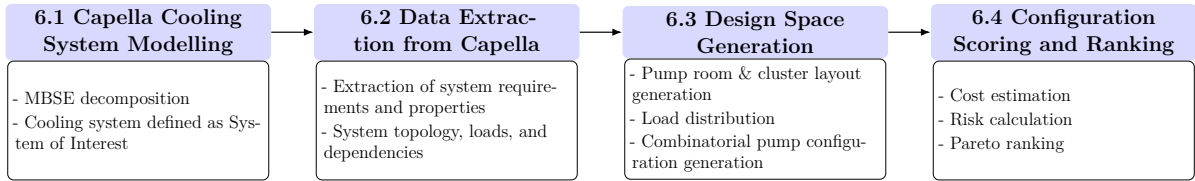


Figure 6.1: Overview of the processing pipeline for cooling water system configuration generation and evaluation.

After applying the DSS, a verification study is performed in Appendix G using a Monte Carlo analysis to assess whether the model behaves as intended and responds consistently to variations in input parameters.

The cooling system is selected as a representative case for the MBSE-DSS because it exhibits strong interactions between cost, redundancy, and system reliability, while also being directly linked to DP performance. These characteristics make it suitable for evaluating how design decisions propagate through system architecture and affect multiple competing objectives, which is central to answering **RQ5**.

To systematically generate alternative cooling system architectures, the MBSE-DSS represents the system using two hierarchical modelling concepts. These concepts form the basis for the design space generation and subsequent evaluation of alternative configurations. Therefore, the terms *pump room* and *cluster* are defined before describing the generation process in more detail.

Definition of Pump Rooms and Clusters

Within the proposed framework, the cooling system architecture is represented using two hierarchical levels: pump rooms and clusters. This abstraction enables systematic generation and evaluation of design configurations independent of a specific vessel layout.

A *pump room* represents a physical compartment within the vessel that contains one or multiple cooling system functions and their associated equipment. It defines the spatial grouping level at which compartment-based failure scenarios are evaluated in the risk model.

Within the proposed MBSE-DSS, each pump room consists of clusters. A *cluster* is defined as a functional subsystem consisting of components connected in series that together form an independent cooling circuit. Clusters therefore represent the lowest level at which redundancy and functional performance are evaluated.

Figure 6.2 provides a conceptual illustration of this decomposition. The example highlights how multiple clusters can coexist within a single pump room (highlighted in the red box), where each cluster corresponds to a distinct functional cooling path (genset, thruster, auxiliary, or mission-related cooling). The colouring is used solely for visual separation of clusters.

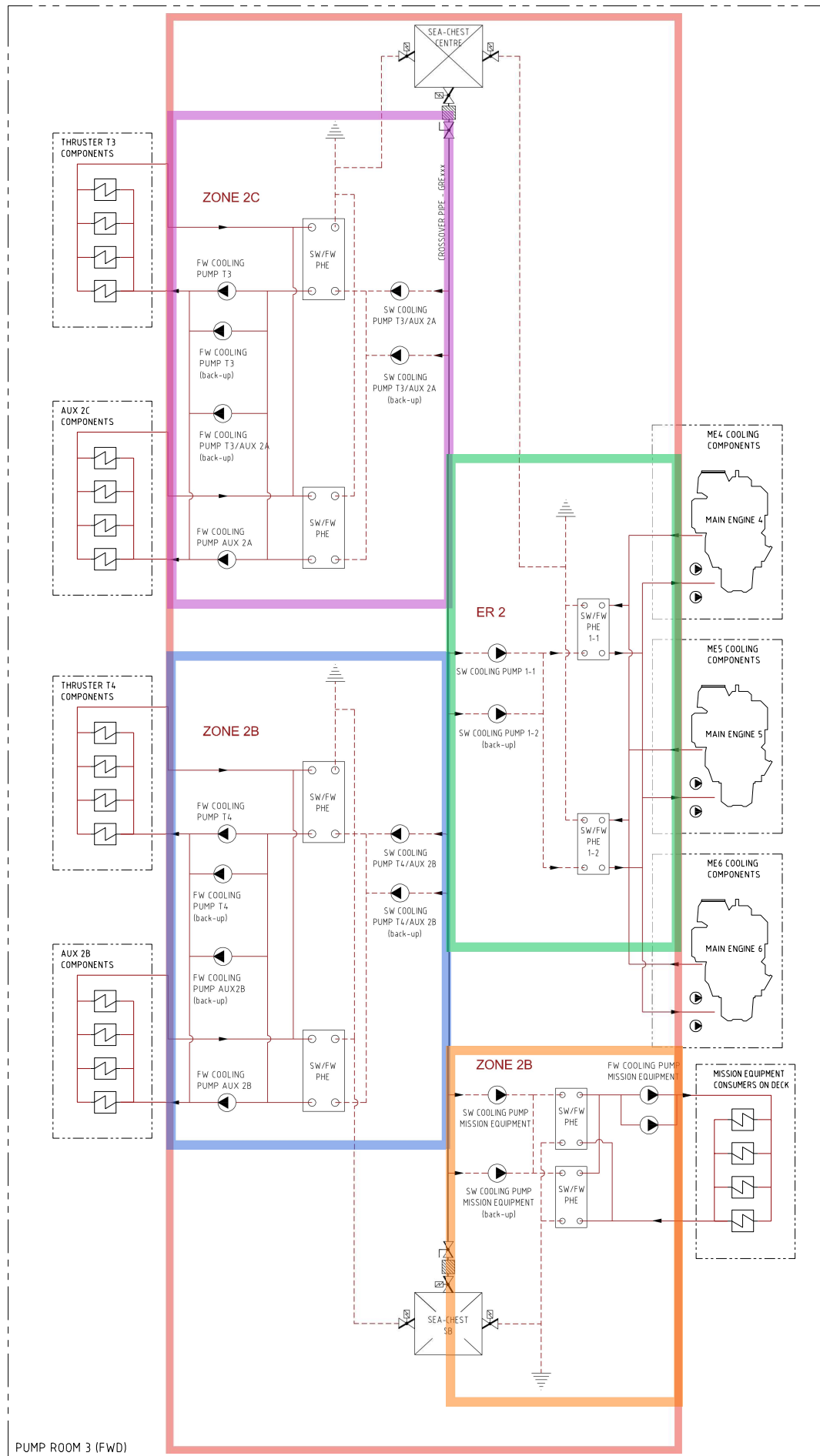


Figure 6.2: Conceptual illustration of pump room and cluster decomposition within the proposed modelling framework [4].

6.1. Capella Cooling System Modelling

Before introducing the DSS, the cooling system is first modelled using an MBSE approach in Capella [57]. Each architectural layer builds upon the previous one, ensuring traceability from operational architecture (OA) to system architecture (SA), logical architecture (LA), and finally physical architecture (PA), as described by Sideris [14] and in Subsection 4.2.1. Each phase is summarised by its blank diagram. By following the Capella methodology, a structured and traceable system model is created that forms the foundation for the DSS. This ensures consistency between stakeholder needs, system functions, and physical realisations, while enabling the systematic evaluation of design alternatives.

In this research context, an offshore vessel is initially considered as the System of Interest (SoI). By applying the transition add-on in Capella (see Figure 6.3), the system is progressively decomposed into lower-level subsystems through a refinement process, consistent with the MBSE system hierarchy.

Within this decomposition, the SoI is not considered static, but is redefined at each modelling level. At the highest level, the vessel is treated as the SoI, while at lower abstraction levels the focus shifts to subsystems of increasing detail. At the lowest relevant level for this research, the cooling system becomes the SoI, as it represents the subsystem under investigation for configuration generation and analysis.

Due to the scope of this research, the intermediate transition steps are omitted, and only the final stage, where the cooling system is treated as the SoI, is explicitly modelled. This does not imply that the other system levels are ignored in the design process, but rather that they are considered part of the underlying MBSE decomposition performed within Capella and are therefore not repeated in detail in this work.

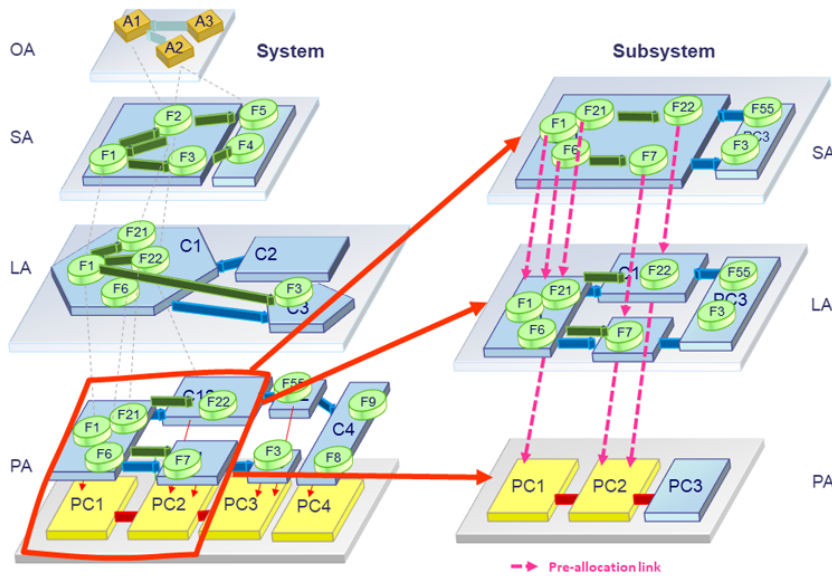


Figure 6.3: Capella Transition Add-on workflow illustrating the transition of system-level elements to subsystem models across the OA, SA, LA, and PA layers. [71]

The modelling process begins with the Operational Architecture Blank (OAB) diagram, shown in Figure 6.4. This diagram captures the operational context by describing what stakeholders expect to achieve with the system. At this stage, only external systems interacting with the SoI are considered. These include the thruster system, power generation system, mission systems, and auxiliary systems. Additionally, seawater is treated as an external system, as it serves as the cooling medium for the seawater cooling loop. The cooling system itself is not yet explicitly defined in this phase.

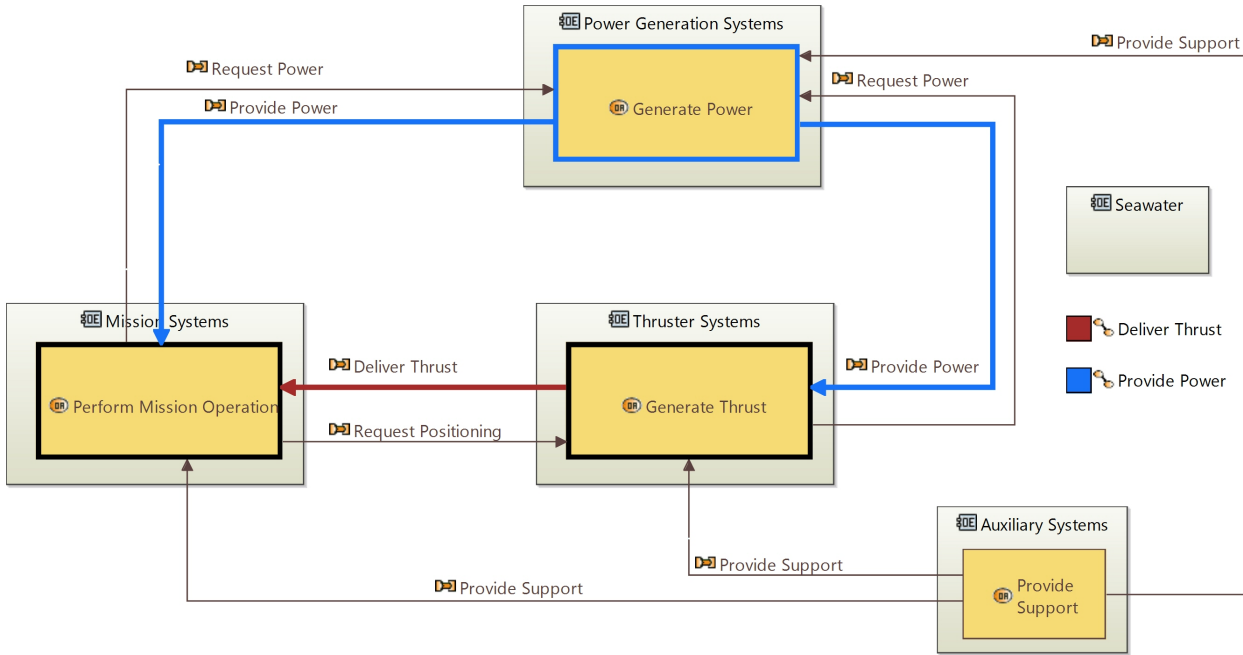


Figure 6.4: OAB Cooling System

Subsequently, the System Architecture Blank (SAB) diagram is developed (see Figure 6.5). This phase focuses on defining what the system must do to fulfil stakeholder needs. The cooling system is introduced as a functional system, and interactions between systems are further decomposed into more detail. At this stage, the seawater system becomes part of the cooling loop, reflecting its functional integration.

Next, the Logical Architecture Blank (LAB) diagram (see Figure 6.6) is constructed, describing how the system should operate. In this phase, the system is decomposed into logical components, and internal functional relationships are defined in greater detail.

Finally, Figure 6.7 presents the Physical Architecture Blank (PAB) diagram of a standard offshore vessel. This phase describes how the system is physically realised, including the allocation of components to physical locations. The PAB serves as the primary input for the Python4Capella add-on, which is used to generate and evaluate the top cooling system configurations for this vessel type.

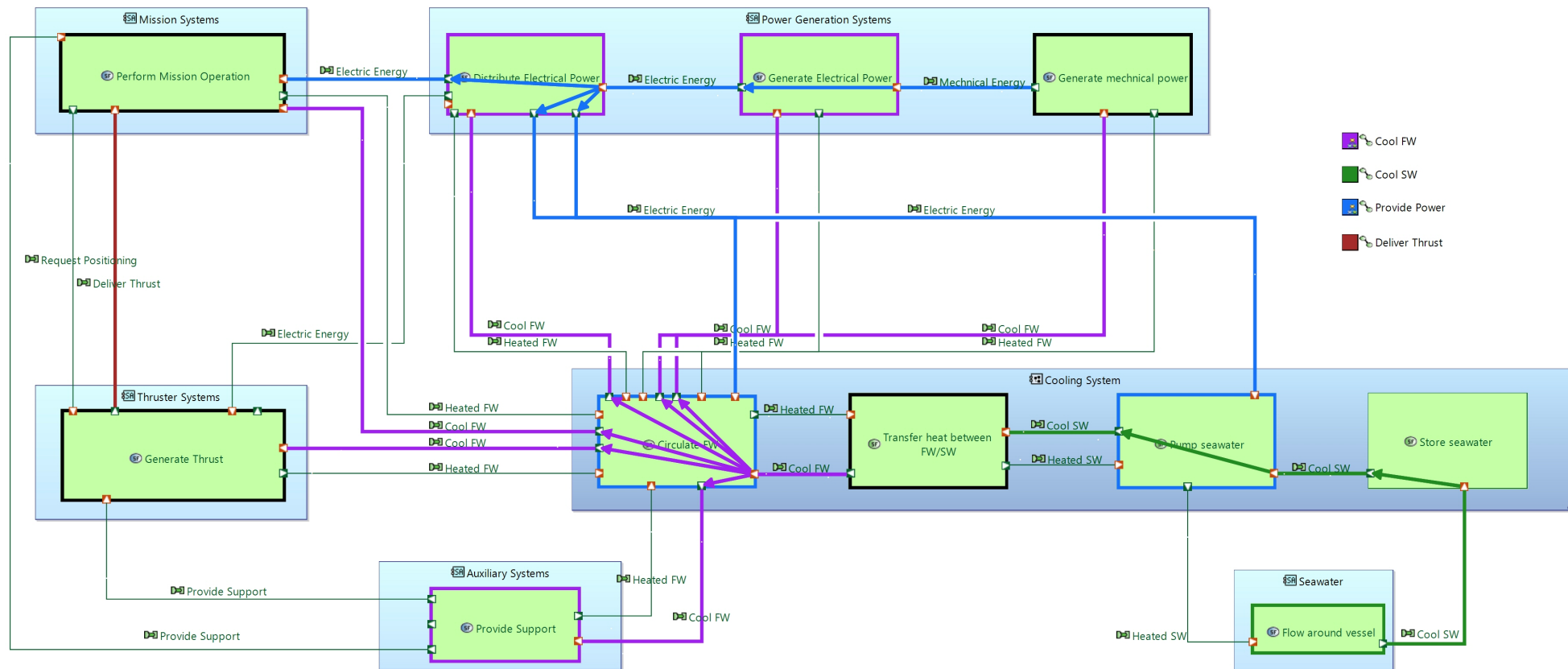


Figure 6.5: SAB Cooling System

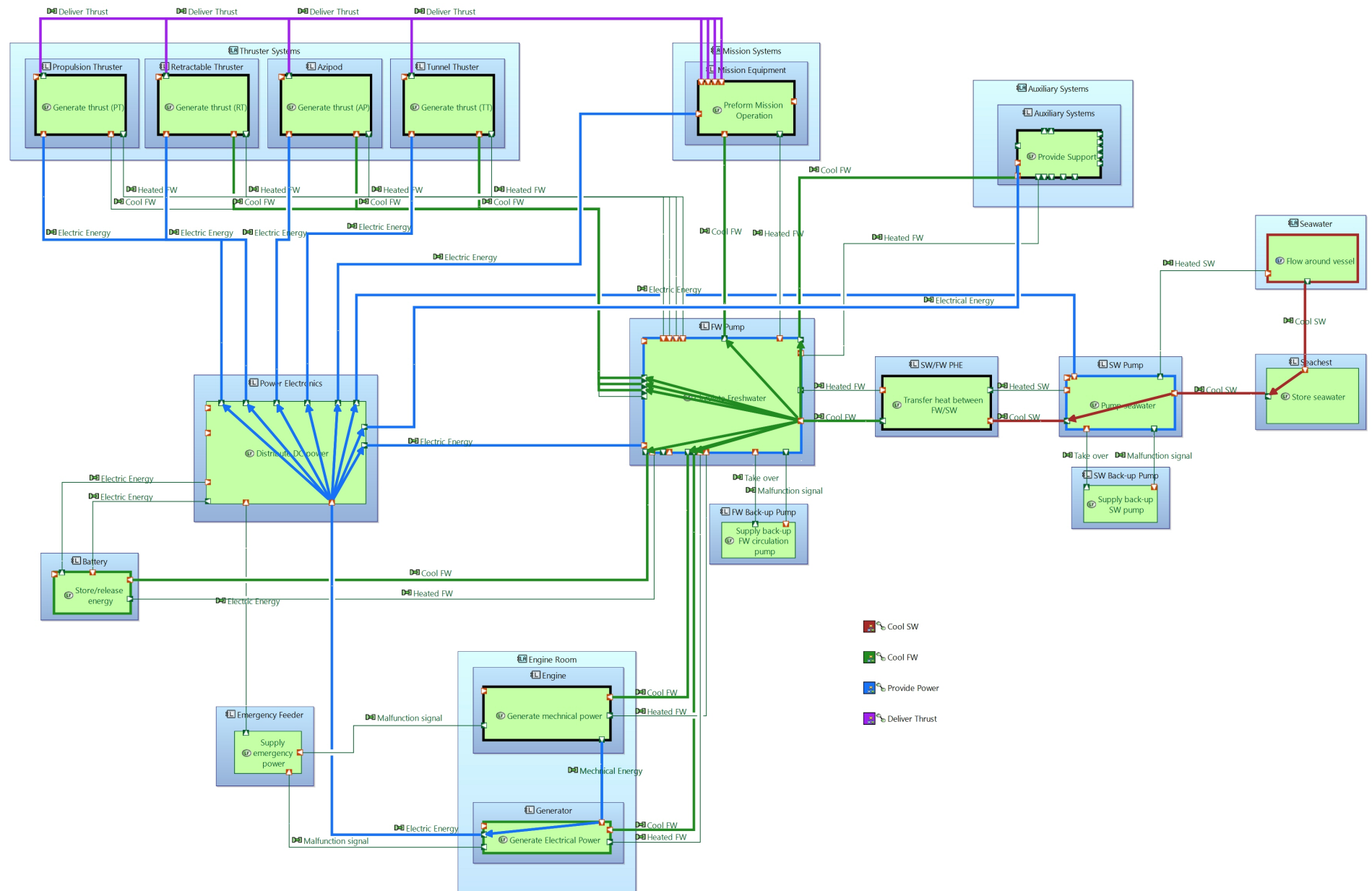


Figure 6.6: LAB Cooling System

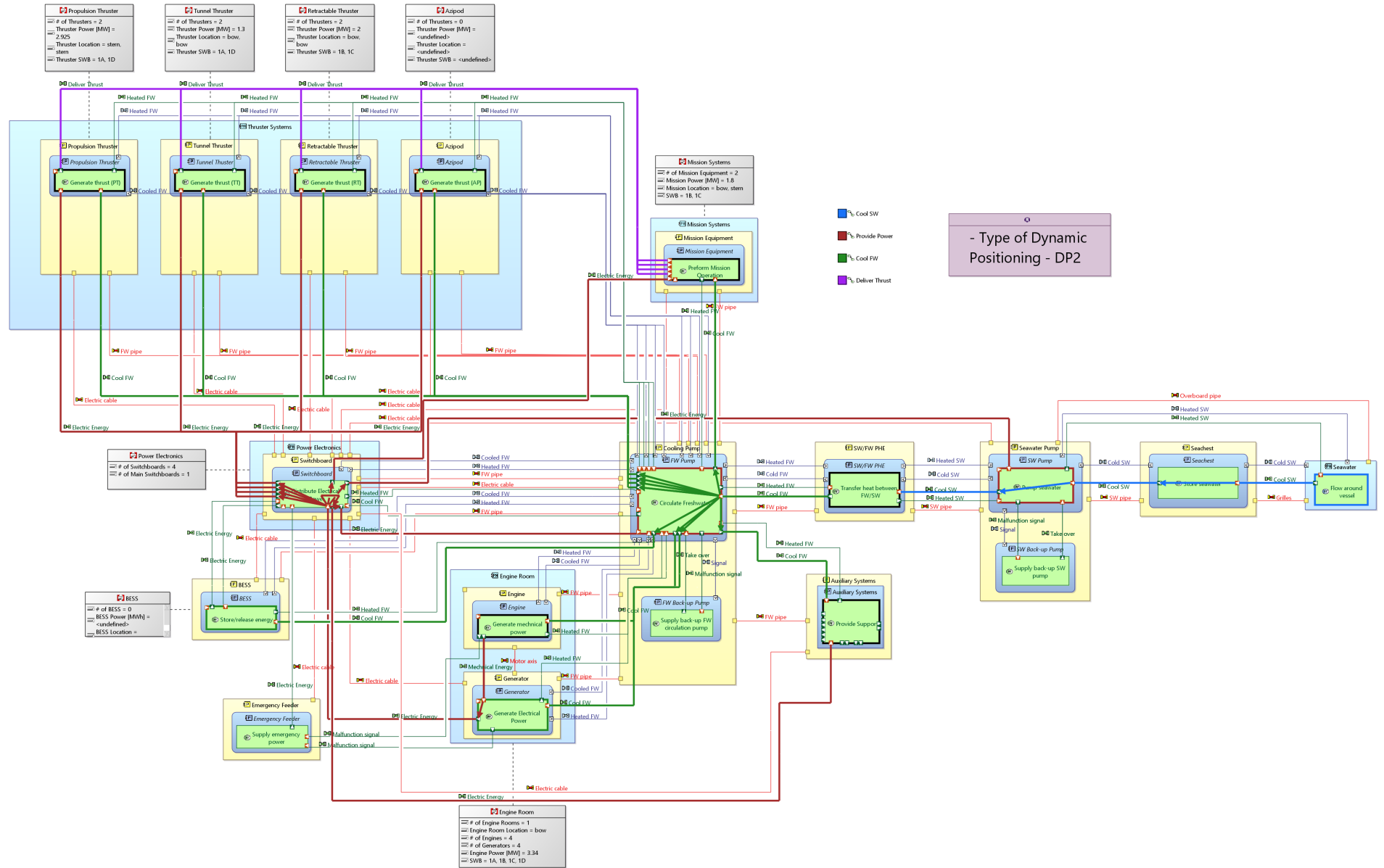


Figure 6.7: PAB Cooling System

6.2. Data Extraction from Capella

The data extraction process forms the first step of the evaluation model and is responsible for converting the system architecture defined in Capella into a structured dataset suitable for quantitative analysis. Using the Python4Capella (P4C) API, the script accesses the Physical Architecture Blank (PAB) diagram of the offshore vessel cooling system and converts the model into usable datasets.

6.2.1. Extraction Methodology

The extracted data from the PAB (Figure 6.7), as described in Section 6.1, consists of two main categories: requirement elements and property value groups. In the Capella diagram visualisation shown, the property value groups are displayed as grey boxes linked to the corresponding physical components, while the requirement elements are shown as purple boxes representing system-level requirements at ship level. Together, they define both system constraints and quantitative system characteristics.

The property values represent a structured abstraction of an underlying electrical power system architecture. They are not arbitrarily defined, but originate from a preliminary E-KOL diagram that ensures a consistent power balance between generation, distribution, and consumers. In this sense, the PAB acts as a higher-level system architecture template derived from the electrical design baseline, from which configuration-relevant parameters are extracted for further system-level analysis.

This electrical baseline is constructed such that installed generation capacity and consumer demand are balanced under design operating conditions, including DP operation. The DP requirement therefore indirectly governs the sizing and distribution of major electrical consumers, while the PAB captures the resulting architectural configuration.

The requirement elements are used to determine high-level system constraints set by the customers, including the DP class of the vessel. Based on the requirement definitions in the model, the system is classified as DP1, DP2, or DP3.

All extracted data is exported into a structured JSON file serving as the primary machine-readable input for the decision-support workflow. An example of this JSON is shown in Appendix D.

6.3. Design Space Generation

Based on the data extracted (Section 6.2) from the Capella model, the design space exploration is constructed in the P4C API. This process is divided into two main steps: pump room load-layout generation 6.3.1 and pump configuration generation 6.3.2.

The first step in the evaluation framework focuses on generating the design space of possible cooling system architectures. This is achieved by transforming the extracted system data into a set of feasible physical configurations.

Following the generation of pump room load-layout, each configuration is further expanded into a detailed pump configuration space. This step defines the sizing and redundancy of cooling equipment for each cluster and pump room.

6.3.1. Pump Room Load-Layout

The pump room load-layout phase explores combinations of layout parameters while enforcing system and regulatory constraints. This process consists of three substeps, which are further detailed below:

- 6.3.1.1 Configuration design generation constraints
- 6.3.1.2 Definition of the number and type of pump rooms
- 6.3.1.3 Spatial distribution of system loads (thrusters, gensets, mission systems, battery energy storage system (BESS), auxiliary systems)

6.3.1.1. Configuration Design Generation Constraints

Before exploring all possible pump room load-layout configurations, the generation process is first constrained to ensure that only viable options are produced. To reduce computational complexity and eliminate infeasible solutions, a set of design rules is applied during the clustering process. These rules were derived through discussions with Ulstein and reflect practical design knowledge and industry experience regarding feasible cooling system arrangements [4]. In this sense, the configuration generation process follows a knowledge-based decision-support approach, where expert knowledge is embedded within the design space exploration.

Each rule is defined both conceptually and through a formal feasibility condition to ensure reproducibility.

- **Separation of critical subsystems**

This rule ensures that critical electrical subsystems are not combined in a way that would violate redundancy requirements. For example, combining different genset switchboard groups within a single cluster would result in a single-point-failure scenario leading to a total loss of power.

Formal feasibility condition:

A cluster C is infeasible if any of the following co-occurrences is present:

$$\{\text{mission, thruster}\} \subseteq C \quad \text{or} \quad \{\text{genset, mission}\} \subseteq C \quad \text{or} \quad \{\text{genset, thruster}\} \subseteq C$$

Additionally, genset switchboard groups must not be merged across clusters (handled separately in the SWB allocation rule).

- **Maximum number of system loads per cluster**

This rule limits the number of mission systems and thrusters assigned to a single cluster to reduce the impact of a cluster failure on vessel performance and redundancy. Although higher limits are technically possible, they are not considered in the baseline case, as they would both reduce system redundancy and significantly increase the computational effort required to explore the design space.

Formal feasibility condition:

$$n_{\text{mission}}(C) \leq 1, \quad n_{\text{thruster}}(C) \leq 2$$

- **Exclusion of incompatible load combinations**

This rule prevents physically and operationally infeasible combinations, such as coupling systems with vastly different cooling demands within the same cooling circuit.

Formal feasibility condition:

A cluster C is infeasible if:

$$\{\text{genset}, \text{thruster}\} \subseteq C \quad \text{or} \quad \{\text{genset}, \text{aux}\} \subseteq C$$

- **Pump room quantity constraints**

This rule prevents the generation of too few stern and bow pump rooms when DP3 compliance is required. This is necessary to ensure adequate separation for compartment-failure scenarios, ensuring that in the event of a stern or bow pump room failure, thrusters in other locations remain operational and can still provide DP capability.

The maximum number of pump rooms is not derived from an explicit geometric optimisation within the model, but is instead defined by the naval architect based on a qualitative assessment of the remaining available layout space in the vessel. This reflects the early-stage design context, where exact spatial allocation is not yet fixed but constrained by practical design experience. For example, in the case study presented in Section 7.2, a configuration containing nine pump rooms would be challenging to accommodate and would introduce considerable design complexity.

Formal feasibility conditions:

DP3 minimum requirement:

$$N_{\text{bow}} \geq 2, \quad N_{\text{stern}} \geq 2$$

Maximum bounds (design input):

$$N_{\text{bow}} \leq N_{\text{bow}}^{\text{max}}, \quad N_{\text{stern}} \leq N_{\text{stern}}^{\text{max}}$$

A configuration is accepted if all rules are satisfied.

6.3.1.2. Definition of the number and type of pump rooms

With the design constraints defined, pump rooms are generated by systematically combining engine room configurations, thruster capacity limits, and spatial thruster distributions.

The generation procedure considers three main inputs:

- Engine room locations
- Thruster positions (bow, stern, midship)
- Maximum number of thrusters per pump room

At this stage, only the pump room topology is defined (the number, type, and location of pump rooms). System loads are assigned in a subsequent step.

First, different configurations for the number of pump rooms associated with engine rooms are generated. Let N_{ER} denote the number of engine rooms. The number of corresponding pump rooms is varied as:

$$N_{PR,ER} \in \{1, 2, \dots, N_{ER}\} \tag{6.1}$$

For each value of $N_{PR,ER}$, pump rooms are created and assigned to the engine room locations defined in the input model. This allows both combined and separated configurations of gensets to be considered within the design space.

Engine rooms are regarded as co-located when they share the same location label (bow, stern, or midship) in the input data. Since the number of engine room pump rooms is varied independently of these locations, both merged and distributed configurations for co-located engine rooms are inherently included.

Next, thrusters are grouped according to their spatial position:

$$\mathcal{T} = \mathcal{T}_{\text{bow}} \cup \mathcal{T}_{\text{stern}} \cup \mathcal{T}_{\text{mid}} \quad (6.2)$$

For each location l , the number of thrusters n_l is determined. The maximum number of thrusters that can be assigned to a single pump room at that location, denoted as k_l , is then varied over all feasible values:

$$k_l \in \{1, 2, \dots, n_l\} \quad (6.3)$$

This range may be further restricted by a user-defined upper bound N_l^{max} reflecting spatial design limitations:

$$k_l \leq N_l^{\text{max}} \quad (6.4)$$

For each selected value of k_l , the number of pump rooms required at location l is determined using:

$$N_{PR,l} = \left\lceil \frac{n_l}{k_l} \right\rceil \quad (6.5)$$

Separate pump rooms are subsequently created for each location (bow, stern, midship) based on this relation. Through the combined variation of $N_{PR,l}$ and k_l , a comprehensive set of feasible pump room configurations is generated, which forms the basis for the subsequent load allocation and clustering process.

6.3.1.3. Spatial distribution of system loads

Once the pump room topology has been defined, system loads are allocated to the available pump rooms. The following load categories are considered:

- Thrusters (tunnel, propulsion, retractable, azimuth)
- Gensets (linked to engine rooms)
- Mission systems
- Auxiliary systems
- BESS systems

Thrusters are first grouped based on their spatial location (bow, stern, midship) and their SWB connection. Only pump rooms located at the same spatial position are considered valid candidates. Within each location, thrusters are sorted based on their switchboard connection and assigned iteratively to pump rooms until the maximum number of thrusters per room is reached. If multiple pump rooms exist at a given location, thrusters are distributed in a cyclic manner across these rooms. This ensures that the predefined capacity per pump room is not exceeded and that thrusters are distributed as evenly as possible across the available rooms.

Gensets are assigned exclusively to pump rooms associated with engine rooms. Let $N_{PR,ER}$ denote the number of engine room pump rooms. If $N_{PR,ER} = 1$, all gensets are assigned to a single pump room. If $N_{PR,ER} > 1$, gensets are grouped based on their main switchboard connection and distributed across engine room pump rooms such that gensets connected to different switchboards are separated. This ensures that electrically independent subsystems are not co-located, thereby avoiding single-point failures ranging across multiple redundancy groups.

Mission systems are allocated based on predefined location inputs provided in the system model. For each mission system, only pump rooms at the specified location are considered. If multiple candidate pump rooms are available, preference is given to pump rooms that already contain a thruster connected to the same switchboard. If no such match exists, the mission system is

assigned to the first available pump room at the required location. This ensures that mission systems are placed in physically feasible locations and remain electrically compatible with the surrounding systems.

Auxiliary loads are assigned based on the number of thrusters present in each pump room:

$$N_{\text{aux,room}} = N_{\text{thrusters,room}} \quad (6.6)$$

This implies that each thruster introduces one auxiliary load, reflecting the modelling assumption that every thruster requires a dedicated auxiliary cooling demand within the same pump room.

Finally, BESS loads are assigned based on both spatial location and switchboard connection. For each BESS unit, pump rooms at the corresponding location are considered. If a matching pump room is found that contains a thruster with the same switchboard connection, the BESS is assigned to that room. Otherwise, the BESS is assigned to the first available pump room at the required location. In the final configuration, auxiliary and BESS loads connected to the same switchboard may be merged into a single combined auxiliary-BESS load, representing shared cooling functionality.

6.3.2. Pump Configurations

For each pump room load-layout, multiple pump configurations are generated by varying:

- Number of cooling pumps (FW and SW systems)
- Number of plate heat exchanger units (PHE)
- Number of backups

Each configuration represents a unique combination of equipment sizing strategies, defined by variations in the number of duty and backup FW, SW, and PHE units. Duty units refer to the actively operating components required to meet the nominal cooling demand, while backup units are redundant components installed to ensure system availability in case of failure or maintenance of duty units. It is assumed that the duty units collectively provide **100%** of the required cooling capacity under normal operating conditions per cluster. Furthermore, each backup unit is assumed to be identical in capacity to a duty unit, providing a one-to-one redundant replacement rather than additional cooling capacity.

Cluster-Based Equipment Sizing

For each cluster, the required number of cooling units is determined based on the cluster load:

$$N_{\text{FW},i} = \lfloor f_{\text{FW},i} \cdot X_{\text{cluster}} \rfloor \quad (6.7)$$

where:

- X_{cluster} = number of loads in the cluster
- $f_{\text{FW},\text{duty}}$ = scaling factor = [0.5, 1.0, 1.5]
- $f_{\text{FW},\text{backup}}$ = scaling factor = [0.0, 0.5, 1.0]

To reduce the number of configurations and remove unrealistic solutions, constraints are introduced based on domain knowledge from Ulstein and general reliability considerations in redundant pump systems, shown below [4]. When the backup factor is 0.0, configurations with a duty scaling factor of 1.5 are excluded, since increasing the number of active pumps without redundancy increases the probability of system-level failure. Conversely, the number of backup

units is limited to a maximum of twice the number of duty units, preventing unrealistic levels of redundancy and overly engineered designs.

$$f_{\text{FW,backup}} = 0 \rightarrow f_{\text{FW,duty}} \neq 1.5$$

$$N_{\text{FW,backup}} \leq 2 \cdot N_{\text{FW,duty}}$$

Similarly, for each cluster the seawater and plate heat exchanger equipment options are explored:

$$\begin{aligned} N_{\text{SW}} &\in \{1, 2\} & N_{\text{SW,backup}} &\in \{0, 1, 2\} \\ N_{\text{PHE}} &\in \{1\} & N_{\text{PHE,backup}} &\in \{0, 1\} \end{aligned}$$

Because of the low failure probability of the PHE subsystem, as shown in Figure F.2, increasing the number of PHE units has only a limited influence on the expected DP performance. Therefore, a reduced number of configuration options is considered for the PHE subsystem in the current implementation. However, this simplification is not fixed and can be adjusted if future analysis or updated reliability data indicate a higher impact on system availability.

Special Configurations

Certain cluster types follow predefined rules. These rules are not strictly fixed and may be adjusted based on naval architectural constraints or customer preferences. Such adjustments do not affect the integrity of the DSS, as the underlying cost and sizing models remain modular and independent of these configuration rules.

- **Genset clusters:** each genset has always one freshwater duty pump and backup pump, as these systems are integrated into each other.
- **Mission clusters:** each mission system has one duty and backup to provide for redundancy reliability and reduce amount of computations.

Configuration Space Exploration

The pump system design space is generated by combining possible configurations of different FW, SW and PHE strategies. Each configuration represents a unique combination of duty and backup assignments for a selected set of system elements. The full configuration space is defined as:

$$\mathcal{C}_{\text{pump}} = \prod_{t \in T} \mathcal{O}_t \quad (6.8)$$

where:

- T = set of cluster categories
- $\mathcal{O}_t$ = possible configurations for category t

This means that for each element in T , multiple operating strategies are defined, and all combinations across these elements are evaluated. Each resulting configuration corresponds to a specific combination of duty and backup units across the cooling system.

The definition of the set T determines the level of detail of the design space exploration. Different configuration modes are introduced to control the size of the design space and the associated computational effort:

- **System load mode:** In this mode, operational strategies are defined per load category:

$$T = \{\text{thruster, genset, mission}\}$$

This means that all thrusters share the same duty/backup strategy, and no distinction is made between locations or types. This results in a limited number of configurations (1,152), but provides only coarse resolution of the design space.

- **Location mode:** In this mode, thrusters are grouped by spatial location:

$$T = \{\text{stern, bow, genset, mission}\}$$

This allows different operational strategies to be assigned to bow and stern thrusters, introducing spatial differentiation while keeping the problem computationally manageable. For the case study, this results in 110,592 configurations.

- **Thruster type mode:** In this mode, thrusters are distinguished by type:

$$T = \{\text{propulsion, tunnel, retractable, genset, mission}\}$$

or, if azipods are included:

$$T = \{\text{propulsion, tunnel, retractable, azipod, genset, mission}\}$$

This results in a highly detailed exploration where each thruster type can have a distinct operational strategy, leading to up to 1.0×10^7 and 1.0×10^9 configurations. While this provides a high level of detail, the computational effort increases significantly.

- **Cluster mode:** In this mode, operational strategies are assigned at the cluster level rather than per component type:

$$T = \{\text{cluster}_1, \text{cluster}_2, \dots, \text{cluster}_n, \text{genset, mission}\}$$

where n is the number of clusters in a given configuration. This approach allows maximum flexibility, as each cluster can be controlled independently. However, the number of configurations grows exponentially with n , reaching up to 7.98×10^{20} configurations, which is computationally infeasible without additional sampling or pruning.

The different configuration modes therefore represent different levels of abstraction within the design space. As the level of detail increases, the analysis becomes more accurate, but the number of possible configurations increases rapidly, leading to an explosion in the size of the design space.

As a result, a trade-off must be made between computational workability and modelling accuracy. Using a reduced set T limits the number of configurations and allows rapid evaluation, but may neglect certain design options or interactions between subsystems. Conversely, a more detailed definition of T captures a larger portion of the design space but requires significantly more computational resources.

For the case studies presented in Chapter 7, the *Location* configuration mode was selected, as it provides a balance between spatial resolution and computational feasibility. This mode captures the primary spatial distinctions in the vessel layout (bow versus stern) without incurring the excessive computational cost associated with thruster type or cluster exploration.

6.4. Configuration Scoring and Ranking

After generating the possible design solutions of the cooling system, the configurations are, in the P4C API, ranked by comparing cost (Subsection 6.4.1) and risk (Subsection 6.4.2). Subsequently, the cost and risk values are normalised (Subsection 6.4.3) and a Pareto front is constructed, resulting in a set of non-dominated configurations that represent the most optimal trade-offs between both criteria.

6.4.1. Cost Model

The total cost of each cooling system configuration is estimated using two cost contributions: the cluster cost and the pump room cost, as defined in Equation 6.9. The cluster cost represents the combined cost of the cooling equipment, valves, instrumentation, and piping required within each cluster. These costs are estimated using reference component costs and scaling relations based on the required cooling capacity. The pump room cost captures the additional cost associated with providing the required pump room infrastructure, including both fixed costs and size-dependent costs. The methodologies used to estimate these contributions are presented in the following sections.

$$C_{\text{total}} = C_{\text{cluster}} + C_{\text{pump room}} \quad (6.9)$$

with:

- C_{cluster} = total cost of all cooling system clusters, including equipment, valves, instrumentation, and piping
- $C_{\text{pump room}}$ = total cost associated with the required pump rooms

Cooling Demand Scaling Function

To estimate the cost of the cooling system components, an approximation of the required component size is needed. In the proposed approach, component sizing is determined indirectly from the cooling demand of each cluster and pump room. The cooling demand is calculated using Equation 6.10.

$$f_{\text{load}} = P \cdot L \quad (6.10)$$

with:

- P = power of cluster or pump room [MW]
- L = cooling load factor per unit [$m^3 h^{-1} MW^{-1}$]

The cooling load factors presented in Table 6.1 are derived from historical E-KOL diagrams and cooling system data from previous Ulstein vessel projects. By comparing installed power ratings with the corresponding cooling capacities, a correlation between installed power and required cooling flow was established. The cooling factor is subsequently used as a scaling parameter to estimate the cooling demand and, consequently, the required component size for each generated configuration.

Table 6.1: Cooling load factor per unit [$m^3 h^{-1} MW^{-1}$] based on Ulstein's historical data [4]

	Propulsion	Tunnel	Retractable	Azipod	Genset	Mission	BESS	Aux
L	1.37	1	1.25	1	5.91	1	1	1

Table 6.1 shows for example that a propulsion thruster needs 1.37 times more cooling than a tunnel thruster.

For the mission system due to the varying cooling requirement of different mission systems for now the cooling factor is just capped at 1, because the mission system is assumed to be a fixed solution in the DSS code, this would not influence the result of the final score. The specific cooling requirements for mission equipment are instead determined at a later design stage based on customer and naval architect preferences.

For auxiliary systems, the power demand is already represented as an estimated percentage of the associated thruster load. Introducing an additional scaling factor would therefore increase compound uncertainty without improving model fidelity.

For azipod configurations, no historical reference data is currently available within Ulstein's project database. However, the proposed framework allows for straightforward integration of such data once vessels with azipod propulsion systems are encountered in future projects.

Cluster cost

The cluster cost is estimated using Equation 6.11 by the summation of the cost of valves, instruments, equipment units, and piping. With use of the size estimations and a reference cost value, obtained from Table E.1, the cost can be estimated. Costs are calculated per cluster, since each cluster has its own cooling demand and configuration in terms of duty and backup units. For the valves and instruments the number of units is derived from previous cooling system designs and are shown in Table E.2.

$$C_{i,\text{cluster}} = \sum_i [C_{i,\text{piping}} + C_{i,\text{ref}} \cdot \left(\frac{f_{i,\text{load}}}{f_{\text{ref}}} \right)^{0.6}] \cdot (N_{i,\text{duty}} + N_{i,\text{backup}}) \quad (6.11)$$

The cost is assumed to follow a six-tenths scaling behaviour, meaning that the rate of cost increase, decreases with increasing system size [72]. This reflects the diminishing marginal increase in cost that is commonly observed as equipment size increases. In this formulation, the first term represents the fixed piping and installation cost per unit, while the second term captures the size-dependent cost contribution of the equipment itself.

It should be noted that these values remain estimates. Using detailed cost data for multiple cooling component sizes would improve accuracy, but this was not feasible due to scope limitations, time constraints, and limited availability of data. For this reason, the presented cost formulation was adopted.

Pump room cost

The pump room cost, similar to the cluster cost, is assumed to follow a six-tenths scaling behaviour with increasing system size, expressed in terms of pump room power. The pump room cost is defined by Equation 6.12. In this formulation, $C_{j,\text{Addtl}}$ represents the fixed cost associated with the existence of a pump room, independent of its size, while the second term captures the size-dependent cost contribution.

$$C_{j,\text{pump room}} = \sum_j [C_{j,\text{Addtl}} + C_{j,\text{ref}} \cdot \left(\frac{f_{j,\text{load}}}{f_{\text{ref}}} \right)^{0.6}] \quad (6.12)$$

If multiple pump rooms share an identical layout, a cost discount of 7% is applied to reflect reduced engineering effort and increased reuse potential. This discount is based on internal engineering judgement in collaboration with Ulstein and represents an approximation of design reuse effects. The discount increases with the number of identical layouts but is capped at 25% to prevent unrealistic cost reductions.

The applied values are intended as configurable parameters within the DSS and may be updated when more detailed shipyard cost data becomes available. However, such data is typically not publicly accessible, making precise validation of reuse-related cost effects challenging.

$$C_{\text{discounted}} = C_{\text{pump room}} \cdot (1 - d) \quad (6.13)$$

with:

- $d = \min(n \cdot \delta, d_{\text{max}})$
- $\delta = 0.07$
- $d_{\text{max}} = 0.25$

6.4.2. Risk Model

As the cooling system design of an offshore vessel is directly linked to its DP capabilities, DP performance is proposed to be used as a metric for estimating the risk of a given cooling system configuration. Risk is divided into two categories: cluster risk and pump room risk. Cluster risk captures the effects of single-point failures, while pump room risk captures compartment-level failure scenarios. These correspond respectively to DP2 and DP3 failure cases.

In this model, risk is defined as the expected loss of DP capability over an exposure period of one year. Due to the rarity of full compartment-level events, pump room and cluster risks are chosen to be scored separately to ensure making it possible to choose between different cluster configurations and different pump room configurations.

- R_{Cluster} = expected DP capability loss per year due to component failures
- $R_{\text{Pump room}}$ = expected DP capability loss per year due to compartment failures

DP Capability Assessment

The risk model is based on the relationship that cooling system failures ultimately affect the DP capability of the vessel. Consequently, DP capability is used as the performance metric from which both cluster and pump room risks are derived.

DP capability is evaluated based on the available thrust capacity after failure events while accounting for the spatial distribution of thrusters across the vessel. Thrusters located in the bow and stern contribute differently to the overall force and moment balance. Due to moment equilibrium requirements ($\sum M = 0$), the loss of a bow thruster cannot always be compensated by the remaining thrusters operating at full capacity.

This is because each thruster contributes not only to a net horizontal force but also to a yawing moment, depending on its position relative to the vessel's centre of rotation. During operations requiring zero yaw, the thrusters are coordinated to collectively ensure moment equilibrium is maintained. However, when a thruster fails and the remaining thrusters are operated at their maximum capacity, non-zero yaw moments can arise.

As a result, opposing thrusters may need to reduce their thrust output to restore moment equilibrium, which in turn reduces the overall available DP capability. This is because a reduced number of opposing yawing moments from the thruster configuration limits the systems ability to counteract external disturbances such as wind and waves.

In addition to spatial effects, electrical dependencies are considered. Genset clusters are linked to switchboards supplying power to multiple thruster systems. Failure of a genset cluster may therefore result in indirect loss of thrust capacity through associated switchboard failures.

The resulting loss of available thrust is translated into a reduction of DP capability. This reduction is represented by the parameter α , which quantifies the contribution of a cluster or pump room to the overall DP performance of the vessel.

Cluster Risk

Due to the single-failure criterion, the loss of an individual component within a cooling cluster does not necessarily lead to a loss of DP capability. Following Tsekouras and Kanellos [73], component reliability with a constant failure rate over time is modelled using an exponential distribution. The time-dependent failure probability $p_i(t)$ over an operational period t is therefore defined as the complement of the reliability function:

$$p_i(t) = 1 - e^{-\frac{t}{\text{MTBF}}} \quad (6.14)$$

The component-specific Mean Time Between Failures (MTBF) values for an exposure time t (expressed in years) used in this study are based on Ware and Collette [74]:

$$MTBF_{FW} = 1.97, \quad MTBF_{SW} = 1.97, \quad MTBF_{PHE} = 6.85$$

Because cooling clusters often include redundancy through duty and backup units, DP cooling clusters often exhibit partial capacity failure rather than full failure. This means that the cluster can still contribute to the overall DP capability, but at a reduced level depending on how many units remain operational.

The methodology used by Tsekouras and Kanellos [73] did not account for this behaviour in parallel configurations. To capture this behaviour, the expected DP performance of a cluster is modelled using a binomial distribution, which represents the likelihood of having exactly k failed units within a cluster of size n over a time horizon t . This makes it possible to consider every possible failure state rather than only full success or full failure.

The expected DP performance of a cluster is therefore computed as a weighted sum over all possible states, as shown in Equation 6.15.

$$E_i(t) = \sum_{k=0}^n \binom{n}{k} p_i(t)^k (1 - p_i(t))^{n-k} \cdot DP(k) \quad (6.15)$$

where:

- n = total number of duty and backup units
- k = number of failed units within time horizon t
- $p_i(t)$ = time-dependent failure probability of a single component

The function $DP(k)$ describes how the remaining operational cooling capacity translates into DP capability. As shown in Equation 6.16, the resulting DP capability depends on whether the number of remaining cooling units is sufficient to satisfy the required cooling load. If the required number of units, req , is not met, the system experiences a reduction in DP capability.

$$DP(k) = 1 - \alpha_{\text{cluster}} \cdot \left(1 - \frac{n - k}{req}\right) \quad (6.16)$$

with:

- α_{cluster} = DP contribution of the cluster
- req = number of required operating units

The parameter α_{cluster} is derived from the DP capability assessment described above and therefore reflects the impact of a cluster on the overall DP performance of the vessel. Clusters containing critical thrusters or power supply elements such as gensets will generally exhibit higher α_{cluster} values than clusters containing less critical loads. Figure 6.8 provides a visual representation of how the binomial formulation operates.

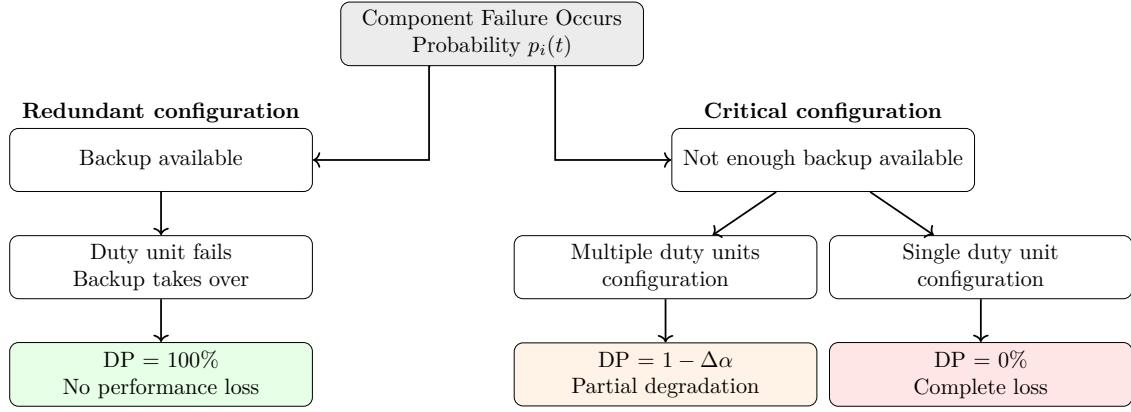


Figure 6.8: Event tree representation of DP outcomes following a component failure under different redundancy configurations.

By incorporating the time-dependent failure probability into the discrete state-space formulation, the expected DP performance of each subsystem can be determined.

The cluster risk is then calculated using Equation 6.17. Here, the individual subsystem performances are assumed to be independent, allowing the combined cluster performance to be calculated as the product of the expected DP capabilities of the freshwater, seawater, and plate heat exchanger subsystems.

$$R_{\text{cluster},i} = 1 - \prod_i E_{\text{DP},i} \quad i \in \{\text{FW}, \text{SW}, \text{PHE}\} \quad (6.17)$$

The total cluster risk is obtained by combining the average risk with a worst-case penalty to avoid asymmetric designs:

$$R_{\text{tot},\text{cluster}} = \frac{1}{2} (R_{\text{avg},\text{cluster}} + R_{\text{worst},\text{cluster}}) \text{ [\%DP}_{\text{loss}}/\text{year}] \quad (6.18)$$

where:

$$R_{\text{avg},\text{cluster}} = \frac{1}{N} \sum_{i=1}^N R_{\text{cluster},i} \quad (6.19)$$

$$R_{\text{worst},\text{cluster}} = \max_i (R_{\text{cluster},i}) \quad (6.20)$$

The inclusion of the worst-case term penalises configurations with highly uneven risk distribution, for example a single highly vulnerable cluster combined with otherwise robust clusters. This aligns the model with DP redundancy principles and single-point failure considerations.

Pump Room Risk

Pump room risk evaluates vulnerability to full compartment-level events such as fire or flooding, which are representative of DP3 failure scenarios. The probability of pump room failure is modelled using a constant failure rate, reflecting the low likelihood of compartment-level events.

Similar to the cluster-level assessment, the DP capability loss is evaluated based on the reduction in available thrust capacity across different spatial groups. This ensures consistency between cluster-level and pump room-level risk modelling.

For each pump room, the risk is defined as the expected DP performance loss associated with complete compartment failure. For example, if a pump room contains three clusters with α values of 0.2 each, the total loss equals 0.6, leaving the vessel at 40% DP capability during

complete pump room failure. Due to the low probability of such events, this value is scaled by the probability that the failure occurs, as shown in Equation 6.21.

$$R_{\text{pump room},j} = 1 - (1 - p(t) \cdot \alpha_{\text{pump room},j}) \quad (6.21)$$

with:

- $\alpha_{\text{pump room},j}$ = DP capability loss due to complete pump room failure
- $p(t)$ = time-dependent failure probability of a compartment failure cases

The compartment-specific MTBF values (expressed in years) used in this study are not directly available in the literature, as no publicly reported data exist for flooding or fire events specifically in offshore vessel cooling-system pump rooms.

Instead, representative order-of-magnitude values were defined as engineering assumptions, constrained by reported vessel-level incident statistics and offshore risk literature.

$MTBF_{\text{Flooding}}$ cannot be directly obtained from maritime statistics as stand-alone events, since flooding is typically a consequence of collision, grounding, or structural damage. Also the chance that this event would occur in the pump room reduces the risk. Therefore with the probability mentioned in Vanem and Skjong [75], a value of $1 \cdot 10^4$ was chosen.

$MTBF_{\text{Fire}}$ is estimated with use of the reported engine-room fire occurrence rates in marine insurance data Gard P&I [76] and assuming only 2-5% of this data would occur in an pump room.

The adopted values are not intended to represent measured or directly derived failure rates, but rather bounded design parameters for comparative system evaluation.

$$MTBF_{\text{Flooding}} = 1 \cdot 10^4, \quad MTBF_{\text{Fire}} = 2 \cdot 10^4,$$

The total pump room risk is determined using the same approach as the cluster risk:

$$R_{\text{tot,pump room}} = \frac{1}{2} (R_{\text{avg,pump room}} + R_{\text{worst,pump room}}) \quad [\%DP_{\text{loss}}/\text{year}] \quad (6.22)$$

where:

$$R_{\text{avg,pump room}} = \frac{1}{N} \sum_{j=1}^N R_{\text{pump room},j} \quad (6.23)$$

$$R_{\text{worst,pump room}} = \max_j (R_{\text{pump room},j}) \quad (6.24)$$

These formulations allow consistent evaluation of both component-level and compartment-level risks within a unified decision-support framework.

6.4.3. Multi-Criteria Decision Making

The most suitable designs are identified using a Pareto-based evaluation considering cost, cluster and pump room risk as the three main criteria. In this step, all configurations are evaluated simultaneously on both objectives, where cost, cluster and pump room risk are treated as competing performance indicators. Pareto-optimality is applied to identify the set of non-dominated solutions, ensuring that only configurations that cannot be improved in one objective without worsening the other are retained. This reduces the design space to the most relevant trade-off solutions for further analysis.

A configuration A is said to dominate configuration B if it performs at least as well in both objectives and strictly better in at least one:

$$C_A \leq C_B \wedge R_{cluster,A} \leq R_{cluster,B} \wedge R_{pumproom,A} \leq R_{pumproom,B} \wedge (C_A < C_B \vee R_{cluster,A} < R_{cluster,B} \vee R_{pumproom,A} < R_{pumproom,B})$$

where C denotes total system cost and R denotes cluster or pump room system risk. The resulting Pareto front therefore consists of all configurations that are not dominated by any other configuration in the evaluated design space and represents the fundamental trade-off between economic efficiency and system robustness.

To enable a meaningful comparison between cost and the risks within this Pareto set, the raw values are normalised using Equation 6.25. In this formulation, higher scores represent better performance. This ensures that both lower cost and lower risk correspond to higher normalised scores, enabling consistent interpretation across both criteria.

$$S_x = 1 + 9 \cdot \frac{C_{x,max} - C}{C_{x,max} - C_{x,min}} \quad (6.25)$$

The overall performance of each Pareto-optimal design is then determined using a weighted aggregation of the normalised cost and risk scores:

$$\text{Final Score} = \frac{w_c \cdot S_{\text{cost}} + w_{cl,r} \cdot S_{\text{cluster,risk}} + w_{pu,r} \cdot S_{\text{pump room,risk}}}{w_c + w_{cl,r} + w_{pu,r}} \quad (6.26)$$

with:

$$\begin{aligned} w_c &= 0.50 \\ w_{cl,r} &= 0.50 - w_{pu,r} \\ w_{pu,r} &= \begin{cases} 0.025 & \text{if } \min(N_{ER}, N_{main,SWB}) = 1 \\ 0.100 & \text{if } \min(N_{ER}, N_{main,SWB}) = 2 \end{cases} \end{aligned}$$

The weights are set to a baseline assumption of equal importance between cost and risk, reflecting the absence of explicit stakeholder preference at this stage of the analysis. The cluster and pump room risk weight distribution is based on the assumption that configurations with higher levels of redundancy in the E-KOL place greater importance on compartment-level failures. As redundancy increases, the relative significance of pump room risk becomes larger compared to cluster risk.

However, these weights can be adjusted in later MBSE-DSS scenarios to reflect different design priorities, such as cost-driven or risk-averse decision strategies.

Finally, the aggregated score is used to rank the Pareto-optimal configurations, allowing the DSS to present a prioritised subset of the most relevant design alternatives for decision-making.

CHAPTER 7

Case Study

To evaluate the contribution of the MBSE-DSS to the decision-making process, as stated in **RQ5**, two case studies are performed. Together, these case studies assess whether the MBSE-DSS can generate realistic cooling system architectures, support design-space exploration, and provide consistent decision support across vessels of different size and complexity.

The first case study concerns the Reference Vessel S, discussed in Section 7.1, with an overall length of 119.50 meters. The delivered E-KOL is used as a reference design and is complemented by several *what-if* variations. This case study is used to evaluate whether the MBSE-DSS produces realistic solutions for different situations.

The second case study, discussed in Section 7.2, considers the Reference Vessel L, with an overall length of 229.60 meters. Owing to its substantially larger size and more complex system architecture, this case study is used to assess the scalability and robustness of the MBSE-DSS when applied to a significantly larger design space. Comparing the results of both case studies further enables the consistency of the methodology to be evaluated across different vessel types.

7.1. Reference Vessel S

The first vessel used for validation of the MBSE-DSS is the Reference Vessel S. As discussed in Chapter 6, the initial step is to apply the Capella cooling system template to define the structure in which the E-KOL data, shown in Figure 7.3, will be incorporated. To provide a better understanding of the vessel systems architecture, Figure 7.1 highlights the load layout of the vessel. The resulting E-KOL inputs are summarised in Table 7.1. The vessel has an overall length of 119.50 metres and represents a relatively small offshore vessel configuration designed to comply with DP2 operational requirements. Consequently, the design focus for the naval architect is primarily on cluster risk and cost.



Figure 7.1: Vessel Load-Layout of the Reference Vessel S [16]

Regarding pump room risk, the selected number of pump rooms is largely driven by the naval architect's design preference, reflecting a trade-off between cost and risk. However, considering the most critical compartment failure scenario, the use of a single engine room implies that a loss of the pump room supplying cooling to the gensets would result in a complete loss of DP capability. In such a case, introducing additional bow or stern pump rooms does not provide meaningful risk reduction for this failure mode. Given the very low probability of a complete pump room loss and the fact that only DP2 redundancy requirements must be met, additional pump rooms would primarily increase cost without a proportional reduction in risk.

Therefore, prior to executing the MBSE-DSS, it is already anticipated that the optimal configuration will consist of one bow and one stern pump room.

Table 7.1: E-KOL input of Case Study Reference Vessel S

Parameter	Eng. rooms	Engines & gen.	Power dist.	Mission	Tunnel	Propulsion	Retractable
N	1	4 (eng), 4 (gen)	4 (swb), 2 (main)	2	2	2	2
Power [MW]	–	3.34	–	1.8	1.3	2.925	2
Location	bow	–	–	bow, stern	bow, bow	stern, stern	bow, bow
SWB Connections	–	–	1A, 1B, 2A, 2B	1B, 2A	1A, 2B	1A, 2B	1B, 2A

7.1.1. Generated Pump Room Configurations

After incorporating all required inputs into Capella, the MBSE-DSS can be executed. This process generates 30 feasible configurations that satisfy the layout constraints. These configurations are listed in Listing 7.1.

Listing 7.1: Generated pump room load-layout configurations for the Reference Vessel S case study

```
Active DP level: DP2

[CFG] ER=1 | B=1 S=1 M=0
CFG_B1_S1_MO_RS(ER[2],BOW[2,1,1],STERN[2,1]) | rooms=6 | clusters=9

[CFG] ER=1 | B=1 S=2 M=0
CFG_B1_S2_MO_RS(ER[2],BOW[2,1,1],STERN[2]) | rooms=5 | clusters=8
CFG_B1_S2_MO_RS(ER[2],BOW[2,1,1],STERN[3]) | rooms=5 | clusters=9

[CFG] ER=1 | B=2 S=1 M=0
CFG_B2_S1_MO_RS(ER[3],BOW[1],STERN[2,1]) | rooms=4 | clusters=7
CFG_B2_S1_MO_RS(ER[3],BOW[2],STERN[2,1]) | rooms=4 | clusters=8
CFG_B2_S1_MO_RS(ER[4],BOW[1],STERN[2,1]) | rooms=4 | clusters=8
CFG_B2_S1_MO_RS(ER[4],BOW[2],STERN[2,1]) | rooms=4 | clusters=9

[CFG] ER=1 | B=2 S=2 M=0
CFG_B2_S2_MO_RS(ER[3],BOW[1],STERN[2]) | rooms=3 | clusters=6
CFG_B2_S2_MO_RS(ER[3],BOW[2],STERN[2]) | rooms=3 | clusters=7
CFG_B2_S2_MO_RS(ER[3],BOW[1],STERN[3]) | rooms=3 | clusters=7
CFG_B2_S2_MO_RS(ER[3],BOW[2],STERN[3]) | rooms=3 | clusters=8
CFG_B2_S2_MO_RS(ER[4],BOW[1],STERN[2]) | rooms=3 | clusters=7
CFG_B2_S2_MO_RS(ER[4],BOW[2],STERN[2]) | rooms=3 | clusters=8
CFG_B2_S2_MO_RS(ER[4],BOW[1],STERN[3]) | rooms=3 | clusters=8
CFG_B2_S2_MO_RS(ER[4],BOW[2],STERN[3]) | rooms=3 | clusters=9

[CFG] ER=1 | B=3 S=1 M=0
CFG_B3_S1_MO_RS(ER[4],BOW[1],STERN[2,1]) | rooms=4 | clusters=8
CFG_B3_S1_MO_RS(ER[5],BOW[1],STERN[2,1]) | rooms=4 | clusters=9

[CFG] ER=1 | B=3 S=2 M=0
CFG_B3_S2_MO_RS(ER[4],BOW[1],STERN[2]) | rooms=3 | clusters=7
```

```

CFG_B3_S2_MO_RS(ER[4],BOW[1],STERN[3]) | rooms=3 | clusters=8
CFG_B3_S2_MO_RS(ER[5],BOW[1],STERN[2]) | rooms=3 | clusters=8
CFG_B3_S2_MO_RS(ER[5],BOW[1],STERN[3]) | rooms=3 | clusters=9

[CFG] ER=1 | B=4 S=1 M=0
CFG_B4_S1_MO_RS(ER[4],STERN[2,1]) | rooms=3 | clusters=7
CFG_B4_S1_MO_RS(ER[5],STERN[2,1]) | rooms=3 | clusters=8
CFG_B4_S1_MO_RS(ER[6],STERN[2,1]) | rooms=3 | clusters=9

[CFG] ER=1 | B=4 S=2 M=0
CFG_B4_S2_MO_RS(ER[4],STERN[2]) | rooms=2 | clusters=6
CFG_B4_S2_MO_RS(ER[4],STERN[3]) | rooms=2 | clusters=7
CFG_B4_S2_MO_RS(ER[5],STERN[2]) | rooms=2 | clusters=7
CFG_B4_S2_MO_RS(ER[5],STERN[3]) | rooms=2 | clusters=8
CFG_B4_S2_MO_RS(ER[6],STERN[2]) | rooms=2 | clusters=8
CFG_B4_S2_MO_RS(ER[6],STERN[3]) | rooms=2 | clusters=9

TOTAL CONFIGURATIONS: 30

```

To clarify the meaning of each configuration code, an example output is provided in Listing 7.2. The notation $B\#$ denotes the number of bow thrusters assigned to a bow pump room. The vessel is equipped with four bow thrusters. In this case the configuration with $B = 2$ results in two bow pump rooms. Due to the physical arrangement of the generators, one of these pump rooms also functions as an engine room pump space. Similarly, $S\#$ represents the number of stern thrusters assigned per stern pump room. The $M\#$ parameter denotes the number of midship pump rooms, which is zero for this case study. Such configurations are mainly relevant for smaller vessels where combined bow and stern cooling within a single pump room may be feasible. Finally, $RS()$ indicates the number of clusters assigned to each pump room based on their physical locations.

Within the room and pump overview, the switchboard (SWB) connections are also included. These are assigned based on the E-KOL inputs and, where possible, physically distributed across separate pump rooms. This is illustrated by the bow clusters, where SWB group 1 is located in $PR1_ER$ and SWB group 2 is located in $PR3_BOW$. This separation ensures that switchboard redundancy is aligned with pump room redundancy and reduces the likelihood that a single pump room failure affects multiple redundant electrical groups.

For each pump room layout, a corresponding cooling system configuration is assigned. Each cluster specifies the required number of seawater pumps, plate heat exchangers, freshwater pumps, and overboard connections. Within the overview, each cluster is represented by the connected loads followed by the selected cooling equipment configuration. The notation $x + y$ indicates the number of duty and backup units, respectively, where the first value represents duty units and the second value represents backup units.

Listing 7.2: Example generated room layout for the Reference Vessel S.

```

CONFIGURATIE CFG_B2_S2_M0_RS(ER[3],BOW[2],STERN[2])

--- PUMP ROOMS & CLUSTERS ---
Total pump rooms      : 3
Total clusters        : 7
  ER      : 3 (sizes: [4, 1, 4])
  STERN   : 2 (sizes: [4, 1])
  BOW     : 2 (sizes: [2, 2])

--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps  : 19 (7 duty + 12 backup)
PHE units : 11 (7 duty + 4 backup)
FW pumps  : 30 (12 duty + 18 backup)
Overboard : 7
Seachest  : 6

=== ROOM & PUMP OVERVIEW ===
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), retractable(bow SWB=1B), aux, aux
    SW 1+2 | PHE 1+0 | FW 2+4 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 3: genset (SWB=1A), genset (SWB=1B), genset (SWB=2A), genset (SWB=2B)
    SW 1+2 | PHE 1+1 | FW 4+4 | OB 1

Room PR2_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), propulsion(stern SWB=2B), aux, aux
    SW 1+2 | PHE 1+1 | FW 2+4 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

Room PR3_BOW (tag: BOW) | SC 2
  - Cluster 1: retractable(bow SWB=2A), aux
    SW 1+2 | PHE 1+0 | FW 1+2 | OB 1
  - Cluster 2: tunnel(bow SWB=2B), aux
    SW 1+2 | PHE 1+0 | FW 1+2 | OB 1

```

7.1.2. Pareto Analysis

After generating 30 configurations, an additional factor was introduced for freshwater systems (factor 2 for duty and 1.5 for backup) to investigate its influence on the solution space, justified by the increased design flexibility available in this relatively small vessel. This adjustment results in a larger set of evaluated configurations compared to the baseline case. A total of 292,032 pump design variants per configuration were evaluated with respect to cost, cluster risk, and pump room risk.

The outcome of this evaluation is a set of Pareto fronts corresponding to different pump room risk levels. The Pareto front per pump room risk level is shown in Figure 7.2. The Pareto fronts show the trade-off between cluster risk and total cost for different pump room configurations. Each colour represents a distinct parameter combination (Pump room risk (R_p), maximum thruster in a stern room (S) and maximum thruster in a Bow room (B), illustrating how risk reduction is achieved at increasing cost. As shown, each step towards a lower pump room risk causes the Pareto front to shift upwards. This is because reducing pump room risk generally requires a larger number of pump rooms, which increases the overall system cost.

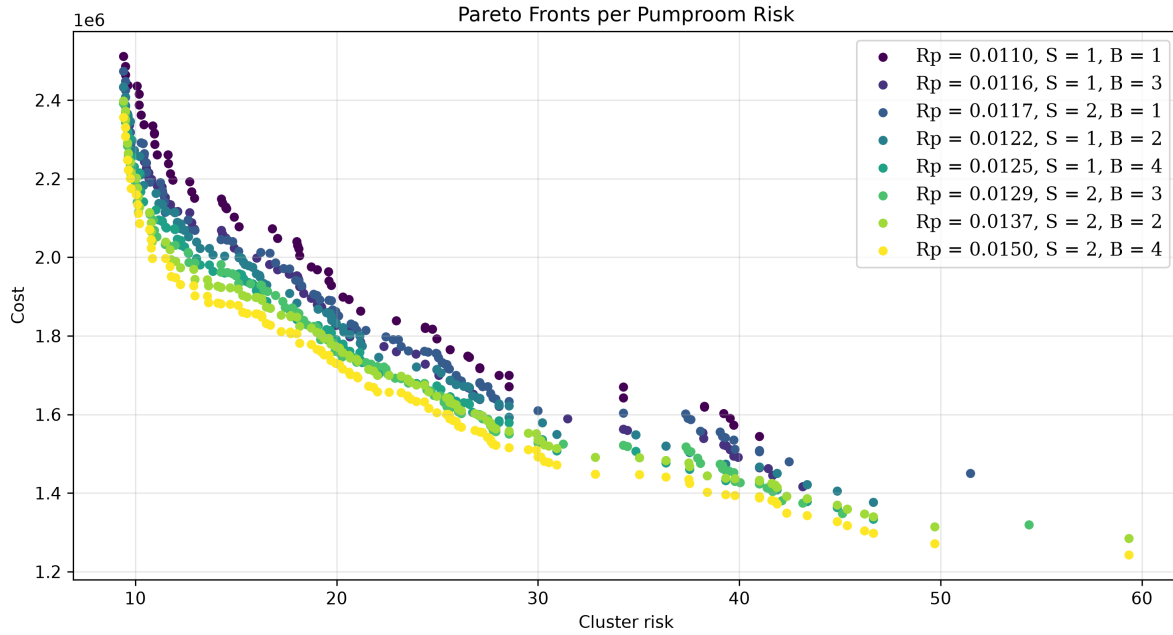


Figure 7.2: Pareto fronts of Baseline Reference Vessel S per Pump room risk

7.1.3. Optimal Configuration and Interpretation

Based on the defined objective weighting and the assumption of a single engine room, the MBSE-DSS identifies the configuration shown in Listing 7.3 as the optimal solution. The selected architecture represents the preferred trade-off between cost, cluster risk, and pump room risk. Furthermore, the result aligns with the intended design philosophy derived from the E-KOL inputs, where a limited number of pump rooms is preferred while maintaining sufficient redundancy to satisfy DP2 requirements.

Listing 7.3: Best-performing architecture for the Reference Vessel S baseline case study

```
CONFIGURATION CFG_B4_S2_M0_RS(ER[4],STERN[2])
Cost          : 1.66    [MEUR]
Cluster risk  : 22.014 [%DP-Loss/year]
Pump room risk : 0.015 [%DP-Loss/year]
Final score   : 7.300

--- PUMP ROOMS & CLUSTERS ---
Total pump rooms      : 2
Total clusters        : 6
  ER      : 4 (sizes: [4, 4, 1, 4])
  STERN   : 2 (sizes: [4, 1])

--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps  : 14 (6 duty + 8 backup)
PHE units : 10 (6 duty + 2 backup)
FW pumps  : 26 (12 duty + 14 backup)
Overboard : 6
Seachest  : 4

=== ROOM & PUMP OVERVIEW ===
Room PR1_ER (tag: ER) | SC 2
- Cluster 1: tunnel(bow SWB=1A), retractable(bow SWB=1B), aux, aux
  SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
- Cluster 2: retractable(bow SWB=2A), tunnel(bow SWB=2B), aux, aux
  SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
```

```

- Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
- Cluster 4: genset (SWB=1A), genset (SWB=1B), genset (SWB=2A), genset (SWB=2B)
    SW 1+2 | PHE 1+0 | FW 4+4 | OB 1

Room PR2_STERN (tag: STERN) | SC 2
- Cluster 1: propulsion(stern SWB=1A), propulsion(stern SWB=2B), aux, aux
    SW 1+2 | PHE 1+0 | FW 2+4 | OB 1
- Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

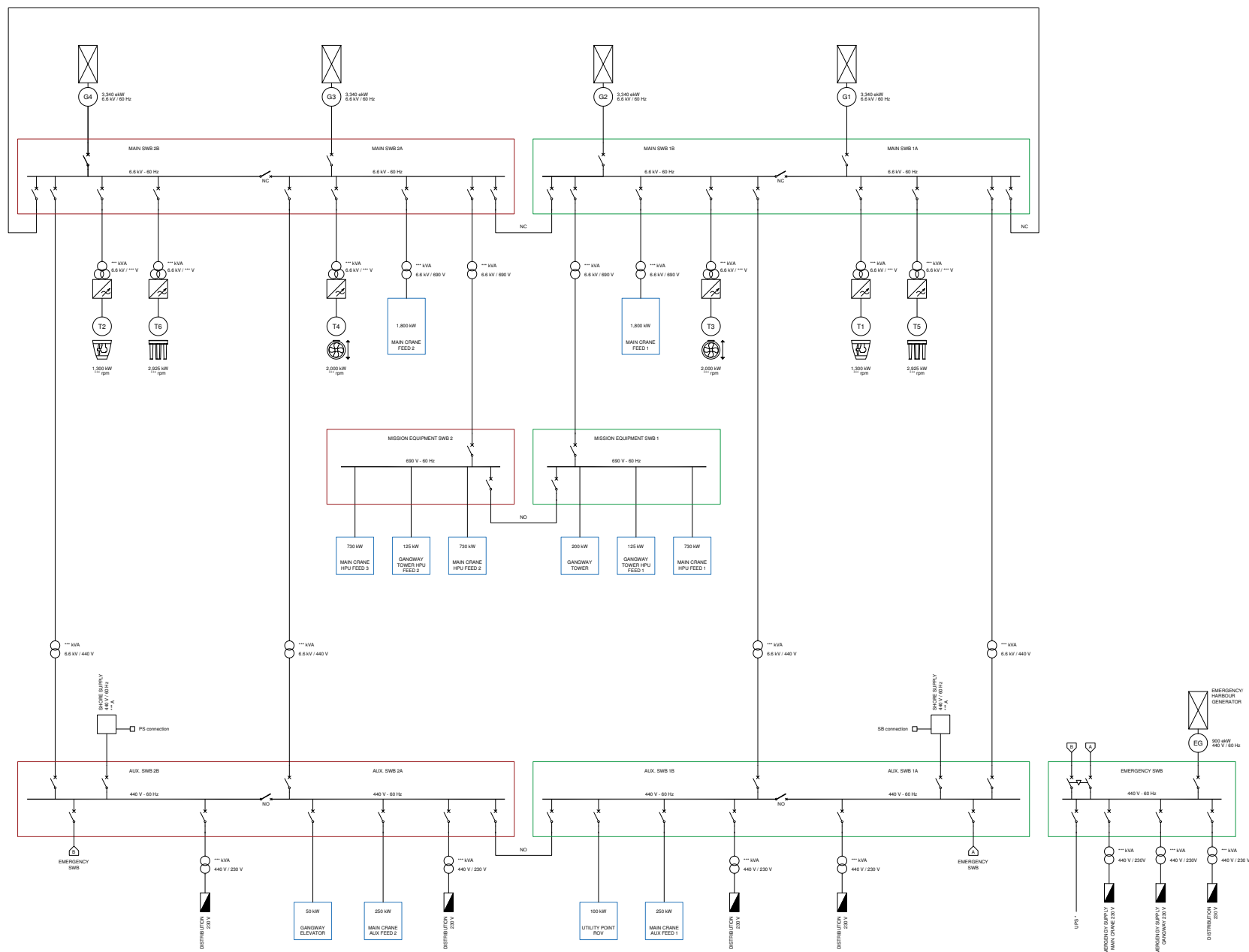
```

Besides the fact that the MBSE-DSS solution follows the intended design philosophy of using only two pump rooms, several other aspects are noteworthy.

Starting with the SW pumps, every cluster is equipped with at least one backup unit, while the genset and propulsion thruster clusters are provided with two backup units. This is because these clusters can result in a 100% DP capability loss if the entire cluster fails. The additional redundancy therefore provides a noticeable improvement in reliability. Also found in Appendix F. As a result, the total installed cooling capacity for these subsystems reaches up to 300% of the required capacity. In practice, the naval architect may choose to operate a single pump at full load or multiple pumps at partial load. However, operational control strategies are outside the scope of this study.

For the PHE units, due to the significantly lower probability of failure and relatively high cost, only one duty unit is chosen for this configuration. Adding backup units to clusters would increase costs more than it would reduce risk, making such configurations less attractive. It can be argued that for adding an additional PHE for the genset cluster, however, due to the very high cooling demand of this subsystem, PHE units become relatively expensive, causing the cost increase to outweigh the associated risk reduction.

For the FW pumps, the preferred solution follows a configuration of one duty and one backup pump per thruster and auxiliary cluster in the bow location, and one duty and two backup pumps per thruster and auxiliary cluster in the stern location. This distinction is made because the stern propulsion cluster has a greater influence on DP capability, which justifies the additional redundancy. This is also consistent with the cost model, which favours larger pumps over multiple smaller units, reflecting the assumption that equipment costs scale according to the six-tenths rule. Consequently, using a single larger FW pump is generally more cost-effective than installing multiple smaller units to provide the same cooling capacity.



SYMBOLS

- DIESEL GENERATOR SET
- CIRCUIT BREAKER
- SWB BREAKER - NORMALLY OPEN
- SWB BREAKER - NORMALLY CLOSED
- FREQUENCY DRIVE, TYPE TBD
- TRANSFORMER
- DOUBLE STOCK TRANSFORMER
- TUNNEL THRUSTER
- RETRACTABLE THRUSTER
- VOTH SCHNEIDER PROPELLER
- POWER DISTRIBUTION BOARD
- INTERLOCK

NOTES

- INDICATED RATING AND SIZING ARE PRELIMINARY AND SUBJECT TO CONFIRMATION UPON FINAL EQUIPMENT SELECTION
- GENERATORS MSWB 1A, 1B, 2A & 2B SHALL BE PROVIDED WITH INDEPENDENT AUXILIARIES
- THRUSTERS MSWB 1A, 1B, 2A & 2B TO HAVE INDEPENDENT AUXILIARIES
- MAIN SWITCHBOARD DESIGNED FOR CLOSED BUS-TIE OPERATIONS

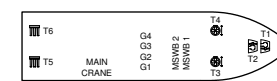
MAIN DIMENSIONS

LENGTH OVERALL	119.50	m
LENGTH BETWEEN PERPENDICULARS	114.69	m
BREADTH (MOULDED)	30.80	m
DEPTH MAIN DECK	8.10	m
DRAUGHT (OPERATIONAL)	6.00	m
FRAME SPACING	700	mm
COMPLEMENT	60	P

CLASS NOTATION

NS*/MNS* (ASR, CV, IP, PSPC-WBT, NC, CyBr) (DPS 2)
 Installation Character: CHG, MPP, LSA, PCF, CAA, MD, AFS, BWM

VESSEL LAYOUT



REV.	DATE:	REMARKS:	DRAWN:	CHECK'D:	APPR.:
F1-T	18 MAR 2020	ISSUE FOR TENDERING	PLA	STR	DAM
F	13 FEB 2020	FINAL ISSUE	PLA	STR	DAM
C1	28 NOV 2020	ISSUE FOR CLIENT COMMENTS AND/OR APPROVAL	RED	STR	DAM
I2	28 NOV 2020	ISSUE FOR INTERNAL CHECK	RED	STR	DAM
I1	27 NOV 2020	ISSUE FOR INTERNAL CHECK	RED	STR	DAM

TITLE: ELECTRICAL KEY ONE-LINE DIAGRAM		DESIGN: ULSTEIN SX182
CLIENT: PENIA OCEAN CONSTRUCTION B.V.		PROJECT NO.: OCV
Ulstein Design & Solutions B.V. Breukelenseweg 12 3045 AP Rotterdam, The Netherlands Tel: +31 (0) 78011 ulstein.info@ulstein.com www.ulstein.com		DRAWING NO.: CE.0.860.00D
SCALE: NTS	SHEET NO.: A1	CLASS: ClassNK
UNIT: METRIC		SCALE: 1/1

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Figure 7.3: Electrical Key-One-Line (E-KOL) of the Reference Vessel S used as input for the case study. [16]

7.1.4. Alternative SWB Configuration

In addition to the baseline configuration of the Reference Vessel S, different E-KOL configurations are explored to assess their influence on the resulting cooling system design. In particular, the current configuration places all gensets within a single compartment. From a DP3 perspective, a compartment-level failure affecting this engine room would therefore result in a complete loss of power.

In contrast, the power distribution system is split into two SWB groups (1 and 2). Consequently, a DP3-type failure would lead to a reduction of approximately 50% of the available SWB capacity. One could argue that, if the probability of such DP3 failure events is comparable between engine rooms and main switchboards, a configuration with a single main switchboard could also be considered a viable alternative, due to the fact that the vessel is made for DP2.

For this what-if scenario, the impact of reducing the system to a single main SWB is investigated. The resulting changes in the E-KOL are shown in Table 7.2. As illustrated, only the number of main SWBs is modified, while the number of downstream SWB connections remains unchanged. This leads to a relabelling of the SWB connections, where codenames 2A and 2B are replaced by 1C and 1D.

Table 7.2: E-KOL input of Case Study Reference Vessel S if only one main SWB is chosen

Parameter	Eng. rooms	Engines & gen.	Power dist.	Mission	Tunnel	Propulsion	Retractable
N	1	4 (eng), 4 (gen)	4 (swb), 1 (main)	2	2	2	2
Power [MW]	–	3.34	–	1.8	1.3	2.925	2
Location	bow	–	–	bow, stern	bow, bow	stern, stern	bow, bow
SWB Connections	–	–	1A, 1B, 1C, 1D	1B, 1C	1A, 1D	1A, 1D	1B, 1C

Below, in Figure 7.4, the Pareto front is shown. Compared to the baseline Pareto of the Reference Vessel S, the Pareto front is identical. This outcome is expected, as the cooling system in the baseline case was already designed to withstand the worst-case failure scenario of losing all gensets within a single engine room. Consequently, reducing the number of main SWBs from two to one does not introduce a more severe failure case and therefore does not affect the preferred cooling system architecture.

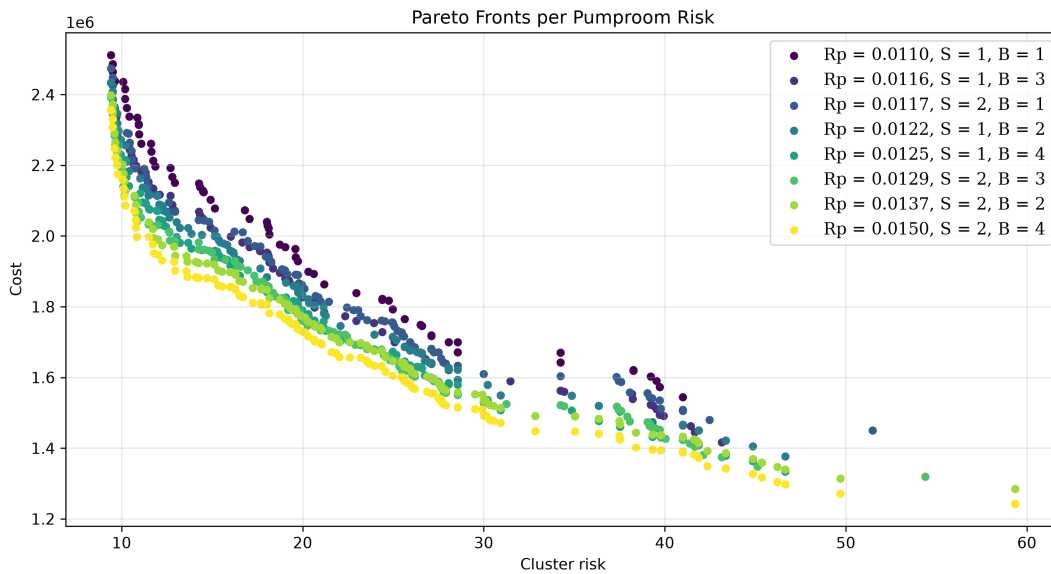


Figure 7.4: Pareto fronts per pump room risk for the Reference Vessel S case study if only one main SWB is chosen

Below, Listing 7.4 shows the best-performing cooling system architecture for the scenario with a single main SWB. As can be seen, the resulting configuration is largely identical to the baseline solution. The only differences are found in the SWB connections, which is a direct consequence of the modified E-KOL input.

Listing 7.4: Best-performing architecture for the Reference Vessel S case study if only one main SWB is chosen

```
CONFIGURATION CFG_B4_S2_MO_RS(ER[4],STERN[2])
Cost          : 1.66      [MEUR]
Cluster risk  : 22.014    [%DP-Loss/year]
Pump room risk : 0.015    [%DP-Loss/year]
Final score   : 7.300

--- PUMP ROOMS & CLUSTERS ---
Total pump rooms      : 2
Total clusters        : 6
  ER      : 4 (sizes: [4, 4, 1, 4])
  STERN   : 2 (sizes: [4, 1])

--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps  : 14 (6 duty + 8 backup)
PHE units : 10 (6 duty + 2 backup)
FW pumps  : 26 (12 duty + 14 backup)
Overboard : 6
Seachest  : 4

=== ROOM & PUMP OVERVIEW ===
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), retractable(bow SWB=1B), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: retractable(bow SWB=1C), tunnel(bow SWB=1D), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 4: genset (SWB=1A), genset (SWB=1B), genset (SWB=1C), genset (SWB=1D)
    SW 1+2 | PHE 1+0 | FW 4+4 | OB 1

Room PR2_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), propulsion(stern SWB=1D), aux, aux
    SW 1+2 | PHE 1+0 | FW 2+4 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
```

7.1.5. Alternative Engine Room Configuration

As discussed in Subsection 7.1.4, the baseline E-KOL design contains more redundancy in the main switchboards than in the engine room arrangement. After investigating the what-if scenario in which the number of main switchboards is aligned with the number of engine rooms, an alternative scenario is considered in which the engine room redundancy is instead increased to match the level of the switchboard system.

In this configuration, an additional engine room is introduced. As a result, a DP3-type compartment failure would no longer lead to a complete loss of power from a single engine room, but instead would result in an approximate 50% reduction in available power. The corresponding adaptation of the baseline E-KOL is shown in Table 7.3. The highlighted changes indicate that only the number of engine rooms and the associated engine room location have been modified.

Table 7.3: E-KOL input of Case Study Reference Vessel S if two Engine Rooms

Parameter	Eng. rooms	Engines & gen.	Power dist.	Mission	Tunnel	Propulsion	Retractable
N	2	4 (eng), 4 (gen)	4 (swb), 2 (main)	2	2	2	2
Power [MW]	—	3.34	—	1.8	1.3	2.925	2
Location	bow, bow	—	—	bow, stern	bow, bow	stern, stern	bow, bow
SWB Connections	—	—	1A, 1B, 2A, 2B	1B, 2A	1A, 2B	1A, 2B	1B, 2A

For this what-if case study the Pareto front should have the same lines but also extra ones for the separation of the gensets (highlighted in red). This is seen in Figure 7.5. Here it is seen that having two pump rooms dedicated for the gensets results in pump room risk reduction and cluster risk reduction. This is due to the gensets now being distributed over multiple compartments, reducing the impact of a single compartment failure.

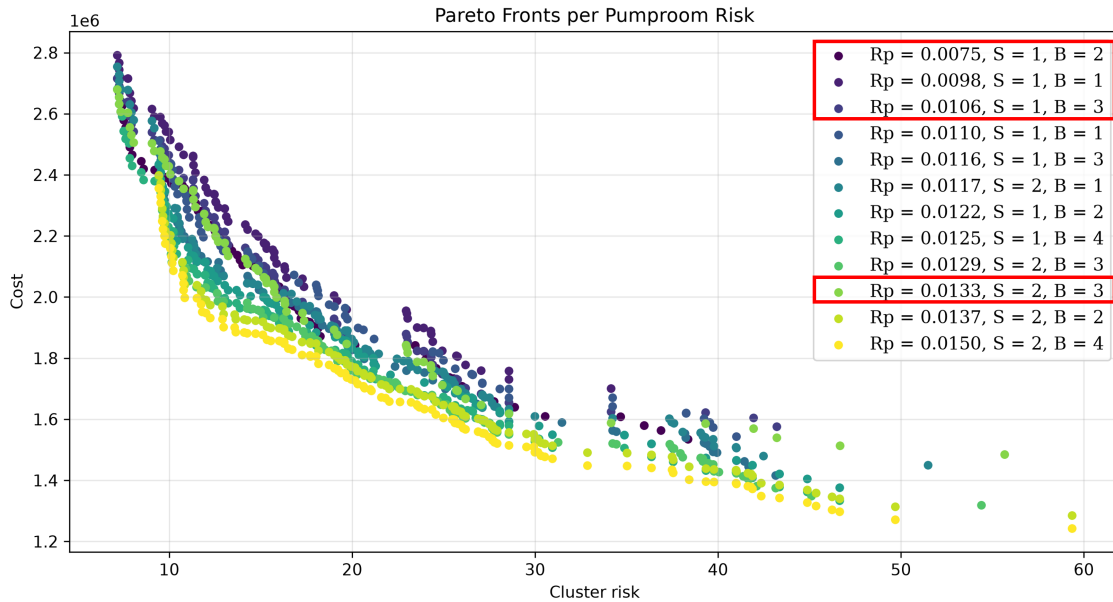


Figure 7.5: Pareto fronts per pump room risk for the Reference Vessel S case study if two engine rooms are considered

Executing the MBSE-DSS with the same weights as used for the baseline and one-SWB scenarios (0.5 for cost, 0.475 for cluster risk, and 0.025 for pump room risk) would result in the same optimal cooling system configuration.

However, as shown in Listing 7.5, the increased redundancy in both the engine rooms and main switchboards justifies assigning greater importance to compartment-level failures. Therefore, the cluster risk and pump room risk weights were adjusted to 0.40 and 0.10 respectively, as defined in Subsection 6.4.3. Under these revised weights, the best-performing solution consists of a configuration with four pump rooms, reducing both cluster risk and pump room risk. Compared to the baseline configuration, this indicates that increasing the number of pump rooms improves overall system robustness, but at the expense of higher cost.

From a design perspective, this alternative may be considered if increased redundancy is desired or if DP3 capability becomes a requirement.

Listing 7.5: Best-performing architecture for the Reference Vessel S case study if two engine rooms are considered

```
CONFIGURATION CFG_B2_S1_M0_RS(ER[3,2],STERN[2,1])
Cost          : 1.87    [MEUR]
Cluster risk  : 18.241  [%DP-Loss/year]
Pump room risk : 0.007  [%DP-Loss/year]
Final score   : 7.493
--- PUMP ROOMS & CLUSTERS ---
Total pump rooms      : 4
Total clusters        : 8
  ER      : 5 (sizes: [4, 1, 2, 4, 2])
  STERN   : 3 (sizes: [2, 1, 2])

--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps : 16 (8 duty + 8 backup)
PHE units : 10 (8 duty + 2 backup)
FW pumps  : 26 (12 duty + 14 backup)
Overboard : 8
Seachest  : 8

=== ROOM & PUMP OVERVIEW ===
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), retractable(bow SWB=1B), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 3: genset (SWB=1A), genset (SWB=1B)
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: retractable(bow SWB=2A), tunnel(bow SWB=2B), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: genset (SWB=2A), genset (SWB=2B)
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), aux
    SW 1+1 | PHE 1+0 | FW 1+2 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), aux
    SW 1+1 | PHE 1+0 | FW 1+2 | OB 1
```

7.2. Reference Vessel L

The first case study demonstrated that the MBSE-DSS is capable of exploring the design space of a relatively small offshore vessel. To further assess the scalability of the approach, a second case study is performed using a larger reference vessel. The Reference Vessel L has an overall length of 229.60 metres and is designed to comply with DP2 operational requirements. As shown in Figure 7.6, Table 7.4, and Figure 7.8, this vessel contains a significantly larger number of system parameters compared to the Reference Vessel S. For example, the vessel is equipped with five bow thrusters and four stern thrusters, compared to four bow thrusters and two stern thrusters for the smaller reference vessel. This increase in system complexity results in a substantially larger design space, as the MBSE-DSS must evaluate a greater number of possible configurations and redundancy combinations.



Figure 7.6: Vessel Load-Layout of the Reference Vessel L [16]

Table 7.4: E-KOL input of Case Study Reference Vessel L

Parameter	Eng. rooms	Engines & gen.	Power dist.	Mission	Energy storage
N	2	6 (eng), 6 (gen)	6 (swb), 2 (main)	2	2
Power [MW / MWh]	–	6.45	–	4.4	2.5 (E)
Location	bow, bow	–	–	bow, stern	–
SWB Connections	–	–	1A, 1B, 1C, 2A, 2B, 2C	1C, 2B	1C, 2B

Parameter	Tunnel	Propulsion	Retractable
N	3	4	2
Power [MW]	3.5	3.3	2.4
Location	bow, bow, bow	stern, stern, stern, stern	bow, bow
SWB Connections	1A, 1C, 2C	1A, 1B, 2B, 2C	1B, 2B

7.2.1. Pareto Analysis

When executing the MBSE-DSS, the design load layout of Subsection 6.3.1 generates 216 options. With the combination of the Subsection 6.3.2 23.8 million configurations are generated. For each pump room risk the Pareto is again made, shown in Figure 7.7. As expected for this vessel the cost scale is higher then for the first case study. This is due to the larger number of system loads which causes the cooling system to have already a higher baseline cost.

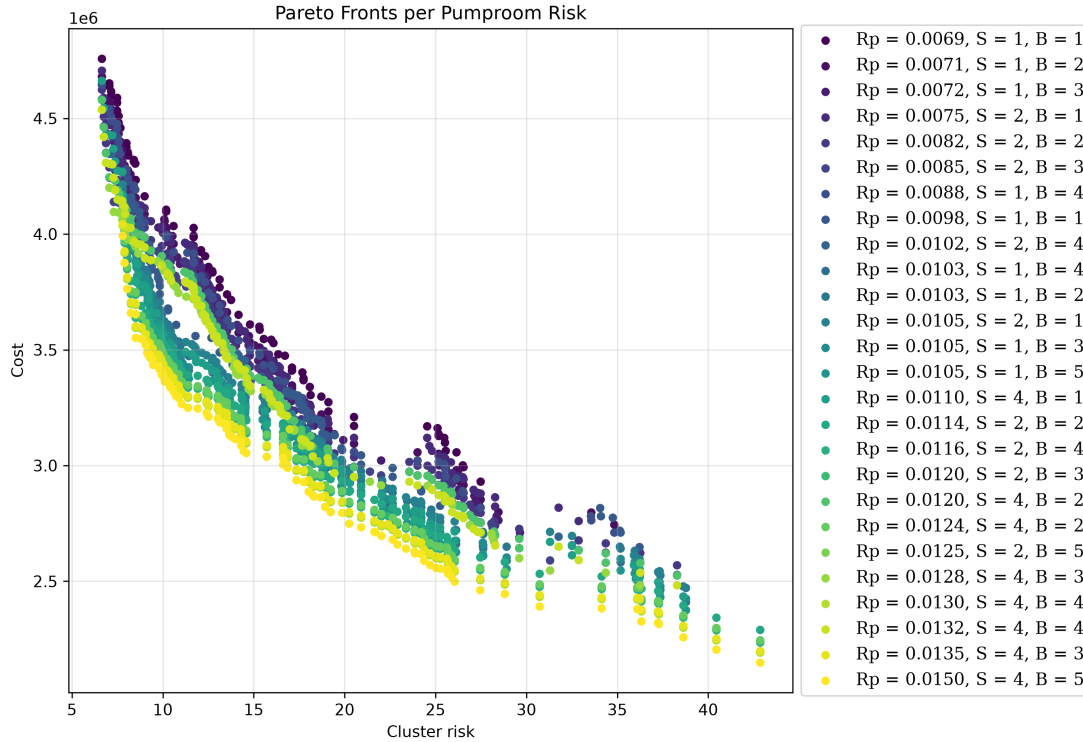


Figure 7.7: Pareto fronts illustrating the trade-off between cluster risk and total cost for different pump room configurations of the Reference Vessel L vessel.

7.2.2. Optimal Configuration and Interpretation

Below in Listing 7.6 the best solution is shown. For the scoring, the weight of 0.5 for cost, 0.4 for cluster risk and 0.1 for pump room risk was used. The solution is again a configuration which matches the E-KOL vision of redundancy.

The solution follows a similar design philosophy as observed for the other case study vessel. The number of duty units is minimised, as larger units reduce overall cost. This also explains the grouping of multiple thrusters within a single cluster, allowing them to share duty and backup capacity, resulting in fewer but larger units and therefore lower cost.

In addition, each cluster is assigned only one PHE unit. This is consistent with the high cost and relatively low failure probability of PHE systems, making additional redundancy less beneficial from a cost-risk perspective.

Overall, the solution appears promising and represents a viable configuration for this vessel. A comparison with the design produced by Ulstein would be valuable to further evaluate the differences and provide insight into the decision-making behaviour of the MBSE-DSS versus industry practice. This comparison is presented in Section 8.1.

Listing 7.6: Best-performing architecture for the Reference Vessel L case study

```

CONFIGURATION CFG_B3_S2_MO_RS(ER[4,2],STERN[1,2])
Cost           : 3.06      [MEUR]
Cluster risk   : 18.513    [%DP-Loss/year]
Pump room risk : 0.0085    [%DP-Loss/year]
Final score    : 7.105

--- PUMP ROOMS & CLUSTERS ---
Total pump rooms      : 4
Total clusters        : 9
  ER      : 6 (sizes: [2, 4, 1, 3, 4, 3])
  STERN   : 3 (sizes: [4, 4, 1])

--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps  : 18 (9 duty + 9 backup)
PHE units : 11 (9 duty + 2 backup)
FW pumps  : 34 (17 duty + 17 backup)
Overboard : 9
Seachest  : 8

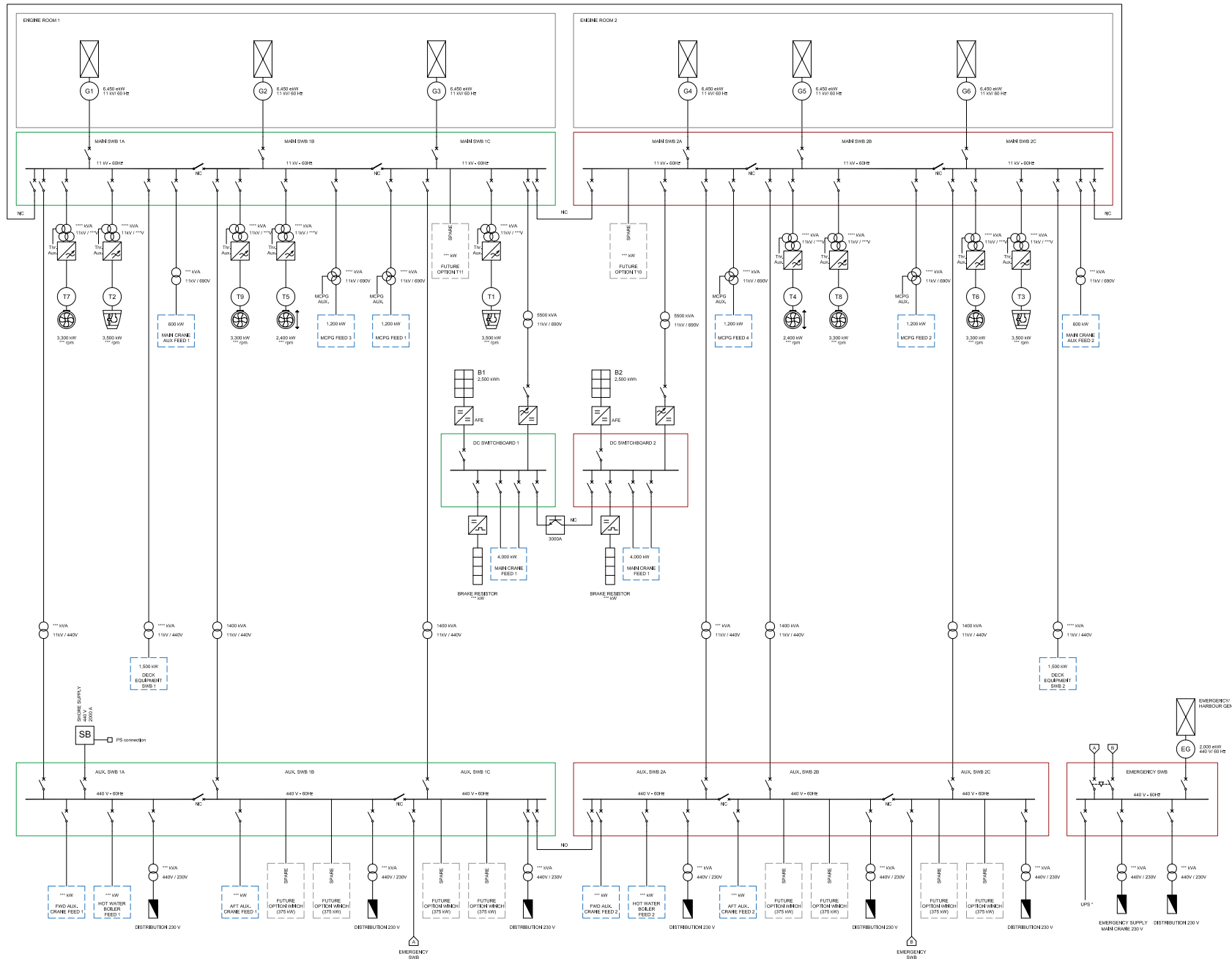
=== ROOM & PUMP OVERVIEW ===
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), aux
    SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 2: retractable(bow SWB=1B), tunnel(bow SWB=1C), aux, aux/bess
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 4: genset (SWB=1A), genset (SWB=1B), genset (SWB=1C)
    SW 1+1 | PHE 1+0 | FW 3+3 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: retractable(bow SWB=2B), tunnel(bow SWB=2C), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: genset (SWB=2A), genset (SWB=2B), genset (SWB=2C)
    SW 1+1 | PHE 1+0 | FW 3+3 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), propulsion(stern SWB=1B), aux, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), propulsion(stern SWB=2C), aux/bess, aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

```



Validation

After applying the MBSE-DSS to the two case studies, the resulting cooling system configurations are evaluated to assess whether the generated solutions are realistic and consistent with established naval engineering practice. The objective of this validation is to determine whether the MBSE-DSS produces credible design outcomes and whether its behaviour aligns with engineering expectations.

The validation is carried out using two complementary approaches. First, the MBSE-DSS-generated solution for the Reference Vessel L case study is compared with the reference design provided by Ulstein in Section 8.1. This benchmark comparison assesses whether the MBSE-DSS is capable of reproducing or approximating an industry-validated design solution. For the Reference Vessel S case study, such a comparison is not possible, as a corresponding reference cooling system layout from Ulstein is not available. Second, a cross-case consistency analysis is performed in Section 8.2, in which the behaviour of the MBSE-DSS is evaluated across both vessel sizes (Reference Vessel S and Reference Vessel L). This analysis assesses whether the model exhibits consistent and logically explainable trends when applied to different system scales, thereby providing insight into the robustness of the MBSE-DSS.

8.1. MBSE-DSS versus Ulstein Solution

With the MBSE-DSS results available, it is interesting to compare the generated cooling system configuration with the cooling system layout selected by Ulstein. Since the MBSE-DSS evaluates all feasible design solutions within the defined constraints, the Ulstein solution is also located within the evaluated design space. This makes it possible to directly compare the cost, cluster risk, and pump room risk of the MBSE-DSS solution with the Ulstein design. The normalised scores of both solutions are shown in Figure 8.1.

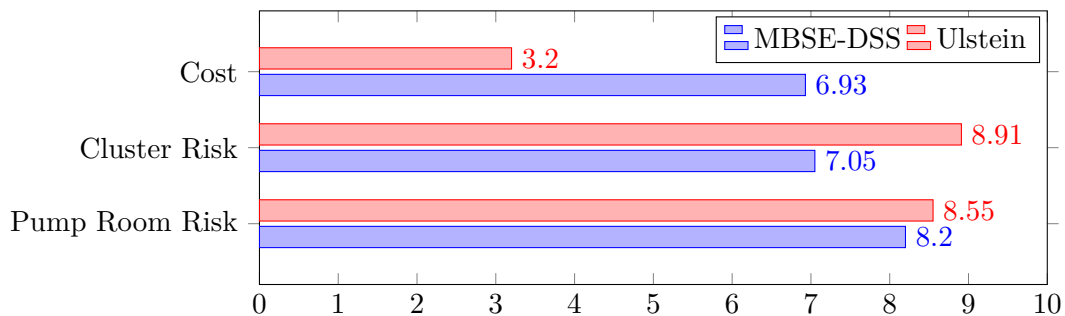


Figure 8.1: Normalised score comparison between the MBSE-DSS-generated design and the Ulstein baseline.

As shown in Figure 8.1, the Ulstein solution performs better in both risk categories, particularly in terms of cluster risk, while the difference in pump room risk is relatively small. However, this improved robustness comes at a significantly higher cost. Before analysing the design differences in more detail, it is useful to examine where the Ulstein solution is located within the design space. Therefore, the Ulstein configuration is plotted together with all MBSE-DSS-generated solutions having the same pump room risk of 0.008182, as shown in Figure 8.2. Note that the MBSE-DSS solution has a different pump room risk value. For clarity, the comparison is presented as a two-dimensional slice of the three-dimensional Pareto space at the pump room risk level of the Ulstein design.

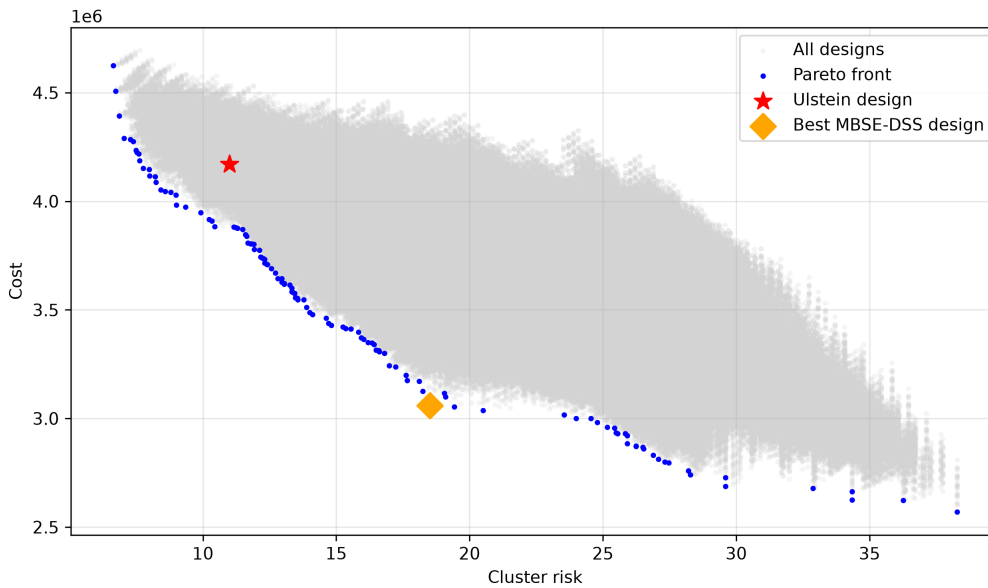


Figure 8.2: Ulstein cooling system design plotted against MBSE-DSS-generated configurations with an equivalent pump room risk.

The Ulstein solution lies close to the Pareto front, indicating that it is already an efficient design. Nevertheless, several configurations achieve a more favourable balance between cost and cluster risk while maintaining a similar pump room risk. It should be noted that Ulstein may have based certain design decisions on company-specific experience, operational considerations, or proprietary data that are not included in the MBSE-DSS. To understand why the Ulstein solution does not lie directly on the Pareto front, the two configurations are compared in more detail in the following sections. Listing 8.1 presents the Ulstein solution, while Listing 8.2 shows the highest-scoring MBSE-DSS configuration.

Overall, the Ulstein solution achieves a normalised score of 6.019, whereas the MBSE-DSS solution achieves a score of 7.105. The difference is primarily driven by cost, as the MBSE-DSS only introduces additional redundancy when it provides a sufficient reduction in cluster or pump room risk.

Pump Room Comparison

The first noticeable difference is the number of pump rooms. Ulstein's design contains one additional pump room compared to the MBSE-DSS solution. According to the MBSE-DSS, the reduction in pump room risk from 0.008494 to 0.008182 does not justify increased cost.

For both designs, the most severe compartment-failure scenario is the loss of pump room PR1_ER. The MBSE-DSS recognises that losing this pump room also results in the loss of all thrusters connected to SWB-A. Consequently, the additional bow pump room provides

only a limited reduction in overall risk while increasing cost, as its SWB-A connection is also lost during a PR1_ER compartment failure. Ulstein's solution included additional spatial constraints, resulting in an extra pump room being the more cost-effective configuration. This demonstrates that identifying and incorporating such spatial requirements is essential when evaluating alternative system architectures. Apart from this difference, the general pump room arrangement of both solutions is largely comparable.

Cluster Comparison

The cluster configurations reveal a more significant difference between the two solutions. The Ulstein design consists of 13 clusters, whereas the MBSE-DSS solution contains only 9 clusters.

In the Ulstein design, each cluster typically serves a single thruster and its associated auxiliary system. This limits the DP impact of a cluster failure and therefore reduces cluster risk. The MBSE-DSS, however, groups multiple loads within the same cluster whenever possible. By sharing cooling equipment between loads, larger cooling units can be installed, resulting in more cost-efficient configurations. This approach increases the potential impact of a cluster failure but reduces overall system cost.

FW Pump Comparison

For the FW pumps, the MBSE-DSS primarily uses a FW factor of 0.5, whereas the Ulstein design effectively follows a factor of 1.0. The MBSE-DSS therefore favours sharing FW pumps between thrusters and auxiliary systems whenever possible. This approach reduces cost by allowing larger and more cost-efficient pumps to be installed. However, it also increases cluster risk because more loads depend on the same cooling equipment. Consequently, the Ulstein design achieves a lower cluster risk through increased separation and redundancy.

The difference in redundancy is clearly visible in the number of installed FW pumps. Ulstein employs 26 duty and backup FW pumps, compared to only 17 in the MBSE-DSS solution. While the larger number of pumps increases the total probability of component failures, the consequences of individual failures are reduced due to the higher level of redundancy and separation.

It should be noted that the FW pump cost model is based on estimated scaling relationships. Detailed supplier cost data could influence the optimal configuration. Certain pump sizes may be unavailable or exhibit non-linear cost behaviour. Nevertheless, the results indicate that sharing cooling capacity and using larger FW pumps is generally more cost-effective than installing many smaller units.

PHE Unit Comparison

For the PHE subsystem, the main difference is the inclusion of backup PHE units in the Ulstein design. The MBSE-DSS does not select backup PHE units because of their relatively low failure probability and high cost.

From the MBSE-DSS perspective, the additional cost of installing backup PHE units outweighs the associated reduction in risk. However, the final decision remains sensitive to the assumed failure probabilities and cost estimates. More detailed reliability and cost data could therefore strengthen or weaken the argument for installing redundant PHE units.

SW Pump Comparison

For the SW pumps, both designs converge towards essentially the same solution. Both the MBSE-DSS and Ulstein identify the SW subsystem as highly influential on overall DP capability and therefore provide substantial redundancy. This similarity provides confidence that the MBSE-DSS correctly identifies the critical role of seawater cooling.

Listing 8.1: Ulstein solution Reference Vessel L

```

CONFIGURATION CFG_B2_S2_MO_RS(ER[4,3],BOW[1],STERN[2,3])
Cost           : 4.17 [MEUR]
Cluster risk   : 10.998 [%DP-Loss/year]
Pump room risk : 0.0082 [%DP-Loss/year]
Final score    : 6.019
--- PUMP ROOMS & CLUSTERS ---
Total pump rooms : 5
Total clusters   : 13
  ER      : 7 (sizes: [2, 2, 1, 3, 2, 2, 3])
  STERN   : 5 (sizes: [2, 2, 2, 2, 1])
  BOW     : 1 (sizes: [2])
--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps : 26 (13 duty + 13 backup)
PHE units : 26 (13 duty + 13 backup)
FW pumps  : 52 (26 duty + 26 backup)
Overboard : 13
Seachest  : 10
--- ROOM & PUMP OVERVIEW ---
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 2: retractable(bow SWB=1B), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 4: genset (SWB=1A), genset (SWB=1B),
    genset (SWB=1C)
    SW 1+1 | PHE 1+1 | FW 3+3 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=2C), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 2: retractable(bow SWB=2B), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 3: genset (SWB=2A), genset (SWB=2B),
    genset (SWB=2C)
    SW 1+1 | PHE 1+1 | FW 3+3 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 2: propulsion(stern SWB=1B), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), aux/bess
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 2: propulsion(stern SWB=2C), aux
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1
  - Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

Room PR5_BOW (tag: BOW) | SC 2
  - Cluster 1: tunnel(bow SWB=1C), aux/bess
    SW 1+1 | PHE 1+1 | FW 2+2 | OB 1

```

Listing 8.2: Best MBSE-DSS solution Reference Vessel L

```

CONFIGURATION CFG_B3_S2_MO_RS(ER[4,2],STERN[1,2])
Cost           : 3.06 [MEUR]
Cluster risk   : 18.513 [%DP-Loss/year]
Pump room risk : 0.0085 [%DP-Loss/year]
Final score    : 7.105
--- PUMP ROOMS & CLUSTERS ---
Total pump rooms : 4
Total clusters   : 9
  ER      : 6 (sizes: [2, 4, 1, 3, 4, 3])
  STERN   : 3 (sizes: [4, 4, 1])
  BOW     : 0
--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps : 18 (9 duty + 9 backup)
PHE units : 11 (9 duty + 2 backup)
FW pumps  : 34 (17 duty + 17 backup)
Overboard : 9
Seachest  : 8
--- ROOM & PUMP OVERVIEW ---
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), aux
    SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 2: retractable(bow SWB=1B), aux,
    tunnel(bow SWB=1C), aux/bess
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 3: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 4: genset (SWB=1A), genset (SWB=1B),
    genset (SWB=1C)
    SW 1+1 | PHE 1+0 | FW 3+3 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: retractable(bow SWB=2B), aux,
    tunnel(bow SWB=2C), aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: genset (SWB=2A), genset (SWB=2B),
    genset (SWB=2C)
    SW 1+1 | PHE 1+0 | FW 3+3 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), aux,
    propulsion(stern SWB=1B), aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), aux/bess,
    propulsion(stern SWB=2C), aux
    SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
  - Cluster 2: mission
    SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

```

Pareto Front Comparison

Besides comparing the overall best MBSE-DSS solution with the Ulstein reference design, it is also valuable to analyse Pareto-optimal solutions located close to the Ulstein configuration. These solutions demonstrate the design changes required to improve one objective while maintaining another at approximately the same level. The solution presented in Listing 8.3 represents the Pareto-optimal configuration with a total cost comparable to the Ulstein design, whereas the solution in Listing 8.4 represents the lowest-cost configuration with a cluster risk comparable to the Ulstein solution.

Cost-Equivalent Solution

The cost-equivalent solution achieves a total cost of 4.19 MEUR, which is nearly identical to the Ulstein configuration (4.17 MEUR), while reducing the cluster risk from 10.998 to 7.632 %DP-loss/year. This improvement is primarily realised by changing the clustering strategy. In the stern, propulsion loads are combined into larger clusters, reducing the total number of clusters from 13 to 10. Although this increases the consequence of a single cluster failure, the additional redundancy introduced within each cluster more than compensates for this effect. Compared with the Ulstein configuration, the number of SW pumps is slightly reduced (24 instead of 26), while the numbers of PHE units and FW pumps are reduced to 20 and 43 respectively. However, these components are distributed differently, with substantially higher levels of redundancy allocated to the larger clusters, resulting in a more robust cooling system without increasing the overall cost.

Cluster Risk-Equivalent Solution

The cluster risk-equivalent solution follows a different optimisation strategy. Here, the objective is to minimise the total cost while maintaining a cluster risk close to that of the Ulstein configuration. The engine room clustering remains identical to the reference design, whereas the stern propulsion clusters are partially merged, reducing the total number of clusters from 13 to 11. This configuration significantly reduces the number of PHE units from 26 to 15 and the number of FW pumps from 52 to 38. However, the duty-to-backup ratio is only decreased for the PHE units, but increased for the FW pumps, resulting in more redundancy for a lower cost. Besides that, the number of SW pumps is increased slightly from 26 to 28, providing additional SW redundancy while requiring fewer plate heat exchangers and freshwater pumps. As a result, the total cost decreases from 4.17 MEUR to 3.88 MEUR, while the cluster risk remains comparable (10.437 versus 10.998 %DP-loss/year).

These two Pareto-optimal solutions demonstrate that the Ulstein reference configuration is not located on the Pareto front. Depending on the design objective, it is possible to achieve either a lower cluster risk or a lower cost. This illustrates the value of the MBSE-DSS framework in providing insight into architectural alternatives that outperform the reference design by exploiting different combinations of clustering and cooling system redundancy.

Listing 8.3: Cost-Equivalent MBSE-DSS Solution

```

CONFIGURATION CFG_B2_S2_MO_RS(ER[3,3],BOW[1],STERN[1,2])
Cost          : 4.19
Cluster risk  : 7.632
Pump room risk : 0.0082
Final score   : 6.393
--- PUMP ROOMS & CLUSTERS ---
Total pumprooms : 5
Total clusters  : 10
  ER      : 6 (sizes: [4, 1, 3, 2, 2, 3])
  STERN   : 3 (sizes: [4, 4, 1])
  BOW     : 1 (sizes: [2])
--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps : 24 (10 duty + 14 backup)
PHE units : 20 (10 duty + 10 backup)
FW pumps  : 43 (17 duty + 26 backup)
Overboard : 10
Seachest  : 10
--- ROOM & PUMP OVERVIEW ---
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), aux,
                retractable(bow SWB=1B), aux
                SW 1+1 | PHE 1+1 | FW 2+4 | OB 1
  - Cluster 2: mission
                SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 3: genset (SWB=1A), genset (SWB=1B),
                genset (SWB=1C)
                SW 1+2 | PHE 1+1 | FW 3+3 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1C), aux/bess
                SW 1+1 | PHE 1+1 | FW 1+2 | OB 1
  - Cluster 2: retractable(bow SWB=2B), aux
                SW 1+1 | PHE 1+1 | FW 1+2 | OB 1
  - Cluster 3: genset (SWB=2A), genset (SWB=2B),
                genset (SWB=2C)
                SW 1+2 | PHE 1+1 | FW 3+3 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), aux,
                propulsion(stern SWB=1B), aux
                SW 1+2 | PHE 1+1 | FW 2+4 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), aux/bess,
                propulsion(stern SWB=2C), aux
                SW 1+2 | PHE 1+1 | FW 2+4 | OB 1
  - Cluster 2: mission
                SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

Room PR5_BOW (tag: BOW) | SC 2
  - Cluster 1: tunnel(bow SWB=2C), aux
                SW 1+1 | PHE 1+1 | FW 1+2 | OB 1

```

Listing 8.4: Cluster Risk-Equivalent MBSE-DSS Solution

```

CONFIGURATION CFG_B2_S2_MO_RS(ER[4,3],BOW[1],STERN[1,2])
Cost [MEUR]   : 3.88
Cluster risk  : 10.437
Pump room risk : 0.0082
Final score   : 6.588
--- PUMP ROOMS & CLUSTERS ---
Total pumprooms : 5
Total clusters  : 11
  ER      : 7 (sizes: [2, 2, 1, 3, 2, 2, 3])
  STERN   : 3 (sizes: [4, 4, 1])
  BOW     : 1 (sizes: [2])
--- PUMPS & EQUIPMENT (TOTAL) ---
SW pumps : 28 (13 duty + 15 backup)
PHE units : 15 (11 duty + 4 backup)
FW pumps  : 38 (17 duty + 21 backup)
Overboard : 11
Seachest  : 10
--- ROOM & PUMP OVERVIEW ---
Room PR1_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1A), aux
                SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 2: retractable(bow SWB=1B), aux
                SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 3: mission
                SW 1+1 | PHE 1+1 | FW 1+1 | OB 1
  - Cluster 4: genset (SWB=1A), genset (SWB=1B),
                genset (SWB=1C)
                SW 2+2 | PHE 1+1 | FW 3+3 | OB 1

Room PR2_ER (tag: ER) | SC 2
  - Cluster 1: tunnel(bow SWB=1C), aux/bess
                SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 2: retractable(bow SWB=2B), aux
                SW 1+1 | PHE 1+0 | FW 1+1 | OB 1
  - Cluster 3: genset (SWB=2A), genset (SWB=2B),
                genset (SWB=2C)
                SW 2+2 | PHE 1+1 | FW 3+3 | OB 1

Room PR3_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=1A), aux,
                propulsion(stern SWB=1B), aux
                SW 1+2 | PHE 1+0 | FW 2+4 | OB 1

Room PR4_STERN (tag: STERN) | SC 2
  - Cluster 1: propulsion(stern SWB=2B), aux/bess,
                propulsion(stern SWB=2C), aux
                SW 1+2 | PHE 1+0 | FW 2+4 | OB 1
  - Cluster 2: mission
                SW 1+1 | PHE 1+1 | FW 1+1 | OB 1

Room PR5_BOW (tag: BOW) | SC 2
  - Cluster 1: tunnel(bow SWB=2C), aux
                SW 1+1 | PHE 1+0 | FW 1+1 | OB 1

```

8.1.1. Ulstein versus MBSE-DSS Discussion

Overall, the comparison shows that the MBSE-DSS converges towards a design philosophy that is largely consistent with the engineering decisions made by Ulstein. Both solutions favour redundancy in the critical SW subsystem and adopt compartment arrangements that limit the consequences of major failures. The primary differences are found in the level of redundancy applied to pump rooms, FW pumps, PHE units, and cluster separation.

Whereas Ulstein adopts a more conservative design approach with additional redundancy, the MBSE-DSS explicitly balances these risk reductions against the associated cost increases. As a result, the MBSE-DSS identifies configurations that achieve comparable risk levels at a significantly lower cost.

This comparison provides confidence that the MBSE-DSS produces realistic and engineering-feasible solutions while simultaneously offering insight into alternative configurations and their associated trade-offs. Rather than replacing engineering judgement, the MBSE-DSS supports naval architects by rapidly exploring a large design space and quantifying the consequences of design decisions in terms of cost and risk.

8.2. Cross-Case Consistency

In addition to validating whether the MBSE-DSS produces realistic solutions compared to designs developed by Ulstein, it is essential to assess whether the methodology behaves consistently across different case studies. Since the Reference Vessel S and Reference Vessel L vessels case studies differ significantly in size and system complexity, they provide a suitable basis for evaluating the robustness and scalability of the MBSE-DSS.

A direct comparison of raw results is not meaningful due to substantial differences in the underlying design spaces, as shown in Table 8.1. Most notably, the Reference Vessel L case contains more than three times as many feasible configurations as the Reference Vessel S case. This increase is expected, as the Reference Vessel L vessel includes more equipment and therefore a larger number of design variables and configuration possibilities.

A similar scaling effect is observed in the cost objective. Due to the larger system size, the cost range of the Reference Vessel L design space is significantly higher than that of the Reference Vessel S vessel, with the minimum cost of Reference Vessel L already approaching the upper range of Reference Vessel S. In contrast, cluster risk and pump room risk remain more comparable between both cases, as they are derived from the same DP-capability-based formulation and are therefore expressed on a consistent scale.

Table 8.1: Overview of the design spaces for case studies Reference Vessel S and Reference Vessel L.

Case Study	Configurations	Cost [M€]		Cluster Risk		Pump Room Risk	
		Min	Max	Min	Max	Min	Max
Reference Vessel S	8,760,960	1.24	2.58	9.41	59.35	0.0110	0.0150
Reference Vessel L	23,887,872	2.15	4.83	6.63	43.51	0.0069	0.0150

To enable a meaningful comparison, the analysis is performed using normalised objective values rather than absolute values. This removes the influence of vessel scale and allows underlying behavioural trends to be compared directly.

Furthermore, a full three-dimensional comparison of the objective space is difficult to interpret. Therefore, the analysis focuses on selected comparable regions of the design space, based on

overlapping pump room risk levels (0.015 and 0.0125) and a consistent thruster distribution strategy (maximum two stern and two bow per pump rooms). This ensures that equivalent architectural regions are compared across both vessels.

8.2.1. Subsystem Behaviour Consistency

SW Pumps

The SW subsystem, shown in Figure 8.3, exhibits consistent behavioural trends across both case studies. In both Reference Vessel S and Reference Vessel L, the number of SW backup units increases when moving from high-cost, low-risk configurations towards lower-cost, higher-risk regions.

Both cases also show distinct regions of increased redundancy usage, which correspond to areas with higher cluster counts and therefore increased flexibility in redundancy allocation. These regions appear as clusters rather than smooth gradients, which can be attributed to the discrete nature of SW pump allocation across clusters.

Overall, the observed trends confirm that increased cost pressure leads to higher SW redundancy requirements across both vessel types.

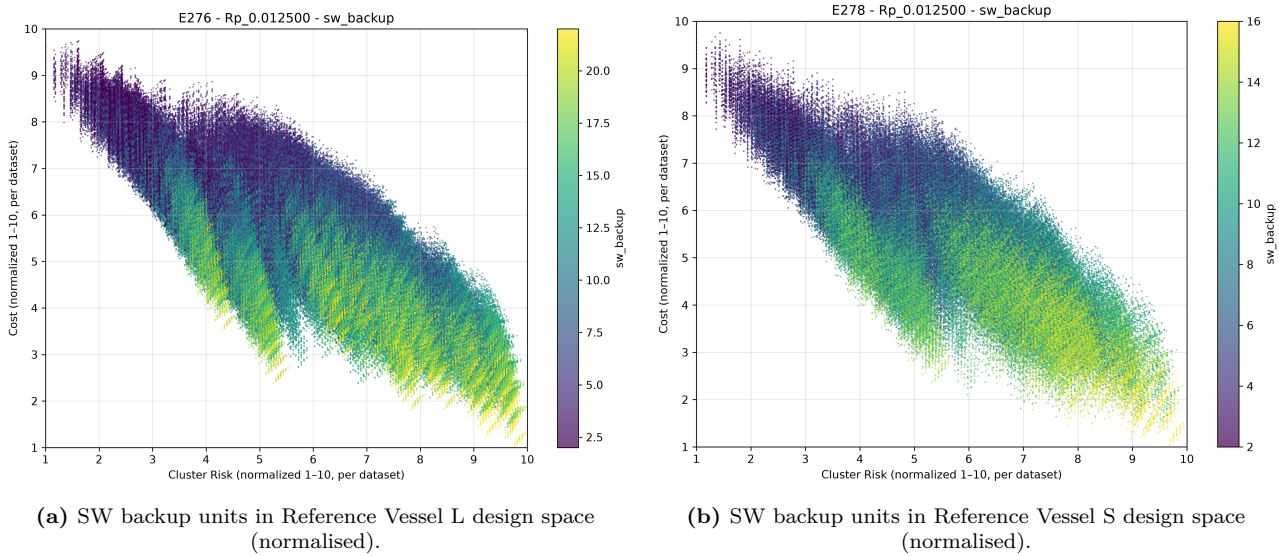


Figure 8.3: Cross-case comparison of SW backup unit distribution for identical pump room risk level ($R_p = 0.0125$), showing consistent redundancy trends across vessel scales.

PHE Units

The behaviour of PHE backup units, shown in Figure 8.4, again demonstrates consistent trends between both vessels. In both cases, higher PHE redundancy levels are primarily associated with regions of higher cluster risk and lower cost sensitivity.

A notable difference is that PHE redundancy appears earlier in the Reference Vessel S case compared to the Reference Vessel L vessel. This can be explained by the smaller overall cooling demand in Reference Vessel S, which results in lower system-level load and reduced PHE sizing requirements. Consequently, redundancy in PHE systems becomes cost-effective at an earlier stage in the design space.

In contrast, the Reference Vessel L vessel prioritises redundancy in FW and SW systems before PHE redundancy becomes optimal, reflecting its higher cooling demand and associated cost structure.

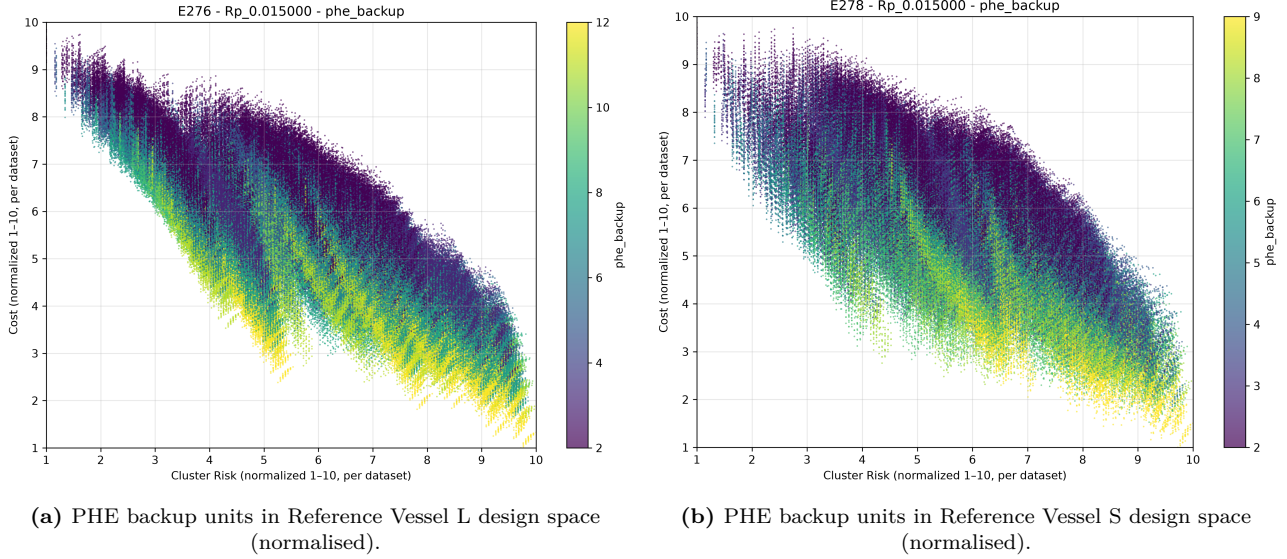


Figure 8.4: Cross-case comparison of PHE backup unit distribution for identical pump room risk level ($R_p = 0.0150$), highlighting differences in redundancy activation between vessel scales.

FW Pumps

The FW subsystem behaviour, shown in Figure 8.5, exhibits similar overall trends across both case studies. In both vessels, lower FW duty configurations are consistently associated with more cost-efficient solutions across the Pareto front.

Although the Reference Vessel L design space is significantly larger and more densely populated, the same dominant trend is observed: configurations with minimal FW duty units tend to dominate the optimal region of the design space in both cases.

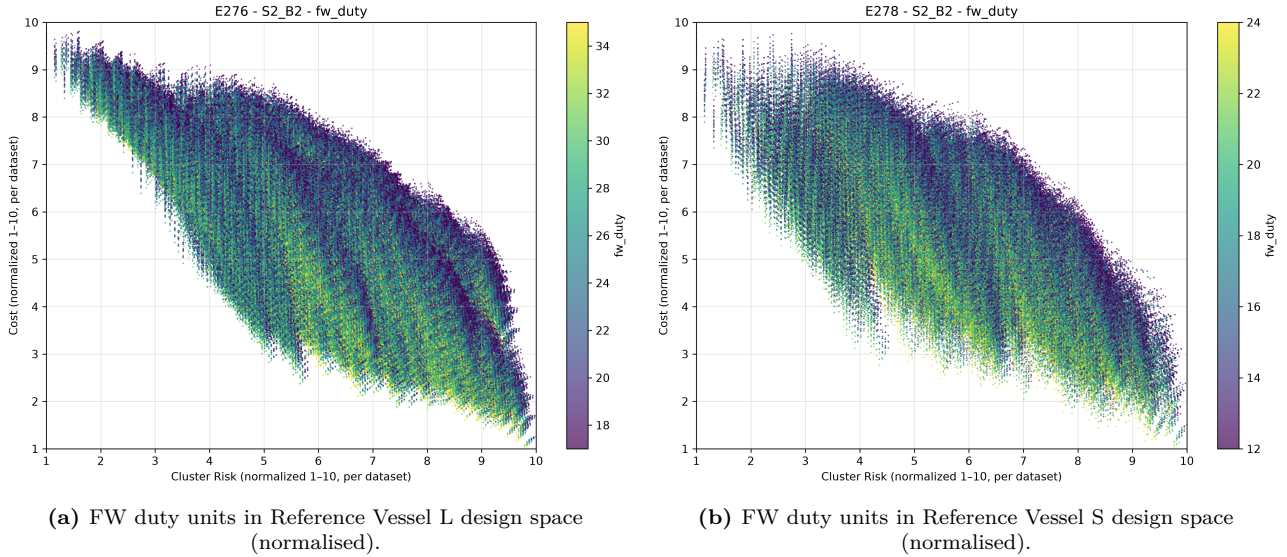


Figure 8.5: Cross-case comparison of FW duty unit distribution, showing consistent optimality of low-duty configurations across both vessels for the same stern,bow strategy.

Overall Observation

Overall, the results demonstrate that the MBSE-DSS exhibits consistent behavioural trends across both case studies despite significant differences in scale and design space size. The observed similarities in subsystem behaviour indicate that the underlying modelling and decision logic is robust and scalable across vessel configurations.

Assessment of the MBSE-DSS Tool

With the case studies, verification, and validation completed, the MBSE-DSS tool can now be assessed in terms of its overall impact on the early-stage offshore vessel design process. This chapter evaluates how the tool influences decision-making, supports design space exploration, and contributes to the generation of robust design insights.

The assessment first discusses the impact on the decision-making process in Section 9.1, focusing on how the tool supports and improves the quality and transparency of design decisions. Second, the role of the tool in enabling systematic design space exploration is discussed in Section 9.2, highlighting its ability to compare and evaluate alternative system architectures. Third, the insights generated during the case studies are examined in Section 9.3.

In addition, the limitations of the MBSE-DSS tool are identified in Section 9.4 to provide a balanced perspective on its applicability and current scope. Finally, the chapter concludes in Section 9.5 by summarising the overall contribution of the tool to the design process and its relevance with respect to addressing **RQ5**.

9.1. Decision-Making Process Improvements

As the MBSE-DSS is developed to improve the decision-making process, its impact must be assessed in terms of how it changes the traditional design workflow. This can be done by comparing it with conventional design practices used at Ulstein.

Traditionally, the cooling system is developed using the design spiral combined with the experience of the naval architect. Through iterative refinement, the design is gradually improved towards an optimal solution, without explicit knowledge of the full Pareto front, but rather by converging towards it through experience and iteration.

The MBSE environment contributes to the decision-making process by providing a structured representation of the cooling system architecture, including the relationships between requirements, functions, logical components, and physical components. This improves system understanding, increases traceability of design decisions, and makes it easier for stakeholders to understand the rationale behind a selected configuration. It also clarifies how the cooling system interacts with other internal and external systems, as previously discussed in Section 3.3. Since this study focuses primarily on the DSS component within the MBSE framework, the most significant improvements are observed on the decision-support side.

In the traditional process, only a limited number of design alternatives are typically evalu-

ated, even though the underlying design space may contain hundreds or thousands of feasible configurations. A key improvement introduced by the MBSE-DSS is the ability to explore a much larger set of design options in a systematic and computational manner. This significantly increases efficiency and enables earlier exploration of design trade-offs within the E-KOL. As a result, fewer late-stage design iterations are required, because the effects of architectural choices can already be evaluated in the early design phase. In short, decisions can be made earlier, as their implications become directly visible through the MBSE-DSS output.

In addition, whereas the traditional process typically aims to identify a single best design, the MBSE-DSS generates a Pareto-optimal set of solutions. This allows the naval architect to explicitly evaluate trade-offs between cost, cluster risk, and pump room risk, and select a solution that best matches project-specific requirements.

Secondly, the scoring mechanism improves both the transparency and explainability of design decisions. Because each configuration is evaluated using consistent cost and risk models, the naval architect can justify design choices using quantitative arguments rather than experience alone. For example, the impact of adding or removing pump rooms can be directly linked to changes in cost-risk performance using consistent model outputs. This also reduces reliance on subjective judgement such as "this solution usually works well", and instead promotes data-driven decision-making. As a result, consistency across different projects is improved, since the MBSE-DSS evaluates all designs using the same methodology, regardless of the engineer performing the analysis.

Furthermore, knowledge that is traditionally embedded in experienced engineers is partially transferred into the MBSE-DSS knowledge base. This reduces dependency on individual expertise and improves reproducibility and traceability of design decisions. It also reduces analysis time, since design knowledge is embedded directly into the computational framework rather than being repeatedly reconstructed for each new project.

Overall, the MBSE-DSS shifts the decision-making paradigm from an experience-driven, iterative search process towards a model-based, data-driven exploration of a structured design space, where trade-offs are explicitly quantified and comparable.

9.2. Design Space Exploration Impact

This section evaluates how the MBSE-DSS influences the exploration of the design space itself, rather than the decision-making process.

9.2.1. Exploration Capability

In contrast to traditional design approaches, where only a limited and experience-driven subset of configurations is evaluated, the MBSE-DSS enables systematic evaluation of a significantly larger portion of the feasible design space.

The generated dataset shows that the MBSE-DSS does not rely on random sampling, but instead evaluates configurations in a structured and repeatable way. This results in a more complete and unbiased representation of the design space, including regions that would typically remain unexplored in conventional workflows.

Furthermore, the discretisation of design variables leads to a combinatorial expansion of the solution space, which is explicitly handled by the MBSE-DSS evaluation framework. In the case studies, this results in a large number of feasible configurations being evaluated, providing broad coverage across different system architectures.

Overall, this enables a shift from selective exploration towards systematic enumeration of feasible designs, forming the basis for analysing the resulting distribution of solutions.

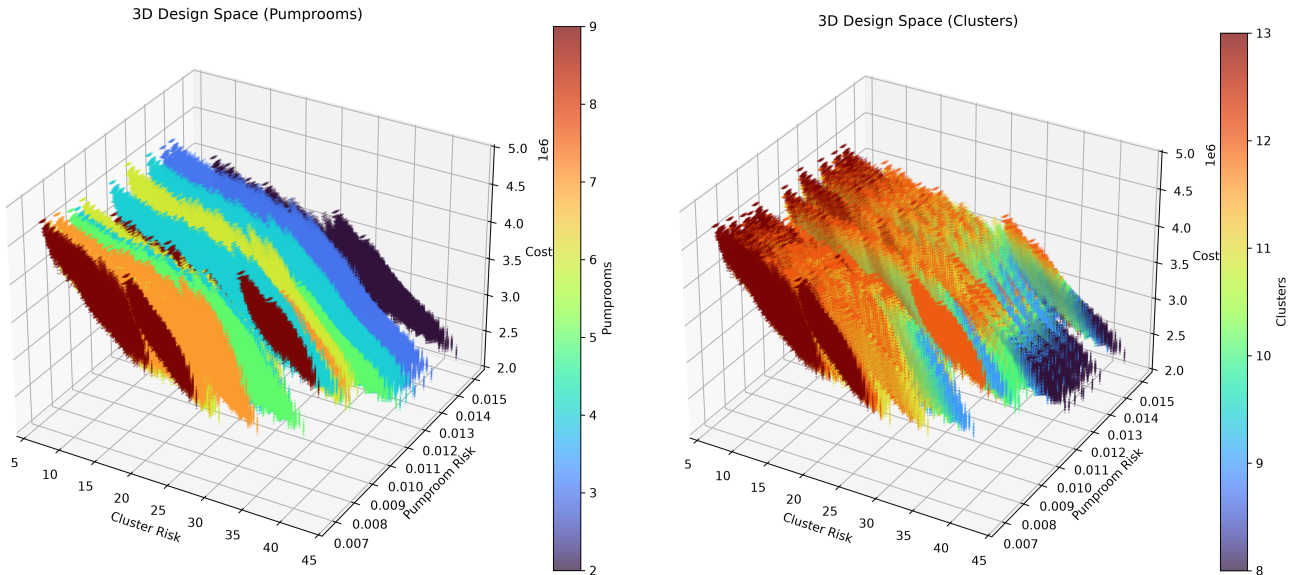
9.2.2. Distribution of Design Alternatives

To better understand the structure of the explored design space, this section discusses the 3D plots of all configurations for the Reference Vessel L case study, where different colour mappings are used to highlight patterns and trends. The following figures therefore do not only illustrate individual configurations, but reveal structural patterns, clustering behaviour, and dependencies between design variables and system-level objectives.

Starting with the overview in Figure 9.1, the relationship between pump room and cluster configurations becomes visible across the design space. For pump rooms, distinct horizontal bands can be observed, since each pump room configuration corresponds to a discrete pump room risk level. When viewed from above, these appear as clear stratified lines. Multiple bands with similar values occur due to the option of varying the number of stern and bow pump rooms. Although configurations such as two stern and three bow pump rooms are structurally similar to the inverse case, they may still result in different pump room risks due to the different subsystem loads assigned to each location.

For clusters, a similar dependency on pump room structure is observed. The maximum number of clusters is constrained by the available pump rooms, since each pump room limits how many independent cooling paths can be formed. As a result, configurations with the lowest pump room risk typically correspond to layouts with the maximum number of pump rooms, where each room contains a minimal number of components. When the number of pump rooms decreases, the flexibility in cluster formation increases accordingly.

Interestingly, the lowest cluster risk configurations are generally found at the highest number of clusters for a given pump room setup. However, it is also observed that moving towards lower cost while keeping cluster and pump room risk constant may lead to fewer clusters. This can be explained by the interaction between component sharing and redundancy: more shared cooling units can reduce cost, but may require restructuring of cluster definitions.



(a) 3D design space coloured by number of pump rooms.

(b) 3D design space coloured by number of clusters.

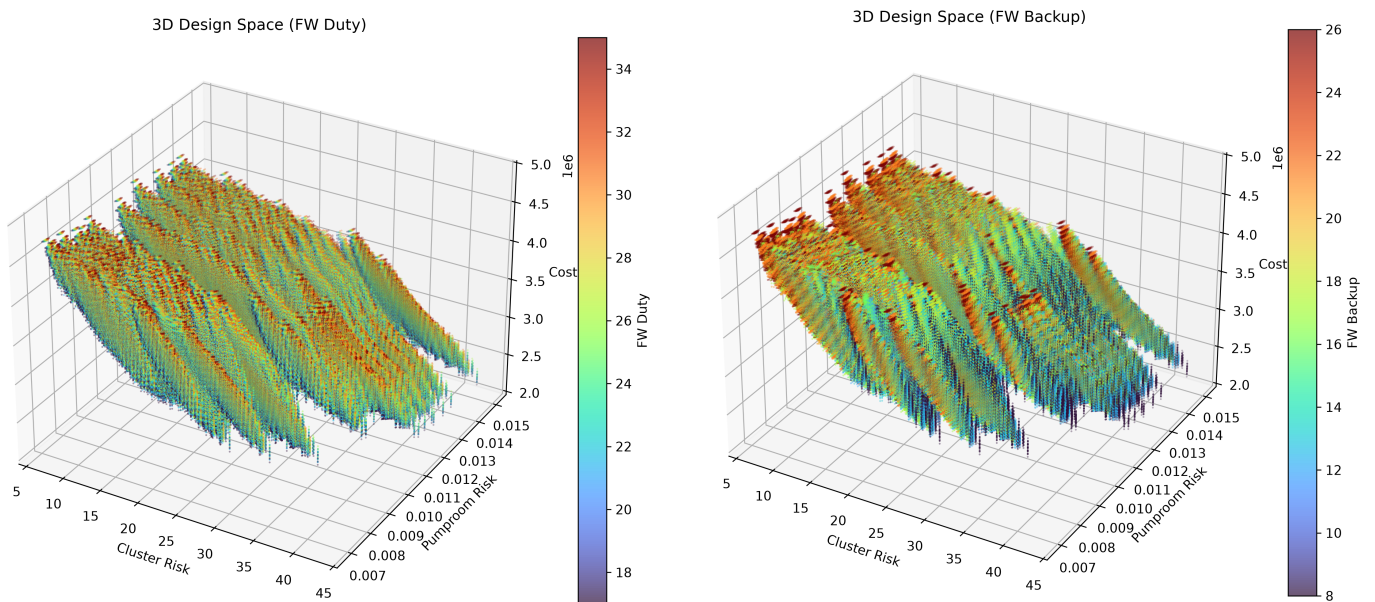
Figure 9.1: Design trade-off space showing the relationship between cluster risk, pump room risk, and cost, with colour indicating pump room and cluster configurations.

Subsystem Behaviour: FW Pumps

Focusing on the cooling subsystem behaviour, Figure 9.2 highlights distinct patterns for FW pumps. For duty units, the highest numbers are consistently located in regions with higher cost. This reflects the fact that excessive use of smaller FW units increases total cost, whereas larger units are generally more cost-efficient. As a result, configurations with fewer duty units tend to appear in lower-cost regions of the design space.

Intermediate regions show variation depending on how FW pumps are allocated across clusters, where assigning pumps to more critical clusters can improve performance but increases cost.

Backup units show a different pattern, as their presence depends on both redundancy requirements and the number of duty units. Increasing the number of duty units reduces the relative contribution of backups to redundancy. This explains why configurations with minimal duty units are often associated with higher backup effectiveness. In general, backup numbers increase as the system moves towards lower cluster risk regions, where redundancy becomes more important than cost.



(a) 3D design space coloured by number of FW duty units.

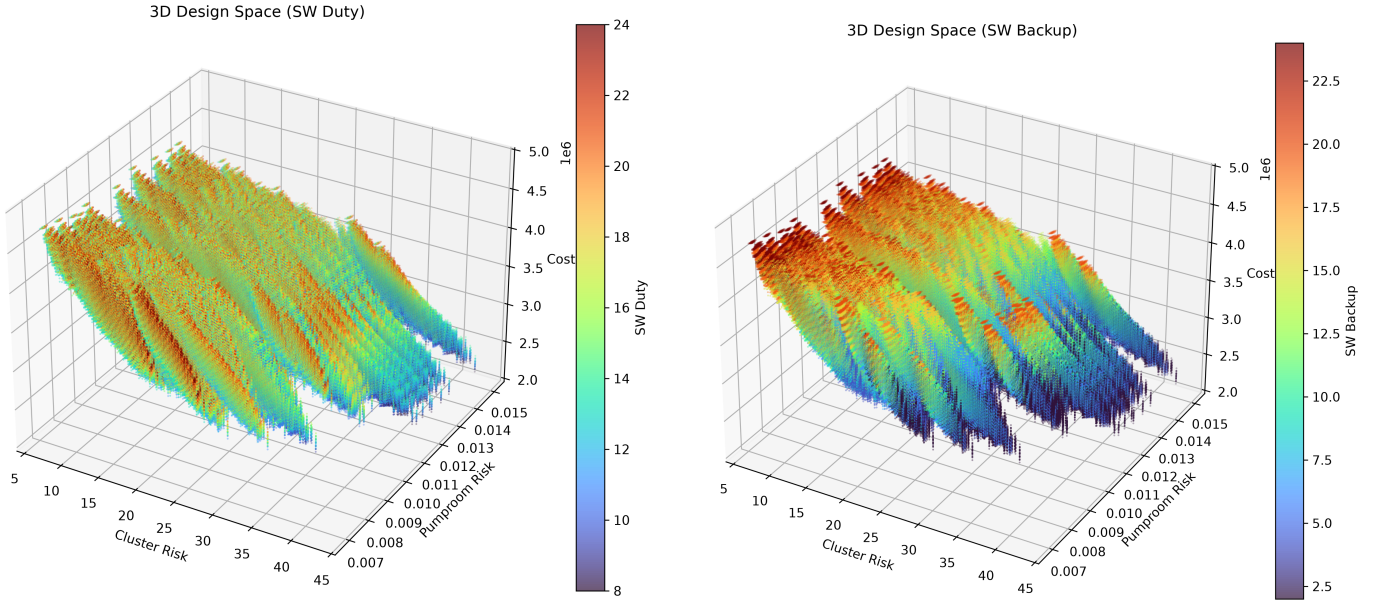
(b) 3D design space coloured by number of FW backup units.

Figure 9.2: Design trade-off space for the FW subsystem illustrating how duty and backup units relate to cluster risk, pump room risk, and cost.

Subsystem Behaviour: SW Pumps

For the SW subsystem, Figure 9.3 shows similar overall trends. However, due to higher unit cost and fewer configuration options compared to FW pumps, the variation in the colour distribution is less pronounced.

In addition, SW pumps are more strongly cluster-dependent, whereas FW pumps are primarily load-dependent. This leads to more configurations with higher pump room risk having relatively high SW redundancy, particularly in designs with maximum clustering. As cost becomes less restrictive, configurations with minimal SW redundancy are again observed, following a trend similar to FW pumps but shifted towards higher cost sensitivity.



(a) 3D design space coloured by number of SW duty units.

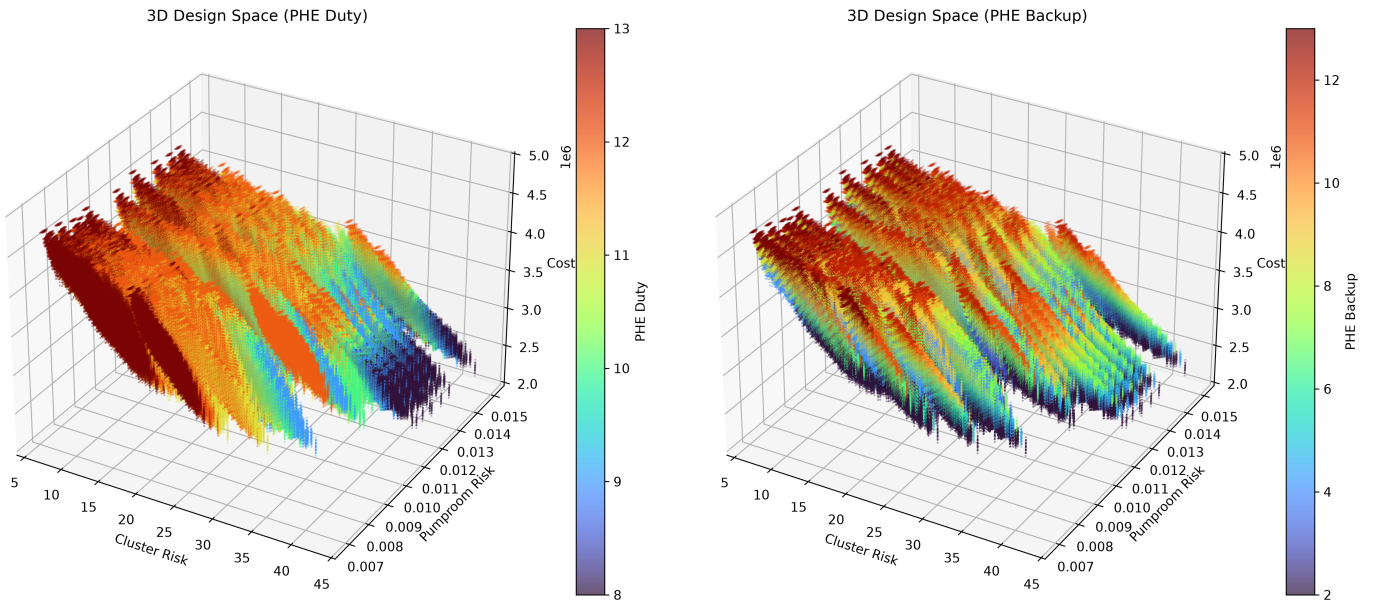
(b) 3D design space coloured by number of SW backup units.

Figure 9.3: Design trade-off space for the SW subsystem illustrating redundancy behaviour across cost and risk objectives.

Subsystem Behaviour: PHE Units

Finally, Figure 9.4 shows the behaviour of the PHE subsystem. For duty units, the pattern closely follows the cluster distribution, which is expected since typically one PHE duty unit is assigned per cluster.

For backup units, the results show that redundancy is only introduced in regions with very low cluster risk, where PHE reliability becomes critical to overall system performance. In most configurations, however, additional PHE redundancy is not selected due to the relatively low failure probability and high associated cost.



(a) 3D design space coloured by number of PHE duty units.

(b) 3D design space coloured by number of PHE backup units.

Figure 9.4: Design trade-off space for the PHE subsystem showing how redundancy decisions vary across the explored design space.

9.3. Design Insights

9.3.1. Emergent Design Rules and Trends

The analysis of the generated solutions reveals several recurring design rules and system-level trends.

A first key observation is that cluster risk and pump room risk must be considered as distinct evaluation dimensions. Cluster risk is primarily associated with DP2-related component failures, while pump room risk is linked to DP3 compartment-level failures. Although both contribute to overall system risk, they represent fundamentally different physical failure mechanisms and should therefore be assessed separately within the cost-risk trade-off.

Building on this distinction, redundancy allocation is found to be non-uniform across the system. The results indicate that redundancy should be prioritised towards the most influential clusters in order to achieve an optimal balance between cost and risk. This highlights that system elements contribute differently to overall performance, and that redundancy decisions should be guided by their system-level impact on DP capabilities rather than uniform distribution.

Within the evaluated design space, a consistent ordering in redundancy introduction can be observed. Redundancy in the FW system is most frequently selected, followed by SW, and finally PHE. This suggests that, under the current failure probabilities and cost assumptions, increasing FW capacity or redundancy first provides the most cost-effective means of improving system resilience.

In line with this, redundancy in the PHE subsystem is only introduced once sufficient redundancy is already present in the FW and SW chains. In most cases, PHE redundancy does not provide sufficient additional system-level benefit to justify its cost, making it a lower priority within the explored design space.

At the subsystem level, it was concluded in the early stages of the development of the MBSE-DSS that introducing a second PHE duty unit per cluster is not selected in any of the evaluated configurations. This is due to the limited marginal gain in redundancy combined with increased cost and reduced flexibility in allocating backup capacity.

Finally, the design of the cooling system should remain consistent with the intended E-KOL architecture. In particular, the risk distribution within the cooling system should align with the broader vessel-level risk allocation, including systems such as gensets and switchboard connections. The gensets impose significantly higher cooling demands, which directly influences the required sizing and cost of the cooling chain components.

9.3.2. Objective Weight Analysis

To assess the influence of stakeholder preferences on the architecture selection process, an objective weight analysis was performed on the Reference Vessel S and Reference Vessel L based on the three objectives: total cost, cluster risk, and pump room risk. Since the relative importance assigned to these objectives may vary between projects, the robustness of the MBSE-DSS was investigated by systematically varying these weights. All objective weight combinations were defined as:

$$\mathcal{W} = \{(w_c, w_r, w_p) \in \{0, 0.01, \dots, 1\}^3 \mid w_c + w_r + w_p = 1\}$$

Here all possible combinations of objective weights were generated with steps of 0.01, subject to the constraint that the sum of the three weights equals one. For each weighting scenario,

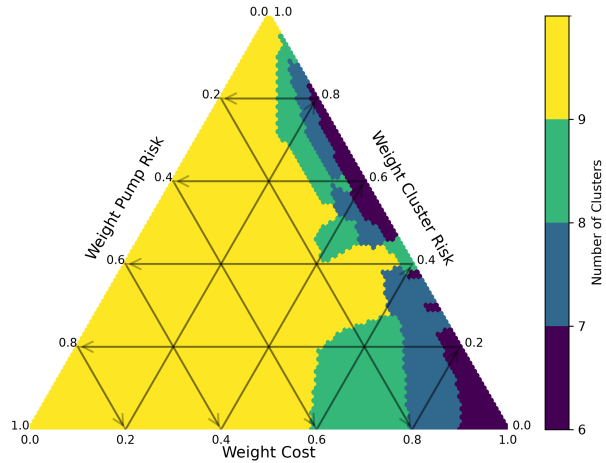
the MBSE-DSS optimisation procedure was repeated based on the Pareto-optimal and where the architecture with the highest weighted score was identified.

Because the objective weighting analysis exhibits the same overall trends for both the Reference Vessel S and Reference Vessel L case studies, only the Reference Vessel S results are discussed in detail in terms of the changes in FW pumps, SW pumps, and PHE units. The corresponding Reference Vessel L figures are included in Appendix H and demonstrate similar behaviour.

The only Reference Vessel L result discussed in this section is the configuration selection graph, as the larger design space leads to additional insights regarding the selection of pump room and cluster layouts under different weighting strategies.

Graph Interpretation

To clarify how the graph is interpreted, an example is provided in this figure. The figure illustrates how the number of clusters varies across different weighting strategies for the Reference Vessel S. To read the three objective weights, consider the combination of cost = 0.4, cluster risk = 0.2, and pump room risk = 0.4. Starting from the cost axis, follow the line corresponding to 0.4 until it intersects with the line from the cluster risk axis at 0.2. From this intersection, tracing the remaining diagonal line to the pump room risk axis yields a value of 0.4, confirming that the weights sum to 1.0. Using this representation, it becomes straightforward to identify which solutions are preferred under different weighting combinations. In this example, the corresponding optimal configuration results in a total of 9 clusters.



Impact on Pump Room and Cluster Configurations

Influence on the Reference Vessel S: Below, Figure 9.5 shows the resulting pump room and cluster layout combinations for the different weighting strategies. For the Reference Vessel S, the default weighting of cost, cluster risk, and pump room risk of (0.500, 0.475, 0.025) results in the configurations highlighted by the pink data points.

A notable observation is that the configuration in which each thruster is assigned to a separate pump room accounts for 64.67% of all generated solutions. This behaviour is explained by the strong trade-off between cost and both risk components. When the weight assigned to cost becomes sufficiently low, the optimisation process increasingly prioritises risk minimisation, causing highly redundant configurations to become dominant.

This trend is also visible at the boundaries of the design space. When the cluster risk weight is fixed at zero, increasing the weight of cost leads to a reduction in the number of pump rooms from $6 \rightarrow 4 \rightarrow 3 \rightarrow 2$. Similarly, when the pump room risk weight is fixed at zero, a comparable trend is observed, although in this case the minimum number of pump rooms is preferred because compartment-level failures are no longer penalised.

When the cost weight is increased, and consequently the cluster risk weight is reduced, the number of clusters decreases rapidly from $9 \rightarrow 8 \rightarrow 7 \rightarrow 6$. This reduction is accompanied by changes in the numbers of FW pumps, SW pumps, and PHE units, reflecting the strong relationship between clustering and cooling system sizing.

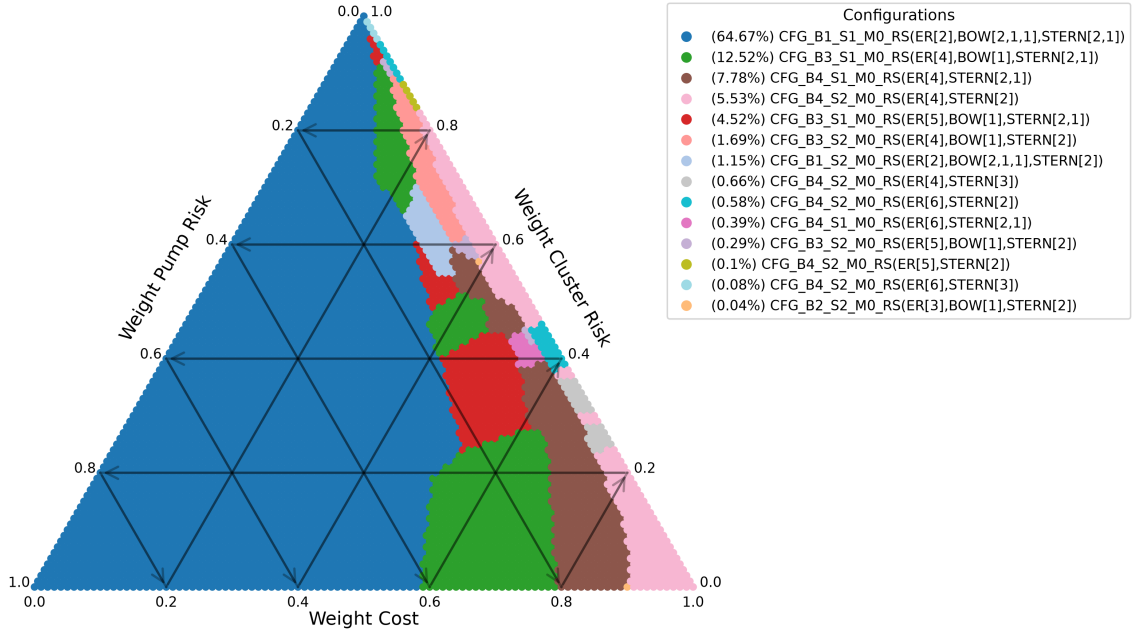


Figure 9.5: (Reference Vessel S) Distribution of optimal pump room and cluster configurations across different weighting strategies (cost, cluster risk, pump room risk).

Influence on the Reference Vessel L: The results for the Reference Vessel L are shown in Figure 9.6. For the default weighting of cost, cluster risk, and pump room risk of (0.500, 0.400, 0.100), the optimal solutions are highlighted by the lime green data points. These points represent only 3.28% of the total weighting combinations. This indicates that relatively small changes in objective preferences can lead to different optimal pump room and cluster arrangements. Consequently, the selected design remains sensitive to stakeholder priorities, highlighting that the MBSE-DSS should be regarded as a decision-support tool rather than a decision-making tool.

Similar to the Reference Vessel S case, reducing the importance of cost causes the MBSE-DSS to favour configurations with the maximum number of pump rooms, thereby minimising pump room risk. However, due to the substantially larger design space of the Reference Vessel L, an additional region of optimal solutions emerges. This region, shown in orange, corresponds to configurations that maximise the number of stern pump rooms while limiting the number of bow pump rooms to the number of engine rooms.

The MBSE-DSS identifies this arrangement as a favourable compromise between cost and risk. Since the engine rooms contain the gensets, the loss of an engine room already results in a severe DP consequence. As a result, additional separation of bow thrusters provides limited benefit compared to further separation of stern thrusters. From a risk-reduction perspective, allocating additional pump rooms to the stern therefore yields a better cost-benefit ratio.

This behaviour may also reflect design decisions embedded in the E-KOL. For example, the placement of all gensets in the bow section may be driven by space constraints or by operational experience suggesting different failure characteristics between bow and stern compartments. If more detailed failure probabilities for individual compartments become available, the MBSE-DSS could incorporate this information to better reflect such engineering considerations.

The Reference Vessel L exhibits the same overall trends as the Reference Vessel S, although with additional intermediate configurations due to the larger design space. When the cluster

risk weight is fixed at zero, increasing the cost weight reduces the number of pump rooms according to the sequence $(9 \rightarrow 6 \rightarrow 4 \rightarrow 3 \rightarrow 2)$. Similarly, when the pump room risk weight is fixed at zero, the preferred number of clusters changes according to $(13 \rightarrow 12 \rightarrow 11 \rightarrow 10 \rightarrow 9 \rightarrow 8 \rightarrow 10 \rightarrow 8)$.

The temporary increase from 8 to 10 clusters may initially appear counterintuitive. However, the figure only visualises the number of clusters and pump rooms, while the numbers of FW pumps, SW pumps, and PHE units are not shown. The MBSE-DSS determines that, for certain weighting combinations, increasing the number of clusters reduces cluster risk sufficiently to offset the associated cost increase. At the same time, the total cost can still be reduced by selecting fewer cooling units within those clusters. Once the numbers of FW and SW pumps have been minimised, reducing the number of clusters again becomes the most cost-effective strategy.

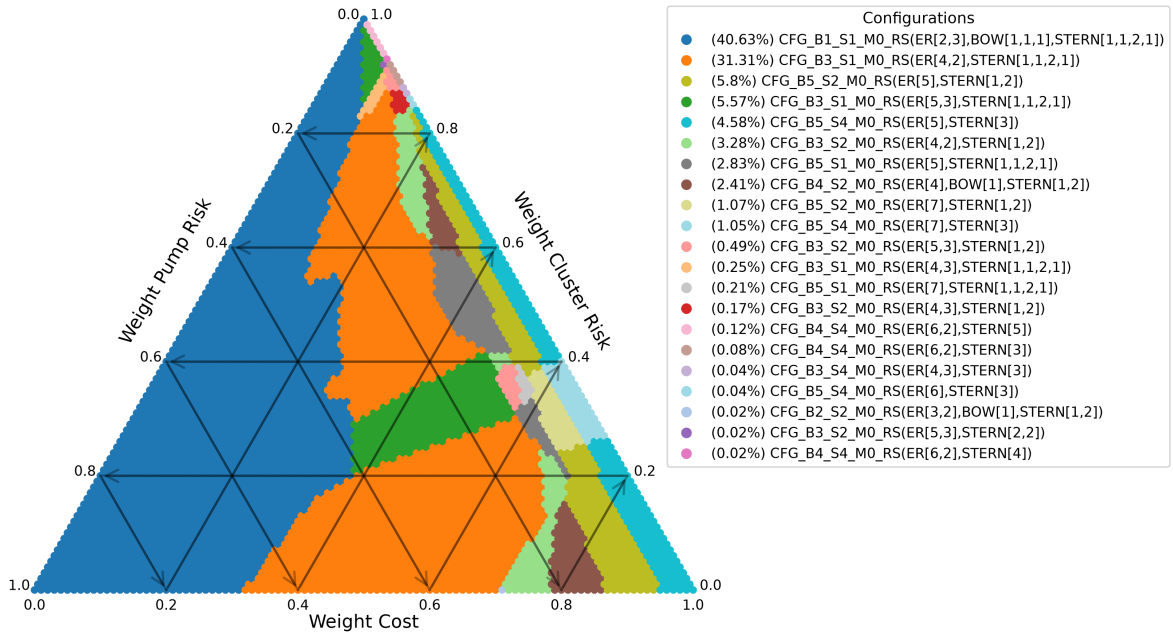


Figure 9.6: (Reference Vessel L) Distribution of optimal pump room and cluster configurations across different weighting strategies (cost, cluster risk, pump room risk).

Influence on Freshwater Pump Configuration

Below, Figure 9.7 presents the number of FW duty and backup pumps for each weighting strategy. An interesting observation is that, for most configurations, the number of duty units remains constant despite changes in the number of clusters and pump rooms. Only when the cluster risk weight becomes sufficiently dominant does the number of duty units increase. This behaviour is a consequence of the modelling approach, in which configurations are generated based on thruster-type grouping rather than cluster-level enumeration due to computational limitations. As a result, changes in duty capacity occur in discrete steps rather than continuously.

Increasing the number of duty units also affects the effectiveness of backup units, since duty units jointly contribute to the required cooling capacity. For example, increasing the number of duty units from 1 to 2 while maintaining one backup unit reduces the effective redundancy from 200% to 150% of the required capacity. In contrast, the number of backup units varies more significantly across weighting strategies. This is expected, as additional backup units directly reduce cluster risk at relatively low cost compared to increasing duty capacity.

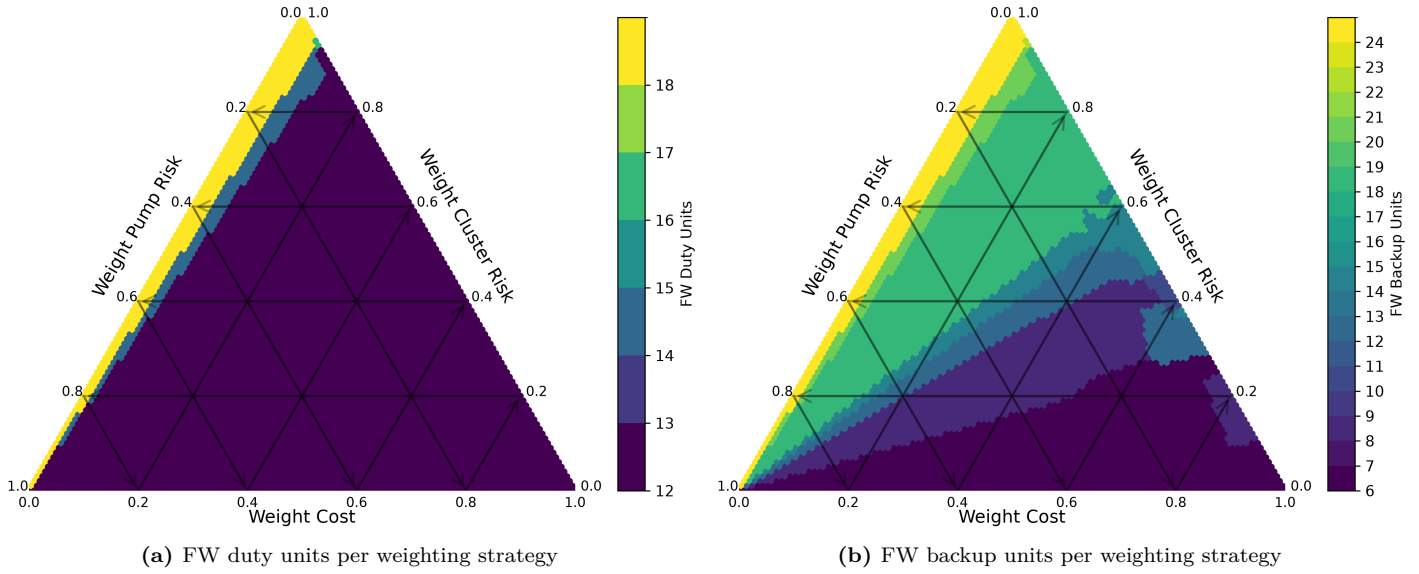


Figure 9.7: (Reference Vessel S) Effect of objective weighting on FW pump redundancy configuration.

Influence on Seawater Pump Configuration

Below, Figure 9.8 shows the number of SW duty and backup pumps for each weighting strategy. The number of SW duty units follows the same trend as the number of clusters, since SW pumps are structurally coupled to the cluster definition. As a result, each cluster effectively contains one SW duty pump, with no incentive for additional duty units due to cost and risk considerations.

For the backup units, however, a clearer trade-off between cost and cluster risk is observed. As expected, pump room risk does not influence this behaviour, since it is only affected by the number of pump rooms rather than internal redundancy.

Although a cost weight of 1.0 might suggest a preference for eliminating all redundancy, this is not observed in practice. This is due to the presence of mission systems with fixed redundancy requirements, which impose a minimum number of backup units of at least two.

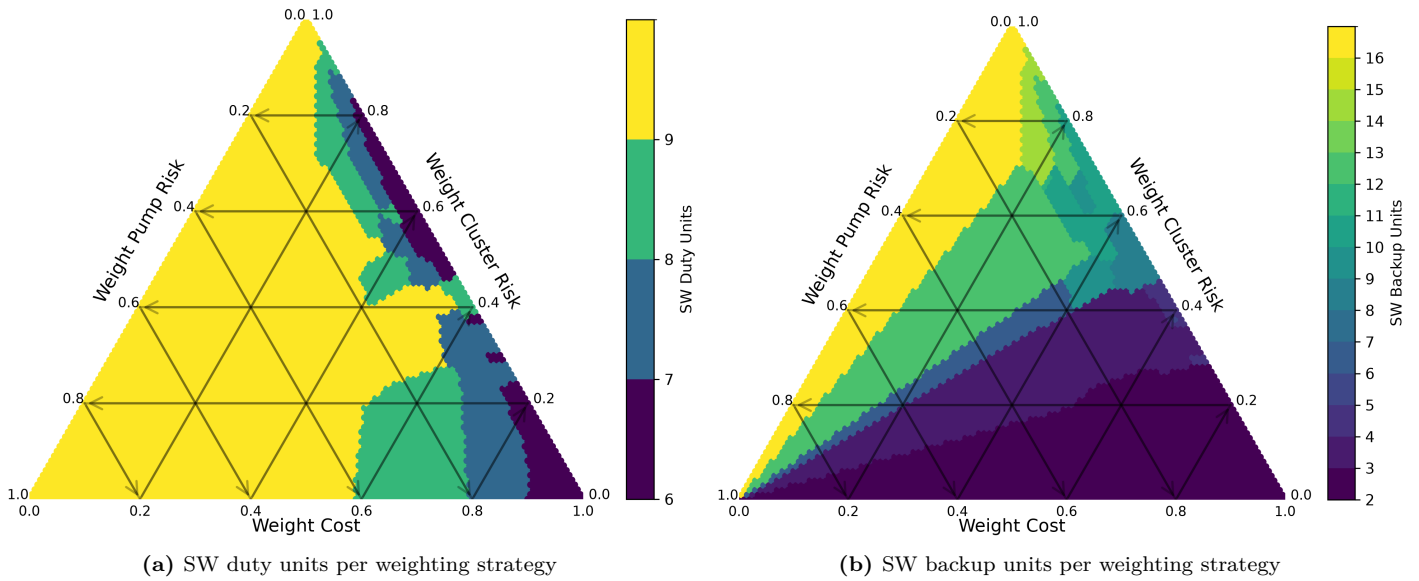


Figure 9.8: (Reference Vessel S) Effect of objective weighting on SW pump redundancy configuration.

Influence on PHE Configuration

Below, Figure 9.9 shows the number of PHE duty and backup units for each weighting strategy. The number of PHE duty units follows the number of clusters, which is expected given the one-to-one mapping used in the design generation process.

For the backup units, a similar trade-off between cost and cluster risk is observed. However, due to the relatively high cost of PHE units combined with their lower failure probability, the number of backup units changes less frequently compared to FW and SW systems. This indicates that redundancy is only increased for PHEs when cluster risk becomes sufficiently dominant in the objective function.

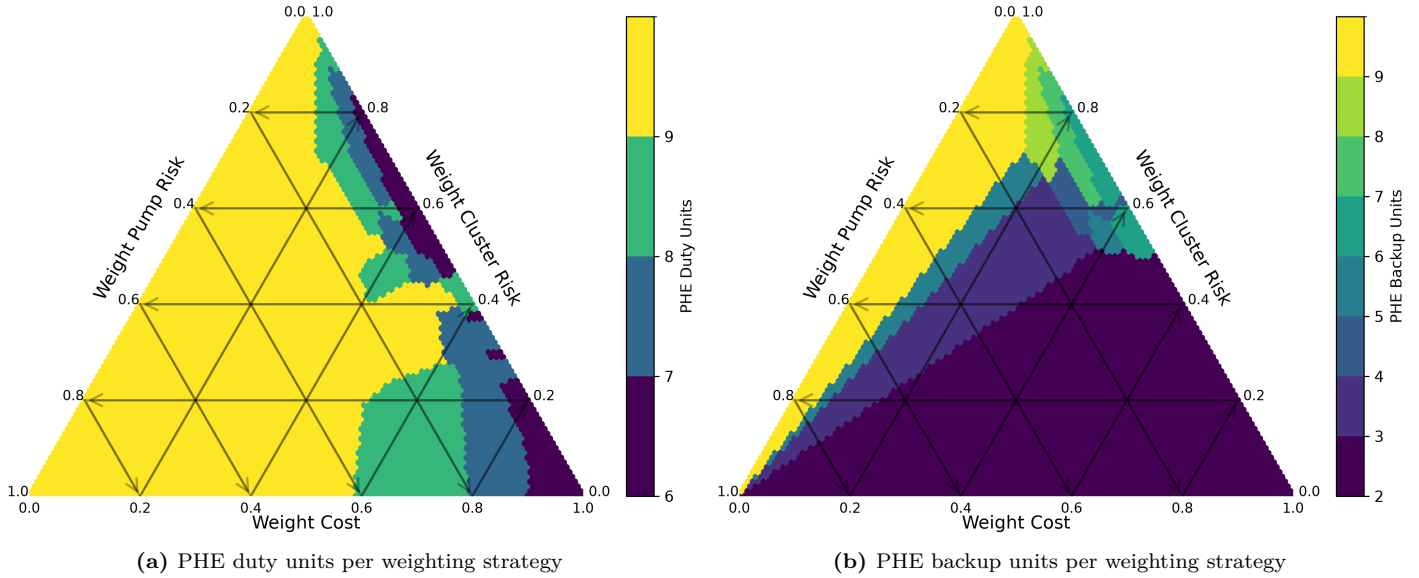


Figure 9.9: (Reference Vessel S) Effect of objective weighting on PHE subsystem redundancy configuration.

Overall Observations

Overall, these results demonstrate how the weighting strategy directly influences the resulting system architecture. The observed trends provide the naval architect with insight into how changes in cost and risk preferences affect optimal cooling system configurations, enabling more informed decision-making within the MBSE-DSS framework.

9.4. Limitations

Despite the improvements in decision-making, design space exploration, and insight generation provided by the MBSE-DSS, several limitations remain.

9.4.1. Data and Input Limitations

First of all, one of the main limitations is the use of estimated failure probabilities and cost data. In practice, these values may differ significantly from the assumed inputs, which can lead to different optimal solutions. Although the MBSE-DSS is designed to allow easy updates of these parameters, its accuracy remains dependent on the quality of the underlying input data.

9.4.2. Computational and Methodological Limitations

Secondly, the computational cost of the MBSE-DSS is relatively high. Due to the large number of possible configurations, evaluation times increase significantly as the design space expands. While the exhaustive evaluation approach ensures broad design space coverage and reduces the risk of overlooking potentially valuable configurations, it limits the scalability of the MBSE-

DSS and reduces its suitability for highly iterative design environments. As a result, future implementations may require more computationally efficient exploration strategies to maintain practical usability for larger design problems.

9.4.3. Knowledge Base and Expert Bias

Another limitation is that the knowledge base of the MBSE-DSS is largely based on assumptions and input from a single naval architecture perspective. This introduces potential bias into the decision rules embedded in the system. A more robust approach would involve multiple experts with different design philosophies, as well as integration of historical project data, including actual cost and failure performance from existing vessels. This would improve the generalisability and robustness of the MBSE-DSS outputs.

9.4.4. Implementation Constraints

Finally, the use of Python4Capella introduces practical limitations. The environment is relatively slow and does not support advanced visualisation features, meaning that results had to be exported to external tools for analysis and plotting. While this does not affect the correctness of the results, it does reduce workflow efficiency. As the tool is still under development, these limitations may be addressed in future versions.

9.5. Conclusion

The assessment of the MBSE-DSS demonstrates that the tool provides value in three main areas. First, it improves the decision-making process by replacing experience-driven exploration with a structured and transparent evaluation framework. Second, it enables systematic exploration of a significantly larger design space than is feasible through traditional design practices. Third, the generated solution space provides valuable insights into the relationships between cost, redundancy, cluster risk, and pump room risk, revealing design trends that would otherwise remain difficult to identify.

At the same time, the results highlight that the quality of the MBSE-DSS output remains strongly dependent on the accuracy of the underlying assumptions, cost estimations, and failure data. Furthermore, computational complexity and modelling simplifications currently limit the practical applicability of the framework for larger design spaces and more detailed system representations.

Overall, the results indicate that the MBSE-DSS successfully supports early-stage cooling system architecture design by enabling systematic design space exploration, transparent trade-off analysis, and quantitative comparison of alternative solutions, thereby answering **RQ5**. The framework therefore provides a promising foundation for further development and refinement.

Conclusion and Recommendations

10.1. Conclusion

The objective of this research was to determine to what extent an MBSE tool with integrated decision-support functionality could support naval architects in configuring and evaluating offshore vessel systems architecture during the ESSD phase.

The results demonstrate that the developed MBSE-DSS provides clear added value compared to a traditional experience-driven design approach. By combining a structured system model in Capella with automated design space exploration and multi-objective evaluation, the DSS enables systematic investigation of alternative system configurations that would be impractical to evaluate manually. For the investigated case studies, the DSS generated and evaluated approximately 8.8 million and 23.9 million feasible cooling system configurations, respectively, providing naval architects with insight into a significantly larger design space.

A key finding of this research is that the MBSE-DSS does not replace engineering expertise but enhances it by making design trade-offs explicit and traceable. The developed evaluation approach allows configurations to be compared based on cost, cluster risk, and pump room risk, thereby supporting more transparent decision-making during the ESSD phase. Furthermore, comparison with Ulstein's existing engineering solutions showed that the MBSE-DSS identified comparable design choices while also revealing alternative solutions with different cost-risk trade-offs.

The research also demonstrates that MBSE provides the necessary foundation for this type of decision support. By capturing system architecture, requirements, and interdependencies in a structured model, MBSE enables traceability between design decisions and their consequences. This is particularly valuable for offshore vessels, where system interdependencies significantly contribute to structural, spatial, and decision-making complexity.

However, the current implementation remains limited by assumptions in cost and reliability data and by the computational effort required for exhaustive design space exploration. These limitations influence the accuracy and scalability of the current MBSE-DSS but do not invalidate the demonstrated potential of the approach.

Based on these findings, it can be concluded that an MBSE tool with integrated decision-support functionality can significantly contribute to offshore vessel systems architecture design during the ESSD phase. The developed MBSE-DSS enables a transition from primarily

experience-based decision-making towards a more structured, quantitative, and traceable design process, providing naval architects with improved insight into the consequences of early-stage design decisions.

10.2. Recommendations

This section presents several recommendations for future research and further development of the proposed MBSE-DSS. The recommendations focus on increasing the realism of the decision support through the integration of empirical operational data, extending the scope of the framework to higher architectural levels, and improving the computational efficiency of the design space exploration.

10.2.1. DP Cost-Risk System Investigation

A further extension of the MBSE-DSS framework would be the integration of cost and risk modelling across multiple ship systems beyond the cooling architecture, based on real-world operational and historical data. In the current implementation, cost and risk parameters are primarily defined using assumed or estimated values specific to the cooling system. While this enables early-stage exploration, it limits the direct connection to observed vessel performance in practice.

Future work could therefore focus on incorporating historical failure data, maintenance records, and cost information from existing vessels to calibrate and validate the underlying risk and cost models. This would enable the MBSE-DSS to move from assumption-driven modelling towards data-driven decision support, improving both the realism and robustness of the generated design outcomes.

Such an approach would also allow failure behaviour and redundancy effectiveness to be derived from empirical evidence rather than purely theoretical assumptions. As a result, both component-level and compartment-level failure models across different ship systems could be refined based on observed operational patterns.

For example, for the E-KOL of the Reference Vessel S vessel the configuration has a single engine room combined with two main switchboards, which could be evaluated using empirically grounded failure probabilities and cost impacts. This would provide a more realistic assessment of the trade-offs currently influenced by engineering judgement, spatial constraints, and design assumptions.

Ultimately, integrating historical and operational data into the MBSE-DSS would significantly enhance the validity and applicability of the framework. It would strengthen the connection between early-stage design decisions and real-world vessel performance, thereby increasing the credibility of the MBSE-DSS as a decision-support tool for practical ship design applications.

10.2.2. Transition to E-KOL

An important direction for future work is the extension of the current MBSE-DSS framework to include the E-KOL level of the vessel architecture. In the current implementation, the E-KOL is treated as a fixed input, while in practice it has a strong influence on the cooling system design. Introducing multiple E-KOL configurations would therefore enable a more integrated and consistent decision-making process across system levels.

Such an extension would allow the exploration of higher-level architectural decisions, including the number, sizing, and spatial arrangement of thrusters, as well as the configuration of engine rooms, gensets, main switchboards, and switchboard groups. Since these design choices directly

influence the DP performance of the vessel, their inclusion would enable a more comprehensive exploration of the trade-off between cost and operational risk. This would effectively extend the current Pareto-based approach from subsystem level (cooling system) to system-of-systems level (E-KOL), providing a more complete representation of feasible design alternatives.

10.2.3. Improved Design Space Exploration Strategy

A promising direction for future work is the reduction of computational effort during design space exploration. In the current implementation, the MBSE-DSS evaluates a very large number of feasible configurations through exhaustive enumeration. While this ensures broad design space coverage, it also results in significant computation times, which could limit usability during iterative design activities.

One potential improvement is to replace the exhaustive generation approach with a guided exploration strategy based on the calculated DP risk. Instead of generating all possible redundancy combinations, the MBSE-DSS could start from a minimal feasible architecture for a given pump room and cluster configuration, where each cooling chain contains only a single duty unit. Subsequently, redundancy could be introduced incrementally by identifying the cluster that contributes most to the overall system risk and adding the most beneficial FW, SW, or PHE redundancy option.

Such a risk-driven exploration strategy would focus computational effort on the most relevant regions of the design space and could significantly reduce the number of evaluated configurations. At the same time, the reduced computational burden would make it feasible to investigate additional redundancy levels and subsystem design variations that are currently constrained by evaluation time.

A trade-off of this approach is that the MBSE-DSS would primarily generate Pareto-optimal solutions for each pump room and cluster layout, rather than providing a complete representation of the design space. Consequently, non-Pareto configurations would no longer be generated automatically. However, this limitation could be mitigated by allowing naval architects to manually define and evaluate specific configurations of interest. These user-defined solutions could then be compared against the generated Pareto front, providing insight into the performance gap between a proposed design and the optimal alternatives identified by the MBSE-DSS.

References

- [1] SEBoK authors. *Complexity*. Guide to the Systems Engineering Body of Knowledge (SEBoK), version 2.13. 2025. URL: <https://sebokwiki.org/w/index.php?title=Complexity&oldid=77300>.
- [2] INCOSE Technical Operations. *SYSTEMS ENGINEERING VISION 2020*. Vol. 2.03. International Council on Systems Engineering (INCOSE), Aug. 2007.
- [3] D. J. Power. *Supporting Business Decision-Making*. Tech. rep. Aug. 2000.
- [4] Ulstein Design & Solutions B.V. *Personal communication*. 2026.
- [5] Dorian Brefort et al. “An architectural framework for distributed naval ship systems”. In: *Ocean Engineering* 147 (Jan. 2018), pp. 375–385. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2017.10.028.
- [6] Vasileios Sideris et al. *Advancing Model-Based Systems Engineering in the Development of Naval Vessel Systems Architecture*. Tech. rep.
- [7] Beyond MBSE. *Pillars of MBSE: Language, Method, Tool*. <https://www.beyondmbse.com/pillars-of-mbse-language-method-tool/>.
- [8] SE-Trends. *MBSE Triangle: Language, Tool, Method*. <https://www.se-trends.de/en/mbse-triangle-language-tool-method/>.
- [9] R Edward Freeman John McVea et al. *A Stakeholder Approach to Strategic Management*. Tech. rep. URL: http://papers.ssrn.com/paper.taf?abstract_id=263511.
- [10] National Aeronautics and Space Administration (NASA). *NASA Systems Engineering Handbook*. NASA, 2016.
- [11] Jeffrey Carter and Caitlyn Singam. *System Architecture Design Definition*. https://sebokwiki.org/wiki/System_Architecture_Design_Definition. 2025.
- [12] INCOSE. *Systems Engineering Definition*. <https://www.incose.org/about-systems-engineering/system-and-se-definitions/systems-engineering-definition>. 2019.
- [13] Lisa Marion. *ASNE 2023 Technology Systems and Ships Is It Time for Ship Design to Align with Model-Based Systems Engineering?* Tech. rep. Nov. 2023.
- [14] 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”. PhD thesis. Delft University of Technology, 2024. URL: <https://repository.tudelft.nl/record/uuid:42c74b48-a4e7-4542-87ae-5320d11a027b>.
- [15] Lisa Marion and Daniel R Herber. *Aligning Ship Design and Model-Based Systems Engineering Methodologies*. Tech. rep. Colorado State University, Jan. 2024. URL: <https://www.researchgate.net/publication/384897178>.

- [16] *Ulstein Design & Solutions B.V.* Dec. 2025. URL: <https://ulstein.com/companies/ulstein-design-solutions-b-v>.
- [17] ReQi Systems Engineering. *What is Model-Based Systems Engineering (MBSE)?* <https://reqi.io/articles/what-is-model-based-systems-engineering-mbse>. 2023.
- [18] Starion Group. *Using MBSE in support of the Netherlands Maritime Master Plan*. <https://www.stariongroup.eu/using-mbse-in-support-of-the-netherlands-maritime-master-plan/>. 2024.
- [19] Tirtha Kaloor. *A MBSE framework for the design and analysis of marine vessel systems using SysML and PCE*. Tech. rep. Eindhoven University of Technology, Nov. 2023.
- [20] Apostolos Papanikolaou et al. “Ship Design in the Era of Digital Transition”. In: *International Marine Design Conference* (May 2024). DOI: 10.59490/imdc.2024.784.
- [21] Henrique M Gaspar, Alesund / Norway, and Henrique Gaspar@ntnu No. *Data-Driven Ship Design*. Tech. rep. Norwegian University of Science and Technology.
- [22] Anne Bouyssou, Raphaël Baumler, and Anna Öhrwall Rönnbäck. “COMPLEX SYSTEMS DESIGN: SUSTAINABILITY CHALLENGES FOR SHIPBUILDING”. In: *Proceedings of the Design Society*. Vol. 3. Cambridge University Press, 2023, pp. 1027–1036. DOI: 10.1017/pds.2023.103.
- [23] Nicolas Pelissero et al. *Towards modeling of naval systems interdependencies for cyber-security*. Tech. rep. URL: <https://www.theg.>
- [24] A. Ebrahimi et al. “AN APPROACH TO MEASURING SHIP DESIGN COMPLEXITY”. In: *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering* 163.A2 (Apr. 2021), A123–A143. ISSN: 17400716. DOI: 10.5750/ijme.v163iA2.763.
- [25] Jean David Caprace and Philippe Rigo. “Ship complexity assessment at the concept design stage”. In: *Journal of Marine Science and Technology* 16.1 (Mar. 2011), pp. 68–75. ISSN: 09484280. DOI: 10.1007/s00773-010-0107-9.
- [26] Henrique M Gaspar et al. *Handling Complexity Aspects in Conceptual Ship Design*. Tech. rep.
- [27] Steven M Rinaldi, James P Peerenboom, and Terrence K Kelly. *Identifying, Understanding, and Analyzing*. Tech. rep.
- [28] Hans Klein Woud and Douwe Stapersma. *Design of auxiliary systems, shafting and flexible mounting*. Delft University of Technology, Feb. 2016.
- [29] American Bureau of Shipping. *Guide for Dynamic Positioning Systems*. Tech. rep. 2024.
- [30] MarinePublic. *3 Classes of Dynamic Positioning (DP1, DP2, DP3) Systems*. <https://www.marinepublic.com/blogs/offshore/621256-3-classes-of-dynamic-positioning-dp1-dp2-dp3-systems>. MarinePublic.
- [31] *MSC.1/Circ.1580*. Tech. rep. International Maritime Organization, June 2017.
- [32] Tom Pedersen and Eilif Pedersen. “Bond graph modelling of marine power systems”. In: *Mathematical and Computer Modelling of Dynamical Systems* 18 (Apr. 2012), pp. 153–173. DOI: 10.1080/13873954.2011.603735.
- [33] Ulstein Design & Solutions B.V. *Ship Functional Identification*. 2026.
- [34] *Ship Marine Engineering Systems*. BoatsGeek. URL: <https://boatsgeek.com/ship-marine-engineering-systems/>.
- [35] *Vessel types*. June 2023. URL: <https://www.lerus.com/articles/vessels-type.html>.

- [36] Hans Klein Woud and Douwe Stapersma. *Design of propulsion and electric power generation systems*. Revised Edition. Institute of Marine Engineering, Science & Technology, 2019.
- [37] D Martinovi et al. *A Model of Ship Auxiliary System for Reliable Ship Propulsion*. Tech. rep. 2. 2012, pp. 125–134.
- [38] Kenneth J. Schlager. “Systems engineering-key to modern development”. In: *IRE Transactions on Engineering Management* EM-3.3 (1956), pp. 64–66. DOI: 10.1109/IRET-EM.1956.5007383.
- [39] Andres Sousa-Poza, Charles Keating, and Samuel Kovacic. “Systems engineering: evolution and challenges”. In: *International Journal of System of Systems Engineering* 5.4 (Jan. 2015), pp. 379–399. ISSN: 1748068X. DOI: 10.1504/IJSSE.2014.067104.
- [40] Hillary Sillitto et al. *Systems Engineering and System Definitions*. Tech. rep. 2019.
- [41] Mattia Bottero and Paola Gualeni. *Systems Engineering and Ship Design: a synergy for getting the right design and the design right*. Tech. rep.
- [42] Nicholas Shallcross. “Quantitative Set-Based Design for Complex System Development”. PhD thesis. July 2021.
- [43] By Kevin Forsberg. *The Relationship of System Engineering to the Project Cycle*. Tech. rep. 1994, pp. 9–11.
- [44] Mattia Bottero and Paola Gualeni. “Systems Engineering for Naval Ship Design Evolution”. In: *Journal of Marine Science and Engineering* 12.2 (2024). Open access, p. 210. DOI: 10.3390/jmse12020210. URL: <https://www.mdpi.com/2077-1312/12/2/210>.
- [45] GTPE Communications. *Model-Based Systems Engineering Fundamentals*. Georgia Tech Professional Education. Mar. 2025. URL: <https://pe.gatech.edu/blog/industry-trends/model-based-systems-engineering-fundamentals>.
- [46] Morayo Adedjouma et al. *From Document-Based to Model-Based System and Software Engineering Experience report of a selective catalytic reduction system development*. Tech. rep. 2016.
- [47] SEBoK (Systems Engineering Body of Knowledge). *Transitioning Systems Engineering to a Model-based Discipline*. 2025. URL: https://sebokwiki.org/wiki/Transitioning_Systems_Engineering_to_a_Model-based_Discipline.
- [48] Roger Kulläng. *Is There a Conflict Between ModelBased Systems Engineering and Modularization?* Blog post, Modular Management. Sept. 2023. URL: <https://www.modularrmanagement.com/blog/is-there-a-conflict-between-model-based-systems-engineering-mbse-and-modularization>.
- [49] Vincenzo Arrichiello and Paola 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* 14.1 (Mar. 2020), pp. 115–122. ISSN: 19552505. DOI: 10.1007/s12008-019-00621-3.
- [50] Fernando Aguado Agelet, Andr Es, and Eduardo Villa. *Part One Systems engineering applied to CubeSats*. Tech. rep.
- [51] Felix Förster et al. “Navigating viewpoints in MBSE: challenges, potential and pathways for stakeholder participation in industry”. In: *Proceedings of the Design Society*. Vol. 5. Cambridge University Press, Aug. 2025, pp. 2531–2540. DOI: 10.1017/pds.2025.10267.

- [52] Ebrahim Aly et al. “MBSE for robust decision support systems: A resilient, mission-centric reference model”. In: *Digital Engineering* 6 (Sept. 2025). ISSN: 2950550X. DOI: 10.1016/j.dte.2025.100044.
- [53] SPEC Innovations Team. *The Ultimate Guide to ModelBased Systems Engineering*. <https://specinnovations.com/blog/guide-to-model-based-systems-engineering>. 2025.
- [54] Francis Bordeleau. *Model-Based Engineering: A New Era Based on Papyrus and Open Source Tooling*. Tech. rep. URL: <http://www.ericsson.com>.
- [55] Object Management Group. *SysML v2 Tools*. 2024. URL: <https://www.omg.org/sysml/sysmlv2/sysml-tool/>.
- [56] MBSE4U. *MBSE Tools Overview*. 2024. URL: <https://mbse4u.com/mbse-tools/>.
- [57] Capella / Open Source MBSE Tool. Capella. URL: <https://mbse-capella.org>.
- [58] Hélder Castro. *Understanding what is the MBSE Arcadia method*. Apr. 2023. URL: <https://iexcelarc.com/model-based-system-engineering-with-arcadia/>.
- [59] Michael Jastram. *Capella and ARCADIA at Thales: Should tool and method be coupled?* June 2017. URL: <https://www.se-trends.de/en/capella-and-arcadia/>.
- [60] Claude Baron et al. “Using the ARCADIA/Capella Systems Engineering Method and Tool to Design Manufacturing Systems Case Study and Industrial Feedback”. In: *Systems* 11.8 (Aug. 2023). ISSN: 20798954. DOI: 10.3390/systems11080429.
- [61] Ahmed Abdul-kareem et al. “Advances in Decision Support Systems design aspects: architecture, applications, and methods”. In: *International Journal of Intelligent Computing and Information Sciences* 23.2 (June 2023), pp. 74–104. DOI: 10.21608/ijicis.2023.160460.1216.
- [62] Andrea Steiner and Austin Kana. *State of the art report on zero-emission shipping decision support systems*. Tech. rep.
- [63] Muhammad Syahid Hasan et al. *Jurnal Teknologi Full Paper DECISION SUPPORT SYSTEM CLASSIFICATION AND ITS APPLICATION IN MANUFACTURING SECTOR: A REVIEW*. Tech. rep. 2017, pp. 2180–3722. URL: www.jurnalteknologi.utm.my.
- [64] CFI Team. *Decision Support System (DSS) Overview, Components, Types*. URL: <https://corporatefinanceinstitute.com/resources/management/decision-support-system-dss/>.
- [65] The Decision Lab. *Decision Support Systems*. URL: <https://thedecisionlab.com/reference-guide/computer-science/decision-support-systems>.
- [66] Radek Silhavy and Petr Silhavy. *Lecture Notes in Networks and Systems 1120*. Tech. rep.
- [67] Jason Papathanasiou Pascale Zaraté and Jorge Freire de Sousa. *EURO Working Group on DSS: A Tour of the DSS Developments Over the Last 30 Years (Integrated Series in Information Systems)*. Tech. rep. URL: https://ntu-sp.primo.exlibrisgroup.com/discovery/fulldisplay/alma991016769056005146/65NTU_INST:65NTU_INST.
- [68] Water Knowledge Hub. *Decision Support Systems IWRM Tools*. 2023. URL: <https://waterknowledgehub.org/learn/iwrms-tools/decision-support-systems>.
- [69] Jacek. Baewicz. *Handbook on parallel and distributed processing*. Springer, 2000, p. 635. ISBN: 9783540664413.
- [70] Kirti Solanki. *Decision Support Systems / Components, functions, Characteristics, Advantages & Disadvantages*. Mar. 2025. URL: <https://www.toppers4u.com/2020/11/decision-support-systems-components.html>.

- [71] Eclipse-Capella. *GitHub - eclipse-capella/capella-sss-transition: System to Sub System transition add-on enables automated and iterative transition between system and subsystems*. URL: <https://github.com/eclipse-capella/capella-sss-transition>.
- [72] M A Tribe and R L W Alpine. *SCALE ECONOMIES AND THE "0.6 RULE"*. Tech. rep. 1986, pp. 271–278.
- [73] George Tsekouras and Fotis Kanellos. “Ship to shore connection Reliability analysis of ship power system”. In: Sept. 2016, pp. 2955–2961. DOI: 10.1109/ICELMACH.2016.7732944.
- [74] Andrey Ware and Matthew Collette. “Statistical reliability analysis of marine systems with varied levels of redundancy”. In: *International Marine Design Conference* (May 2024). DOI: 10.59490/imdc.2024.901.
- [75] Erik Vanem and Rolf Skjong. *Collision and Grounding of Passenger Ships-Risk Assessment and Emergency Evacuations*. Tech. rep. URL: <http://www.imo.org>.
- [76] Gard P&I. *Engine Room Fires are still a Major Concern*. Accessed: 2026-06-05. 2023. URL: <https://www.gard.no/en/insights/engine-room-fires-are-still-a-major-concern/>.
- [77] *Marine Control Systems*. SGN Marine. URL: <https://sgnmarine.com/marine-control-systems-pdf/>.
- [78] Spec Innovations. *LML Supports ALM*. 2025. URL: <https://specinnovations.com/blog/lml-supports-alm>.
- [79] Lifecycle Modeling Organization. *Why LML?* 2025. URL: <https://www.lifecyclemodeling.org/why-lml-lifecycle-modelign-language>.
- [80] Lifecycle Modeling Language Consortium. *Lifecycle Modeling Language (LML) Specification, Version 2.0*. Technical Specification. 2025. URL: <https://www.lifecyclemodeling.org/hubfs/LML%20Specification%20v2.0-1.pdf?hsLang=en>.
- [81] Innoslate. Spec Innovations. URL: <https://specinnovations.com/innoslate>.
- [82] *COMET Documentation for CDF*. URL: <https://comet.io.esa.int/>.
- [83] *CDP4-COMET User Manual*. Tech. rep. RHEA Group.
- [84] *POOSL / Early Validation by Simulation*. URL: <https://www.poosl.org/>.
- [85] *Parallel Object-Oriented Specification Language*. URL: <https://poosl.estue.nl/>.
- [86] TNO ESI. *POOSL*. URL: <https://esi.nl/research/output/tools/poosl>.
- [87] Jacob Harris. *How Eclipse POOSL enables early system validation*. June 2022. URL: <https://newsroom.eclipse.org/eclipse-newsletter/2022/june/how-eclipse-poosl-enables-early-system-validation>.
- [88] *SySON / The NextGen SYSML Modeling Tool*. URL: <https://mbse-syson.org/>.
- [89] Mélanie Bats. *Introducing methodology support for SYSMLV2 with SYSON*. May 2025. URL: <https://blog.obeosoft.com/introducing-methodology-support-for-sysmlv2-with-syson>.
- [90] *Eclipse Papyrus: Modeling environment*. Eclipse Foundation. URL: <https://eclipse.dev/papyrus/index.html>.
- [91] *Modelio Open Source - UML and BPMN free modeling tool*. Modelio. URL: <http://www.modelio.org/>.

-
- [92] Sensmetry. *Syside - enabling Digital twin*. Nov. 2025. URL: <https://sensmetry.com/products>.
- [93] Juozas Vaicenaviius et al. “SysIDE: SysML v2 textual editing and analysis system: overview and applications”. In: *CEAS Space Journal* (Feb. 2025). DOI: 10.1007/s12567-025-00595-x. URL: <https://doi.org/10.1007/s12567-025-00595-x>.

Dynamic Positioning Regulation

This appendix provides an overview of the IMO DP regulations relevant to this study, as defined in [31]. The listed requirements are included to clarify the functional and safety constraints that form the basis for the DP-related modelling assumptions used in the DSS.

A.1. Power System

DP1 For DP1, the power system need not be redundant.

DP2 For DP2, the power system should be divisible into two or more systems so that, in the event of failure of one sub-system, at least one other system will remain in operation and provide sufficient power for station keeping. The power system(s) may be run as one system during operation, but should be arranged by bus-tie breaker(s) to separate the systems automatically upon failures which could be transferred from one system to another, including, but not limited to, overloading and short circuits.

DP3 For DP3, the power system should be divisible into two or more systems so that, in the event of failure of one system, at least one other system will remain in operation and provide sufficient power for station keeping. The divided power system should be located in different spaces separated by A-60 class divisions. Where the power systems are located below the operational waterline, the separation should also be watertight. Bus-tie breakers should be open during DP3 operations unless equivalent integrity of power operation can be accepted according to paragraph 3.1.4.

A.2. Cables and Piping systems

DP2 For DP2, piping systems for fuel, lubrication, hydraulic oil, cooling water and cables should be located with due regard to fire hazards and mechanical damage.

DP3 For DP3, cables for redundant equipment or systems should not be routed together through the same compartments. Where this is unavoidable, such cables may run together in cable ducts of A-60 class, the termination of the ducts included, which are effectively protected from all fire hazards except that represented by the cables themselves. Cable connection boxes may not be provided within such ducts.

Redundant piping systems (e.g. piping for fuel, cooling water, lubrication oil, hydraulic oil, etc.) should not be routed together through the same compartments. Where this is unavoidable, such pipes may run together in ducts of A-60 class, the termination of the ducts included, which are effectively protected from all fire hazards except that represented by the pipes themselves.

A.3. Requirements for Essential Non-DP Systems

For DP2 and DP3, systems not directly part of the DP system, but which in the event of failure could cause failure of the DP system (e.g. common fire suppression systems, engine ventilation, heating, ventilation and air conditioning (HVAC) systems, shutdown systems, etc.), should also comply with relevant requirements of these Guidelines.

Excess Offshore Systems

This chapter describes the excess offshore vessel systems that are not part of the vessel systems architecture, but still impose constraints on the overall design. Although these systems are not the primary focus of the DSS, they influence available space, integration requirements, and overall vessel layout and must therefore be considered at a conceptual level during the ESSD phase [4].

B.1. Safety and Control Systems

Safety and control systems encompass the systems required to ensure both the protection of the vessel and its personnel, as well as the safe and efficient execution of vessel operations. This system group includes safety- and fire-related installations such as fire detection and alarm systems, fixed firefighting systems, the DP control system, lifeboats sized according to vessel capacity and regulatory requirements, and emergency shutdown systems. [77] In addition, it contains navigation and communication systems, including GPS, AIS, satellite communication, and gyro and magnetic compasses, which support safe navigation and operational awareness.

At the ESSD phase, these systems do not require detailed design, as they do not strongly drive overall system complexity. The complexity of these systems is primarily driven by structural factors, particularly the number and variety of safety features implemented. Consequently, they score medium in structural complexity, while decision-making and spatial complexity are low, as most design choices are standardised and the spatial requirements are relatively straightforward. Nevertheless, they must be considered at a conceptual level to ensure that sufficient space, interfaces, and integration provisions can be accommodated within the overall vessel layout and system architecture.

B.2. Hull Structure Systems

Hull structure systems encompass all components related to the vessel's hull [34]. This includes the plating and framing of the structure, as well as the arrangement of compartments, specifying which are watertight and which may include features such as moon pools for cable laying, ROV operations, or diving support.

The hull structure is a prime example of a physical interdependency, as it must provide the required space, deck strength, and structural support for all onboard systems. The watertightness of compartments is determined not only by safety requirements but also by operational needs, such as those imposed by DP systems.

This means that the complexity of hull structure systems is almost entirely driven by spatial considerations, as they must accommodate and connect all other systems within the vessel. Consequently, they score very high in spatial complexity. Structural and decision-making complexity are very low, as the hull design generally follows decisions made for the more complex systems and does not itself drive complexity.

B.3. Accommodation Systems

Accommodation systems encompass all systems required to provide a safe and habitable environment for the crew. These include living quarters, fresh water storage, and food provision facilities. While these systems are not major drivers of overall vessel complexity, they must still be considered in the design. In some offshore vessels, the need to transport large platforms or wind turbine components can constrain the available space for accommodations, influencing layout and capacity decisions. Therefore, they score only medium in spatial complexity.

Open-Source MBSE Frameworks

This appendix provides an overview of the MBSE frameworks considered in the trade-off analysis in Chapter 4. Its purpose is to support transparency of the framework selection process by briefly describing each candidate framework.

Capella is discussed in more detail in the main text due to its relevance for this study, while the other frameworks are presented in a more concise form as they serve mainly as comparison cases. The appendix concludes with the quantitative evaluation results used to rank the frameworks.

C.1. Innoslate

Innoslate makes use of Lifecycle Modelling Language (LML), which focuses on a balanced and stakeholder-friendly modelling framework with easy graphing and visualisation [78]. This simplicity can be highly beneficial for the ESSD phase [79], particularly in the maritime sector where many stakeholders are not systems engineering experts.

If a language becomes too complex, it may hinder meaningful stakeholder interaction, risking the loss of valuable input [79]. LML addresses this by providing intuitive visualisations, such as spider diagrams, to represent interdependencies between elements, improving system understanding and traceability.

Given the limited MBSE experience within the maritime sector, starting with a language that is easy for all stakeholders to understand can promote early involvement and improve communication. Furthermore, LML is designed to be extendable to other languages such as SysML, enabling a smooth transition toward more advanced modelling capabilities as project maturity and stakeholder familiarity increase [80].

Innoslate enables users to import or create requirements, model complex systems, execute simulations, track issues, and manage projects [81]. Collaboration is supported through a built-in real-time group chat. Data can be imported from documents such as Word files, Excel spreadsheets, or plain text files. Innoslate is a commercial tool but is available with open access for academic purposes and operates via a web browser, requiring no installation.

C.2. COMET

CDP4-COMET, which stands for CONcurrent Model-Based Engineering Tool [82], emphasises parallel and collaborative working. It offers a free community edition that can be used as either

a desktop or web application and includes an Excel add-in. The tool is relatively easy to learn, which is advantageous for the maritime sector, where familiarity with MBSE is often limited.

COMET promotes reusability by supporting modular model development, enabling naval architects to reuse previously developed solutions across different projects. In addition, it can be integrated with tools such as Capella and MATLAB, increasing flexibility and facilitating transitions or collaboration between different MBSE frameworks [83].

The framework provides a wide range of functionalities, including engineering models, product trees, reference data libraries, Python scripting, requirement creation and linking, custom report generation, and diagram-based creation and editing of relationships and interfaces.

However, [6] concludes that COMET performs particularly well in the later design stages. This makes it less suitable as a primary tool for the ESSD phase, although it remains relevant as a complementary tool, for example when Capella is selected as the main MBSE framework.

C.3. POOSL

POOSL [84], which stands for Parallel Object-Oriented Specification Language, is an open-source framework developed by Eindhoven University of Technology [85] and TNO-ESI [86]. It was developed to support the exploration activities of (naval) architects in the early phases of complex system development, including the ESSD phase [86, 87].

The framework provides both textual and visual representations of the system. When modelling a system, changes made in either representation are automatically reflected in the other, ensuring consistency. This enables the creation of interactive models and allows systems to be analysed immediately once all components are defined [87].

During modelling, a debugging view is available to identify and resolve errors in a structured manner, reducing the time spent searching for mistakes. In addition, the visualisation of relationships between subsystems improves traceability [84]. POOSL can also be integrated into Capella, allowing models to be reused when transitioning to another MBSE framework [87].

C.4. SysON

SysON [88] is an open-source, web-based MBSE framework based on SysML v2. As it operates through a web browser, no installation is required. The stated goal of SysON is "to provide system engineers with super easy access to this new standard, at minimal cost and great ease of use, with the guarantee of interoperability with other open-source MBSE tools, notably Capella and Papyrus" [88].

SysON offers various visualisation options, including general system visualisation and interconnection views that enable improved analysis of interdependencies. It also provides model libraries in which standard elements commonly used in the ESSD phase can be stored and reused. In addition, textual import and export tools allow users to access required documents and generate outputs when needed. SysON includes specialised graphical editors, allowing each engineering task to be supported by its own dedicated visual view [89].

Despite these capabilities, SysON is still under active development and is not yet intended for production use [88]. For example, basic functionalities such as undo and redo operations and copy-and-paste actions within diagrams are not yet supported. These limitations must be taken into account during the selection process.

C.5. Papyrus

Eclipse Papyrus [90] is an industrial-grade open-source MBSE framework that uses standards-based languages such as UML and SysML. The tool is fully customisable, allowing it to be tailored to specific domains and organisational practices.

This high degree of customisation makes it possible to design an MBSE framework specifically for the ESSD phase and aligned with Ulstein's practices. However, achieving this would require substantial effort and expertise in MBSE. As Ulstein primarily employs naval architects, this could introduce challenges and require significant time and resources to develop and maintain an effective modelling environment.

Papyrus supports system visualisation through diagrams, tables, and textual representations, facilitating collaboration during the ESSD phase. In addition, it enables document generation and the use of model views, which can reduce the time spent producing static documentation and support naval architects in their daily workflows [54].

C.6. Modelio

Modelio [91] is an open-source modelling environment that supports SysML, BPMN, and ArchiMate, providing a workspace for developers, analysts, and software and systems architects.

BPMN (Business Process Modelling Notation) focuses on providing a structured and graphical means of describing organisational processes. ArchiMate similarly addresses the business domain but places stronger emphasis on business construction and operational processes, organisational structures, information flows, IT systems, and technical infrastructure.

As the focus of this study is on improving the quality of decision-making by naval architects during the ESSD phase, BPMN and ArchiMate are not considered relevant for further analysis.

C.7. SysIDE

SysIDE [92] is a SysML v2-based modelling and analysis framework that is available in both open-source and commercial versions. It operates as an extension within the Visual Studio Code (VS Code) environment and focuses on textual system modelling.

By operating within VS Code, SysIDE can leverage built-in AI support, enabling naval architects to receive assistance during system modelling and decision-making in the ESSD phase. This integration with a known environment with AI support can lower the barrier to entry for technically oriented users.

However, SysIDE has several limitations. The free version is restricted to textual modelling and does not support system visualisation, making it more difficult for stakeholders who are not directly involved in modelling to understand the system. In addition, elements cannot be assigned unique identifiers, which reduces traceability. The absence of unique IDs, combined with the possibility of cyclical inheritance and cyclical source file dependencies, increases the risk of errors. Furthermore, the ability to express the same concept in multiple ways reduces structural consistency and increases the likelihood of modelling errors [93].

C.8. MBSE Evaluation Results

Below in Table C.1 and Figure C.1 the results of the trade-off analysis are shown. The frameworks are ranked in descending order based on their total scores. Papyrus, Modelio, and SysIDE are considered infeasible, as each received a score of 1 on at least one evaluation criterion, indicating that they fail to satisfy the minimum requirements for an ESSD environment suitable for naval architects.

Table C.1: Trade-off Table for MBSE Frameworks against Evaluation Criteria

MBSE Framework	D1	D2	W1	W2	W3	W4	Total
Capella	5	5	4	5	3	3	4.25
Innoslate	5	4	5	4	3	4	4.20
COMET	4	4	4	2	5	5	4.00
POOSL	3	4	3	4	3	4	3.50
SysON	4	3	2	3	4	4	3.35
Papyrus	4	4	1	4	5	4	3.70
Modelio	3	3	3	1	3	3	2.70
SysIDE	1	1	3	3	4	2	2.20

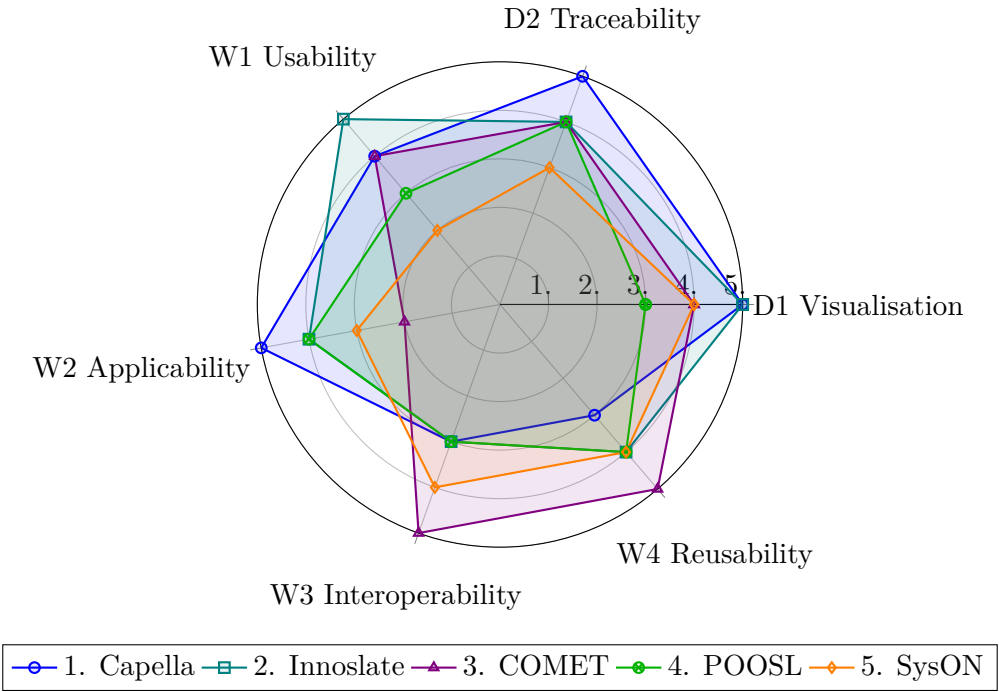


Figure C.1: MBSE Frameworks Comparison and Ranking against Evaluation Criteria

APPENDIX D

Capella JSON File

This appendix presents an example of the JSON input file extracted from the Capella model and used as input for the DSS. The file contains the system properties and requirements that define the vessel configuration, and serves as the bridge between the MBSE and the DSS.

Listing D.1: Example of a Capella JSON file used as input for the DSS

```
1 { "requirements": [
2   { "name": "DP2", "text": null }
3 ],
4   "properties": [
5     { "element": "Engine_Room", "property": "#_of_Engine_Rooms", "value": "2"},
6     { "element": "Engine_Room", "property": "Engine_Room_Location", "value": "bow,_bow"},
7     { "element": "Engine_Room", "property": "#_of_Engines", "value": "6"},
8     { "element": "Engine_Room", "property": "#_of_Generators", "value": "6"},
9     { "element": "Engine_Room", "property": "Engine_Power_[MW]", "value": "6.45"},
10    { "element": "Engine_Room", "property": "SWB", "value": "1A,_1B,_1C,_2A,_2B,_2C"},
11
12    { "element": "Power_Electronics", "property": "#_of_Switchboards", "value": "6"},
13    { "element": "Power_Electronics", "property": "#_of_Main_Switchboards", "value": "2"},
14
15    { "element": "Mission_Systems", "property": "#_of_Mission_Equipment", "value": "2"},
16    { "element": "Mission_Systems", "property": "Mission_Power_[MW]", "value": "4.4"},
17    { "element": "Mission_Systems", "property": "Mission_Location", "value": "bow,_stern"},
18    { "element": "Mission_Systems", "property": "SWB", "value": "1B,_2B"},
19
20    { "element": "BESS", "property": "#_of_BESS", "value": "2"},
21    { "element": "BESS", "property": "BESS_Power_[MWh]", "value": "2.5"},
22    { "element": "BESS", "property": "BESS_Location", "value": "bow,_stern"},
23    { "element": "BESS", "property": "SWB", "value": "1C,_2B"},
24
25    { "element": "Tunnel_Thruster", "property": "#_of_Thrusters", "value": "3"},
26    { "element": "Tunnel_Thruster", "property": "Thruster_Power_[MW]", "value": "3.5"},
27    { "element": "Tunnel_Thruster", "property": "Thruster_Location", "value": "bow,_bow,_bow"},
28    { "element": "Tunnel_Thruster", "property": "Thruster_SWB", "value": "1A,_1C,_2C"},
29
30    { "element": "Propulsion_Thruster", "property": "#_of_Thrusters", "value": "4"},
31    { "element": "Propulsion_Thruster", "property": "Thruster_Power_[MW]", "value": "3.3"},
32    { "element": "Propulsion_Thruster", "property": "Thruster_Location", "value": "stern,_stern,_stern,_stern"},
33    { "element": "Propulsion_Thruster", "property": "Thruster_SWB", "value": "1A,_1B,_2B,_2C"},
34
35    { "element": "Retractable_Thruster", "property": "#_of_Thrusters", "value": "2"},
36    { "element": "Retractable_Thruster", "property": "Thruster_Power_[MW]", "value": "2.4"},
37    { "element": "Retractable_Thruster", "property": "Thruster_Location", "value": "bow,_bow"},
38    { "element": "Retractable_Thruster", "property": "Thruster_SWB", "value": "1B,_2B"},
39
40    { "element": "Azipod", "property": "#_of_Thrusters", "value": "0"},
41    { "element": "Azipod", "property": "Thruster_Power_[MW]", "value": ""},
42    { "element": "Azipod", "property": "Thruster_Location", "value": ""},
43    { "element": "Azipod", "property": "Thruster_SWB", "value": ""}
44 ] }
```

Cost Assessment Model Example

This appendix provides a further explanation of the cost assessment model. Section E.1 presents the assumed cost ranges for valves, instruments, equipment units, and other system elements. Section E.2 defines the required number of valves and instruments per equipment unit. Finally, Section E.3 and Section E.4 describe how these costs scale with a given system cooling load at both cluster and pump room level.

E.1. Cost database

Below in Table E.1, the assumed cost ranges for valves, instruments, equipment units, and infrastructure elements are shown. These values are based on engineering judgement and representative industry ranges for offshore cooling systems. This introduces a degree of uncertainty, and it can be argued that including valve and instrumentation costs in the overall cost evaluation may have limited impact due to their relatively small contribution. Although this enables Ulstein to integrate company-specific cost parameters, it introduces a trade-off between model flexibility and predictive accuracy, as the use of broad representative industry ranges increases uncertainty in the resulting cost estimates.

Table E.1: Piping and the reference cost for 20 cooling load for components, equipment units, and infrastructure elements.

	C_{piping} [EUR]	C_{ref} [EUR]
<i>Valves & Instruments</i>		
Butterfly valve	-	800
Butterfly valve (LT)	-	1 500
NR valve	-	1 200
Pressure indicator	-	250
Pressure transmitter	-	1 200
Temperature indicator	-	200
Temperature transmitter	-	1 000
Mud box	-	3 000
<i>Equipment units</i>		
FW pump unit	5 000	20 000
SW pump unit	8 000	35 000
PHE unit	10 000	45 000
Sea chest unit	5 000	15 000
Overboard unit	2 000	3 000

	C_{piping} [EUR]	C_{ref} [EUR]
<i>Other</i>		
Pump room cost	25 000	50 000
Cluster cost	-	30 000

E.2. Component composition database

To support the cost estimation at component level, a configuration database is defined that specifies the required number of valves, instruments, and auxiliary components per equipment unit. This ensures consistency in the cost build-up across different system configurations. The numbers were developed based on previous cooling system diagrams developed by Ulstein.

Equipment unit	Required components
FW pump	Butterfly valve $\times 2$ NR valve $\times 1$ Pressure indicator $\times 2$
SW pump	Butterfly valve $\times 2$ NR valve $\times 1$ Pressure indicator $\times 2$ Pressure transmitter $\times 1$
PHE	Butterfly valve $\times 6$ Pressure indicator $\times 3$ Temperature indicator $\times 4$ Temperature transmitter $\times 3$
Overboard	Butterfly valve (LT) $\times 1$ NR valve $\times 1$
Sea chest	Butterfly valve $\times 1$ Butterfly valve (LT) $\times 1$ NR valve $\times 1$ Mud box $\times 1$

Table E.2: Component composition per equipment unit used for cost estimation.

E.3. Cluster cost scaling and load sensitivity

Below, Figure E.1a shows the total cluster cost as a function of cooling load, and Figure E.1b in percentages. In this analysis, each component within the cooling cluster chain is assumed to consist of a single unit. This assumption is made to provide an intuitive baseline for illustrating relative cost scaling behaviour with increasing cooling demand, rather than representing a full system configuration.

The purpose of these figures is therefore to provide insight into the cost sensitivity of individual components, isolating the effect of load-dependent sizing effects. It should be noted that configurations with multiple duty units do not result in a proportional increase in cost.

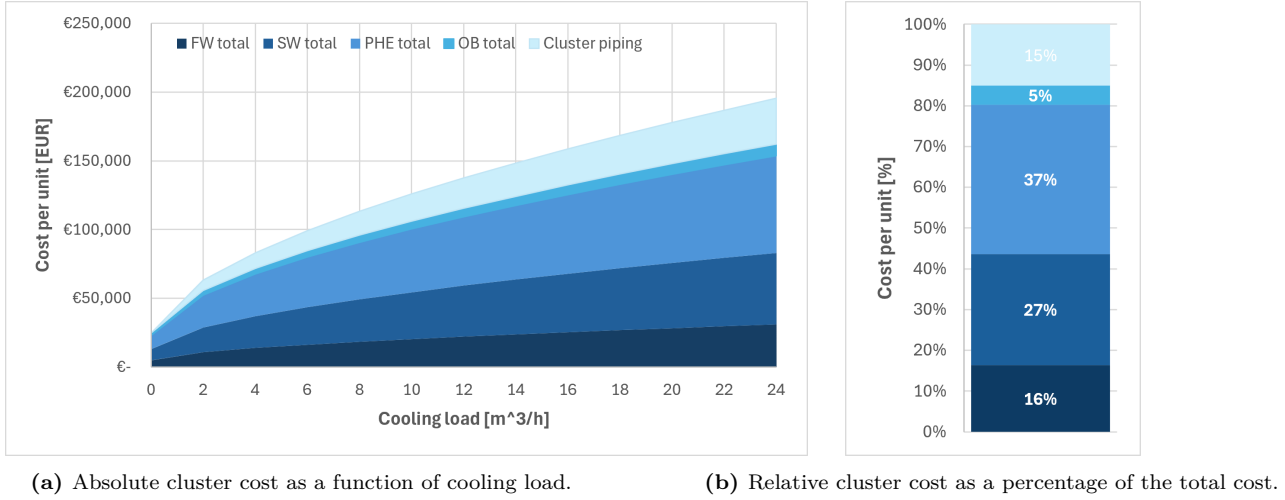


Figure E.1: Relationship between cooling load and the estimated cluster cost for clusters containing a single operating unit, shown as (a) absolute cost and (b) percentage contribution to the total cost.

To quantify the non-proportional cost behaviour of multi-duty configurations, a simplified comparison is made for a FW pump cluster with a total cooling load of:

$$f_{load} = P \cdot L = 1.3 + 2 \cdot 1.25 + 0.825 = 4.625 \quad [m^3/g]$$

For a single FW pump configuration the resulting cost of a FW pump is:

$$C_{1,FW} = 5,000 + 20,000 \cdot \frac{4.625^{0.6}}{20} = 13,308 \quad \text{EUR}$$

For a two-pump configuration, the load is distributed equally ($\frac{1}{2}P \cdot L \approx 2.312$ per pump), giving:

$$C_{2,FW} = 5,000 + 20,000 \cdot \frac{2.312^{0.6}}{20} \cdot 2 = 20,986 \quad \text{EUR}$$

This corresponds to a cost increase of 51.9% compared to the single-pump configuration, demonstrating that introducing additional duty units leads to non-proportional cost growth due to both fixed cost duplication and non-linear load-dependent scaling. Although smaller FW units are cheaper individually, multiple units are required and additional piping is needed within the cluster, which increases the total cost. This effect is visible in Figure E.1a, where even at a cooling load factor of zero, a non-zero cost remains due to baseline infrastructure and piping requirements.

Figure E.2 illustrates the relative cost increase associated with different duty/backup redundancy configurations for FW pumps, using the [1;0] duty/backup configuration as the reference. The costs include not only the pumps themselves but also the associated valves and instrumentation. Although SW pumps and PHE units exhibit a similar trend, their absolute costs differ due to variations in equipment, valve arrangements, and instrumentation requirements. The figure further demonstrates that, from a cost perspective, installing the largest feasible pump units is generally the most economical solution. However, increasing unit size also increases the potential impact of a single failure. Therefore, these cost trends must be evaluated together with the DP capability risk calculations to determine the most suitable redundancy configuration. The resulting cost relationships form one of the inputs to the MBSE-DSS during the multi-objective evaluation.

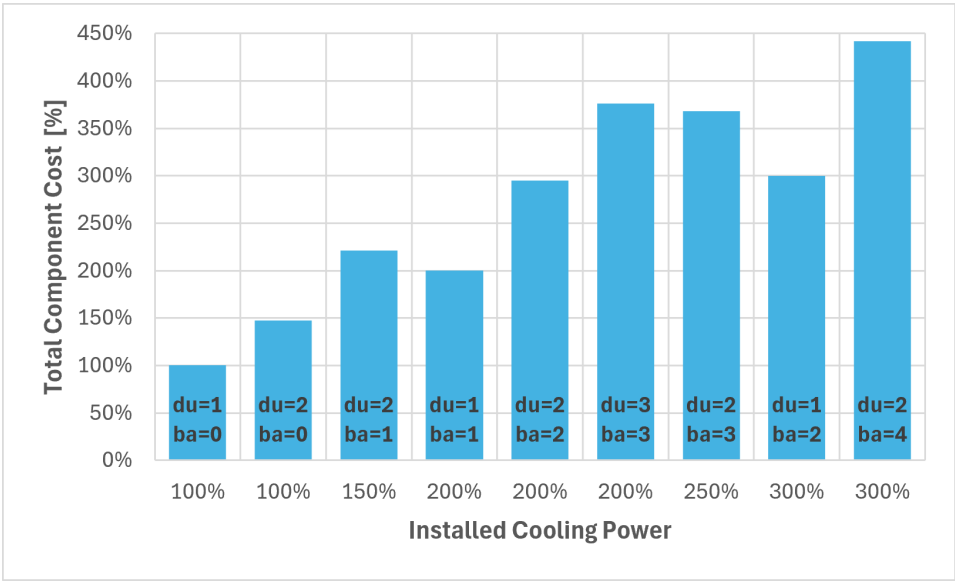


Figure E.2: Relative cost increase of FW pump duty/backup redundancy configurations with respect to the [1;0] duty/backup reference configuration.

E.4. Pump room cost scaling

Below, Figure E.3 shows the total pump room cost as a function of cooling load. In this figure, the cooling loads appear higher because the pump room cost is based on the sum of all clusters within the pump room. In addition to the pump room cost, the sea chest cost is also included, since each sea chest provides seawater supply to all cooling clusters within a pump room. As a result, the sea chests are functionally shared by all clusters connected to that pump room, making their number dependent on the pump room rather than on the number of individual clusters. Each pump room contains two sea chests to ensure redundancy and continuous seawater intake capacity, independent of the number of clusters assigned to that pump room, as defined by Ulstein.

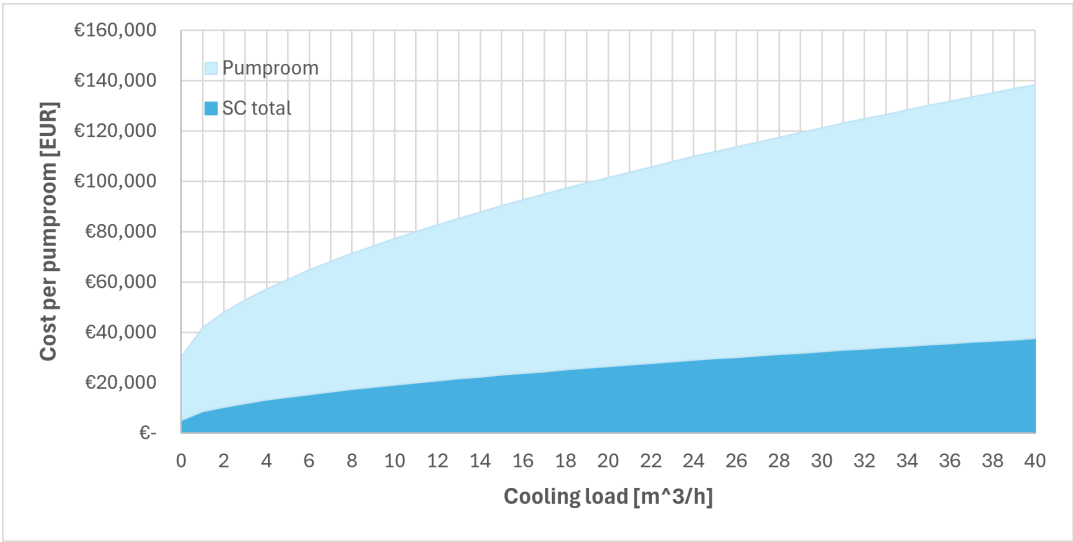


Figure E.3: Total pump room cost as a function of cooling load

DP Risk Assessment Model Example

This appendix provides a more detailed explanation of the DP risk model. Section F.1 illustrates the redundancy configurations for the FW/SW and PHE subsystems across various duty and backup combinations, providing insight into the behaviour of the risk model and the configurations with the greatest potential to improve DP performance.

In addition, a visualisation of the pump room risk is presented to demonstrate its relatively low contribution, which was one of the key motivations for treating pump room risk separately from cluster risk. Section F.2 presents a detailed application of the DP risk model to a specific pump configuration from the Reference Vessel S case study, illustrating how both cluster and pump room risks are calculated.

F.1. Effect of Redundancy on DP Performance

To illustrate the behaviour of different redundancy configurations, Figure F.1 shows the expected DP performance for the freshwater pump subsystem. Note that the same behaviour applies to the seawater pumps because both use identical MTBF values in this case. In this context, α represents the DP contribution of the subsystem. A value of $\alpha = 0.2$ indicates that loss of the subsystem reduces DP capability to 80%, whereas $\alpha = 1.0$ corresponds to complete loss of DP capability. This demonstrates that increasing redundancy has a stronger effect for more critical subsystems with higher α values.

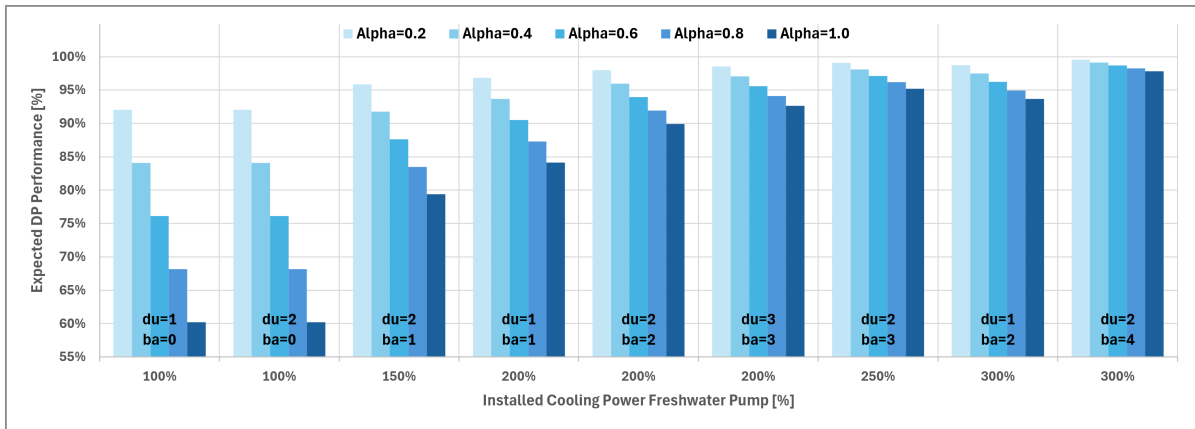


Figure F.1: Expected DP performance of the freshwater pump subsystem, where du = denotes the number of duty pumps and ba = the number of backup pumps.

For the plate heat exchangers, the expected DP performance shows less variation compared to the freshwater and seawater pumps, as shown in Figure F.2. This is mainly due to their higher MTBF. As a result in combination with the high costs, fewer design options were considered for the PHE subsystem compared to the SW and FW systems.

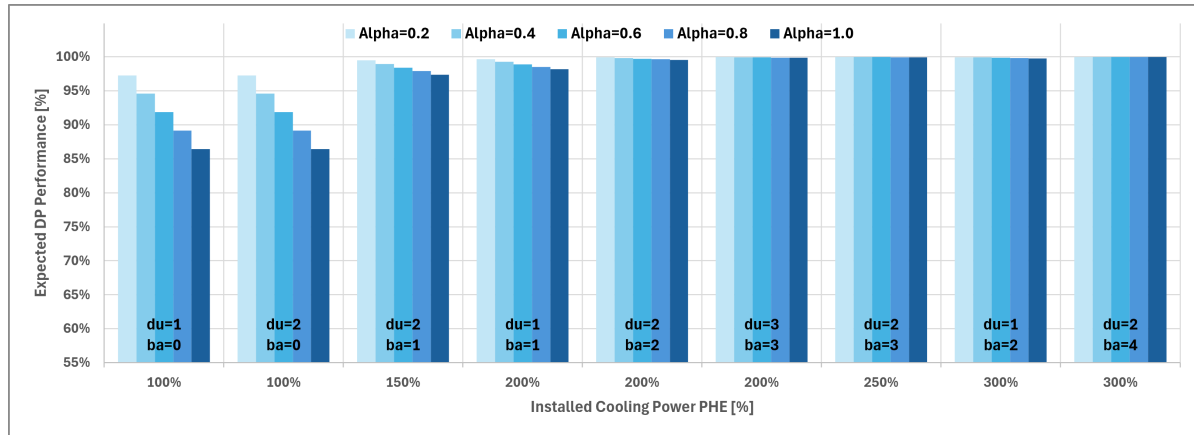


Figure F.2: Expected DP performance of the plate heat exchanger subsystem, where du = denotes the number of duty PHE units and ba = the number of backup PHE units.

To illustrate the behaviour of pump room configurations, Figure F.3 shows the expected DP of a pump room as a function of α . As can be observed, the risk shows a linear behaviour with a minimum value of 99.985% in the case of complete DP loss due to compartment failure. This occurs, for example, when a pump room contains all gensets or all stern or bow thrusters. This shows that due to the low probability contribution of the pump room risk, simply summing the cluster and pump room risks would make the pump room contribution nearly negligible in the total risk.

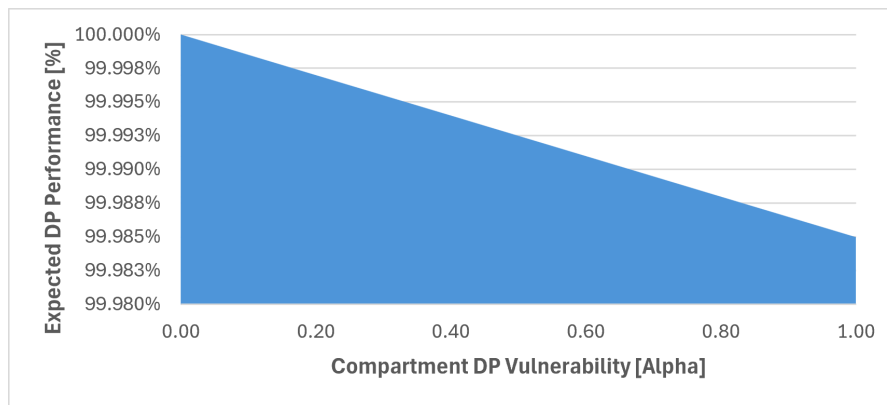


Figure F.3: Expected DP performance of a pump room

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS110

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS

This example focuses on configuration CFG_B4_S2_M0_RS, which corresponds to the best-performing solution identified in the basic study. The reported results are:

- Cluster risk: $R_{\text{tot,cluster}} = 17.711\%$
- Pump room risk: $R_{\text{tot,pump room}} = 0.015\%$

The following steps illustrate how these values are obtained.

F.2.1. Step 1: Failure probabilities

For an exposure period of $t = 1$ year, the failure probability is:

$$p_i(t) = 1 - e^{-t/MTBF} \quad (\text{F.1})$$

This yields:

$$\begin{aligned} p_{\text{FW}} &= 1 - e^{-1/1.97} = 0.397 \\ p_{\text{SW}} &= 1 - e^{-1/1.97} = 0.397 \\ p_{\text{PHE}} &= 1 - e^{-1/6.85} = 0.136 \\ p_{\text{flood}} + p_{\text{fire}} &= 1 - e^{-1/10^5} + 1 - e^{-1/2 \cdot 10^5} \approx 1.5 \cdot 10^{-4} \end{aligned}$$

F.2.2. Step 2: Example cluster calculation

Consider **Cluster 1** in PR1_ER:

Listing F.1: Room PR1_ER (tag: ER) | SC 2

```
- Cluster 1: tunnel(bow SWB=1A), retractable(bow SWB=1B), aux, aux
SW 1+1 | PHE 1+0 | FW 2+2 | OB 1
```

$$SW : n = 2, req = 1 \quad PHE : n = 1, req = 1 \quad FW : n = 4, req = 2$$

Assume cluster DP contribution:

$$\alpha_{\text{cluster}} = 0.50$$

FW subsystem

$$E_{\text{FW}} = \sum_{k=0}^4 \binom{4}{k} p^k (1-p)^{4-k} \cdot DP(k) \quad (\text{F.2})$$

With:

$$DP(k) = 1 - \alpha \left(1 - \frac{n-k}{req} \right)$$

Evaluating terms:

$$\begin{aligned} k = 0, 1, 2 : DP &= 1.0 \\ k = 3 : DP &= 1 - 0.50 \left(1 - \frac{1}{2} \right) = 0.75 \\ k = 4 : DP &= 0.50 \end{aligned}$$

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS111

Therefore:

$$\begin{aligned} E_{FW} &= (1-p)^4 \cdot 1 + 4p(1-p)^3 \cdot 1 + 6p^2(1-p)^2 \cdot 1 + 4p^3(1-p) \cdot 0.75 + p^4 \cdot 0.50 \\ &= (0.603)^4 + 4(0.397)(0.603)^3 + 6(0.397)^2(0.603)^2 + 4(0.397)^3(0.603)(0.75) + (0.397)^4(0.50) \\ &= 0.131 + 0.347 + 0.344 + 0.114 + 0.013 \\ &= 0.949 \end{aligned}$$

SW subsystem

$$E_{SW} = \sum_{k=0}^2 \binom{2}{k} p^k (1-p)^{2-k} \cdot DP(k) \quad (F.3)$$

Evaluating terms:

$$\begin{aligned} k=0 : \quad DP &= 1.0 \\ k=1 : \quad DP &= 1.0 \\ k=2 : \quad DP &= 1 - 0.50 = 0.50 \end{aligned}$$

Therefore:

$$\begin{aligned} E_{SW} &= (1-p)^2 \cdot 1 + 2p(1-p) \cdot 1 + p^2 \cdot 0.50 \\ &= (0.603)^2 + 2(0.397)(0.603) + (0.397)^2 \cdot 0.50 \\ &= 0.364 + 0.479 + 0.079 \\ &= 0.921 \end{aligned}$$

PHE subsystem

$$E_{PHE} = \sum_{k=0}^1 \binom{1}{k} p^k (1-p)^{1-k} \cdot DP(k) \quad (F.4)$$

Evaluating terms:

$$\begin{aligned} k=0 : DP &= 1.0 \\ k=1 : DP &= 0.50 \end{aligned}$$

Therefore:

$$\begin{aligned} E_{PHE} &= (1-p) + p \cdot 0.50 \\ &= 0.864 + 0.136 \cdot 0.50 \\ &= 0.932 \end{aligned}$$

Cluster risk

$$R_{\text{cluster},1} = 1 - (E_{FW} \cdot E_{SW} \cdot E_{PHE}) \quad (F.5)$$

$$\begin{aligned} R_{\text{cluster},1} &= 1 - (0.949 \cdot 0.921 \cdot 0.932) \\ &= 1 - 0.815 \\ &= 0.185 \end{aligned}$$

$$R_{\text{cluster},1} = 18.5\%$$

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS112

F.2.3. Step 3: Total cluster risk

The individual cluster risks are computed similarly for all six clusters. Clusters that have no direct relationship with the vessel's DP capability, such as clusters containing only mission systems, are excluded from the cluster risk calculation. Due to variations in cluster composition, installed redundancy, cooling loads, and DP contribution, each cluster results in a different risk score.

$$\begin{aligned} R_{\text{avg,cluster}} &= 16.9\% \\ R_{\text{worst,cluster}} &= 18.5\% \\ R_{\text{tot,cluster}} &= \frac{1}{2}(18.5 + 16.9) = 17.711\% \end{aligned} \tag{F.6}$$

F.2.4. Step 4: Pump room risk

The configuration consist only of two pump rooms:

$$PR1_ER \text{ (4 clusters)} \qquad PR2_STERN \text{ (2 clusters)}$$

Assuming:

$$\alpha_{PR1} = 1.0 \qquad \alpha_{PR2} = 1.0$$

PR1 & PR2 risk

$$\begin{aligned} R_{PR1} = R_{PR2} &= p(t) \cdot \alpha_{PR1} \\ &= 1.5 \cdot 10^{-4} \cdot 1.0 \\ &= 1.5 \cdot 10^{-4} \end{aligned}$$

Total pump room risk

$$\begin{aligned} R_{\text{avg}} &= 1.5 \cdot 10^{-4} \\ R_{\text{worst}} &= 1.5 \cdot 10^{-4} \\ R_{\text{tot,pump room}} &= \frac{1}{2}(1.5 + 1.5) \cdot 10^{-4} = 1.5 \cdot 10^{-4} \\ R_{\text{tot,pump room}} &\approx 0.015\% \end{aligned} \tag{F.7}$$

Overall, the results show that the system risk is strongly dominated by cluster-level subsystem failures, while the contribution of pump room related failure is negligible in comparison.

Numerical Verification and Sensitivity Checks

Verification is performed to ensure that the implemented models, calculations, and system logic behave in a consistent and technically correct manner. Since the MBSE-DSS integrates multiple modelling assumptions and introduces a structured approach for scoring cost and risk within cooling system architectures, it is essential to confirm the internal correctness and numerical stability of the underlying implementation.

G.1. Monte Carlo Analysis

To verify whether the MBSE-DSS behaves as intended and to assess the sensitivity of the decision-making process to modelling assumptions, a Monte Carlo analysis was performed. In this analysis, key model parameters and weighting factors were varied randomly within predefined bounds. A variation range of $\pm 50\%$ was selected, meaning that a parameter could assume values between 50% below and 50% above its baseline value. This relatively large range was chosen to ensure that the effect of parameters with small absolute values would remain visible in the resulting analysis. The parameters that were varied are shown below in Table G.1.

Table G.1: Varied parameters during Monte Carlo analysis

Parameter	Description
FW failure probability	Probability of failure for freshwater pump components.
SW failure probability	Probability of failure for seawater pump components.
PHE failure probability	Probability of failure for plate heat exchanger components.
Pump room failure probability	Probability of failure for pump rooms.
Backup cost scaling factor	Multiplier used to account for variable cost associated with backup units (standard = 1).
Pump room discount factor	Factor representing cost reduction effects due to repeatable pump room layout.
Maximum pump room discount	Upper bound limiting the cost reduction achievable through pump room aggregation.

Continued on next page

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS114

Table G.1 – Continued from previous page

Parameter	Description
Cost weight	Weighting factor determining the importance of cost in the multi-criteria decision model.
Cluster risk weight	Weighting factor determining the importance of cluster-level DP risk in the multi-criteria decision model.
Pump room risk weight	Weighting factor determining the importance of compartment-level DP risk in the multi-criteria decision model.
Auxiliary cooling factor	Fraction of thruster load assigned to auxiliary cooling demand.

By varying these parameters, different optimal cooling system configurations can be selected by the MBSE-DSS. Due to computational limitations, the analysis was performed on the Pareto front of the Reference Vessel L and a random sampling of 25,000 configurations rather than the complete design space. In total, 2500 Monte Carlo iterations were executed. This approach was necessary because a full evaluation of all configurations required approximately eight hours of computation time per run, making a complete 2000-run analysis impractical.

After completing the simulations, the relationships between the varied parameters and the resulting MBSE-DSS outputs were analysed using the Pearson correlation coefficient:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \quad (\text{G.1})$$

where:

- x_i and y_i are individual observations.
- $\bar{x}$ is the mean value of variable x .
- $\bar{y}$ is the mean value of variable y .

The Pearson correlation coefficient ranges from -1 to 1 . A value of -1 indicates a perfect negative correlation, while a value of 1 indicates a perfect positive correlation. Values close to zero indicate little or no linear relationship between the variables. The magnitude of the coefficient reflects the strength of the correlation.

Applying Equation G.1 to the Monte Carlo results yielded the correlation heatmaps shown in Figure G.1 and Figure G.2. The first only displays correlations with an absolute value greater than 0.2 in order to highlight the most influential relationships, while the second heatmap presents the complete correlation matrix.

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS115

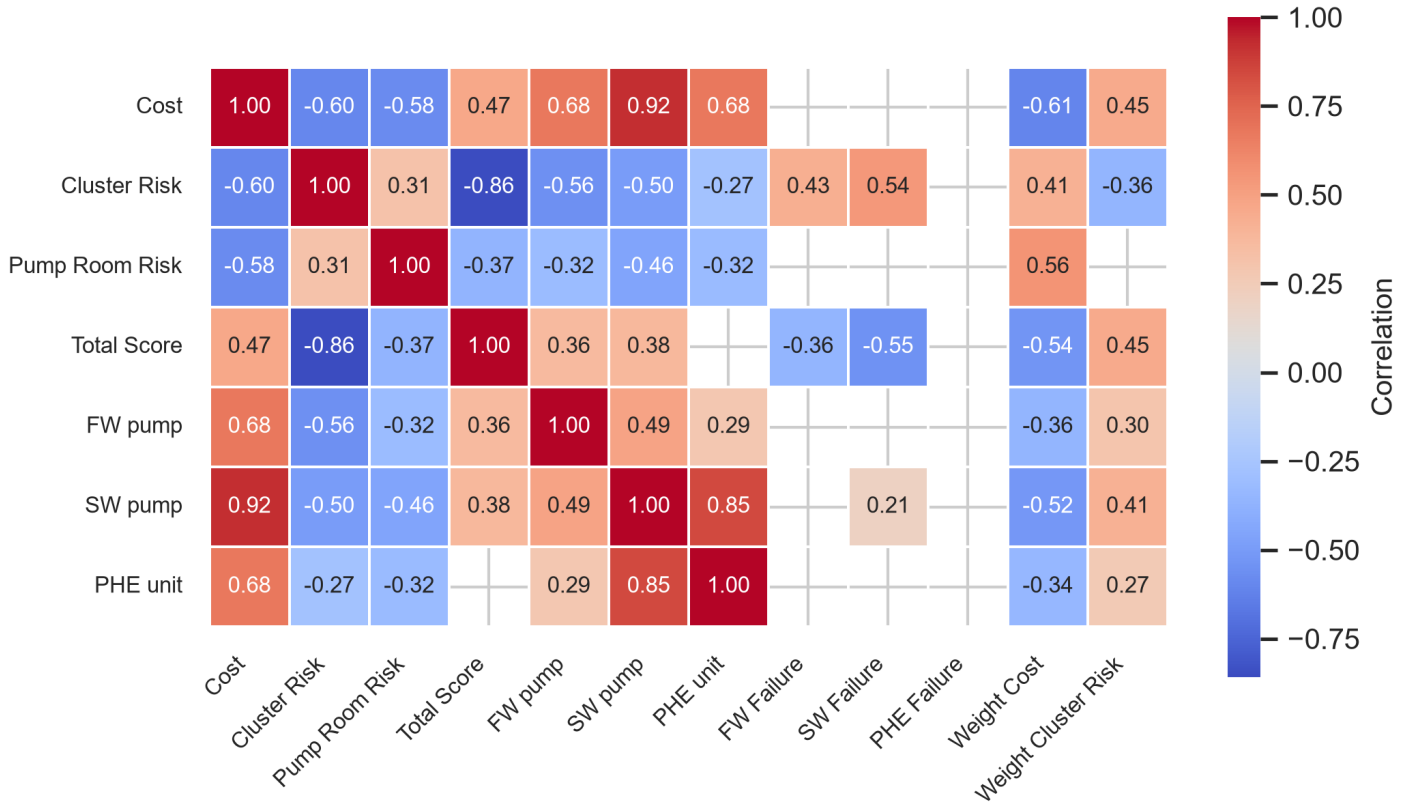


Figure G.1: Correlation between constants and parameters for vessel Reference Vessel S (only showing the $0.2 \leq |\text{correlation}|$)

As shown in Figure G.1, several conclusions can be drawn from the correlation analysis that are consistent with the underlying MBSE-DSS logic.

First, the cost score shows a positive correlation with redundancy-related parameters. Configurations with increased redundancy generally require more equipment, resulting in higher system costs. The SW pumps exhibit a stronger influence on cost than the FW pumps, despite having identical failure probabilities. This is explained by the higher unit cost of SW pumps, making redundancy additions more expensive.

For the cluster risk, both redundancy levels and component failure probabilities influence the resulting risk score. This behaviour is expected, as these parameters are directly incorporated into the risk model described in Subsection 6.4.2. In contrast, the pump room risk shows little correlation with component failure probabilities because it is determined by compartment-level vulnerability rather than component reliability.

An interesting observation is the negative correlation between pump room risk and the number of components. Increasing the weight or severity of pump room risk encourages the MBSE-DSS to favour configurations with fewer pump rooms and clusters. As a result, fewer component are required to distribute cooling capacity across the system.

For the number of FW pumps, the SW pump failure probability also exhibits a noticeable influence. This can be explained by the relative cost difference between FW and SW pumps. Since FW pumps are considerably less expensive, the optimisation process often favours adding additional FW redundancy to compensate partially for increased SW risk, rather than increasing

F.2. Risk Example: Calculation for CFG_B4_S2_M0_RS116

the number of SW pumps themselves.

For the PHE, the dominant influencing parameters is the SW pump failure probability. The influence of the PHE failure probability is also expected to be present, as it directly affects subsystem reliability. However, due to its relatively low failure rate and higher cost compared to the FW and SW systems, its impact is not clearly observable in the results. The influence of the SW pump failure probability is less obvious but can be explained by the series nature of the cooling chain. In many configurations, the SW pumps represent the highest-risk component due to their relatively high failure probability and cost. Consequently, when redundancy reduces the SW risk sufficiently, the PHE subsystem becomes the limiting factor in the cluster risk calculation, causing additional PHE units to be selected by the MBSE-DSS.

Below, Figure G.2 illustrates the correlation structure between the explored parameters and constants of the Reference Vessel S design case.

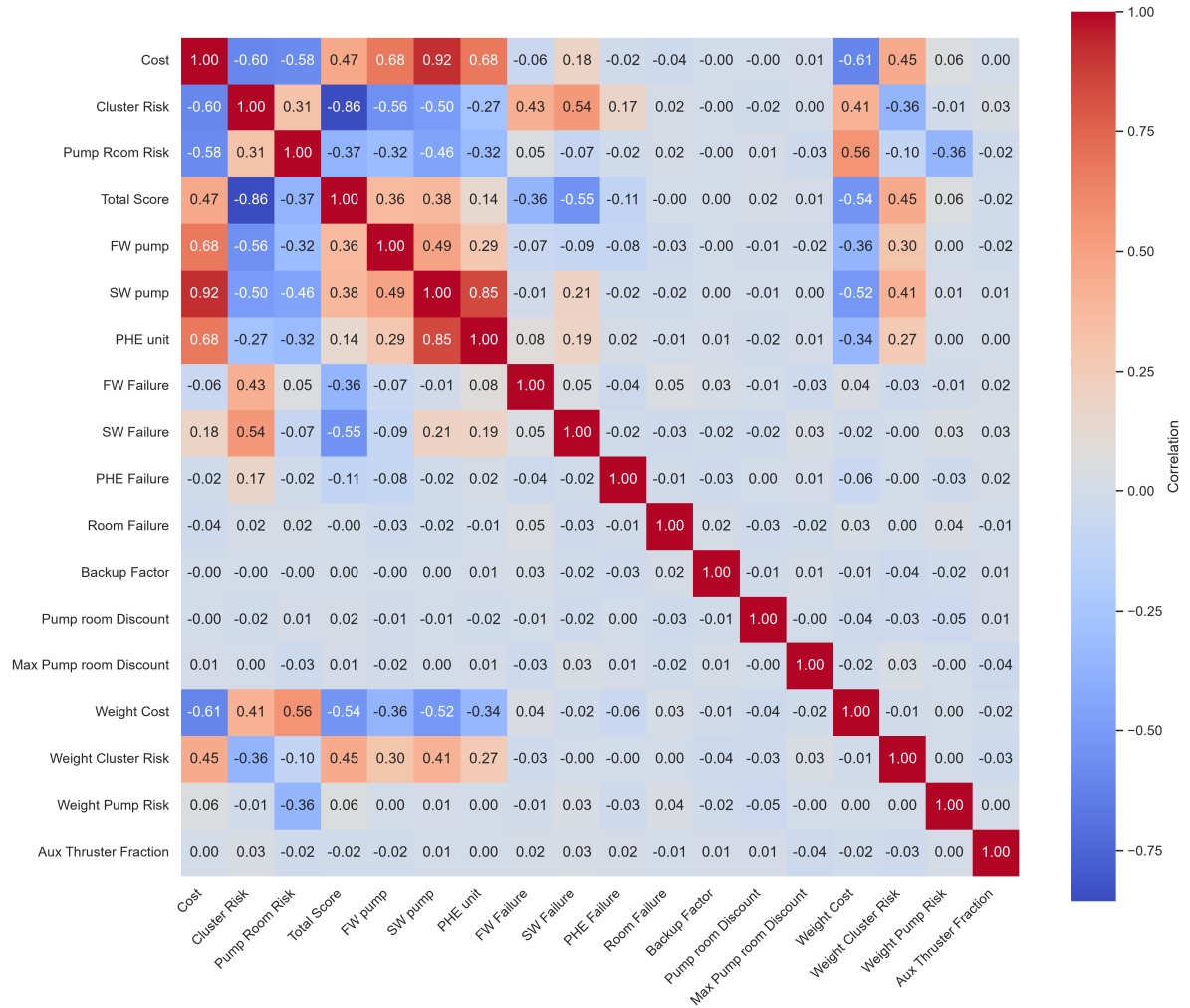


Figure G.2: Correlation matrix of parameters and constants for the Reference Vessel S case study

Objective Weighting Figures

Reference Vessel L

This appendix presents the results of the objective weighting sensitivity analysis. The figures illustrate how different weighting strategies influence the selected subsystem configurations for the Reference Vessel L case study. In particular, the effect on redundancy decisions for FW, SW, and PHE systems is shown, highlighting the robustness of the DSS outcomes with respect to changes in objective prioritisation.

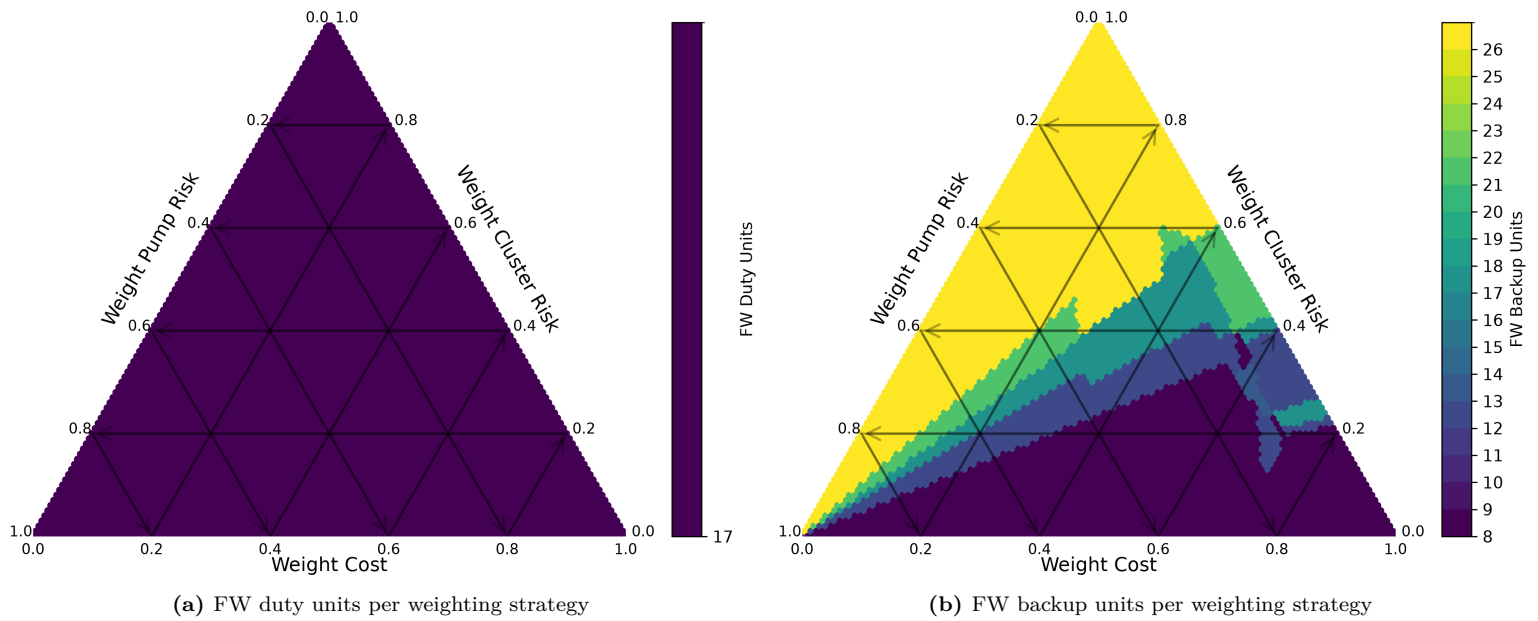
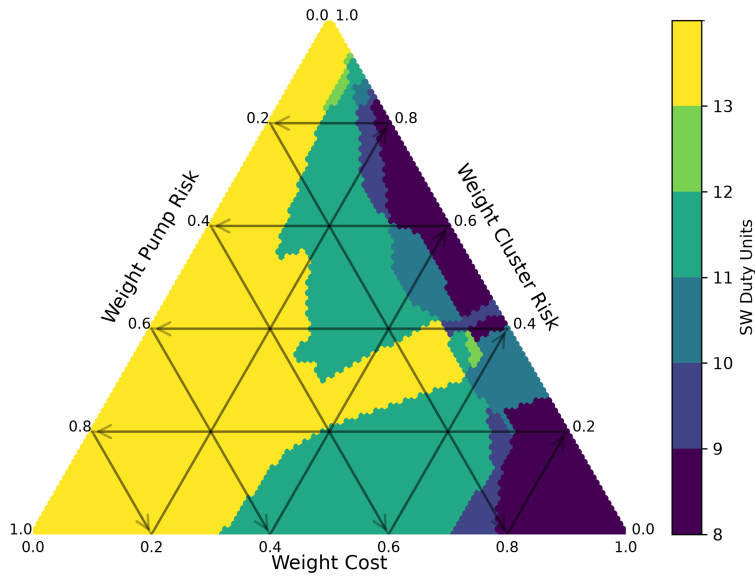
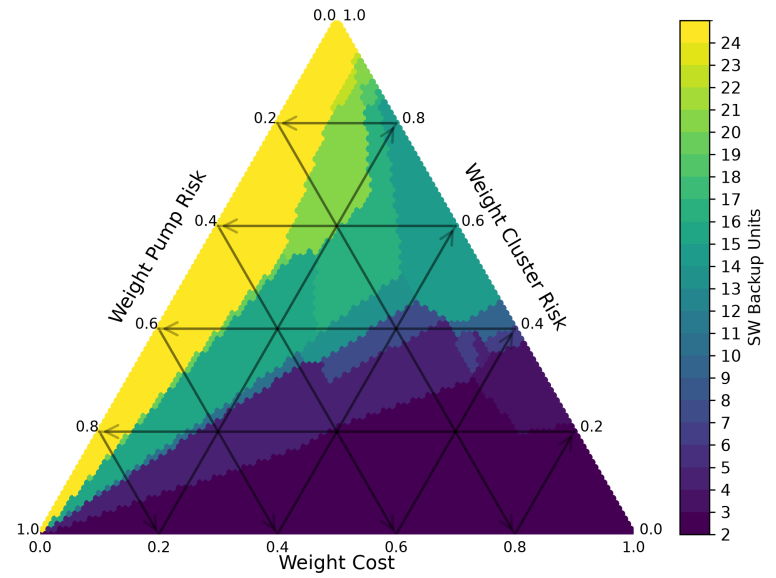


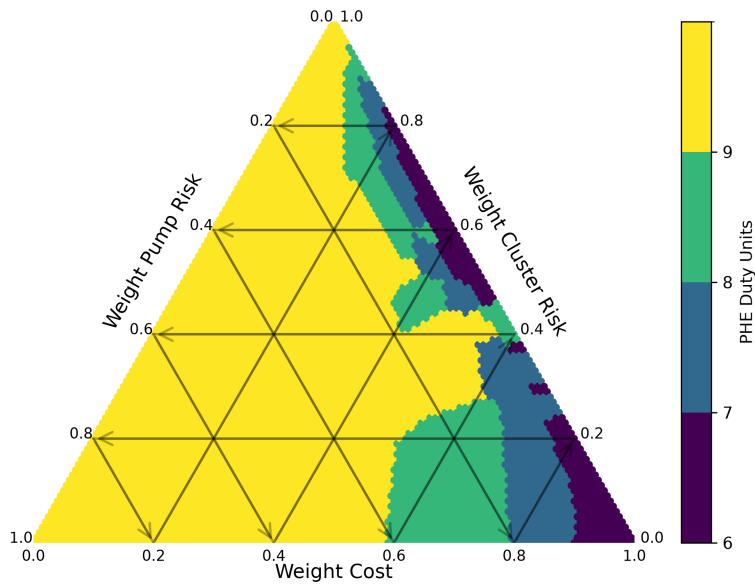
Figure H.1: (Reference Vessel L) Effect of objective weighting on FW pump redundancy configuration.



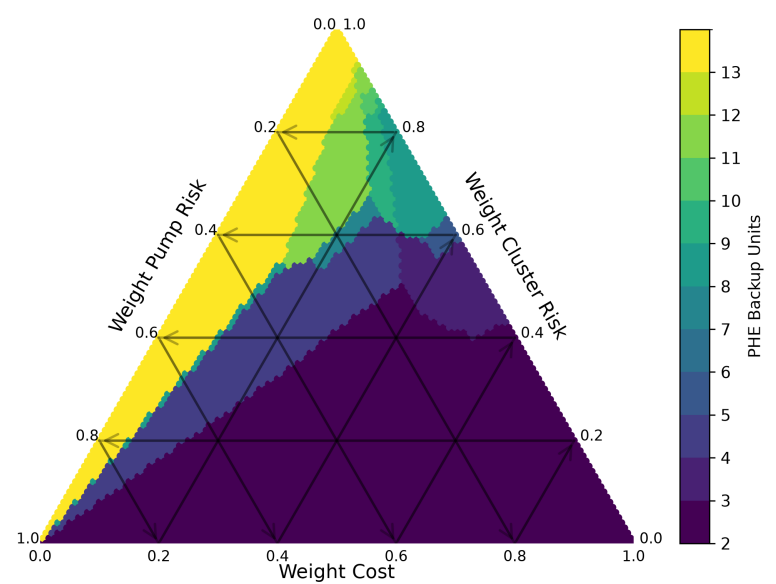
(a) SW duty units per weighting strategy



(b) SW backup units per weighting strategy

Figure H.2: (Reference Vessel L) Effect of objective weighting on SW pump redundancy configuration.

(a) PHE duty units per weighting strategy



(b) PHE backup units per weighting strategy

Figure H.3: (Reference Vessel L) Effect of objective weighting on PHE subsystem redundancy configuration.